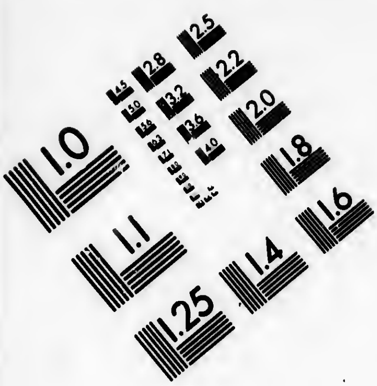

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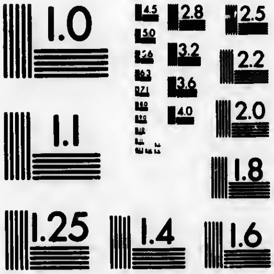

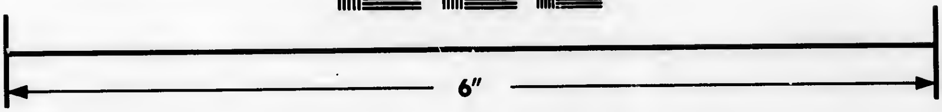

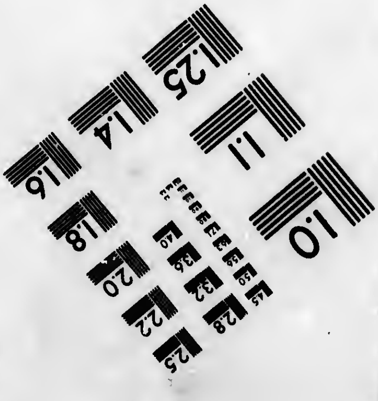

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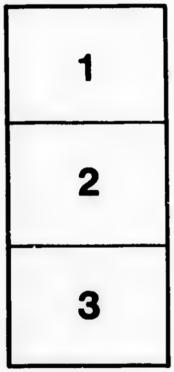

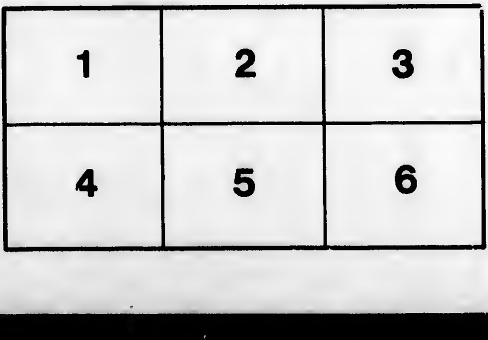

BY THE SAME AUTHOR.

CHEMICAL AND GEOLOGICAL ESSAYS.

Second Revised Edition, with a New Preface;
pp. xlvi. and 489; 8vo.

IN PREPARATION:

MINERALOGY

ACCORDING TO

A NATURAL SYSTEM.

THE outlines of this system — the result of more than thirty years of study — are given in the author's MINERAL PHYSIOLOGY AND PHYSIOGRAPHY, pp. 279-401, 687, 688, where a tabular view of Classes and Orders appears on page 382. The principal points in the new treatise are: (1) Arrangement of all native and artificial species of the mineral kingdom in classes and orders, upon a Chemical basis; (2) Their complex chemical structure and high combining numbers, or so-called molecular weights; (3) Application to them of the principles of polymerism and of homologous or progressive series; (4) Direct relations of the constitution of solids, not only to their specific gravity, but to their hardness and their greater or less chemical indifference, which latter are shown to be connected with the variations in the volume of the chemical unit, or so-called atomic volume; (5) Recognition of the wide distinction between crystalloid and colloid or amorphous species; (6) Division, on the above grounds, of the orders and sub-orders into tribes, which generally correspond with the orders of the Natural-History system; (7) Sub-division of tribes into genera and species, and designation of these by a binomial Latin nomenclature; (8) Systematic descriptions of native and of some related artificial species; (9) Genetic history of native species, and their artificial production; (10) Their relations to the great groups of rocks in the earth's crust.

MINERAL
PHYSIOLOGY AND PHYSIOGRAPHY.

A SECOND SERIES OF

CHEMICAL AND GEOLOGICAL ESSAYS

WITH

A GENERAL INTRODUCTION.

BY

THOMAS STERRY HUNT, M.A., LL.D. (CANTAB.)

Fellow of the Royal Society of London; Member of the National Academy of Sciences of the United States, the Imperial Leopoldo-Carolinian Academy, the American Philosophical Society, the American Academy of Sciences, the Royal Society of Canada, the Geological Societies of France, Belgium, and Ireland; Officer of the Orders of the Legion of Honor, SS. Mauritius and Lazarus, etc., etc., etc.

BOSTON:
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TO

The Memory

OF

BENJAMIN SILLIMAN,

WHO DIED 1885.

MINERAL
PHYSIOLOGY AND PHYSIOGRAPHY.

A SECOND SERIES OF CHEMICAL AND
GEOLOGICAL ESSAYS.

PREFACE.

THE second title assigned to this volume, — namely, CHEMICAL AND GEOLOGICAL ESSAYS, — fails to indicate its character and scope, by reason of the indefiniteness of the word Geology, which is now commonly used to designate both the Natural Philosophy and the Natural History of our earth, except so far as modern geography and meteorology, and the existing flora and fauna, are concerned; descriptive mineralogy and lithology being inseparable from the study of the earth's crust. In this popular sense, geology is made to include the whole history of organic life in past ages, — a field which rightfully belongs to botany and zoölogy. The fossil remains of extinct organic forms, valuable as they may be in the diagnosis of stratified sedimentary strata, have, however, no geognostic significance save in their chemical and lithological relations; and paleontology should, therefore, be distinguished alike from geogeny and geognosy.

The proper application of these two terms is defined farther on, in an essay on The Order of the Natural Sciences. Therein will be seen the subordination of geogeny to dynamics and chemistry, and of geognosy to descriptive and systematic mineralogy, which are included under the respective heads of Mineral Physiology and Mineral Physiography, suggesting, as the more definite title of the volume, MINERAL PHYSIOLOGY AND PHYSIOGRAPHY. The essays of which it is made up have been written in accordance with a predetermined plan, which is now accomplished. The first and second are intended to serve as a General Introduction, and to show the relations of the natural sciences to each other and to that complex study which we call geology. In writing the six succeeding essays it was the author's design to bring together, in a concise form, the facts and the reasonings from which are deduced what he regards as the *Principia* of geogeny, geognosy, and mineralogy.

The chemistry of the atmosphere, and the relations of the earth's aerial envelope alike to outer space and to the gases condensed and the waters precipitated on the surface of the globe, as set forth in the third and fourth essays, constitute a necessary preliminary to the study of rock-masses. These, in Essays V., VI., VII., are considered from three different points of view; the genesis and the geognostic relations of the various crystalline rocks, and finally the decay of these, which has determined their present surface-outlines, and has given rise to the materials of the uncrystalline sedimentary strata. In the fifth essay an attempt has been made to show the defects of each of the many contradictory hypotheses hitherto proposed to explain the origin of the crystalline rocks, and to set forth a new one, according to which they have been derived — for the most part indirectly and by aqueous solution — from a single primary plutonic mass, which itself, however, modified both by the action of water, and by partial separations through crystallization and eliquation, has been the direct source of many exotic rocks. All of these points are more fully discussed in Essay VI.

The new hypothesis, as set forth in Essays V. and VI., is the result of nearly thirty years of studies having for their object to reconstruct the theory of the earth on the basis of a solid nucleus, to reconcile the existence of a solid interior with the flexibility of the crust, to find an adequate explanation of the universally inclined and plicated condition of the older crystalline strata, and at the same time to discover the laws which have governed the formation and the changing chemical composition of the crystalline rocks through successive geologic ages.

The mineral species which make up the earth's crust next demand attention. A system of classification which should consider their physical characters, in connection with the chemical composition and the mode of formation of mineral species, has hitherto been wanting. The possibility of such a system, and the principles upon which it might be founded, were pointed out by the author in a series of papers more than thirty years since. He has now, in the eighth essay of the present volume, attempted to apply these principles to the study of the natural silicates, which are the most important elements of the crystalline rocks, and to give for these species what he believes to be a natural classification, — followed by an outline of the system as applied to all other native mineral species.

The origin of mineral species, their succession, their associations, and the modes of their occurrence alike in massive and in stratified rocks, in veinstones, and in the chemist's laboratory, — in other words, the physiological history of mineral species and their various aggregates, considered both dynamically and chemically, as set forth in Essays V. to VIII., must form the basis of a rational mineralogy and lithology. In this connection are discussed some fundamental principles long maintained by the author, and believed by him to form the basis of "a correct mineralogical system," and, moreover, to "enlarge and simplify the plan of chemical science."

That, contrary to the teachings of the Huttonian or metamorphic school in geology, there is an order in the succession of the rocks from the ante-gneissic granite, and that mineralogical constitution and lithological characters, when rightly interpreted, are a sure guide to the relative ages of the various groups of stratified crystalline rocks, was a conclusion early forced upon the author by his studies of these alike in North America and in Europe; and has led him to propose stratigraphical divisions and a nomenclature which are to-day more or less generally recognized on both sides of the Atlantic. These studies, from 1847 to 1878, were presented in a volume on Azoic Rocks,* published in the latter year, and, with additions up to 1885, are now briefly resumed in the ninth essay.

Intimately connected with this subject, and at the same time bearing directly upon the different hypotheses touching the genesis of crystalline rocks, is the history of the serpentines, which have been alternately regarded as igneous and as aqueous, as exotic and as indigenous masses, and in either case were supposed to have been the subject of various metasomatic changes. In the tenth essay, the origin and the geognostic relations of these rocks, as found alike among eozoic and paleozoic strata, are considered, and in this connection the history of many crystalline eozoic groups on both continents, but especially in central and southern Europe, has been reviewed, — thus continuing the subject begun in the preceding essay.

In concluding, in the eleventh and final essay, the review of the geognostical history of the crystalline rocks, continued from Essays IX. and X., the question of the so-called Taconic rocks has been discussed at some length, and for two reasons. First, because the Lower Taconic series, which has been designated Taconian, appears, as is

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* Azoic Rocks, etc., by T. Sterry Hunt: Part I. Historical Introduction, 1878, 8vo, pp. xxi. and 253, being Report E of the Second Geological Survey of Pennsylvania, Harrisburg, Penn.; Part II., which would have been a special study of these rocks in Pennsylvania, has never appeared, but many details thereon are given in Essay XI. of this volume.

here shown, to be widely spread over both continents, and to mark the latest known period in the genesis of crystalline stratified rocks; and, secondly, because this Taconian series has been by some geologists supposed to represent one of the stages in an imagined process of regional metamorphism by which one and the same group of uncrystalline paleozoic sediments has been made to assume successively, in contiguous areas, the characters of the various crystalline series from the Taconian down to the Laurentian, both included. To expose the fallacies of this ancient error, and to clear up many of the obscurities which it has thrown alike over the history of these groups of crystalline rocks and the succeeding Cambrian and Ordovician strata, it was found necessary to examine in some detail the record of stratigraphical research in the pre-Silurian areas of North America, and in so doing to render justice to the work of Amos Eaton, who, more than fifty years since, laid on a sound basis the foundations of American geology.

In a volume of selected papers, published by the author in 1874, with the title of CHEMICAL AND GEOLOGICAL ESSAYS, in which were discussed the geognostic relations of the Appalachians, of the Alps, and of the Cambrian and Silurian rocks of North America and Europe as known up to that time, the outlines of the present stratigraphical scheme for the eozoic and the lower paleozoic rocks were already, for the greater part, defined; but the true relations of the Taconian were not then understood. In a Preface to a second edition of that volume, in 1878,* the Taconic question was, however, reconsidered (pp. xix–xxvi), and the author's present conclusions are there briefly set forth.

The volume just named contains, moreover, essays on

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* Chemical and Geological Essays, by Thomas Sterry Hunt, 2d ed., 1878, 8 vo., pp. xlvi. and 489. S. E. Cassino, Salem [now of Boston], Mass.

the origin of limestones, dolomites, and gypsums; on the chemistry of natural waters, and on petroleum, asphalt, and coal; on granitic and other veinstones; and on the theory of ore-deposits. Elsewhere therein, and especially in the first eighty pages, will be found the beginnings of the theoretical views maintained in the present volume, including disquisitions on the nature and the seat of volcanic action, and on various other points of dynamical geology, considered in connection with the solidity of the earth's interior. Farther on, in pages 426–448 of that volume, are defined the principles of the mineralogical system which is here developed in the essay on A Natural System in Mineralogy.

The essays in the present volume, with the exception of the sixth, have already appeared in the Transactions of the Royal Society of Canada, in the Proceedings of the Philosophical Society of Cambridge, England, the American Journal of Science, or the London, Edinburgh, and Dublin Philosophical Magazine. A brief notice here prefixed to each essay gives the date and the conditions of its first appearance. Changes have occasionally been made in revision, but wherever there is an addition of significance it is placed within brackets. The same has been done in the case of additional notes.

The plan of the present volume was discussed not many months since with the author's honored master and his friend of forty years, Benjamin Silliman, to whom the volume would have been inscribed. It is now dedicated to his memory.

Boston, Massachusetts,
August, 1886.

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APPENDIX.

POSTSCRIPTUM.

IN discussing the "Question of Molecular Weights," on pages 383–395 of this book, it is said that while solid species must be regarded as polymerids, and their molecular weight as some multiple of the unit-weight deduced from chemical analysis, "the molecular weights of these are as yet unknown"; and, moreover, that "the relations alike of this unit-weight and unit-volume to those of the molecule to which it belongs are unknown." From the principles stated on those pages, and farther on pages 284–304, we may, however, readily fix the weights of these polymerids if we consider that the volume, instead of being an arbitrary quantity, is the unit adopted in the chemistry of gases and vapors; and, moreover, that the law of volumes is not limited to these, but is universal, and applies equally to their condensation into liquids and solids, which are different polymerids of their corresponding vapors, — the conversion of gases into liquids and solids, and, conversely, the vaporization of these, being a chemical process. If we take as the unit the volume of water-vapor ($H_2O = 18$) at 100° C., we find that 1487 volumes of this are condensed into one volume of ice at 0° C., with a specific gravity of 0.9167, so that the molecular weight — or, strictly speaking, the *equivalent weight* — of ice is $1487 \times 18 = 26,766$; while water is $1628(H_2O) = 29,304$. This quantity being the equivalent weight of water (which is the species adopted as the unit of specific gravity for liquids and solids), shows, when divided by two, the number of times that the weight of the hydrogen volume, H_2, is contained in one volume of that unit. From it we calculate the equivalent weight and the true chemical formula of any liquid or solid species, when its specific gravity (water = 1.000) and its empirical formula are known.

The so-called volume of the chemical unit, atom or molecule is the reciprocal of its coefficient of condensation.

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I.

NATURE IN THOUGHT AND LANGUAGE.

This Essay was presented and read in abstract to the National Academy of Sciences at Washington, April 18, 1881. Privately printed in June, it was published in the London, Edinburgh and Dublin Philosophical Magazine for October, 1881 ([V] xii., 233-253) under the title of The Domain of Physiology, or Nature in Thought and Language, and again in a second edition, separately, by S. E. Cassino, Boston, in 1882.

I. — HISTORICAL.

§ 1. THE importance of a correct and well-defined terminology in science cannot be overestimated, since a want of precision in language leads to vagueness in thought, and often to errors in philosophy. There are few more striking examples of indefiniteness in language than can be found in the use of the words physic, physiology, and their derivatives. The material universe is designated with etymological correctness as physical, that is to say, natural — a term which belongs alike to the organic and the mineral kingdoms; but in the use of this and of other words having a similar etymology (Gr. φύσις, Lat. natura) we find in modern language many restrictions, limitations, and ambiguities. It will aid us in our present inquiry if we bear in mind that both the Greek *physis* and the Latin *natura* involve the notion of a generation or growth, and that the adjectives physical and natural, in their origin, imply the results of a formative process or evolution. The term *physis* (which we translate by nature), as employed by Aristotle, denotes that which is at once self-producing, self-determined, and uniform in its mode of action.

§ 2. The substantive physic (φυσική, physica, physique), has been employed by philosophers since the time of Aristotle to signify the knowledge of all material nature.

"Physical science," as well defined by Clerk Maxwell at the beginning of his little treatise on *Matter and Motion*, "is that department of knowledge which relates to the order of nature, or in other words, to the regular succession of events. The name of physical science, however, is often applied, in a more or less restricted manner, to those branches of science in which the phenomena are of the simplest and most abstract kind, excluding the consideration of the more complex phenomena such as are observed in living beings."

§ 3. To the student of natural phenomena, Aristotle gave the names of φυσικός and φυσιολογος. These words were adopted in the same sense by the Romans, who made use of the substantives *physicus* and *physiologia* to designate natural philosophers and natural science. Cicero writes of the physicus or physician Anaxagoras, and employs the word physiology to denote "the science of natural things," in accordance, as he tells us, with Greek usage.[*]

§ 4. The earlier English writers followed the Greek and Latin usage, and employed the substantive physic (or physike) in the same sense as Aristotle. Thus, in the fourteenth century, Gower defines physic as that part of philosophy which teaches the knowledge of material things, the nature and the circumstances of man, animals, plants, stones, and everything that has bodily substance.[†] Des-

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[*] Cicero, Varr. lib. I. R. R. cap. 40. "Si sunt semina in aëre, ut ait physicus Anaxagoras"; also De Nat. Deorum, I, 4. "Rationem naturae quam physiologiam Graeci appellant." In the Totius Latinitatis Lexicon of Facciolatus and Forcellinus we find the definition: Physiologia, scientia quae de naturis rerum disserit, eadem ac Physica.

[†] Gower, dividing theoretical philosophy into three parts, Theologia, Physica, and Mathematica, tells us:—

> "Physike is after the seconde,
> Through which the philosophre hath fonde,
> To teche sondrie knowlechynges
> Upon the bodeliches thinges
> Of man, of beast, of herb, of stone,
> Of fish, of fowl, of euerich one
> That be of bodily substance,
> The nature and the circumstance."
>
> CONFESSIO AMANTIS, book vii.

cartes, in the seventeenth century, employed the word (in French *physique*) with the same signification, and it was subsequently used by Locke in a still more comprehensive sense. He writes of "the knowledge of things as they are in their own proper beings, their constitutions, properties, and operations; whereby I mean not only matter and body, but spirits also, which have their proper natures, constitutions, and operations, as well as bodies. This, in a little more enlarged sense of the word, I call φυσικὴ or natural philosophy." *

§ 5. We have seen that in Latin the words physic and physiology were used synonymously. That they were thus understood by English writers is apparent from the Universal English Dictionary of Edward Phillips (6th edition, 1706), where Physiology is defined as "a discourse on natural things; physics or natural philosophy; being either general, that relates to the affections or properties of matter, or else special and particular, which considers matter as formed or distinguished into such and such species." Cotgrave, a lexicographer of the seventeenth century, in his "French and English Dictionary," also defines Physiologie as "a reasoning, disputing, or searching-out of the nature of things," a definition which is cited by Charles Richardson in his English Dictionary, under Physiology.

§ 6. It was to those who occupied themselves with abstract or *general physiology* (as defined by Phillips) that the Greeks gave the name of physiologists, first applied to the philosophers of the Ionian school, who sought to derive all things from one or more material elements, and thus had a physical basis for their system of the universe, as distinguished from the school of Pythagoras, whose system was based on numbers and forms. Of Empedocles, the author of a didactic poem on Nature in which we first find enunciated the doctrine of the four elements, fire, air, earth, and water, Aristotle, in his Poetics, makes the criticism that he was more of a physiologist than a poet.

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* Human Understanding, b. vii., c. 21.

Humboldt repeatedly employs the word physiology and its derivatives in the same general sense. Thus, he writes of "the natural philosophy of the Ionian physiologists" (physiologien), which "was devoted to the fundamental ground of origin, and the metamorphoses of one sole element"; of the "physiological fancies of the Ionian school," and of the teachings of Anaxagoras of Clazomenae, "in the latter period of development of the Ionian physiology." * Of Anaxagoras it may be observed that his views marked a great advance over those of his predecessors, and that he merited the encomium pronounced by Aristotle that he was the first philosopher who had written soberly of nature.

§ 7. We find the word physiology and its derivatives employed in the same general sense by English writers in the seventeenth century. Thus, Cudworth speaks of "the old physiologers before Aristotle," and writes "they who first theologized did physiologize after this manner, inasmuch as they made the Ocean and Tethys to have been the original of generation," † while Henry Moore says, "It will necessarily follow that the Mosaical philosophy, in the physiological part of it, is the same with the Cartesian." ‡ Coming down to later writers, we find the word physiologist used in a general sense, as equivalent to our modern term naturalist. Thus, Dugald Stewart calls Cuvier "the most eminent and original physiologist of the present age," and Burke writes, "The national menagerie is collected by the first physiologists of the time." §

We may note in this connection the two series of abridgments of the Philosophical Transactions of the Royal Society — the first, from its commencement to 1700, and the second to 1720 — both published with the *imprimatur* of Newton as president of the Society. In these collections

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* Cosmos, Otte's translation, Harper's ed., II., 108, and III., 11.

† Intellectual System, pp. 120, 171.

‡ Philosophical Cabbala, Appendix, c. 1.

§ Stewart, Philosophy of the Human Mind, II., c. 4; and Burke, Letter to a Noble Lord.

the classification of the papers is as follows: (1) "Mathematical," including pure and applied mathematics; (2) "Physiological," embracing all meteorological phenomena, tides, terrestrial magnetism, mineralogy, geology, botany, zoölogy, and the study of the physical world in general. Subjects relating to the human body, however, such as anatomy and medicine, were excluded from part 2, and, with chemistry, made a first division of part 3, in the second and last division of which were included philological and miscellaneous papers.

§ 8. Of the "special and particular physiology," as distinguished by Phillips, we have an example in Glanvil, who, in the seventeenth century, writes of the physiology of comets.* The citation from Burke, identifying physiologists with zoölogists, may also perhaps be taken as an example of a special use of the word, while in later times we have come to speak of Vegetable Physiology, Animal Physiology, Human Physiology, and even of Mental Physiology, a term employed by Dr. Thomas Brown of Edinburgh,† who speaks of "physiology corporeal or mental."‡

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* "So that we need not be appalled at blazing stars, and a comet is no more ground for astrological presages than a flaming chimney. The unparalleled Descartes hath unravelled their dark physiology, and to wonder solved their motions." Joseph Glanvil, Scepsis Scientifica, . . . an Essay on the Vanity of Dogmatizing, 1665, c. xx.

† The grounds upon which Brown based this extension of the term physiology may be gathered from the following passages: "There is, in short, a science which may be called *mental physiology*, as there is a science relating to the structure and offices of our corporeal frame, to which the term *physiology* is more commonly applied." He farther speaks of the "*physiology of the mind*, considered as a substance capable of the various modifications or states which, as they succeed each other, constitute the phenomena of thought and feeling," and declares that "the mind is as an object of study . . . to be comprehended, with every other existing substance, *in a system of general physics*." Brown, The Philosophy of the Human Mind, lectures I., II., and V.

‡ Since the writing of this essay, Prof. Osborne Reynolds, in *Nature* for June 9, 1881 (vol. xxiv, page 123), has made a happy use of the word in question in writing of the locomotive engine of George Stephenson, of which he says, "the physiology of the machine resembled that of the human system"; while he speaks of its inventor as "he who produced the locomotive physiologically perfect."

§ 9. There is an example of a special application of the words physiology and physic which requires farther consideration. We have already cited Cotgrave's first definition of the word Physiologie, to which he adds, as a secondary meaning, "anatomizing physic, or that part of physic which treats of the composition or structure of man's frame." In more recent times, however, the term has come to mean, not the anatomy, composition, or structure of the human frame, but its functions, to which signification physiology is, in popular language, limited, though now by didactic writers extended to include the functions of the lower animals, of plants, and even of the human mind.

The word physic, as we have seen, was used by Gower in the general sense of a knowledge of all material things, but his contemporary, Chaucer, employed it, in a special and restricted sense, to designate the science of medicine. Thus, he calls his practitioner of the medical art "a doctor of physic," and in his description of this personage adds that "gold in physic is a cordial." * Subsequently, and to our own time, we find the term applied, in Chau-

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* "With us there was a doctour of phisik,
In all the world ne was there non him lyk
To speke of phisik and of surgerye,
For he was grounded in astronomye.
. . . . . .
He knew the cause of every maladye,
Were it of hot or cold or moyste or drye,
And where engendered and of what humoure;
He was a very parfight practisour.
. . . . . .
Well knew he the old Esculapius,
And Dioscorides, and eke Rufus,
Old Hippocras, Hali and Gallien,
Serapion, Rasis and Avicen,
Averrois, Damascene and Constantin,
Bernard, and Gatisden and Gilbertin.
. . . . . .
For gold in phisik is a cordial.
Therefore he loved gold in special."
CHAUCER, *Canterbury Tales, Prologue.*

cer's sense, alike to the art of healing and to its medicaments. If we search for the origin of this peculiar use of the word physic, we shall find it employed with the same meaning in medieval Latin.* In French also, according to Littré, the term *physique* was in the thirteenth century applied to the science of medicine, the professors of which were then called *physiciens*, † a designation which they kept till the time of Rabelais, and, as we know, still retain in English, though the term *physicien* is at present applied in French only to students of physical science in the restricted sense mentioned in § 2, including what, in didactic phrase, is now called *physique* in French and physics in English.

§ 10. It is a curious inquiry how these terms came to have this restricted use in the middle ages, and how the name of *physicus* or physician, originally applied to the student of material things — and by pre-eminence to Anaxagoras of Clazomenae, who was called "the physician," (ὁ φυσικὸς) — came to signify in medieval France and England the *medicus*, *médecin*, or mediciner — the master of the art of healing diseases in the human frame. Menage assigns as a reason for this, that the art "consists principally in the contemplation of nature," and in this imperfect statement will be found the answer to our inquiry, upon which much light is thrown by the use, in medieval times, of the words *naturien* and *naturiste*. *Naturien*,‡

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* Du Cange, Glossarium ad Scriptores mediae et infimae Latinitatis; ed. Henschel, sub voce Physica.

† "Nous établissons . . un fisicien juré et pensionnaire du couvent." Réglement de l'Abbaye Royale de Soissons, A. D. 1282; cited by Menage, Dictionnaire Etymologique, sub voce Physicien.

‡ The following satirical rhyme of the fourteenth century is cited by Littré, in his Dictionnaire, sub voce *Naturien*, —

Où le physicien fait fin, Là commence le médecin,
Supposant pour physicien, Le très-savant naturien.

Gower, who uses the word more than once, writes, —

And thus seyth the naturien,
Which is an astronomien.
CONFESSIO AMANTIS, book vii.

which is found in the fourteenth century, both in English and in French, is etymologically equivalent to *physicien*, and was applied to certain professors of the art of healing, being apparently synonymous with *naturiste*, which, as stated by the learned Littré, in his Dictionnaire, meant "a mediciner who practised expectant medicine," that is to say, who trusted to the conservative influences of nature to heal his patient.

§ 11. For the origin of the physician or naturian in medicine, we must go back more than twenty centuries to the great Hippocrates, justly styled the father of medicine. It was a maxim of his school that "nature is the healer of diseases," * and himself it was who wrote of medicine that "the art consists in three things, the malady, the patient, and the mediciner. The mediciner is the servant of nature, and the patient must help the mediciner to combat the disease." †

Nature, in the language of the time, was spoken of as a *vis medicatrix*, or healing power; but Virchow justly remarks that from a careful perusal of the works left us by the great master, we cannot doubt that by nature he meant the whole bodily constitution of man. Hippocrates insisted upon a treatment of diseases based not upon magic nor upon supernatural agencies, but upon the belief that nature works according to a divine necessity. In other words, he taught a system of pathology founded on the recognition of physical laws, which he opposed to the superstitious notions of his caste and his age. The *iatros*, or mediciner, was henceforth no longer a magician, nor a priest, but a physiologist, physician, or naturist,

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* *Νουσῶν φύσιες ἰητροί.* Hippocrates, Epidem., book VI., sec. 5, 1.

† Epidem., book I., sec. 2, 5. The received text makes the mediciner "the servant of the art," but Galen, in his Commentary, tells us that some manuscripts in his time had, instead of *ὁ ἰητρὸς ὑπηρέτης τῆς τέχνης*, the word *φύσεως* for *τέχνης*. This latter reading I have followed as more consonant with the previously cited dictum, for if "nature is the healer of diseases," the mediciner must be "the servant of nature." See Adams's Genuine Works of Hippocrates, vol. i., p. 360, note; also Littré's Hippocrates, vol. ii., *in loco*.

seeking for healing agencies in the study of the physical organization of the patient. The pathology of the Dogmatists, who were the disciples of Hippocrates, was based upon a knowledge of the structure and functions of the human organism, and of the structural and functional modifications produced alike by disease and by the action of drugs.

§ 12. But Hippocrates had still another claim to the title of physician, or physiologist, since, not content with studying the physical constitution of man, he insisted upon the importance of a knowledge of all his relations to external nature. In his celebrated treatise "On Airs, Waters, and Localities," Hippocrates declares that whoever would understand medicine must study the movements of the heavenly bodies, and all meteorological phenomena, together with physical geography, including climate, soil, vegetation, rocks, minerals, and waters; to which he adds that the mediciner, if he would preserve the health of his patients, and succeed in his art, must investigate "everything else in nature."*

§ 13. The teachings of Hippocrates and his followers were maintained in the school of Alexandria, where, we are told, the studies were arranged in four divisions or faculties: letters, mathematics, astronomy, and medicine; under which last, as we know from the history of the Museum, were included botany, geology, chemistry, optics, and mechanics. The learning of the Alexandrian school was preserved by the Jews and the Nestorians, and by them handed down to the Arabians, who brought it with them into southern Europe. It suffices to speak of Djafar, Rhazes, Avicenna, and, later, of the schools of Salerno, Cordova, Montpellier, Narbonne, and Arles, where were gathered together men famed alike in medicine, anatomy, zoölogy, botany, optics, mechanics, and astronomy, who merited in the widest sense the name which they then

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* Hippocrates "On Airs, Waters, and Localities"; sections 1-8.

bore, of physicians; since they were not simply iatrophysicians, but philosophers who had taken all natural science for their province. Draper, speaking of the Arabians of that age, says, "Their physicians were their great philosophers; their medical colleges were their foci of learning. Arab science emerged out of medicine, and in its cultivation physicians took the lead, its beginnings being in the pursuit of alchemy." * It is to be noted that Chaucer's doctor of physic (§ 9) was not only learned in astronomy, and read in the works of the Greeks, Hippocrates, Galen, Rufus, and Dioscorides, but knew well those of Ali, Avicenna, Averroës, Rhases, and Damascenus, all of them renowned Arab mediciners and natural philosophers.

§ 14. The French language, as we have seen, soon came to distinguish between the physician and the professional healer of diseases. From *medicare* came the medieval Latin verb, *medicinare*, whence the French verb, *médeciner*, and the substantive, *médecin*, corresponding to which we find in German and in English the substantive, *mediciner*. Sir Walter Scott puts into the mouth of King Richard the words, "It is unbecoming a mediciner of thine eminence to interfere with the practice of another," † and Jamieson gives a Scotch proverb, "Live in measure, and laugh at the mediciners." ‡ It is to be wished that this word were generally adopted in our speech, since the name of physician is now given to empirics who, whatever their claims to be called curers, mediciners, or medicasters, have no right to be called physicians. The antagonism between the two schools is humorously shown in the old French quatrain cited in the note to § 10.

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* Draper, Intellectual Development of Europe, I., c. 13; II., c. 4.

† The Talisman, chap. xviii.

‡ Jamieson's Scottish Dictionary has Medcinarc, Medicinar, and Mediciner, meaning the practitioner of medicine, thus showing a derivation from the Latin verb *medicinare*, the second vowel being dropped in the first form.

II. — PHILOSOPHICAL.

§ 15. Having, in the first part of this essay, considered the words physic, physiology, and physician etymologically and historically, we proceed to notice them in their application by modern writers. We have already seen that the term physical science is often restricted to those phenomena which are common to organized and unorganized matter (§ 2). The study of these is now generally designated in didactic language as physics, or in French *physique*; the votary of such studies being called in English a physicist, and in French a *physicien.*

Physical, as an adjective, is, however, used in a wider sense than the above, when applied to organized beings. It then designates their organism and all pertaining thereto, as in the expression, the physical life of man, or in the common tautological phrase, "man's physical nature."

§ 16. While the word physic, or rather physics, is in modern English generally limited to the study of the phenomena of the inorganic world, the once synonymous term physiology has come to mean, both in English and in French, the study of the organic functions of plants and animals (and, by an extension of the term, that of the functions of the human mind); which are designated as physiological, in contradistinction to the so-called physical phenomena of inorganic nature. Examples of these limitations, respectively, of the words physic and physiology, and their derivatives, are familiar to every reader. Thus, William B. Carpenter constantly distinguishes between physical, chemical, and vital forces, the consideration of the latter only, according to him, belonging to physiology.*

On the other hand, we find well-known writers employing the word physical and its congeners indifferently, in

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* Relation of the Vital to the Physical Forces, Philos. Transactions, 1850, p. 727.

their wider and their more restricted meanings. Thus, in his address before the British Association for the Advancement of Science, at Belfast, in 1874, Tyndall, in discussing the activities of the animal, speaks successively of "the work of the physicist, . . . the comparative anatomist, and the physiologist." Following this, the influence of the nervous system "over the whole organism, physical and mental," is spoken of, and, a few lines farther on, "the physical life dealt with by Mr. Darwin" is distinguished from "a psychical life"; while, in the next paragraph, we read of "organisms whose vital actions are almost as purely physical" as the coalescence of drops of oil suspended in a watery medium of the same density, in the classic experiments of Plateau.* In the first citation, the investigations by the dynamo-physicist of the nervous and muscular activities of the animal are distinguished from those of the biologist. In the second and third citations, the physical organism and the physical life are distinguished, not as in the preceding, from the chemical and vital (which they evidently include), but from the mental organization and the psychical life; while in the fourth the antithesis is between physical, in the sense of dynamical, on the one hand, and chemical and vital processes on the other.

§ 17. Thomson and Tait, in their treatise on "Natural Philosophy," wherein are considered only those simpler phenomena of matter which are neither chemical nor vital, employ the term *Dynamics* for the forces thus manifested, and divide the study of them into *Kinetics* and *Statics*, or the phenomena of actual motion and of rest. Some writers have used static as the antithesis of dynamic (see farther, § 24), but statics, as implying simply equilibrium, are, as W. K. Clifford has well remarked, "but a particular case of kinetics," and hence are to be included with the latter under the common title of dynamics. Thomson and Tait

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* Tyndall's Belfast Address. Appleton's ed., pp. 50, 51.

consider under this head, besides the phenomena of ordinary motion, the vibrations which produce sound, and those motions by which we seek to explain the phenomena of temperature, radiant energy, and electricity and magnetism. The whole of the phenomena to which, in the modern and restricted sense, the name of Physics is generally applied, are thereby included under the head of Dynamics; a term which is thus employed not only by the authors just cited, but by Clerk Maxwell, Helmholtz, and Clifford,* and will be so used in the following pages, while the term *dynamicist* will replace physicist. [Berzelius had previously included electricity, magnetism, light, and heat—all of which he regarded as affections of matter, and compared their phenomena with those of sound—under the common name of Dynamids,† thus anticipating the use of the term dynamics as here applied.]

§ 18. Dynamics in the abstract regard matter in general, without relation to species, the genesis of which is the office of the chemical process, or chemism. This gives rise to mineralogical, or so-called chemical, species, which, theoretically, may be supposed to be formed from a single element or *materia prima*, by the chemical process.

"It is necessary to distinguish between the production of new species differing in physical characters ‡ and that reproduction which belongs to organic existences. The distinction arises from that individuation which marks the results of organic life, and is eminently characteristic of its higher forms. The individuality, not only of the organism, but of its several parts, is more evident as we ascend the scale of organic life, while inorganic bodies have a specific existence, but no individuality; division

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* W. K. Clifford, Essays, II., 17. This author, following the French usage, employed the substantive Dynamic in a treatise on the subject, thus entitled; but the plural form, Dynamics, is preferable, as serving to distinguish it from dynamic used adjectively.

† Berzelius, Traité de Chimie. Second edition. Paris: 1885. pp. 14, 35.

‡ That is to say, differing in dynamic relations.

does not destroy them. Crystallization is a commencement of individuation.

"That mode of generation which produces individuals like the parent, can present no analogy to the phenomena under consideration; metagenesis, or alternate generation, and metamorphosis are, however, to a certain extent, prefigured in the chemical changes of bodies. Their metagenesis is effected in two ways: by condensation and union, on the one hand, and by expansion and division on the other. In the first case, two or more bodies unite and merge their specific characters in those of a new species. In the second case, this process is reversed, and a body breaks up into two or more new species. Metamorphosis is, in like manner, of two kinds: in metamorphosis by condensation only one species is concerned, and in metamorphosis by expansion the result is homogeneous and without specific difference. The chemical history of bodies is a record of these changes; it is, in fact, their genealogy.

"The processes of union and division embrace by far the greater number of chemical changes, in which metamorphosis sustains a less important part. By union, we rise to indefinitely higher species; but in division, a limit is met with in the production of species which seem incapable of further division, and these, being regarded as primary or original species, are called chemical elements. These two processes continually alternate with each other, and a species produced by the first may yield, by division, species unlike its parents. From this succession results double decomposition or equivalent substitution, which always involves a union followed by division, although, under the ordinary conditions, the process cannot be arrested at the intermediate stage."

§ 19. I have quoted the three preceding paragraphs from an essay published by myself in 1853, on "The Theory of Chemical Changes." Therein I also wrote, "Chemical combination is interpenetration, as Kant has taught. When bodies unite, their bulks, like their specific characters, are lost in that of the new species." In 1854, in an essay entitled "Thoughts on Solution,"* I, however, declared, with regard to Kant's view, that "the conception is mechanical, and therefore fails to give an adequate idea. The definition of Hegel, that the chemical process is an identification of the different, and a differentiation of the identical, is, however, completely adequate. Chemical union involves an identification not only of the volumes (interpenetration, mechanically considered), but of the specific characters of the combining bodies, which are lost in those of the new species. . . . We may say that all chemical union is nothing else than solution; the uniting species are, as it were, dissolved in each other, for solution is mutual."

The above considerations will serve to show the essential nature of chemism, a process resulting in the genesis of chemical species, which are mineral or inorganic.

§ 20. The force involved in the chemical process manifests itself as radiant energy and electricity, and there is apparently a tendency among modern dynamicists to confound these activities with chemism itself, and thus to lose sight of the essential significance of the chemical process as already defined. Thus Clifford wrote of molecular motion "which makes itself known as light, or radiant heat, or chemical action," † while Faraday was wont "to express his conviction that the forces termed chemical affinity and electricity are one and the same." Helmholtz, from whom I here quote, adds, "I think the facts leave no

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* Of the two essays above quoted, the first appeared in 1853, in the American Journal of Science for March, and also in the L., E. and D. Philos. Magazine [4] v., 526, and was translated into German in the Chemisches Centralblatt for 1853, page 849. The second was published in the American Journal of Science for January, 1854, and also in the Chemical Gazette for 1855, page 90. Both will be found in the author's volume of "Chemical and Geological Essays," in which, for the extracts here given, see pages 427, 428, and 450.

† W. K. Clifford, Essays II., 17.

doubt that the very mightiest among the chemical forces are of electrical origin, . . . but I do not suppose that other molecular forces are excluded, working directly from atom to atom." *

The activities which appear in dynamic and in chemic phenomena are one in essence, for force is one. The same is true of the activities manifested in organic growth, and even in thought; but the unity and mutual convertibility of different manifestations of force afford no ground for confounding, as some would do, dynamics with chemics, or with vital or mental processes. All of these phenomena are but the evidences of universal animation, or, in other words, of an energy which is inherent in matter, the manifestations of which, as matter rises to higher stages of development, become more complex, as organic individuals are themselves more complex than mineral forms. †

§ 21. From the process which generates chemical species we pass to that which gives rise to organized individuals,

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* Helmholtz, The Faraday Lecture, April 5, 1881; abstract prepared by its author; Nature, vol. xxiii., p. 539.

† [This view of hylozoism was well set forth by Rosmini. According to him, in the words of his interpreter, Davidson, "the ultimate particles of matter are animate, each atom having united with it, and forming its unity or atomicity, a sensitive principle. When atoms chemically combine, their sensitive principles become one. . . . The unit of natural existence is neither force nor matter, but sentience, and through this all the material and dynamical phenomena of nature may be explained." From the unifications of these sensitive principles, or elementary souls, which take place in the combinations of matter, higher and higher manifestations of sentience appear, constituting the various activities displayed in crystals, in plants, and in animals. From these elementary souls organic souls are built up, and "when these are resolved into the elementary ones through the dissolution of the organized bodies, the existence of the souls does not cease, but is merely transformed." [See "The Philosophical System of Rosmini," by Thomas Davidson (1882), pp. 284–301.] This volume was unpublished, and these views of Rosmini were unknown to me, at the time of writing the above pages. The eminent biophysiologist, the late William B. Carpenter, in an essay on "Life," published in 1847, in Todd's "Cyclopedia of Anatomy and Physiology," Vol. III., p. 151, contends that organization and biotical functions arise from the natural operation of forces inherent in elementary matter.]

in which appear a new class of phenomena, distinguished alike from those of dynamics and those of chemism. These new manifestations, which are called vital, involve dynamical and chemical activities, but display, in addition to these, still higher ones. Matter, on this more elevated plane, not only becomes individualized, but adapts itself to external conditions, by organization, and exhibits in the resulting forms the power of growth by assimilation, and of reproduction. The study of these forms in all their relations is the object of Biology. Organogeny, or the process of morphological growth and development, distinguishes the biological from the mineralogical individual. The activities of the crystal are purely dynamic, and its crystalline individuality must be destroyed before it can become the subject even of chemism, while the plant and the animal exhibit not only dynamical and chemical, but organogenic activities, which last are designated as vital phenomena. The study of these constitutes a third division of physics, which may be conveniently designated as Biotics (from βιοτικός, pertaining to life), and has to do with organic growth, development, and reproduction, activities which do not appear in the mineral kingdom.

Mineralogy is the science of inorganic matter, and studies its dynamical and chemical relations, while Biology, which is the science of organic matter, adds to these the study of biotic relations. The dynamic and chemic activities which in the mineral kingdom give rise to the crystalline individual, are therein in static equilibrium. The organic individual, on the contrary, is kinetic, and maintains its equilibrium only by perpetual adjustment with the outer world.

§ 22. General physic, or the study of nature, presents itself under a twofold aspect, the historical and the philosophical; the former gives rise to physiography, while to the latter the name of physiology more properly belongs. Physiography describes specific and individual forms, and their external relations, while physiology investigates the processes by which these forms are produced, and gives us the logic of nature. The physiology of matter in the abstract is dynamic, that of mineral forms is both dynamic and chemic, while that of organic forms is at once dynamic, chemic, and biotic.

Nature in all its manifestations constitutes a unity, and it is the object of general phsyiology to study the process of creation in the material world from primal matter upward through its various forms until it attains to organization, and at length, in man, to self-consciousness, where the domain of physiology ends and that of psychology begins.

§ 23. In accordance with the views here enunciated, all matter is in a sense living, "all movement is radically vital," * though we, in common language, refuse the designation of vital to those lower forms of material activity which appear in dynamic and chemic phenomena, reserving it for such as are supposed to be peculiar to organized forms, which, to prevent misconception, I have called biotic. When matter, through chemism, attains the condition of protoplasm, which may be chemically described as a colloidal albuminoid united with more or less water, it begins to exhibit that form of activity which we term vital, or biotic. "The mobility and the spontaneous movements of this substance," says Allman,† "result from its proper irritability. From the facts there is but one legitimate conclusion, that life is a property of protoplasm." ‡

§ 24. Many of the peculiar characters of protoplasmic

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* Stallo, Philosophy of Nature, p. 66.

† Allman, Presidential Address before the British Association for the Advancement of Science, in 1879.

‡ The views set forth in this and the three sections preceding may be compared with those concisely expressed by Huxley since the preceding pages were first printed, in his address in August, 1881, before the International Medical Congress in London. He therein concludes that the "contrast between living and inert matter, on which Bichat lays such stress, does not exist. . . . Living matter differs from other matter in degree, and not in kind; the microcosm repeats the macrocosm, and one chain of causation connects the nebulous original of suns and planetary

matter appear to be common to chemical species in the colloidal condition. The remarkable properties exhibited by colloids led their discoverer, Graham, twenty years since, to declare, "The colloidal is, in fact, a dynamical [kinetic] state of matter, the crystalloidal being the statical condition. The colloid possesses *Energia;* it may be looked upon as the probable primary source of the force appearing in the phenomena of vitality. To the gradual manner in which colloidal changes take place (for they always require time as an element) may the characteristic protraction of chemico-organic changes also be referred." *

Following Graham, Herbert Spencer has noted that pliability, elasticity, the power of absorbing water with change of bulk, and the phenomenon of osmosis, — the whole of which are well designated by him as showing sensitiveness to external agencies which are mechanical or quasi-mechanical — are possessed in common by mineral colloids and by organized substances. These phenomena are examples of that "continuous adjustment of internal relations to external relations" which characterizes organic life.† When the chemist shall have succeeded by his synthesis in producing a colloidal albuminoid having the same chemical constitution as protoplasm, there is, as Barker has well said, reason to expect that it will exhibit all the phenomena of life which appear in the protoplasmic matter common to plants and animals.

§ 25. Barker has, in this connection, asked the important question: What are we to understand by organic life, and what is the true meaning of vital, as applied to a function? ‡ If, with him, we answer, following Küss, —

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systems with the protoplasmic foundation of life and organizations." (*Nature*, Aug. 11, 1881, vol. xxiv., p. 346.)

* Thomas Graham. Chemical and Physical Researches, p. 554, from Philosophical Transactions for 1861, p. 183.

† Herbert Spencer, Principles of Biology, vol. i., part 1, chapters 1 and 2.

‡ Geo. F. Barker, Address as President of the American Association for the Advancement of Science, Boston, August, 1880. I have in this paragraph closely followed Professor Barker's argument.

"life is all that cannot be explained by dynamics and chemism," we shall find, restricting our inquiries to the animal economy, that a large part of the phenomena commonly called vital, — and as such included under the head of animal physiology, — are dynamic or chemic. The law of the conservation of energy applies as rigidly to a living animal as to a thermic engine, and the amount of work done, or of heat evolved, is measured by food consumed in the former as it is by the fuel burned in the latter; the energy manifested in both cases being dependent on the oxydation of carbon and hydrogen. Recent inquiries go far to confirm the view that muscular contraction is electrical, and that electrical manifestation in the muscles is, as in our ordinary batteries, dependent on chemism. The tendency of late investigations is to bring nervous activity into the same category, and the electrical nature of capillarity has been shown by Draper and by Lippmann. The animal circulation is a mechanical result of muscular contraction; the aeration and the coagulation of the blood, and the process of digestion, are chemical, while absorption finds an explanation in the phenomena of diffusion and osmosis.

When the energy which is in matter is manifested without reference to species, we call it simply dynamics; when it results in the production of mineral species, we call it chemics, or chemism; and when it gives rise to organisms, which may be defined as kinetic individuals, we distinguish it as vital, or biotic. In matter, we must recognize with Tyndall "the promise and the potency of all terrestrial life." *

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* [Address as President of the British Association, Belfast, 1874. Appleton's ed., p. 59. In another version of this address, cited by Stallo, Tyndall declares that he discerns in matter "the promise and the potency of every form and quality of life," respecting which Stallo remarks: "Tyndall's words were little more than a new wording of an old thought of Francis Bacon, who said, more than two centuries ago: 'And matter, whatever it is, must be held to be so adorned, furnished, and formed, that all virtue, essence, action, and natural motion may be the natural consequence and emanation thereof' ('Atque asserenda materia, qualiscunque ea sit, ita ornata et apparata et formata ut omnis virtus, essentia, actus

§ 26. It follows, from what has been said, that the word physiology, as popularly limited to the functions of living beings, is made to include many phenomena which are not biotic, but are common to the organic and mineral kingdoms, and that we need some further definition to distinguish those which are characteristic of organic life. I therefore venture to designate the study of these by the distinctive name of Biophysiology, while those phenomena which are recognized as simply dynamic, or dynamic and chemic, whether manifested in organisms or in mineral species, may be included under the name of Abiophysiology.

General physiology, comprehending these two divisions, will thus be restored to its original and proper signification, as an inquiry into the reason of all things in the material universe, and as distinguished from physiography, whose province is the description of universal nature. Scientific precision demands a reform in our terminology, and requires us to extend the name of physiology once more to the processes and the activities of the three kingdoms of nature. The inorganic, not less than the organic world, has its physiology. On the other hand, the study of mind and spirit, and the phenomena of consciousness, which Locke and Thomas Brown included under the head of physic and physiology, should be relegated to the domain of psychology.

§ 27. The kindred term physiography is now correctly employed in a general sense, with a meaning co-extensive

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atque motus naturalis ejus consecutio et emanatio esse possit.' Baco, De Princ. atque Origg., Opp. ed. Bohn, vol. ii., p. 691). The same thing has been repeated many times since by the metaphysical evolutionists, in terms substantially like those of Schelling: 'Matter is the general seed-corn of the universe wherein everything is involved that is brought forth in subsequent evolution' ('Die Materie ist das allgemeine Samenkorn des Universums, warin Alles verhüllt ist was in späteren Entwickelungen sich entfaltet.' Schelling, Ideen zu einer Philos. der Natur, 2d ed., p. 315)" Stallo, The Concepts and Theories of Modern Physics, pp. 153, 154. Compare with this the view of W. B. Carpenter cited in a note to § 20, *supra*, page 16.]

with that which we claim for physiology. A great living teacher, Professor Huxley, has given us, under the title of "Physiography; an Introduction to the Study of Nature," an elementary treatise, wherein, after describing the rocks, the waters, and the atmosphere, which make up the inorganic portions of the earth, he proceeds to consider the development of plants and animals, and their relations to each other and to the mineral kingdom, and concludes with an account of the astronomical relations of our planet as a part of the solar system.

It was the conception of the essential unity of nature, without which a true science is impossible, which inspired Humboldt to attempt, in his "Cosmos," a complete physiography, which was to be "a physical description of the universe, embracing all created things in the regions of space and in the earth." Humboldt elsewhere speaks of "the idea of vitality . . . so intimately associated with that of the existence of the active, ever-blending natural forces which animate the terrestrial sphere," and, recalling the fact that the inorganic crust of the earth includes the same chemical elements that enter into the structure of animal and vegetable organisms, adds, "A physical cosmography would therefore be incomplete if it were to omit a consideration of these forces,—and of the substances that enter into solid and liquid combinations in organic tissues under certain conditions,—which, from our ignorance of their actual nature, we designate by the vague term of *vital forces*. The natural tendency of the human mind involuntarily prompts us to follow the physical phenomena of the earth through all their varied series, until we reach the final stage of the morphological evolution of vegetable forms, and the self-determining powers of motion in animal organisms." *

§ 28. The necessary complement to a scientific physiography is thus, as Humboldt has here pointed out, a philos-

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* Humboldt's Cosmos, Otte's translation, Harper's ed., 1851, Author's Preface, p. viii.; and vol. i., pp. 339–341.

ophy of the material universe, or, in other words, a general physiology. The most complete attempt at thus systematizing nature is that of Lorenz Oken, who divided all philosophy into Pneumatophilosophy and Physiophilosophy, corresponding respectively to Spirit and to Nature. Physiophilosophy, as defined by him, is the science of the conversion of Spirit into Nature, and has for its object to show how, and in accordance with what laws, the material universe has been formed; to portray the first periods of the world's development from naught; to show how the heavenly bodies and the chemical elements originated; in what manner, by self-evolution into higher and manifold forms, these generated mineral species became at length organic, and in man attained to self-consciousness.

Physiophilosophy is therefore the generative history of the world, or, in other words, the history of the process of creation. It aims, in the language of Stallo, to describe "the genetic evolution of the material world; therefore, also, its first origin in naught, and its subsequent development up to its limit, man, who is a complex of all preceding forms, includes all particular developments, and is, as it were, the focus where all the various tendencies of Nature converge. . . . In man, all eternal activities, all divine ideas are gathered"; and thus it is that, in the words of the poet, he is enabled "to think again the great thought of the creation" *

§ 29. The origin of matter itself, Hylogeny, belongs to Pneumatophilosophy. The genetic process in the primal undifferentiated matter, with which Physiophilosophy first concerns itself, is by Oken considered under the two

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* "Schön ist, Mutter Natur, deiner Erfindung Pracht
Auf die Fluren verstreut; schöner ein froh Gesicht
Das den grossen Gedanken
Deiner Schöpfung noch einmal denkt."
KLOPSTOCK, *Ode, Der Zürchersee.*

Compare this with the language of Schelling, cited by Hegel: "Über die Natur philosophiren heisst die Natur schaffen."

heads of Ontology and Biology. The successive steps in the ontological process are, first, Cosmogony, or the fashioning of the heavenly bodies from the previously formed matter; followed by the genesis therefrom of the chemical elements; Stoichiogeny. These elements give rise to mineral species, which together make up the earth; Geogeny. Biology, which has for its object the study of the organic world, is by Oken divided into Organogeny, with its sub-divisions, and Phytosophy and Zoösophy, treating respectively of the development of plants and animals. In the organism we have "a combination of all the activities of the universe in a single individual body." The inorganic and the organic worlds are not only in harmony with each other, but are one in kind. Man, in whom self-consciousness or Spirit manifests itself, represents the whole universe in miniature.*

§ 30. The physiophilosophy of Oken, of which we have given an outline, is thus identical in its aim and its plan with the earlier attempts of the Greek philosophers to which the name of physiology was given, and the two terms are, in fact, synonymous. The study of nature, as has been shown, divides itself into physiography and physiology, and this division applies equally to each one of the three great kingdoms of nature. Thus, for example, Physiographical Botany studies the relations of plants to each other as members of the vegetable kingdom, and investigates their external forms and relationships, by which we arrive at Systematic and Descriptive Botany, with its classification and terminology. These together

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* Lorenz Oken, Physiophilosophy; Introduction, pp. 1-3, of Tulk's translation, published by the Ray Society, London, 1847. See also an excellent analysis of the system by J. B. Stallo in his Philosophy of Nature, Boston, 1848, pp. 221-330, from which we have quoted above. Errors in detail, and defects, and obscurities, are to be found in the system of Oken, which even novices in science can to-day point out and criticise; but it must not be forgotten that his physiophilosophy has been a most potent influence in shaping and directing the scientific thought of the last two generations. Oken has been the inspirer and the teacher of the teachers of science.

give us Botany as a great division of Natural History. Physiological Botany, on the other hand, considers the individual plant in itself, as seen in its structure, growth, and development, and in its relations to the other kingdoms of nature. It is properly divided into Structural Botany, which investigates the anatomy, organography, and morphology of the plant, and Vegetable Physiology, which studies the functions of the vegetable organism, its growth, nutrition, and decay, and the interdependence of the vegetable, animal, and mineral kingdoms.* The same distinctions and definitions will apply, *mutatis mutandis*, to Physiographical and Physiological Zoölogy.

§ 31. The vastness and the complexity of the inorganic as compared with the organic world of nature, make it difficult to grasp at once a conception of the true relations of Mineralogy, which comprehends the study of all forms of unorganized matter.† Physiographical Mineralogy, in its widest sense, has thus for its object not only this earth, but all other matter in space, and includes, so far as our planet is concerned, Geognosy and Petrography, besides Systematic and Descriptive Mineralogy as generally understood.

In the study of mineralogy in its physiological aspect, we have to consider the various conditions of mineral matter, distinguished as gaseous, liquid, or solid, as amorphous, crystallized in different geometric forms, or colloidal. These unlike conditions of matter, and their different relations to gravity, pressure, temperature, sound, radiant energy, electricity, and magnetism, the phenomena of capillarity, and of the occlusion, diffusion, and transpiration of gases and liquids, indicate structural, or, as we sometimes term them, molecular differences in mineral species, which make up what we must include under the title of Structural Mineralogy.

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* Asa Gray, Structural and Systematic Botany ; Introduction.

† See the author on the Objects and Methods of Mineralogy ; Chemical and Geological Essays, p. 453.

§ 32. The changes of mineral species from one condition to another, and their transformations under the influences of the agencies already noticed, including the phenomena of chemism, which give rise to new species, make up together the dynamic and chemic activities of matter, which constitute the secular life of the planet. They are the geogenic agencies which, in the course of ages, have moulded the mineral mass of the earth, and from primeval chaos have evolved its present order, formed its various rocks, filled the veins in its crust with metals, ores, gems, and spars, and determined the composition of its waters and its atmosphere. They still regulate alike the terrestrial, the oceanic, and the aerial circulation, and preside over the constant change and decay by which the face of the earth is incessantly renewed, and the conditions necessary to organic life are maintained. To the study of these processes we may, with propriety, apply the name of Mineral Physiology.*

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* I have elsewhere made use of this term in speaking of the phenomena connected with the decay and transformations of silicated rocks, as belonging to "the domain of what I venture to call mineral physiology." Canadian Naturalist, 1880, new series, vol. ix., page 435.

As a comment upon the views expressed on pages 16–18, we here cite from an address by the writer on "The Relations of the Natural Sciences," Trans. Roy. Soc. Can., I., sec. iii., p. 4: "When we have attained to the conception of hylozoism, — of a living material universe, — the mystery of Nature is solved. The Cosmos is not, as some would have it, a vast machine wound up and set in motion with the certainty that it will run down, like a clock, and arrive at a period of stagnation and death. The modern theory of thermodynamics, though true within its limitations, has not grasped the problem of the universe. The force that originated and impelled, sustains, and is the Divine Spirit, which

"'Lives through all life, extends through all extent,
Spreads undivided, operates unspent.'"

"The law of birth, growth and decay, of endless change and perpetual renewal, is everywhere seen working throughout the Cosmos — in nebula, in world, and in sun, as in rock, in herb, and in man, all of which are but passing phases in the endless circulation of the universe, — in that perpetual new birth which we call Nature. This, it will be said, is the poet's view, but it is at the same time the one which seems forced upon us as the highest generalization of modern science."

II.

THE ORDER OF THE NATURAL SCIENCES.

The system of classification set forth in the preceding essay on Nature in Thought and Language was embodied in the following note presented to the American Association for the Advancement of Science, at Minneapolis, August, 1883. This was published at the time in Science, in the Proceedings of the Association, and also the same year as an appendix to an address, by the author, on The Relation of the Natural Sciences, in the Transactions of the Royal Society of Canada. Volume I., section iii., pages 7-8.

§ 1. THE study of material nature constitutes what the older scholars correctly and comprehensively termed physics (the words physical and natural being synonymous), and presents itself in a twofold aspect, first as descriptive, and second as philosophical, — a distinction embodied in the terms Natural History and Natural Philosophy, or more concisely, in the words Physiography and Physiology. The latter word has, from the time of Aristotle, been employed in this general sense to designate the philosophical study of nature, and will so be used in the present classification.

§ 2. The world of nature is divided into the inorganic or mineralogical, and the organic or biological kingdoms, the division of the latter into vegetable and animal being a subordinate one. The natural history or physiography of the inorganic kingdom takes cognizance of the sensible characters of chemical species, and gives us descriptive and systematic mineralogy, which have hitherto been restricted to native species, but in their wider sense include all artificial species as well. The study of native mineral species, their aggregations, and their arrangement as constituents of our planet, is the object of geognosy and of geography. The physiography of other worlds gives rise to descriptive astronomy.

§ 3. The natural philosophy of the inorganic kingdom, or mineral physiology, is concerned, in the first place, with what is generally called dynamics or physics, including the phenomena of ordinary motion, sound, temperature, radiant energy, electricity and magnetism. Dynamics, in the abstract, regards matter in general, without relation to species; chemism generates therefrom mineralogical or so-called chemical species, which, theoretically, may be supposed to be formed from a single elemental substance, or *materia prima*, by the chemical process. Dynamics and chemistry build up our inorganic world, giving rise to geogeny and, as applied to other worlds, to theoretical astronomy.

§ 4. Proceeding now to the organic kingdom, its physiographical study leads us first to organography, and then to descriptive and systematic botany and zoölogy, two great subdivisions of natural history. Coming next to consider the physiological aspect of organic nature, we note, besides the dynamical and chemical activities manifested in the mineral, other and higher ones, which characterize the organic kingdom. On this higher plane of existence are found portions of matter which have become individualized, exhibit irritability, the power of growth by assimilation, and of reproduction, and, moreover, establish relations with the external world by the development of organs, all of which characters are foreign to the mineral kingdom. These new activities are often designated as vital, but since this word is generally made to include at the same time other manifestations which are simply dynamical or chemical, I have elsewhere proposed for the activities characteristic of the organism the term biotics (βιοτικός, pertaining to life).

§ 5. The philosophy of matter in the abstract is dynamical, that of mineral species is both dynamical and chemical, while that of organized forms is at once dynamical, chemical, and biotical. The study of the biotical activities of matter leads to organogeny and morphology, while the relations of organisms to one another, and to the inorganic kingdom, give us physiological botany and zoölogy. We thus arrive at a comprehensive and simple scheme for the classification of the natural sciences, which is set forth in the subjoined table:—

Natural Sciences.	Inorganic Nature.	Organic Nature.
Descriptive. — General Physiography or Natural History.	Mineral Physiography. — Descriptive and Systematic Mineralogy; Geognosy; Geography; Descriptive Astronomy.	Biophysiography. — Organography; Descriptive and Systematic Botany and Zoölogy.
Philosophical. — General Physiology or Natural Philosophy.	Mineral Physiology. — *Dynamics or Physics;* *Chemistry.* Geogeny; Theoretical Astronomy.	Biophysiology. — *Biotics.* Organogeny; Morphology; Physiological Botany and Zoölogy.

III.

THE CHEMICAL AND GEOLOGICAL RELATIONS OF THE ATMOSPHERE.*

In addition to the details given in the footnote, it need only be said that this paper was published in the American Journal of Science for May, 1880 ([III.] xix., 349–363), and that a further discussion of some of the questions raised herein will be found in the following essay on Celestial Chemistry from the Time of Newton.

§ 1. QUESTIONS concerning the condition of the terrestrial atmosphere in former periods of the earth's history, and its geological relations, have occupied the attention of naturalists, physicists, and chemists. Brongniart long since suggested that the abundant vegetation of the coal period indicated the existence of a large proportion of carbonic acid in the air at that time. Ebelmen, however, appears to have been the first to clearly understand the great geological significance of the atmosphere, and in his two remarkable memoirs on the decomposition of rocks, published in the Annales des Mines in 1845 and 1847,† treated the subject in its atmospheric relations with much research and philosophic breadth. Starting from the chemical changes of crystalline silicate rocks, he considered both the conversion of feldspars into kaolin, and the

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* A summary of the views presented in this memoir was given at Dublin, in August, 1878, before the British Association for the Advancement of Science. An abstract thereof appeared in the Proceedings, and will be found in *Nature* for Aug. 29, 1878 (vol. xviii., p. 475). The principal conclusions of the memoir are also embodied in a communication made by the author to the French Academy of Sciences, and published in the Comptes Rendus of Sept. 23, 1878 (vol. lxxxvii., p. 452). They will moreover be found set forth in the preface to a second edition of the writer's Chemical and Geological Essays (pp. ix.–xix.) published in the spring of the same year.

† Fourth Series, vols. vii. and xiii. These memoirs will also be found in the Receuil des Trav. Scient. de M. Ebelmen; Paris, 1855, vol. ii., pp. 1–79.

decay of protoxide-silicates, such as amphibole and olivine. The sub-aerial decomposition of the feldspars had already been shown by Berthier to result in the separation, in a soluble form, of the protoxide-bases together with a portion of silica, from an insoluble aluminous silicate of definite composition. The analyses of Ebelmen now established the fact that the protoxide-silicates just mentioned, lose, under similar conditions, the whole of their lime and magnesia, and nearly the whole of their silica, leaving little behind save the higher oxides resulting from the fixation of atmospheric oxygen by the ferrous and manganous oxides of the silicates; the soluble bases being in all cases removed by atmospheric waters in the form of carbonates. Such a decomposition of these silicates shows that the removal of silica in soluble form does not depend on the intervention of alkalies.

§ 2. The atmosphere of our earth, at a pressure of 760 millimetres, has a weight of 10,333 kilograms to the square metre, of which the oxygen equals 2376, and the carbonic dioxide (if we take Boussingault and Léwy's determination of four and a half parts in 10,000 parts by weight) 4.64* kilograms. The alkali of 100 parts of orthoclase would require for its neutralization 7.8 parts of carbonic dioxide, so that a cubic metre of this silicate, of specific gravity 2.5, would, by the calculation of Ebelmen, fix, in the process of decay, 195 kilograms of the gas. From this it results that a layer of orthoclase over the earth of 0.0238 metre, or one of less than 1.0 metre over one-fortieth of its surface, would, in its decomposition, absorb the whole amount of this gas now present in the atmosphere. Ebelmen further calculated that the formation of a layer of kaolin by this process, 500 metres in thickness, would require an amount of carbonic dioxide equal to many times the weight of the present atmosphere.

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* This, by an error in Ebelmen's memoir, is given as only 1.24 kilograms.

§ 3. We have repeated and extended these calculations, with revised molecular weights, and with the following results: A cubic metre of orthoclase, with a density of 2.5, and containing theoretically 16.9 per cent of potash, equivalent to 7.89 of carbonic dioxide, would absorb in kaolinization 197.3 kilograms of this gas, while a cubic metre of albite of density 2.6, containing 11.8 of soda, equivalent to 8.37 of carbonic dioxide, would require not less than 217.6 kilograms of the same. The figure of 195 kilograms, adopted by Ebelmen, was thus below the truth, and we may, in view of the considerable proportion of soda-feldspar in the oldest crystalline rocks, conveniently assume 200 kilograms as the amount of carbonic dioxide required to unite with the alkali from a cubic metre of orthoclase or albite, and form therewith a neutral carbonate.

§ 4. In such a decomposition, 100 parts of orthoclase give theoretically about 46.5 parts of kaolin, so that 1.0 metre in thickness of orthoclase of the above density should yield 0.447 metre of kaolin of density 2.6. If we assume this process to have consumed for a cubic metre or 2500 kilograms of orthoclase, 200 of carbonic dioxide, we find that a layer of 51.66 metres of orthoclase, or its equivalent of quartzo-feldspathic rock, in undergoing the same change, would absorb 10,333 kilograms of this gas, equal to the entire weight of the present atmospheric column, and would yield a layer of pure kaolin 23.7 metres in thickness. The production of a stratum of kaolin 500 meters in thickness over the whole surface of the globe, would thus require an amount of carbonic dioxide equal to more than twenty-one times the entire weight of our present atmosphere.

§ 5. The absorption of this gas in the decay of silicates like hornblende, pyroxene, and olivine is far greater. If we assume, for convenience, a hornblende containing 20.0 per cent of magnesia, and 14.0 of lime, with a density of 3.0 (which figures are not above the average), we find that it will require 33.0 per cent, or, in round numbers, one-third its weight of carbonic dioxide to convert these two bases into neutral carbonates; so that a metre-cube of hornblende, weighing 3000 kilograms, would consume not less than 1000 kilograms of carbonic dioxide. In other terms, the decay of 10⅓ metres of such hornblende (or its equivalent in hornblendic rock) would absorb 10,333 kilograms, or a whole atmosphere of this gas, being five times as much as is taken up in the kaolinization of the same volume of orthoclase.

§ 6. The hornblendes in question are seldom without several hundredths of iron as ferrous oxide, which is peroxidized in the process of decay, and, with a little silica, is the chief insoluble residue in the case of non-aluminous hornblendes. In this connection, we revert to a farther calculation by Ebelmen, who pointed out that the conversion of 21,357 kilograms of ferrous oxide into 23,750 kilograms of ferric oxide would consume the whole of the 2373 kilograms of oxygen contained in the present atmosphere; so that if we suppose the existence over the whole earth of 1000 metres of sediments derived from the decay of crystalline rocks, and containing only one per cent of ferric oxide thus formed, this amount would equal 25,000 kilograms per square metre of surface, requiring for its production from ferrous oxide the absorption of a quantity of oxygen more than equal to that now contained in our atmosphere.

§ 7. Ebelmen, at the same time, referred to the well-known deoxidation of carbonic dioxide by growing vegetation, and also to the reduction, by decaying organic matters, of sulphates to sulphides, with reproduction of carbonic dioxide, through which the generation of metallic sulphides in nature gives to the atmosphere, in union with carbon, a portion of the oxygen previously combined with sulphur and with the metals.

The following calculations may serve to bring still more fully before us the great geological significance of these atmospheric changes. The weight of a layer of pure carbon, with a density of 1.25 and a thickness of 0.7 metre, would require for its conversion into carbonic dioxide the whole of the oxygen of our present atmosphere. The separation of such an amount of carbon by the process of vegetable growth must therefore have liberated the same volume of oxygen. Again, a stratum of carbonate of lime of specific gravity 2.7, covering the earth with a thickness of 8.69 metres (or one of dolomite of 2.85, and 7.58 metres thick), would contain an amount of carbonic dioxide equal in weight to the present atmosphere.*

§ 8. It was in view of these processes that Ebelmen declared, in 1845, that "the decomposition and the reproduction of certain mineral species very abundant on the surface of the globe corresponds to important modifications in the composition of the atmosphere." He farther said, "Many circumstances tend to prove that in ancient geological periods the atmosphere was denser, and more rich in carbonic acid, and perhaps in oxygen, than at present. To a greater weight of the atmospheric envelope would correspond a stronger condensation of the solar heat, and atmospheric phenomena of a much greater intensity." † Similar conclusions with regard to the physical relations of a denser primeval atmosphere were subsequently announced by the late Edwin B. Hunt, in an essay on Terrestrial Thermotics, presented to the American Association for the Advancement of Science, in 1849, and published in its Proceedings for that year, page 135.

§ 9. We may get a clearer notion of the problem before us by inquiring into the probable amounts of carbonic dioxide which have, in past ages, been abstracted from the atmosphere. In a communication to the British

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* T. Sterry Hunt on the Primeval Atmosphere, Proc. Amer. Assoc. Adv. Science, 1866, and Can. Naturalist, II., iii., 118.

† Ann. des Mines, IV., vii., 65; also Receuil des Trav. Scient. de M. Ebelmen. vol. ii., p. 55.

Association for the Advancement of Science, in 1877,* Mr. J. L. Mott concludes, as the result of calculations, that the average amount of unoxidized carbon to a square mile of the earth's crust cannot be less, and is probably many times greater than 3,000,000 tons; while a layer of 0.7 metres of carbon of density 1.25 (about that of coal), which we have calculated to be equal to the total atmospheric oxygen, would weigh only about 2,200,000 tons to the square mile. Mr. Mott rightly argues that the presence in the atmosphere of so great an amount of carbon in the form of dioxide would imply a condition of things incompatible with the existence of animal life, and at the same time concludes that its deoxidation would yield an excessive amount of oxygen. He is hence led to assume the existence in the earth of a constant amount of carbon, which is subject to an annual subterranean oxidation equal to the amount of carbon annually removed by vegetation; the source of the original amount of carbon being, in his hypothesis, left unexplained.

§ 10. While some have imagined an inorganic origin to the carbon found in the form of graphite, and even to petroleum and to coal, sound reasoning is, we think, on the side of those who, starting from the conception of an originally oxidized globe, see no evidence of any process of deoxidation therein which does not, directly or indirectly, depend upon vegetable life, and hence assign an organic origin to all carbons and hydrocarbons. When we take into account the vast amounts of these, from the graphite of Eozoic times to the coals, lignites, and petroleums of the Tertiary, we can scarcely doubt that the total amount of carbon which has been reduced from carbonic dioxide is equal to many times the equivalent of the oxygen now present in the atmosphere. Whether the great excess of oxygen thus liberated may perhaps have been absorbed in the production of ferric oxide, as above indicated, is a part of the problem before us.

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* Nature, vol. xvi., p. 406.

§ 11. It may here be noted that in addition to the fossil carbonaceous bodies already mentioned, the rocky strata of the earth include great thicknesses of pyroschists, which are argillaceous sediments more or less impregnated with hydrocarbonaceous matters allied to coal in composition. To give a single example, Newberry estimates the proportion of such matters diffused through the three hundred or four hundred feet of Devonian black shales which underlie the eastern half of Ohio, to equal fifteen per cent, and to be equivalent to a layer of coal fifty feet in thickness over the whole area.*

In this connection it must be considered that the chemical composition of the various hydrocarbonaceous fossil substances implies a deoxidation not only of carbonic dioxide but of water. The amount of liberated oxygen from the latter would equal, for the different coals and asphalts, from one-eighth to one-fourth, and for the petroleums, one-half of that set free in the deoxidation of the carbon which these hydrocarbonaceous bodies contain.

§ 12. The amount of carbon removed from the atmosphere in a deoxidized form by vegetation is, however, small when compared with that which has been absorbed during the decomposition of silicates, and is now fixed as insoluble carbonates, chiefly in the form of limestones and dolomites. That both the alkaline carbonates liberated in the decay of feldspars, and the magnesian carbonate set free in like manner from magnesian silicates, must decompose the chlorid of calcium contained in the primitive ocean, thereby giving rise to alkaline and magnesian chlorides on the one hand, and to carbonate of lime on the other, is a consequence which seems to have escaped Ebelmen, and was pointed out by the present writer in 1858. In 1862, however, there was opened a sealed packet which had been in 1844 deposited by Cordier with the French Academy of Sciences, and was found to contain views as

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* Geology of Ohio, vol. i., page 162.

to the origin of limestones and of sea-salt similar to those just stated.* Thus, in the present state of our knowledge, we conclude that all carbonates of lime, whether directly formed by the decay of calcareous silicates, or indirectly through the intervention of carbonates of magnesia or alkalies, derive their carbonic dioxide from the atmosphere. The same must be said for the dolomites, magnesites, and siderites.

§ 13. We have already shown that a weight of carbonic dioxide equal to more than twenty-one times that of our present atmosphere would be absorbed in the production from orthoclase of a layer of kaolin extending over the earth's surface with a thickness of five hundred metres, an amount which evidently represents but a small proportion of the results of feldspathic decay in the sedimentary strata of the globe. The aluminous silicates in the oldest crystalline rocks occur in the forms of feldspars and related species, and are, so to speak, saturated with alkalies or with lime. It is only in more recent formations that we find aluminous silicates either free or with reduced amounts of alkali, as in the argillites and clays, in micaceous minerals like muscovite, margarodite, damourite, and pyrophyllite, and in kyanite, fibrolite, and andalusite, all of which we regard as derived indirectly from the more ancient feldspars.†

§ 14. It has been shown that the disengagement of the carbonic dioxide from a layer of limestone covering the

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* Hunt, Chem. and Geol. Essays, pp. 2 and 20.

† These considerations, and their stratigraphical bearings, first set forth in 1863 (Chem. and Geol. Essays, pp. 27 and 28), will be found further developed in the writer's report on Azoic Rocks, 2d Geol. Survey of Penn., 1878, p. 210. It is a question how far the origin of the various crystalline aluminous silicates named above is to be sought in a process of diagenesis in ordinary aqueous sediments holding the ruins of more or less completely decayed feldspars. Other aluminous rock-forming silicates, such as chlorites and magnesian micas, are however connected, through aluminiferous amphiboles, with the non-aluminous magnesian silicates, and to all these various magnesian minerals a very different origin must be assigned. [See in this connection Essay V., The Origin of Crystalline Rocks, etc.]

earth's surface with a thickness of 8.69 metres, would double the weight of the atmosphere. The existence of vast formations of limestone and dolomite, often many hundred metres in thickness, throughout all geological periods, will, it is believed, justify the conclusion that the carbonates of the earth's crust are equal to a continuous layer of limestone 869 metres thick, and probably to more than double this amount. From this it would follow that the earth contains, fixed in the form of carbonates, a quantity of carbonic dioxide, which, if liberated in a gaseous form, would be equal in weight to one hundred if not to two hundred atmospheres like the present. A considerable portion of this was doubtless absorbed at an early period in the history of our globe, since the limestones of the Eozoic age are of great thickness, and those of more recent times have been in part formed by the solution and re-deposition of portions of these older limestones.

§ 15. The question now arises, whence came this enormous volume of carbonic dioxide which, since the dawn of life on our planet, has been fixed in the form of carbon and carbonates? The presence of even a small proportion of it at any one time in the terrestrial atmosphere is evidently incompatible with the existence of vegetable and animal life. and it may be added that the pressure of a column of this gas less than the minimum of 100 atmospheres which we have supposed, would suffice, at ordinary temperatures, for its partial liquefaction; the tension of liquid carbonate dioxide at 30°.7 C. being, according to Marcska and Donny, but eighty atmospheres. We are therefore forced to the conclusion that this gas was gradually supplied from a source either within the earth or beyond our atmosphere.

§ 16. The difficulties of this problem were not overlooked by Ebelmen, though he apparently failed to recognize their full weight. He takes care to remark: "I do not pretend that this immense proportion of carbonic acid ever made part, at any one time, of the terrestrial atmosphere. . . . I see in volcanic phenomena the principal agent which restores to the atmosphere the carbonic acid which the decomposition of rocks removes from it." He then inquires whether the carbonic acid (carbonic dioxide) evolved from the earth's interior, comes from the decomposition of carbonates at great depths and high temperatures by reactions with silicious matters, or whether we may imagine, with Élie de Beaumont, the existence of an immense reservoir of carbonic acid dissolved in the supposed liquid interior of the earth as oxygen is held in fused litharge or in molten silver. In either case, remarks Ebelmen, the cessation of volcanic phenomena would be followed by the removal from the atmosphere of the last traces of carbonic acid, a process which would entail the extinction of all vegetable and animal life.

§ 17. Of these two suggested sources of the terrestrial carbonic dioxide, a little reflection will show that although the first is doubtless a true one, and will serve to account for that which is so often disengaged from the earth, both in volcanic and non-volcanic regions (having a similar origin to the chlorhydric, sulphuric and boric acids evolved under analogous conditions — namely, the decomposition of saline compounds of aqueous origin),* it by no means meets the requirements of the problem. As preceding calculations have shown, it is not a question of a small amount of carbonic dioxide alternately removed from our atmosphere by sub-aerial reactions and restored to it by subterranean processes, but of a vast quantity of this gas which, at one time or another, has existed in the terrestrial atmosphere, but is now removed from the aerial circulation and locked up in the form of carbonates.

§ 18. As regards the second source of carbonic dioxide, suggested by Ebelmen after Élie de Beaumont, it is, unlike the last, purely hypothetical. That the globe has a molten interior is, in the present state of our knowledge

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* Hunt, Chem. and Geol. Essays, pp. 8 and 111.

of terrestrial physics, very improbable, and if such exists, the notion that it intervenes directly in volcanic phenomena is still more so. The suggestion that such a molten interior might hold dissolved a great volume of carbonic dioxide appears, moreover, to be inconsistent with what we know of the behavior of furnace-slags, which, though formed in atmospheres highly charged with this gas, do not, as shown by their behavior in cooling, hold it in solution. The tendencies of modern geological thought and investigation, it may be said, lead to the conclusion that the seat of volcanic phenomena is to be found in sedimentary strata,* and that although the earth's interior intervenes as a source of heat, the carbonic dioxide disengaged from its crust is derived, as in the first hypothesis mentioned by Ebelmen, from the decomposition of carbonates previously generated by subaerial re-actions.

§ 19. The problem still before us is then to find the source of the vast amount of carbonic dioxide continuously supplied to the atmosphere throughout the geologic ages, and as continuously removed therefrom, and fixed in the form of carbonaceous matters and limestones. We have shown reasons for rejecting the theory which would derive this supply either from the earth's interior or from its own primal atmosphere, and must therefore look for it to an extra-terrestrial source. The new hypothesis, which we here advance, starts with the assumption that our atmosphere is not primarily terrestrial but cosmical, and that the air, together with the water surrounding our earth (whether in a liquid or a vaporous state), belongs to a continuous elastic medium which, extending throughout the interstellary spaces, is condensed around attracting bodies in amounts proportional to their mass and temperature. This universal atmosphere (if the expression may be permitted) would then exist in its most attenuated form in the regions farthest distant from these centres

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* Chem. and Geol. Essays, pp. 59–67; also, farther, V. § 127.

of attraction; while any change in the gaseous envelope of any globe, whether by the absorption or condensation, or by the disengagement of any gas or vapor, would, by the laws of diffusion and static equilibrium, be felt everywhere throughout the universe.

§ 20. The precipitation of water at the surface of a cooling globe, and its chemical or mechanical fixation there, would thus diminish the proportion of gaseous water throughout all space. The oxygen liberated in the growth of terrestrial vegetation would be shared with the remotest spheres, while the condensation of carbonic dioxide at the surface of our own or any other planet, would not only bring in a supply of this gas from the atmospheres of other bodies, but by reducing the total amount of it, would diminish, *pro tanto*, the barometric pressure at the surface of this and of all other worlds.

§ 21. The hypothesis here advanced is not wholly new. Sir William R. Grove, in 1842, suggested that the medium of light and heat may be "a universally diffused matter," and subsequently, in 1843, in his celebrated Essay on the Correlation of Physical Forces, in the chapter on Light, concludes, with regard to the atmospheres of the sun and planets, that there is no reason why these atmospheres "should not be, with reference to each other, in a state of equilibrium. Ether, which term we may apply to the highly attenuated matter existing in the interplanetary spaces, being an expansion of some or all of these atmospheres, or of the more volatile portions of them, would thus furnish matter for the transmission of the modes of motion which we call light, heat, etc., and *possibly minute portions of these atmospheres may, by gradual accretions and subtractions, pass from planet to planet, forming a link of material communication between the distant monads of the universe.*" Subsequently, in his address as President of the British Association for the Advancement of Science, in 1866, Grove further suggested that this diffused matter might become a source of solar heat, inasmuch as the sun "may condense gaseous matter as it travels in space, and so heat may be produced."

§ 22. This bold speculation of a universally diffused matter, constituting an interstellary medium, though thus repeatedly insisted upon by Grove, has passed almost unnoticed. It seems to have been unknown to Mr. W. Mattieu Williams, who, in 1870, published his very ingenious work entitled "The Fuel of the Sun,"* which is based on a similar conception, without citing in support of it the high authority of Grove. The solar heat, according to Williams, is maintained by the sun's condensation of the attenuated matter everywhere encountered by that body in its motion through interstellary space. The irregular movements impressed upon the sun by the varying attractions of the planets — stirring up and intermingling the different strata of the solar atmosphere, and producing the great perturbations therein of which the telescope affords evidence — are, in his hypothesis, the efficient agents in this process. The diffused matter or ether, which is the recipient of the heat-radiations of the universe, is thereby drawn into the depths of the solar mass; expelling thence the previously condensed and thermally exhausted ether, it becomes compressed, and gives up its heat, to be, in turn, itself driven out in a rarefied and cooled state, and to absorb a fresh supply of heat, which he supposes to be in this way taken up by the ether, and again concentrated and re-distributed by the suns of the universe. (Loc. cit., chap. v.)

§ 23. Neither Grove nor Williams has considered the hypothesis of an interstellary medium in its geological relations. Dr. P. Martin Duncan, however, in his address as President of the Geological Society of London, in May, 1877, without noticing the priority of Grove, has adopted

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* See also Williams on The Radiometer and its Lessons. Quart. Jour. Science, October, 1876.

it from Williams,* but instead of supposing, with these, that the atmospheres of all bodies are in equilibrium, conceives the sun, in virtue of its greater mass, to be slowly attracting to itself the earth's terrestrial envelope. He then proceeds to deduce therefrom important geological considerations, maintaining that from the greater height of the terrestrial atmosphere which, according to this view, must have prevailed in former ages, there would have resulted a higher temperature at the earth's surface, more aqueous vapor, and a more equable climate. From a more abundant precipitation would also follow greater sub-aerial denudation, while the formation of ice, though it might occur in elevated regions, would be impossible at or near the sea-level.

§ 24. The correctness of all these deductions by Duncan from the condition of a denser terrestrial atmosphere appears to be indisputable, and, as we shall endeavor to show in the sequel, they are in harmony with the geological record. But, while admitting that changes in the earth's atmosphere conducing to such results have taken place, we maintain, in accordance with the principles already laid down, that these changes have not been due to solar attraction and absorption, but to the chemical and mechanical processes going on at the surface of the earth and other bodies in space, whereby the atmospheric elements are condensed in the forms of liquid and solid water, or fixed as hydrates, oxides, carbonates and hydrocarbonaceous matters.

§ 25. The changes which have thus been produced in the terrestrial atmosphere are, by our hypothesis, reduced in amount by being shared with other worlds, and the consequences which Ebelmen, and others after him, have

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* It is due to my friends, Mr. Williams and Dr. Duncan, to say that they have both, in conversation, informed me that they were ignorant of the priority of Sir William Grove. The conception appears to have been original and independent in the mind of Mr. Williams. [For the views of Zöllner as to the interstellary atmosphere, see below, page 64.]

deduced with regard to the temperature of the earth's surface in former geological periods, would seem, at first sight, to be invalidated. Tyndall, however, in 1861, from a consideration of the great power of absorbing heat possessed alike by aqueous vapor and by certain gases, such as carbonic dioxide, and the consequent effects of small quantities of these in the atmosphere on terrestrial radiation, and thus on climate, was led to remark, "It is not therefore necessary to assume alterations in the density and height of the atmosphere to account for different amounts of heat being preserved to the earth in different times; a slight change in its variable constituents may have produced all the mutations of climate which the researches of geologists reveal."* Thus, although the amount of carbonic dioxide which in past geological ages has been, by chemical processes at the surface of our own and other worlds, abstracted from the universal medium, may not have sufficed to diminish by more than a small fraction the barometric pressure at the earth's surface, this change would still meet all the requirements of geological history, so far as temperature and climate are concerned. From this point of view the suggestion of Tyndall assumes a weight and a significance not hitherto suspected.

§ 26. We have thus briefly endeavored to show how the hypothesis of a universal atmosphere serves to explain certain chemical and physical facts in the history of our globe. To discuss it in all its bearings would require a volume. The climatic influences of a denser terrestrial atmosphere, or one of greater absorptive power than the present, have been indicated by Ebelmen, E. B. Hunt, and Duncan, and, as we have seen, the gradual changes in the composition of the atmosphere imply a slow progressive diminution of the mean annual temperature of the earth's

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* Tyndall, Bakerian Lecture for 1861; L., E. & D. Phil. Mag., October, 1861, and Hunt, Chem. and Geol. Essays, pp. 42 and 46.

surface. This conclusion is in contradiction with the hypothesis of secular oscillations of the earth's temperature, due to astronomical causes, and giving rise to successive periods characterized by general glaciation, and leads us to interrogate on this point the geological record. We may inquire (1) whether, since the appearance of terrestrial vegetation, the mean annual temperature of the earth has ever been less, and (2) whether it has ever been greater than at present. It is clear from paleontological evidence that a very warm climate prevailed over the arctic regions during the Carboniferous, Triassic, Jurassic, and Lower Cretaceous periods, and that the refrigeration apparent in the Upper Cretaceous gradually augmented up to the Pliocene, the cold of which has continued till now, subject to certain variations in its distribution which are readily accounted for by changed geographical conditions. Such changes of sea and land are, however, inadequate to explain the elevated temperature which, according to the observations of Nordenskiöld, prevailed in the Carboniferous age, when the arctic climate permitted the development, over a great area of land, of a vegetation not unlike the Carboniferous flora of the inter-tropical regions. It is not easy to conceive that, with an atmosphere like that of the present time, any geographical conditions could maintain during the long polar winter the mild climate required for such a vegetation, even in insular regions, and still less over a continental area within the polar circle.

§ 27. We are thus led to the conclusion that geographical changes, though adequate to explain the greater refrigeration of certain areas since the beginning of Pliocene time, are not sufficient to account for the warmer climates of previous ages, and to find the explanation of these in the different relations of the earlier atmosphere alike to solar and to terrestrial heat. It is, however, obvious that, with such an atmosphere as we have supposed, the more elevated portions of the earth's surface might, as is now the case in inter-tropical lands, be lifted into regions where glaciation was possible, while a warm climate prevailed everywhere at the sea-level. Neither the glacial periods of more recent times, nor those of remoter geological ages, of which evidence is not wanting, necessarily depend upon any diminution in the earth's mean annual temperature at the sea-level. Glacial periods are, in this view, as has been well said by J. F. Campbell, not celestial, but local and terrestrial,* while, on the contrary, the warmer polar climates of Paleozoic and Mesozoic times are to be regarded as evidence of a generally elevated temperature at the earth's surface depending on atmospheric conditions, as already set forth.

§ 28. In a note in the Comptes Rendus of the French Academy of Sciences for October 7, 1878, criticising my previous one of September 23, "Sur les relations géologiques de l'atmosphère," already referred to at the beginning of this paper, Mr. Stanislas Meunier has argued in favor of the terrestrial origin of the atmospheric carbonic dioxide, the source of which he supposes to be a subterranean oxidation of a primitive store of carbon, a view that seems unsupported by any facts or analogies in nature. He opposes to the hypothesis which I have advocated, the fact of the absence of an atmosphere from the moon, while he asserts the existence of an abundant one around both Mercury and Venus. The evidences of such an atmosphere around the latter planet are well known, but the observations of recent astronomers leave it doubtful, on the contrary, whether Mercury possesses a perceptible one, while, as regards our satellite, the conclusion, as stated by Newcomb, is that the lunar atmosphere, if it exists, is not equal to more than one four-hundredth that of the earth.

§ 29. A little reflection will, however, show that the absence of any apparent atmosphere from the moon in no

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* Campbell, on Glacial Periods; Quart. Jour. Geol. Soc., 1879, vol. xxxv., p. 98.

way militates against our hypothesis, since a completely refrigerated globe, such as our satellite must probably be, would long since have absorbed mechanically into its interstices its share of the universal gaseous medium. It was many years since pointed out by Sæmann * that, as a consequence of the progressive refrigeration of our planet, the ocean and the air which surround it must one day disappear from its surface. The total volume of our atmosphere, at the density which it has at the sea-level, is, according to his calculation, less than four thousandths of that of the earth, the volume of the ocean being very much less. There is no known mass of cooled rock which has not a greater porosity than is represented by these figures, so that the conclusion seems inevitable that, with the complete refrigeration of the earth which must come in the course of ages, its atmosphere, following the ocean, will have so completely sunk into the pores of the cooled mass that its tension at the surface would be very small. Such a condition of things Sæmann supposes to have been already attained in our satellite, a view which may be, with equal probability, extended to Mercury.

§ 30. The hypothesis that interstellary space is filled with an attenuated matter which, in a more condensed form, constitutes the atmosphere and the waters of our own and other worlds, which we have already discussed in some of its chemical and geological bearings, assumes a new interest in connection with recent speculations as to evolution in the stellar universe. In considering the increasing chemical complexity revealed by the spectroscope in passing from nebulæ to white, yellow, and red stars, Prof. F. W. Clarke, of Cincinnati, was led in 1873 † to suggest the possibility of a generation of the higher from simpler forms of matter by a process of cosmical

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* Sur l'unité des phénomènes géologiques dans le système planétaire du soleil, Bull. Soc. Géol. de Fr., 1860–61, vol. xviii., p. 322, translated by the present writer for the Amer. Jour. Science, II., xxxiii., p. 36.

† Popular Science Monthly, Jan., 1873, vol. ii., p. 32.

chemistry. A similar view was a few months later advanced by Mr. Lockyer, who reiterated and enforced these suggestions, showing that the chemical elements make their appearance in the cooling stars in the order of their vapor-densities — and moreover connected these considerations with the conjectures of Dumas as to the probably compound nature of the so-called elements.* Mr. Lockyer has since extended this inquiry by his ingenious and beautiful spectroscopic studies, the results of which are embodied in his "Discussion of the Working Hypothesis that the so-called Elements are Compound Bodies," communicated to the Royal Society, December 12, 1878.† In his first note, of 1873 (which is embodied in the later paper), he suggested that we see in the stars evidences of a celestial dissociation under the influence of intense heat, which, continuing the work of our furnaces, would break up the metalloids, and leave only the metallic elements of low equivalent weight which are found in the hottest stars. In his later memoir he further suggests that as there may be no superior limit to temperature, so of dissociation there may be no end.

§ 31. With these may be compared the views enunciated by the present writer in a lecture before the Royal Institution, May 31, 1867, wherein, discussing the problems of stellar chemistry, he declared that the "dissociation of elements by intense heat is a principle of universal application," and with regard to the chemical elements, that their "further dissociation in stellar or nebulous masses may give us evidence of matter still more elemental than that revealed by the experiments of the laboratory, where we can only conjecture the compound nature of many of the so-called elementary substances." ‡ In

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* Comptes Rendus, Nov. 3, 1873.

† Amer. Jour. Science, III., xvii., 93-116; and farther, Clarke, Science News, Feb. 15, 1879, p. 114.

‡ Reprinted from Proc. Royal Institution in Chem. and Geol. Essays, p. 37.

1874, while discussing the speculations of Dumas, Clarke, and Lockyer, he further suggested that the green line in the spectrum of the solar corona, which had been supposed to indicate a hitherto unknown element, may be a "more elemental form of matter, which, though not seen in the nebulæ, is liberated by the intense heat of the solar sphere, and may possibly correspond to the primary matter conjectured by Dumas, having an equivalent weight one-fourth that of hydrogen." * Regarding this supposed element in the solar atmosphere, Prof. C. A. Young remarks that it must be of excessive tenuity, "a near relative, so far as gravity is concerned, to the luminiferous ether, and to the *Urstoff* of the German speculators." † In this connection it should be mentioned that Hinrichs, in 1866, put forth an argument ‡ in favor of the existence of such a primitive matter or *Urstoff* from a consideration of the wave-lengths in the spectra of the various elements. §

§ 32. Lavoisier long since suggested that hydrogen, nitrogen, and oxygen are, with heat and light, the simpler forms of matter from which all others are derived, and

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* A Century's Progress in Theoretical Chemistry, by T. S. Hunt, being an address delivered on the Centennial of Chemistry, at Northumberland, Penn., July 31, 1874; Amer. Chemist, vol. v., pp. 46-51, and Pop. Science Monthly, vii., 420.

† Amer. Jour. Science, II., xlii., 350-368.

‡ *Ibid*, III., i., 319.

§ Since these pages were in type my attention has been called to a paper read before the Literary and Historical Society of Quebec in January, 1870, by James Douglas, Jr., then President of the Society, and one of the Canadian expedition to observe the total solar eclipse of August 7, 1869. Therein, while discussing the spectroscopic observations made during the eclipse, he refers to those of Professor Young, who had suggested a comparison between certain lines in the spectrum of the solar corona and those observed by Winlock in that of the aurora borealis. With regard to these lines, Mr. Douglas then adds, "May they not therefore belong to some unknown element;—a gas lighter than hydrogen, which, like the hypothetical ether, fills space?" To this he adds the suggestion that electricity, both "in the auroral light of our own heavens and the corona of the sun, may render this hypothetical gas luminous." *Trans. Lit. and Hist. Soc. of Quebec*, New Series, part 7, p. 82.

when it is considered that the first two of these are the only elements of which we have yet any certain evidence in the nebulæ, it will be seen that the speculation of Lavoisier is really an anticipation of that view to which spectroscopic study has led the chemists of to-day. The three elements named by him are those which, in the forms of air and watery vapor, make up nine hundred and ninety-nine thousandths of the atmosphere which, in accordance with our hypothesis, constitutes the interstellary medium. It was in view of all these considerations that the writer in 1874 ventured to say that "the nebulæ and their resultant worlds may be evolved by a process of chemical condensation from this universal atmosphere; to which they would sustain a relation somewhat analogous to that of clouds and rain to the aqueous vapor around us."* Such a speculation, which seeks for a source of the nebulous matter itself, is perhaps a legitimate extension of the nebular hypothesis.

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* A Century's Progress, etc., cited above; also Chem. and Geol. Essays, preface to 2d ed., p. xix.

IV.

CELESTIAL CHEMISTRY FROM THE TIME OF NEWTON.

This Essay, read before the Philosophical Society of Cambridge, England, November 28, 1881, and published in its Proceedings (Vol. IV., part iii.), was reprinted in the Chemical News, and also in the American Journal of Science for February, 1882 ([III.] xxxiii., 123–133). A paper on "The Conservation of Solar Energy," by C. W. Siemens, was received by the Royal Society of London, February 20, 1882, and published in its Proceedings, Number 219, and also in Nature, vol. xxv., p. 440. Its author therein called attention to my recent essay which had made known to him the ideas of Newton, and, after repeating my story of the "Hypothesis touching Light and Color," adds, "And now once more a philosopher on the other side of the Atlantic brings back to the birthplace of Newton his forgotten and almost despised work of two hundred years ago." Siemens admitted, with Grove, Williams, and myself, the existence of attenuated matter in space, which he supposed to include oxygen, nitrogen, hydrogen, aqueous vapor, and carbon compounds, besides solid materials, probably exhalations from the sun which constitute the so-called cosmic dust. In my review of the paper of Siemens (Nature, April 27, 1882; vol. xxv., p. 613) I have called attention to the fact that already in a communication to the French Academy of Science, September 23, 1878, cited below (Comptes Rendus, vol. xxxviii., p. 452), on the subject of an interstellary medium as affording a means of material communication between celestial bodies, I suggested a similar origin of cosmic dust, saying, "Cette théorie d'une échange universelle me paraît fournir une explication de l'origine des poussières cosmiques." My criticism from Nature will be found reprinted, with much other literature on the subject, in a volume by Siemens, in 1883, "On the Conservation of Solar Energy."

In explanation of its concluding paragraph it should be said that the author, who had sketched the outline of the present essay in Italy, some weeks before, and proposed to complete it in London, was unexpectedly called thence to Cambridge, a few days before the time which had been assigned for its presentation, and was a guest in quarters in the Master's Court of Trinity College, where, near the rooms formerly occupied by Newton, in the same court, he was obliged to finish the essay which had been promised to the Philosophical Society.

§ 1. THE late W. Vernon Harcourt, in 1845,[*] called attention to the remarkable perception of great chemical truths which is apparent in the Queries appended to the third book of Newton's *Optics*, as well as in his Hypothesis touching Light and Color. With regard to the latter, Harcourt then remarked, "It has, I think, scarcely been quoted, except by Dr. Young, and its existence is but little known, even among the best-informed scientific

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[*] L., E. and D. Philos. Magazine, III., xxviii., 106 and 478; also xxix., 185.

men." The essay in question was read before the Royal Society, December 9 and 16, 1675, but remained unpublished till 1757, when Birch, at that time secretary to the Society, printed it, not without verbal inaccuracies, in the third volume of his History of the Royal Society; a work intended to serve as supplement to the Philosophical Transactions up to that date. In 1846, at the suggestion of Harcourt, the Hypothesis of Newton was again printed in the L., E. and D. Philosophical Magazine (volume xxix.), and it subsequently appeared in the Appendix to the first volume of Brewster's Memoirs of Sir Isaac Newton, in 1855.

The time has come for further inquiries into the science of Newton, and I shall endeavor to show that a careful examination of the writings of our great natural philosopher, in the light of the scientific progress of the last generation, renders still more evident the wonderful prevision of him who already two centuries since had anticipated most of the recent speculations and conclusions regarding cosmic chemistry.

§ 2. As an introduction to the inquiries before us, and in order to show the real significance of the speculations of Newton, it will be necessary to review, somewhat at length, the history of certain views, enunciated almost simultaneously by the late Sir Benjamin Brodie, of Oxford, and the present writer, and subsequently developed and extended by the latter. In part I. of his Calculus of Chemical Operations, read before the Royal Society, May 3, 1866, and published in the Philosophical Transactions for that year, Brodie was led to assume the existence of certain ideal elements. These, he said, "though now revealed to us through the numerical properties of chemical equations only as *implicit and dependent existences*, we cannot but surmise may sometimes become, or may in the past have been, *isolated and independent existences*." Shortly after this publication, in the spring of 1867, I spent several days in Paris with the late Henri Sainte-

Claire Deville, repeating with him some of his remarkable experiments in chemical dissociation, the theory of which we then discussed in its relations to Faye's solar hypothesis.

§ 3. From Paris, in the month of May, I went, as the guest of Brodie, for a few days to Oxford, where I read for the first time, and discussed with him, his essay on the Calculus of Chemical Operations, in which connection occurred the very natural suggestion that his ideal elements might perhaps be liberated in solar fires, and thus be made evident to the spectroscope. I was then about to give, by invitation, a lecture before the Royal Institution in London on the Chemistry of the Primeval Earth, which was delivered May 31, 1867. A stenographic report of the lecture, revised by the author, was published in the Chemical News of June 21, 1867, and in the Proceedings of the Royal Institution.* Therein, I considered the chemistry of nebulæ, sun, and stars in the combined light of spectroscopic analysis and Deville's researches on dissociation, and concluded with the generalization that the "breaking-up of compounds, or dissociation of elements, by intense heat is a principle of universal application, so that we may suppose that all the elements which make up the sun, or our planet, would, when so intensely heated as to be in the gaseous condition which all matter is capable of assuming, remain uncombined; that is to say, would exist together in the state of chemical elements; whose further dissociation in stellar or nebulous masses may even give us evidence of matter still more elemental than that revealed in the experiments of the laboratory, where we can only conjecture the compound nature of many of the so-called elementary substances."

§ 4. The importance of this conception, in view of subsequent discoveries in spectroscopy and in stellar chemistry, has been well set forth by Lockyer in his late

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* See also Hunt's Chemical and Geological Essays, pp. 35–45.

lectures on Solar Physics,* where, however, the generalization is described as having been first made by Brodie in 1867. A similar but later enunciation of the same idea by Clerk-Maxwell is also cited by Lockyer. Brodie, in fact, on the 6th of June, one week after my own lecture, gave a lecture on Ideal Chemistry before the Chemical Society of London, published in the Chemical News of June 14, in which with regard to his ideal elements, in further extension of the suggestion already put forth by him in the extract above given from his paper of May 6, 1866, he says, "We may conceive that in remote ages the temperature of matter was much higher than it is now, and that these other things [the ideal elements] existed in the state of perfect gases — separate existences — uncombined." He further suggested, from spectroscopic evidence, that it is probable that "we may one day, from this source, have revealed to us independent evidence of the existence of these ideal elements in the sun and stars."

During the months of June and July, 1867, I was absent on the continent, and this lecture of Brodie's remained wholly unknown to me until its republication in 1880, in a separate form, by its author,† with a preface, in which he pointed out that he had therein suggested the probable liberation of his ideal elements in the sun, referring at the same time to his paper of 1866, from which we have already quoted the only expression bearing on the possible independence of these ideal elements somewhere in time or in space.

§ 5. The above statements are necessary in order to explain why it is that I have made no reference to Sir Benjamin Brodie on the several occasions on which, in the interval between 1867 and the present time, I have reiterated and enforced my views on the great significance of the hypothesis of celestial dissociation as giving rise to

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* Nature, August 25, 1881, vol. xxiv., p. 396.

† Ideal Chemistry, a Lecture. Macmillan, 1880.

forms of matter more elemental than any known to us in terrestrial chemistry. The conception, as at first enunciated in somewhat different forms alike by Brodie and myself, was one to which we were both naturally, one might say inevitably, led by different paths from our respective fields of speculation, and which each might accept as in the highest degree probable, and make, as it were, his own. I write, therefore, in no spirit of invidious rivalry with my honored and lamented friend, but simply to clear myself from the charge, which might otherwise be brought against me, of having on various occasions within the past fourteen years put forth and enlarged upon this conception without mentioning Sir Benjamin Brodie, whose only publication on the subject, so far as I am aware, was his lecture of 1867, unknown to me until its reprint in 1880.

§ 6. It was at the grave of Priestley, in 1874, that I for the second time considered the doctrine of celestial dissociation, commencing with an account of the hypothesis put forward by F. W. Clarke, of Cincinnati, in January, 1873,* to explain the growing complexity which is observed when we compare the spectra of the white, yellow, and red stars; in which he saw evidence of a progressive evolution of chemical species, by a stoichiogenic process, from more elemental forms of matter. I next referred to the further development of this view by Lockyer in his communication to the French Academy of Sciences in November of the same year, wherein he connected the successive appearance in celestial bodies of chemical species of higher and higher vapor-densities with the speculations of Dumas and Pettenkofer as to the composite nature of the chemical elements.† I then quoted from my lecture of 1867 the language already cited, to the effect that dissociation by intense heat in stellar

* Clarke [now of Washington, D. C.], on "Evolution and the Spectroscope," Popular Science Monthly, New York, vol. ii., p. 32.

† Lockyer, Comptes Rendus, November 3, 1873.

worlds might give us more elemental forms of matter than any known on earth, and further suggested that the green line in the spectrum of the solar corona, which had been supposed to indicate a hitherto unknown substance, may be due to a "more elemental form of matter, which, though not seen in the nebulæ, is liberated by the intense heat of the solar sphere, and may possibly correspond to the primary matter conjectured by Dumas, having an equivalent weight one-fourth that of hydrogen."

§ 7. The suggestion of Lavoisier, that "hydrogen, nitrogen, and oxygen, with heat and light, might be regarded as simpler forms of matter, from which all others are derived," was also noticed in connection with the fact that the nebulæ, which we conceive to be condensing into suns and planets, have hitherto shown evidences only of the presence of the first two of these elements, which, as is well known, make up a large part of the gaseous envelope of our planet, in the forms of air and aqueous vapor. With this, I connected the hypothesis that our atmosphere and ocean are but portions of the universal medium which, in an attenuated form, fills the interstellary spaces; and further suggested, as "a legitimate and plausible speculation," that "these same nebulæ and their resulting worlds may be evolved by a process of chemical condensation from this universal atmosphere, to which they would sustain a relation somewhat analogous to that of clouds and rain to the aqueous vapor around us." *

§ 8. These views were reiterated in the preface to a second edition of my Chemical and Geological Essays, in 1878, and again before the British Association for the Advancement of Science at Dublin,† and before the French Academy of Sciences in the same year.‡ They were still further

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[*] A Century's Progress in Theoretical Chemistry, being an address at the grave of Priestley in Northumberland, Penn., July 31, 1874; Amer. Chemist, vol. v., pp. 46–61 and Pop. Science Monthly, vi., p. 420.

[†] Nature, August 29, 1878, vol. xviii., p. 475.

[‡] Comptes Rendus, September 23, 1878, vol. xxxviii., p. 452.

developed in an essay on the Chemical and Geological Relations of the Atmosphere, published in May, 1880 (*ante* pages 30–50), in which attention was called to the important contribution to the subject by Mr. Lockyer in his ingenious and beautiful spectroscopic studies, the results of which are embodied in his "Discussion of the Working Hypothesis that the so-called Elements are Compound Bodies," communicated to the Royal Society, December 12, 1878. It was then remarked that the already noticed "speculation of Lavoisier is really an anticipation of that view to which spectroscopic study has led the chemists of to-day"; while it was said that the hypothesis put forth by the writer in 1874, "which seeks for a source of the nebulous matter itself, is perhaps a legitimate extension of the nebular hypothesis."

§ 9. To show the connection of the above views with the philosophy of Newton, it now becomes necessary to give some account of the conception of the universal distribution of matter throughout space, both as regards its dynamical relations and its chemical composition. Passing over the speculations of the Greek physiologists, we come to the controversies on this subject in the seventeenth century, and find, in apparent opposition to the plenum maintained by Descartes and his followers, the teaching of Newton that "the heavens are void of all sensible matter." This statement is, however, qualified elsewhere by his assertion, that "to make way for the regular and lasting movements of the planets and comets, it is necessary to empty the heavens of all matter, except perhaps some very thin vapors, steams, and effluvia, arising from the atmospheres of the earth, planets, and comets, and from such an exceedingly rare ethereal medium as we have elsewhere described," etc. (*Optics*, Book III. Query 28.)

§ 10. In order to understand fully the views of Newton on this subject, it is necessary to compare carefully his various utterances, including the Hypothesis, in 1675, the first edition of the *Principia*, in 1687, the second edition, in 1713, and the various editions of the *Optics*. This work appeared in 1704, the third book, with its appended queries, having, according to its author's preface, been "put together out of scattered papers," subsequent to the publication of the first edition of the *Principia*. The Latin translation of the *Optics*, by Dr. Clarke, which was published in 1706, and the second English edition, in 1718, contain successive additions to these queries, which are indicated in the notes to Horsley's edition of the works of Newton, and are important in this connection. From a collation of all these, we learn how the conceptions of the Hypothesis took shape, were reinforced, and in great part incorporated in the *Principia*.

§ 11. In the Hypothesis, he imagines "an ethereal medium much of the same constitution with air, but far rarer, subtler, and more elastic." "But it is not to be supposed that this medium is one uniform matter, but composed partly of the main phlegmatic body of ether, partly of other various ethereal spirits, much after the manner that air is compounded of the phlegmatic body of air intermixed with various vapors and exhalations." Newton further suggests in his Hypothesis that this complex spirit or ether, which, by its elasticity, is extended throughout all space, is in continual movement and interchange. "For nature is a perpetual circulatory worker, generating fluids out of solids, and solids out of fluids, fixed things out of volatile, and volatile out of fixed, subtile out of gross, and gross out of subtile; some things to ascend and make the upper terrestrial juices, rivers, and the atmosphere, and by consequence others to descend for a requital to the former. And as the earth, so perhaps may the sun imbibe this spirit copiously, to conserve his shining, and keep the planets from receding farther from him; and they that will may also suppose that this spirit affords or carries with it thither the solary fuel and material principle of life, and that the vast ethereal spaces between us and the stars are for a sufficient repository for this food of the sun and planets."

§ 12. The language of this last sentence, in which his late biographer, Sir David Brewster, regards Newton as "amusing himself with the extravagance of his speculations," at which "we may be allowed to smile," * was not apparently regarded as unreasonable by its author when, more than ten years later, he quoted it in the postscript of his letter to Halley, dated Cambridge, June 20, 1686. The views therein contained, with the single exception of the suggestion regarding gravitation, have not wanted advocates in our own time, and many of them were embodied in the *Principia*, which Newton was then engaged in writing.

§ 13. But this was not all: Newton saw in the cosmic circulation and the mutual convertibility of rare and dense forms of matter a universal law, and rising to a still bolder conception, which completes his Hypothesis of the Universe, adds: "Perhaps the whole frame of nature may be nothing but various contextures of some certain ethereal spirits or vapors, condensed, as it were, by precipitation, much after the same manner that vapors are condensed into water, or exhalations into grosser substances, though not so easily condensible; and after condensation wrought into various forms, at first by the immediate hand of the Creator, and ever since by the power of nature, which, by virtue of the command 'increase and multiply,' became a complete imitator of the copy set her by the great Protoplast. Thus, perhaps, may all things be originated from ether."

§ 14. If now we look to the third book of the *Principia*, we shall find in Proposition 41 the remarkable chemical argument by which Newton was led to regard the interstellary ether as affording "the material principle of life" and "the food of planets." Considering the exhalations from the tails of comets, he supposes that the

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* Brewster's Memoirs of Newton, vol. i., pp. 121 and 404.

vapors thus derived, being rarefied, dilated, and spread through the whole heavens, are by gravity brought within the atmospheres of the planets, where they serve for the support of vegetable life. Inasmuch, moreover, as all vegetation is supported by fluids, and subsequently, by decay, is, in part, changed into solids, by which the mass of the earth is augmented, he concludes, that if these essential matters were not supplied from some external source, they must continually decrease, and at last fail. This vital and subtile part of our atmosphere, so important, though small in amount, might, he then supposed, come from the tails of comets.*

§ 15. This appeared in the first edition of the *Principia*, in 1687. It was not until later that the conception of exhalations from other celestial bodies took shape in the mind of Newton, as we may learn from the *Optics*. Thus, in the first edition of this work, in Query 11, the sun and fixed stars are spoken of as great earths, intensely heated, and surrounded with dense atmospheres which, by their

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* "Vapor enim in spatiis illis liberrimis perpetuò rarescit ac dilatatur. Quâ ratione fit ut cauda omnis ad extremitatem superiorem latior sit quám juxta capita cometae. Eâ autem rarefactione vaporem perpetuò dilatatum diffundi tandem et spargi per coelos universos, deinde paulatim in planetas per gravitatem suam attrahi et cum eorum atmosphaeris misceri, rationi consentaneum videtur. Nam quemadmodum maria ad constitutionem Terrae hujus omninò requiruntur, idque ut ex iis per calorem Solis vapores copiosè satis excitentur, qui vel in nubes coacti decidant in pluviis, et Terram omnem ad procreationem vegetabilium irrigent et nutriant; vel in frigidis montium verticibus condensati (ut aliqui cum ratione philosophantur) decurrant in fontes et flumina: sic ad conservationem marium et humorum in planetis requiri videntur cometæ, ex quorum exhalationibus et vaporibus condensatis, quicquid liquoris per vegetationem et putrefactionem consumitur et in Terram aridam convertitur, continuò suppleri et refici possit. Nam vegetabilia omnia ex liquoribus omninò crescunt, dein magnâ ex parte in Terram aridam per putrefactionem abeunt, et limus ex liquoribus putrefactis perpetuò decidit. Hinc moles Terrae aridae in dies augetur, et liquores, nisi aliunde augmentum sumerent, perpetuò decrescere deberent, ac tandem deficere. Porro suspicor spiritum illum, qui aëris nostri pars minima est, sed subtilissima et optima, et ad rerum omnium vitam requiritur, ex cometis praecipue venire."—*Newton*, *Principia*, lib. iii., prop. xli.

weight, condense the exhalations arising from these hot bodies. To this Query is added, in 1706, the suggestion that the weight of such an atmosphere "may hinder the globe of the sun from being diminished except by the emission of light"; while in the second English edition, in 1718, we find a further addition in the words, "and a very small quantity of vapors and exhalations." A similar change of view appears in the Query now numbered 28, wherein we read of "places [almost] destitute of matter," and also that "the sun and planets gravitate towards each other without [dense] matter between." In these quotations the two words in brackets are wanting in the edition of 1706, and first appear in that of 1718; while the language which we have in a previous page quoted from this same Query, is found in the edition of 1706.

§ 16. The Queries now numbered 17–24, appeared for the first time in the edition of 1718, and herein we find, in 18, the ethereal medium spoken of as being "by its elastic force expanded through all the heavens." Of this medium, "which fills all space adequately," he asks, "may not its resistance be so small as to be inconsiderable," and scarcely to make any sensible alteration in the movements of the planets?* This complex ether of the interstellary space was thus, in the opinion of Newton, made up in part of matter common to the planetary and stellar atmospheres, the origin and importance of which is concisely stated in the paragraph which appears for the first time in 1713, in the second edition of the *Principia*, in the third book, at the end of Proposition 42, here much augmented. In this statement, which serves to supplement and complete that already made in 1687, in Proposition 41, we read that the vapors which arise alike from the sun, the fixed stars, and the tails of comets, may by gravity fall into the atmospheres of the planets, and there be condensed, and pass into the form of salts, sulphurs (*id est,*

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* Compare this with Prop. x., Book III., of the Principia.

combustible matters), tinctures, clay, sand, coral, and other terrestrial substances.*

§ 17. The conception of Newton, who, while rejecting alike the plenum of the Cartesians, with its vortices, and an absolute vacuum, imagined space to be filled with an exceedingly attenuated matter, through which a free circulation of gaseous substances might take place between distant worlds, has found favor among modern thinkers, who seem to have been ignorant of his views. Sir William Grove in 1842 suggested that the medium of light and heat may be "a universally diffused matter," and subsequently, in 1843, in the chapter on Light, in his "Essay on the Correlation of Physical Forces," concluded with regard to the atmospheres of the sun and the planets, that there is no reason "why these atmospheres should not be, with reference to each other, in a state of equilibrium. Ether, which term we may apply to the highly attenuated matter existing in the interplanetary spaces, being an expansion of some or all of these atmospheres, or of the more volatile portions of them, would thus furnish matter for the transmission of the modes of motion which we call light, heat, etc.; and possibly minute portions of the atmospheres may, by gradual accretions and subtractions, pass from planet to planet, forming a link of material communication between the distant monads of the universe." Subsequently, in his address as President of the British Association for the Advancement of Science, in 1866, Grove further suggested that this diffused matter may become a source of solar heat, "inasmuch as the sun may condense gaseous matter as it travels in space, and so heat may be produced."

§ 18. Humboldt, also, in his *Cosmos*, considers the ex-

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* "Vapores, autem, qui ex Sole et stellis fixis et caudis cometarum oriuntur, incidere possunt per gravitatem suam in atmosphaeras planetarum, et ibi condensari et converti in aquam et spiritos humidos, et subinde per lentum calorem in sales, et sulphura, et tincturas, et limum, et lutum, et argillam, et arenam, et lapides, et coralia, et substantias alias terrestres paulatim migrare."—*Newton*, *Principia*, lib. iii., prop. xlii.

istence of a resisting medium in space, and says "of this impeding ethereal and cosmical matter," it may be supposed that it is in motion, that it gravitates, notwithstanding its great tenuity, that it is condensed in the vicinity of the great mass of the sun, and that it may include exhalations from comets; in which connection he quotes from the 42d Proposition of the third book of of the *Principia*. He further speaks comprehensively of "the vaporous matter of the incommensurable regions of space, whether, scattered without definite limits, it exists as a cosmical ether, or is condensed in nebulous masses and becomes comprised among the agglomerated bodies of the universe." * Humboldt also cites in this connection a suggestion made by Arago in the *Annuaire du Bureau des Longitudes* for 1842, as to the possibility of determining, by a comparison of its refractive power with that of terrestrial gases, the density of "the extremely rare matter occupying the regions of space." †

§ 19. In 1854, Sir William Thomson published his note on the Possible Density of the Luminiferous Ether,‡ wherein he remarks, "that there must be a medium of material communication throughout space to the remotest visible body, is a fundamental conception of the undulatory theory of light. Whether or no this medium is (as appears to me most probable) a continuation of our own atmosphere, its existence cannot be questioned." He then attempts to fix an inferior limit to the density of the luminiferous medium in interplanetary space, by considering the mechanical value of sunlight, as deduced from the value of solar radiation and the mechanical equivalent of the thermal unit. He concludes "that the luminiferous medium is enormously denser than the continuation of the terrestrial atmosphere would be in inter-

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* Cosmos, Otte's translation, Harper's ed., vol. i., pp. 82, 86.

† Ibid., vol. iii., p. 40.

‡ Trans. Roy. Soc. Edinburgh, vol. xxi., part 1; and Phil. Mag., 1855, vol. ix., p. 36.

planetary space if rarefied according to Boyle's law always, and if the earth were at rest in a state of constant temperature, with an atmosphere of the actual density at its surface." The earth itself in moving through space "cannot displace less than 250 pounds of matter." [P. Glan, who has since examined the question, concludes that the lower limit of density would be more than 7000 times greater than that calculated by Thomson.*]

§ 20. In 1870, W. Mattieu Williams published his very ingenious work entitled "The Fuel of the Sun," in which, apparently without any knowledge of what had been written before with regard to an interstellary medium, he attempts to find therein the source of solar heat — the "solary fuel" of Newton. To quote his own language, "the gaseous ocean in which we are immersed is but a portion of the infinite atmosphere that fills the whole solidity of space, that links together all the elements of the universe, and diffuses among them light and heat, and all the other physical and vital forces which heat and light are capable of generating." (Loc. cit. p. 5.)

§ 21. [In 1872, appeared the remarkable work of Zöllner, "*Über die Natur der Cometen*," in which the view of an interstellary atmosphere is set forth with great clearness. His conclusions may be gathered from the following extracts from an extended review and analysis of the volume, published in the same year. Reasoning from known facts it is maintained that even such fixed bodies as the metals, at very low temperatures, are constantly giving off vapor, though in amount too small to be recognized by ordinary tests; whence "it follows that a mass of matter in space will ultimately surround itself with its own vapor, and the tension of the latter will depend upon the mass of the body — that is, upon its gravitative energy —

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* Annalen der Physik und Chemie, No. viii., 1879; cited by the author in a review of Siemens, in "Nature" for April 27, 1882; also in "Conservation of Solar Energy," by Siemens, 1883, p. 33.

and the temperature. If the mass of the body is so small that its attractive force is insufficient to give to the enveloping vapor its maximum tension for the existing temperature, the evolution of vapor will be continuous, until the whole mass is converted into it."

§ 22. ["Then comes the question whether a mass of gas or vapor under these circumstances would be in a state of stable equilibrium. The analytical discussion of this point leads to the result that in empty and unlimited space, a finite mass of gas is in a condition of unstable equilibrium and must become dissipated by continual expansion and consequent decrease of density. A necessary consequence of this result is that the celestial spaces, at least within the limits of the stellar universe, must be filled with matter in the form of gas, preëminently that of the terrestrial atmosphere. Any solid body in space must, by virtue of its gravitative energy, condense the gas, to form an atmosphere upon its surface, and the density of this gaseous envelope can readily be calculated when the size and mass of the body are known." Zöllner then proceeds to discuss the density of the atmospheres surrounding the various bodies of the solar system, and to calculate that of the interstellary spaces, where he concludes that the gaseous medium would be so rare that it "could have no appreciable effect either upon the rays of light or upon the motion of bodies in space." *]

§ 23. Since the days of Newton, however, no one, so far as I am aware, had hitherto considered the interstellary matter from a chemical point of view. In 1874, as already shown, the writer had, in extension of the conception of Humboldt that its condensation gives rise to nebulæ, ventured the suggestion that from an ethereal medium having the same composition as our own atmosphere, the chemical elements of the sun and the planets have been evolved, in accordance with the views of Brodie, Clarke, and Lockyer, by a stoichiogenic process:

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* Amer. Jour. Science, 1872, iii., 476.

so that, in the language of Newton's Hypothesis, "all things may be originated from ether."

§ 24. It was not, however, until 1878, that, from a consideration of the chemical processes which have gone on at the earth's surface within recorded geological time, I was led to another step in this inquiry. That all the deoxidized carbon found in the earth's crust in the forms of coal and graphite, as well as that existing in a diffused state, as bituminous or carbonaceous matter, has come, through vegetation, from atmospheric carbonic acid, appears certain. To the same source we must ascribe the carbonic acid of all the limestones which, since the dawn of life on our earth, have been deposited from its waters. It is through the sub-aerial decay of crystalline silicated rocks, and the direct formation of carbonate of lime, or of carbonates of magnesia and alkalies which have reacted on the calcium-salts of the primeval ocean, that all limestones and dolomites have been generated. These, apart from the coaly matter, hold, locked up and withdrawn from the aerial circulation, an amount of carbonic acid which may be probably estimated at not less than 200 atmospheres equal in weight to our own. That this amount, or even a thousandth part of it, could have existed at any one time in our terrestrial atmosphere since the beginning of life on our planet is inconceivable, and that it could be supplied from the earth's interior is an hypothesis equally untenable.

§ 25. I was therefore led to admit for it an extra-terrestrial source, and to maintain that the carbonic acid has thence gradually come into our atmosphere to supply the deficiencies created by chemical processes at the earth's surface. Since similar processes are even now removing from our atmosphere this indispensable element, and fixing it in solid forms, it follows that, except volcanic agency, which can only restore a portion of what was primarily derived from the atmosphere, there are on earth, besides organic decay, only the artificial processes of human industry which can furnish carbonic acid; so that but for a supply of this gas from the interstellary spaces now, as in the past, vegetation, and consequently animal life itself, would fail and perish from the earth, for want of this "food of planets."

§ 26. Such were the conclusions, based on an induction from the facts of modern chemistry and geology, which I enunciated in my papers in 1878 and 1880, already quoted in the first part of this essay. I was at that time unacquainted with the Hypothesis of Newton, and with his remarkable reasoning contained in the 41st Proposition of the third book of the *Principia*, in which he, so far as was possible with the chemical knowledge of his time, anticipated my own argument, and showed how and in what manner the interstellary ether may really afford the "food of planets" and, in a sense, "the material principle of life."

I have thus endeavored to bring before the Philosophical Society of Cambridge a brief history of the development of this conception of an interstellary medium, and to show that the thought of two centuries has done little more than confirm the almost forgotten views of Newton. It is with feelings of peculiar gratification that I have been able to indite these pages within the very walls of the college in which our great philosopher lived and labored, and where, combining all the science of his time with a foresight which seems well-nigh divine, he was enabled, in the words of the poet, "to think again the great thought of the creation." *

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* *Ante*, page 23.

V.

THE ORIGIN OF CRYSTALLINE ROCKS.

This Essay, under the title of "The Origin of Crystalline Rocks, a Historical and Critical Review, with an account of the Crenitic Hypothesis," was presented and read in abstract to the Royal Society of Canada at Ottawa, May 20, 1884, a previous abstract having been given to the National Academy of Sciences at Washington, April 15, as explained below in a footnote to § 70. It was published in its present form in the Transactions of the Royal Society of Canada for 1884 (Vol. II., sec. iii., pp. 1 - 67). The observations of Vanhise, cited in § 116, appeared after the presentation of this paper. The same is true of those of Murray and Rénard, referred to in § 95, though these had previously been communicated to the writer.

I. — HISTORICAL AND CRITICAL.

§ 1. THE problem of the origin of the crystalline rocks which cover so large a part of the earth's surface, is justly regarded as one of fundamental importance to geology, and its solution has been attempted during the past century by many investigators, who have advanced widely different hypotheses. These it is proposed to review briefly in a historical sketch before proceeding to suggest a new one, which it is the object of the present memoir to bring forward. Without going back to the speculations of the ancient philosophers, we find those of the last two centuries, Newton, Descartes, Leibnitz, and Buffon, among others, accepting the hypothesis of a former igneous condition of our planet. Starting from this basis, the phenomena of volcanoes, and the resemblances between their consolidated lavas and many of the crystalline rocks, naturally gave rise to the notion of the igneous origin of these, which was formulated in the hypothesis that all such rocks, whether massive or schistose, were directly formed during the cooling and consolidation of a molten globe.

§ 2. Playfair, in his "Illustrations of the Huttonian Theory of the Earth," tells us that it was Lehman, who, in 1756, first distinguished by the name of Primitive the ancient crystalline rocks, described by him as arranged in beds, vertical or highly inclined in attitude, and overlaid by horizontal strata of secondary origin. These primitive rocks were by Lehman regarded "as parts of the original nucleus of the globe, which had undergone no alteration, but remained such as they were first created." This view was shared by Pallas and by De Luc, the latter of whom at one time considered the primitive rocks "as neither stratified nor formed by water," though, as Playfair informs us, De Luc subsequently admitted "their formation from aqueous deposition, as the neptunists do in general." *

Pallas held a similar view, and, according to Daubrée, both Pallas and Saussure "admitted, as Linnæus had done, that all the terranes have been formed by the agency of water, and that volcanic phenomena are but local accidents." Pallas published his "Observations on Mountains" in 1777, and Saussure the first volume of his "Voyages dans les Alpes" in 1779. It was about 1780 that the celebrated professor of Freiberg began, in his lectures, the exposition of his views, called by Playfair "the Neptunian system as improved by Werner"; though his Classification of the Rocks, in which these views were finally embodied, dates only from 1787.

§ 3. According to Werner, the materials which now form the solid crust of the globe were deposited from the waters of a primeval ocean, in which the elements of the crystalline rocks were at one time dissolved, and from which they were separated as chemical precipitates. The granite, which he regarded as the fundamental rock, was first laid down, and was closely followed by the gneisses and the hornblendic and micaceous schists. When the dissolving ocean covered the whole globe to a great depth,

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* John Playfair, loc. cit., pp., 160, 162. The Theory of the Earth, by James Hutton, first appeared in 1785, and in a second edition in 1795. Playfair's celebrated exposition of it, here quoted, was published in Edinburgh in 1802.

and its waters were tranquil and pure, the rocks deposited were exclusively crystalline, and, like the ocean, they were universal. These he distinguished as the Primitive rocks.

At a later period, the depth of the ocean was supposed to have been diminished by the retreat of a portion of the waters to cavities within the globe; a notion apparently borrowed from Leibnitz, who imagined caverns, left by the cooling of a formerly fused mass, to have subsequently served as reservoirs for a part of the universal ocean. In this second period, according to Werner, a chemical deposition of silicates still went on, but dry land having been exposed and shallows formed, currents destroyed portions of the previously deposited masses, which were also attacked by atmospheric agents. By these actions were formed mechanical sediments, which became interstratified with those of chemical origin. It was during this period of coincident chemical and mechanical deposition that were formed the Intermediate or Transition rocks of Werner, which, from the conditions of their formation, necessarily covered portions only of the universal Primitive series. At a still later period, marked by a farther diminution of the superficial waters, were laid down the Secondary rocks of Werner, at a time when the sea no longer produced mineral silicates, and had assumed essentially its present composition.

§ 4. The Primitive rocks, according to this hypothesis, were those composed entirely of chemical deposits, which are either crystallized or have a tendency to crystallization, and in which the action of mechanical causes cannot be traced. In the Transition series, the products of chemical and mechanical processes are intermingled, and materials derived from the disintegration and decay of Primitive rocks are present; while the rocks of the Secondary series were formed from the ruins alike of the Primitive and the Transition series. During the process of their consolidation, the various strata having been broken, fissures were formed through which the surplus waters retired to the internal cavities, depositing on the walls of the fissures through which they descended the various matters still held in solution. In this way were formed metalliferous and other mineral veins.

The aqueous solution in which all these crystalline rocks were at first dissolved was described by Werner and his disciples as a chaotic liquid, and he even designated the rocks themselves as chaotic, "because they were formed when the earth's surface was a chaos." These Primitive rocks, consisting of the granite and the overlying crystalline schists, covered the whole earth, and their geographical inequalities were due to the original deposition, which did not yield a regular surface, but presented elevations, upon the slopes of which were subsequently laid down the Transition strata.

Such, according to Werner, was the origin of all rock-masses except recent alluvions, deposits of obviously organic origin, and the ejections of volcanoes, which he conceived to be due to the subterraneous combustion of carbonaceous deposits. In the earlier ages of the world there were, according to him, no volcanoes and no evidences of subterranean heat. Neither in the formation of granite, of basalt, of the crystalline schists, or of mineral veins, or in the displacements of the strata to be seen in the deposits of various ages, did he recognize any manifestations of an internal activity of the earth.*

§ 5. We now pass to the consideration of the rival geological theory of Hutton, which was developed at the same time with that of Werner. Saussure, as early as

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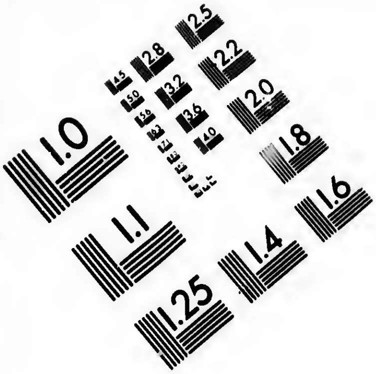
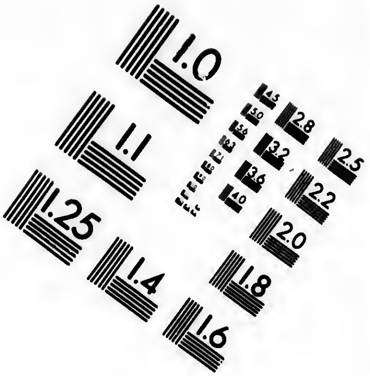
* In preparing the foregoing synopsis of the views of Werner, I have followed in part, the exposition of his system given by Murray in his Review of Playfair's Illustrations of the Huttonian Theory, published anonymously in Edinburgh in 1802; in part the statements to be found in Playfair, in Bakewell, in Lyell, and in Naumann; and also the excellent analysis given by Daubrée in his Études et Expériences Synthétiques sur le Métamorphisme, et sur la Formation des Roches Cristallines; Paris, 1860.





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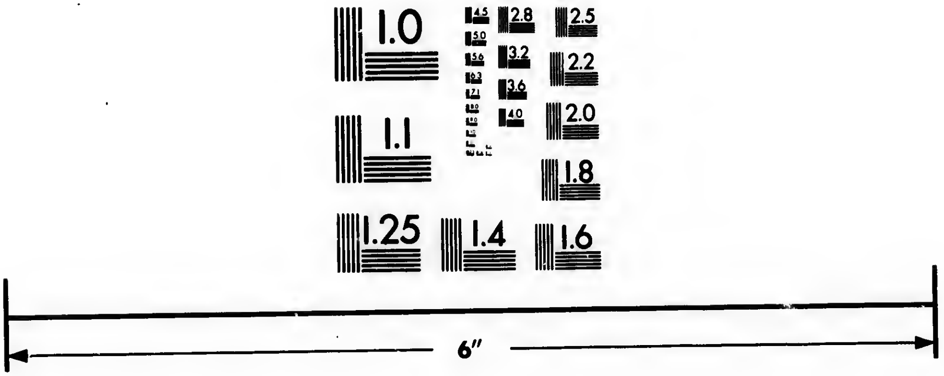

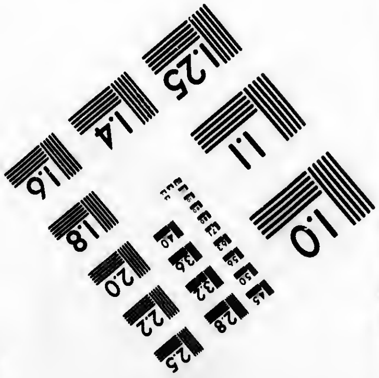

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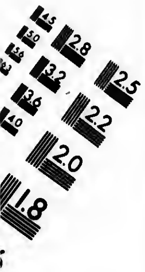
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1776, had ascribed to aqueous infiltration the granitic veins in the Valorsine, and others near Lyons — a view which was shared by Werner, who, from their similar constitution, conceived that the formation of massive and stratiform granitic rocks had taken place under conditions like those which gave rise to the veins in question, and then extended this view to other veins and masses of what we must regard as injected or irrupted rocks, including not only granites but dolerites and basalts.

Hutton and his interpreter, Playfair, on the other hand, regarded all granitic veins as having been filled by injection with matter in a state of igneous fusion, repudiating the notion of Saussure and of Werner that such materials could be formed by crystallization from aqueous solutions. Granitic veins, according to Hutton, are in all cases but ramifications of great masses of granite, themselves often concealed from view. "In Hutton's theory, granite is regarded of more recent formation than the strata incumbent upon it; as a substance which has been melted by heat, and which, forced up from the mineral regions, has elevated the strata at the same time." * From this condition of igneous liquidity, he supposed, had crystallized alike quartz and feldspar, as well as tourmaline and the other minerals sometimes found in granitic veins. Granite is elsewhere declared by him to be matter fused in the central regions of the earth.

§ 6. With Werner, granite was the substratum underlying all other known rocks, simply because it had been the first deposit from the chaotic watery liquid, and it was said to pass into or to alternate with the distinctly stratiform or schistose crystalline rocks. In this view of its geognostical relations, Werner was strictly correct if by granite we understand the massive or indistinctly stratiform aggregate which makes up what some call granite and others fundamental granitoid gneiss. This is what I have called an INDIGENOUS rock, which may be with or

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* Playfair, Illustrations, etc., p. 89.

without apparent stratification. We must, however, distinguish, besides this first type of crystalline rock, — the underlying granite of Werner, — two others which, though mineralogically similar, and often confounded, are geognostically distinct. Of these, what I have called EXOTIC rocks consist apparently of softened and displaced portions of aggregates of the first type, and are met with alike in dikes and in masses of greater or less size, intruded or irrupted among the stratified or indigenous rocks. These are the typical granites of Hutton. The third type includes those concretionary masses of granitic material formed in fissures or cavities, which are evidently deposits from aqueous solutions. These are the infiltrated veins of Saussure and of Werner, and are what I have designated ENDOGENOUS rocks.

§ 7. By keeping in view this threefold distinction between indigenous, exotic, and endogenous granitic aggregates, as I have long since endeavored to show, the obscurities and apparently contradictory views of different observers are easily explained. These distinctions are recognized in other crystalline rocks than granite. Under the name of crystalline limestones, as is well known, have been included both indigenous and endogenous masses. The question whether or not certain crystalline silicated rocks are to be regarded as eruptive, is seen to be of minor importance, when we consider that it is possible for indigenous crystalline deposits to appear in the relation of exotic masses, whether displaced in a softened and plastic condition, as more generally happens, or else forced, in rigid masses, among softer and more yielding strata, as appears, from the observations of Stapff, to be the case of the serpentines of Mount St. Gothard.*

§ 8. Werner argued, and, as we shall endeavor to show, correctly, from their analogies with concretionary granitic veins, that all granitic rocks were deposited from water, and are consequently indigenous or endogenous in origin.

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* See Essay X., § 128–130.

He denied the existence of exotic and of igneous rocks. Hutton, on the contrary, from the phenomena of exotic granites, and the analogies observed between these and basalts and modern volcanic rocks, was led to assume an igneous and exotic origin for all save the clearly stratiform crystalline rocks. Metalliferous lodes, also, he supposed to have been formed, like granitic veins, by igneous injection from below. While the disciples of Werner denied the igneous origin of basalts, and even of obsidian, Hutton and his school, on the other hand, maintained that the agates often found in erupted rocks were formed by fire. Playfair reasons: — "The fluidity of the agate was therefore simple and unassisted by any menstruum"; that is, it was due to heat, and not to solution; while, in the case of mineral veins, their closed cavities were held to "afford a demonstration that no chemical solvent was ever included in them." * These cavities were regarded as due to the contraction consequent on the cooling of injected igneous material.

§ 9. The basic rocks, included by Hutton under the common names of basalt and whinstone, are regarded by him as similar in origin to granite, and called "unerupted lavas." He elsewhere says that "whinstone is neither of volcanic nor of aqueous, but certainly of igneous origin," that is to say plutonic. Playfair distinguishes between what he calls the volcanic and the plutonic theory of basalt.

But while Hutton ascribed a plutonic origin to basalt and to granite, he did not, as some have done, assign a similar plutonic origin to gneiss and other crystalline schists. These were by Werner declared to result from a continuation of the same process which gave rise to granite, and to graduate into it. Gneiss is held both by Wernerians and by modern plutonists to be but a stratiform granite, and both of these rocks are believed by the one school to be aqueous and by the other to be igneous in origin.

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* Playfair, Illustrations, etc., pp. 79 and 260.

In the system of Hutton, however, a wide distinction is made between the two rocks. Gneiss was no longer a primitive or original rock, as taught by Lehman and by Werner, but, like the other crystalline schists, designated by Hutton as Primary, was supposed to be "formed of materials deposited at the bottom of the sea, and collected from the waste of rocks still more ancient." In his system "water is first employed to arrange, and then fire to consolidate, mineralize, and lastly to elevate the strata; but with respect to the unstratified or crystallized substances the action of fire alone is recognized." * Hutton also conceived the pressure of the waters of a superincumbent ocean to exert an important influence in the consolidation of the sediments. He was thus a plutonist only so far as regards granite and other unstratified rocks, while in maintaining a detrital origin for the crystalline schists he, as Naumann has remarked, may be regarded as the author of the so-called metamorphic hypothesis of their origin. Playfair himself declares of Hutton's system: "We are to consider this theory as hardly less distinguished from the hypothesis of the vulcanists, in the usual sense of this appellation, than it is from that of the neptunists or disciples of Werner." †

§ 10. It was no part of Hutton's plan to discuss the origin of those more ancient rocks, which had, according to him, furnished by their disintegration the materials for the primary stratified rocks. It was, in the language of Playfair, a system "where nothing is to be seen beyond the continuation of the present order." "His object was not . . . like that of most other theorists — to explain the first origin of things." This system, as interpreted by his school, asserts the conversion of detrital rocks into masses indistinguishable from those of truly igneous origin, which were the sources of the first detritus. The changes which it assumed to be wrought by the alternate action of water

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* Playfair, Illustrations, etc., pp. 12, 131.

† Biography of Hutton; Playfair's Works, vol. iv., p. 52.

and fire on the earth's crust were not supposed to be limited by any external conditions in the nature of things, and were compared by Playfair to the self-limited perturbations in the movements of the heavenly bodies, in which, as in the geological changes of the earth's crust, "we discern no mark either of the commencement or termination of the present order."

§ 11. Hutton's system is thus concisely resumed by Daubrée: — "The atmosphere is the region in which the rocks decay; their ruins accumulate in the ocean, and are there mineralized and transformed, under the double influence of pressure and the internal heat, into crystalline rocks having the aspect of the older ones. These re-formed rocks are subsequently uplifted by the same internal heat, and destroyed in their turn. The disintegration of one part of the globe thus serves constantly for the reconstruction of other parts, and the continued absorption of the underlying deposits produces incessantly new molten rocks, which may be injected among the overlying sediments. We have thus a system of destruction and renovation of which we can discern neither the beginning nor the end." *

§ 12. It was this perpetual round of geological changes, which took no account either of a beginning or an end, that led the theologians of his day to oppose the system of Hutton. On the other hand, in the system of Werner, which taught the fashioning of the present order of our globe from a primeval chaos beneath the waters of a universal ocean, they saw a conformity with the Hebrew cosmogony, which recommended to them the neptunian hypothesis. Hence the theological element which, as is well known, entered so largely into the controversies of the vulcanists and the neptunists at the beginning of this century, and the suspicion with which the partisans of Hutton were then regarded by the Christian world.

The extreme neptunian views of Werner, however, soon

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* Daubrée, Études et Expériences, etc., p. 12.

fell into disfavor. The visible evidences of the extrusion of trappean rocks in a heated and softened state, observations showing the augmentation of the temperature in mines, and the phenomena of thermal springs and volcanoes, soon turned the scale in favor of Hutton's views. There were not wanting those who attempted to unite the Wernerian hypothesis with that of an igneous globe, and who supposed a primeval chaotic ocean, to the waters of which, heated by the mass below, and kept at a high boiling-point by the pressure of an atmosphere of great density, was ascribed an exalted solvent power.

§ 13. Such a modified neptunian view was advanced by De la Beche. In his "Researches in Theoretical Geology," published in 1837, he favored the notion of an unoxidized nucleus, as suggested by Davy, and held to a solid crust resting on a liquid interior, and presenting, from the first, irregularities of surface. He then speaks of "the much debated question" whether the crystalline stratified rocks "have resulted from the deposit of abraded portions of pre-existing rocks mechanically suspended in water, or have been chemically derived from an aqueous or an igneous fluid in which their elements were disseminated." We have in this paragraph three distinct hypotheses presented. Two years later he clearly declared for the second of them.

While admitting the crystallization of detrital matter in proximity to intrusive rocks, De la Beche objected to what he called the "sweeping hypothesis" of Hutton and his school. He supposed that, in the cooling of our planet from an igneous fluid state, "there must have been a time when solid rock was first formed, and also a time when heated fluids rested upon it. The latter would be conditions highly favorable to the production of crystalline substances, and the state of the earth's surface would then be so totally different from that which now exists, that mineral matter, even when abraded from any part of the earth's crust which may have been solid, would be placed under very different conditions at these different periods." He suggests that there would be "a mass of crystalline rocks produced at first, which, however they may vary in minor points, should still preserve a general character and aspect, the result of the first changes of fluid into solid matter, crystalline and sub-crystalline substances prevailing, intermingled with detrital portions of the same substances abraded by the movements of the heated and first-formed aqueous fluids. In the gneiss, mica-slate, chloritic-slate, and other rocks of the same kind, associated together in great masses, and covering large areas in various parts of the world, we seem to have those mineral bodies which were first formed. The theory of a cooling globe, such as our planet, supposes a transition from a state of things highly favorable to the production of crystalline rocks, to one in which masses of these rocks would be more rarely formed. Hence we could never expect to draw fine lines of demarcation between the products of one state of things and those of the other." *

§ 14. Still later, in 1860, we find a similar view suggested by Daubrée as a probable hypothesis. He goes back in imagination to a time when the waters of our planet, as yet uncondensed, surrounded the globe with a dense envelope estimated to possess a weight equal to 250 atmospheres. "The surface of the earth was at this time at a very high temperature, and if silicates then existed they must have been formed without the co-operation of liquid water. Later, however, when it began to assume a liquid state, the water must have reacted upon the pre-existing silicates upon which it reposed, and then have given rise to a whole series of new products. By a veritable metamorphic action, the water of this primitive ocean, penetrating the igneous masses, caused their primitive characters to disappear, and formed, as in our tubes, crystallized minerals from the matters which it was able

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* De la Beche, Geology of Cornwall and Devon, pp. 33–34; also Researches in Theoretical Geology.

to dissolve. These matters, formed or suspended in the liquid, would then be precipitated, and give rise to deposits presenting different characters as the temperature of the liquid diminished." He then inquires, "Were these different periods of chemical decomposition and recomposition, in which aqueous action (*la voie humide*) intervenes under extreme conditions which approach those of igneous action (*la voie sèche*), the era of the formation of granite and of the azoic and crystalline schists? We cannot affirm this in an absolute manner, but we may presume it, especially when we consider that on this hypothesis there must have been formed two principal products, the one massive and the other presenting evidences of sedimentation, passing into each other gradually, as is the case with granite and gneiss. In any case, it cannot be contested that if there was a time when the rocks were exclusively under the dominion of fire, they passed under that of water at an epoch much more remote than we have hitherto admitted. The influence, now established, of water in the crystallization of silicates, no longer permits any doubt on this point. We cannot perhaps now find anywhere upon the globe rocks of which it may be affirmed with certainty that they have been formed by igneous action, without the intervention of water." *

§ 15. To give some notion of the temperature of the first water precipitated on the earth's cooling surface, Daubrée calculates that the waters of the present ocean, estimating their mean depth at 3500 metres, would, if spread uniformly over the earth's surface, have a thickness of 2563 metres, which, if converted into vapor, would correspond to a pressure of 248 atmospheres, a weight which would be augmented by the presence of other vapors and gases. "No liquid water could therefore rest upon the earth until its temperature had fallen below that which would give to the vapor of water a tension of 250 atmospheres" at least. When we consider

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* Daubrée, Études et Expériences Synthétiques, etc., pp. 121, 122.

that a tension of only fifty atmospheres of steam corresponds, according to Arago and Dulong, to a temperature of 265°.89 centigrade, we can form some conception of the temperature corresponding to a tension five times as great; which, on this hypothesis, would have been that of the first waters precipitated on the cooling planet, realizing many of the conditions attained by this ingenious experimenter when he subjected mineral silicates to the action of water in tubes, at temperatures of from 400° to 500° centigrade.

It is unnecessary to point out that Daubrée here attempts to adapt Werner's neptunian hypothesis to that of a once fused and cooling globe, and to find, like De la Beche, in the highly heated primeval ocean, the chaotic liquid which, according to the master of Freiberg, was the menstruum which at one time held in solution the elements of the primitive rocks. The experiments of Daubrée in his tubes, above referred to, are of great importance in this connection, and will be considered farther on, in the third part of this paper.

§ 16. The Huttonians early borrowed the notion of a granitic substratum from Werner, and supposed the earth when first cooled to have had a surface of granite. Hutton, true to his thesis, avoided the question of the primal rock. His reasonings, according to Playfair, "leave no doubt that the strata which now compose our continents are all formed from strata more ancient than themselves;* while, as we have seen, the intruded granites were looked upon as but fused and displaced portions of underlying strata. The granitic character of the rocks which antedated aqueous disintegration was, however, a matter of legitimate inference, and his disciple, Macculloch, supposed the earth when first cooled to have been "a globe of granite." Later, in 1847, Élie de Beaumont,

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* Playfair's Biography of James Hutton, in Playfair's complete works, 4 vols., Edinburgh, 1822; see vol. iv., pp. 33-81. His Illustrations of the Huttonian Theory will there be found reprinted in vol. i.

starting from the hypothesis of a cooling liquid globe, imagined it "a ball of molten matter, on the surface of which the first granites crystallized." *

§ 17. It should here be mentioned that Poulett Scrope, in 1825, put forth what he called "A New Theory of the Earth," in which he supposes "the mass of the globe, or at least its external zone to a considerable depth, to have been originally (that is at or before the moment in which it assumed the position it now holds in the planetary system) of a granitic composition, composed probably of the ordinary elements of granite, and having a very large grain; the regular crystallization having been favored by the circumstances under which it previously took place, though, as to what these circumstances were, I do not venture to hazard a supposition." He farther says, "If then we imagine a general intumescence of an intensely heated bed of granite, forming the original surface of the globe, to have been succeeded by a period in which the predominance was acquired by the repressive force occasioned by the condensation of the waters on its surface, and the deposition from them of various arenaceous and sedimental strata (the transition series), the structure of the gneiss-formation is at once simply explained. This structure may have been subsequently increased by the friction of the different laminæ against one another as they were urged forward in the direction of their plane surfaces, towards the orifice of protrusion, along the expanding granite beneath; the laminæ being elongated, and the crystals forced to arrange themselves in the direction of the movement." This implies an exoplutonic origin of gneiss.

Later in the same essay, however, Scrope supposes an intensely heated ocean, holding in solution great amounts of silica, and having, at the same time, suspended in its waters, feldspar, quartz, and mica, derived from the disin-

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* Sur les Émanations Volcaniques et Métallifères. Bull. Soc. Géol. de Fr. (2) iv.

tegration of the underlying granite. These suspended materials were deposited and consolidated into gneiss, and later, the dissolved silica precipitating, with some enclosed mica, as the ocean cooled, gave rise to mica-schists. In this last, we see the germ of the thermochaotic hypothesis, while in preceding statements of Scrope we have outlined the volcanic and metamorphic hypothesis of Dana, to be noticed farther on.*

§ 18. That such a primitive granite had been the source of gneiss, was taught by Beroldingen, "who maintained that all the rocks of granitic character having an appearance of stratification, are granites of secondary formation, or regenerated granites, similar in their origin to sandstones"; a notion which was vigorously combated by Saussure,† who held, as we have seen, to the neptunian theory of the origin of these rocks. The detrital hypothesis, which he opposed, was however strenuously defended by Hutton and his school, and especially by Boué and by Lyell. To the former belongs the first definite attempt to explain how uncrystalline sediments like graywacke and clay-slate might be changed into crystalline rocks such as gneiss and mica-schist. Of his views, put forth in 1822 and 1824, Naumann remarks, "Boué first understood how to bring this theory into more decided harmony with the details of geological phenomena, and besides invoking the internal heat, brought to his assistance emanations of gases and vapor from the earth's interior to explain the alteration of sedimentary slates into gneiss and mica-schist." He imagined under these conditions "a sort of

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* Scrope, Considerations on Volcanoes, etc., 1825, pp. 225–228. The cosmogony of Scrope was fantastic in the extreme; he conjectured the solid granitic earth to have been detached from the sun as an irregular mass, and compared it to an aerolite. [In rewriting his book on Volcanoes for a new edition, in 1862, Scrope omitted his Theory of the Earth, and did not attempt a cosmogony, but maintained the views already expressed by him as to the granitic nature of the exterior of the primitive earth, which he supposed to be intensely heated, and solid to the centre. (Ed. of 1872, pp. 300, 305.)]

† Voyages dans les Alpes (1796), vol. viii., pp. 55, 64.

igneous liquefaction, followed by a cooling process, which permitted a crystalline arrangement and a development of new mineral species without destroying or deranging notably the original laminated structure." *

§ 19. These views were adopted in 1833, in his "Principles of Geology," by Lyell, who designated strata supposed to have been thus transformed by the name of "hypogene metamorphic rocks"; a title intended to indicate a metamorphism which took place in the depths of the earth's crust, and proceeded from below upwards. Under this name, Lyell first popularized the Huttonian view as extended by Boué, which may be conveniently designated as the METAMORPHIC hypothesis of the origin of crystalline rocks.

Its plausibility has led to the adoption of this theory by many geologists during the past fifty years. Some, unwilling to admit the influence of a high temperature in such change, have imagined it to result from causes operating at ordinary temperatures during very long periods. As regards "the nature of these transforming processes, Gustaf Bischof and Haidinger were inclined to suppose that a long-continued percolation of water through the rocks produced an alteration of their substance and a recrystallization, in the same way as must have taken place in the production of certain pseudomorphs by alteration." † Hence the significance of the often repeated dictum that "metamorphism is pseudomorphism on a broad scale."

By a further application of the notions derived from the study of epigenic or replacement-pseudomorphs, which show in many cases the partial or even the total replacement of the original elements of a mineral species, constituting what has been appropriately designated metasoma-

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* Boué, Annales des Sciences Naturelles, August, 1824, p. 417, cited by Naumann.

† Naumann, Lehrbuch der Geognosie (1857), 2d ed., vol. ii., pp. 160-170. We shall have frequent occasion in these pages to quote from this section of Naumann's Lehrbuch.

tism, a METASOMATIC hypothesis of the origin of crystalline rocks has been arrived at, to which we shall revert farther on.

§ 20. Regarding the metamorphic hypothesis, we may remark, as Naumann has done, that the very transformation assumed, namely, that of mechanical sediments into crystalline rocks, remains to be proved. In his "Lehrbuch der Geognosie" in 1857, while still admitting the metamorphic origin of certain limited areas of crystalline schists, Naumann declared that the facts were "not all favorable to the baseless hypothesis which is now carried to extremes." Such an origin of crystalline rocks was denied by the neptunians, who held to the direct crystallization of these rocks from a chaotic watery liquid, for which reason we may conveniently and appropriately call their view the CHAOTIC hypothesis. It is also denied by those who hold these rocks to be of simple igneous origin, the first products of a cooling globe, a view which we may call the ENDOPLUTONIC hypothesis; and in part by those who advocate what we shall call the EXOPLUTONIC or VOLCANIC hypothesis of their origin.

We have already noticed at length the chaotic hypothesis, both as originally held by Werner, and modified by intervention of internal heat, as taught by De la Beche and by Daubrée, constituting what we may call the THERMOCHAOTIC hypothesis. It remains to notice first the two plutonic hypotheses just named, and finally to consider the metasomatic hypothesis, both as applied to rocks consisting of crystalline silicates, and to limestones.

§ 21. Reasoning, as Naumann has said, from "the great resemblance which gneiss and most of the rocks accompanying it bear to granite and to other eruptive rocks; the probability that most of these eruptive rocks have been solidified from a state of igneous fluidity; the almost unavoidable assumption that our planet was originally in the same state, and was only later covered with a solidified crust; finally the fact that in the primitive gneissic series, granite and gneiss are found regularly interstratified with each other," we are led to what we have designated the endoplutonic hypothesis, which is, that the primitive rocks form the "first solidified crust of our planet." Naumann remarks of this, that although it has "not found so many supporters as that of the metamorphic origin of the primitive rocks, the objections against it are probably neither greater nor more numerous than against the latter." Of this hypothesis, he adds that "it leads necessarily to the inference that the succession of the primitive rocks downward corresponds to their age from oldest to youngest, because it was, of course, through a solidification from without inward that the strata in question were formed." Those who would maintain, on the contrary, that the succession of these in age is from below upward, must suppose, as he explains, that the material of the younger crystalline rocks "has been protruded from the interior, through the earth's crust, in an eruptive form." For these two opposite modes of formation, both essentially plutonic, we may properly adopt the names of 'endoplutonic,' already used above, to designate the hypothesis which supposes the rocks to be generated within the first-formed crust; and 'exoplutonic' for that which conceives them to have been formed outside of the same crust, by eruptive or what are popularly called volcanic processes.

§ 22. The endoplutonic hypothesis has not wanted defenders, among whom are some of the most distinguished names of geology. In 1882, we find Hébert, the eminent professor at the Sorbonne, declaring of the ancient crystalline schists: "These mineral masses appear to be due to a crystallization in place, consequent upon the cooling of the fluid terrestrial globe." "The absence from these of rolled masses or of detritus of pre-existing rocks" —assumed by him— "indicates that water did not at that time as yet exist in the state of a liquid mass." This series, including various gneisses, micaceous, hornblendic and chloritic schists, with crystalline limestones, "should form a group clearly distinct from all others. It is anterior to granite, and constitutes a truly primitive series, which is neither eruptive nor sedimentary, but is due to a third mode of formation, which, borrowing the name from d'Omalius d'Halloy, we may call *crystallophyllian*." * It is difficult to conceive that this can be any other than that imagined by Naumann, which we have called endoplutonic.

§ 23. Thomas Macfarlane, in a learned essay in 1864, on "The Origin of Eruptive and Primary Rocks," † has developed the hypothesis of the endoplutonic origin of the primitive rocks with much ingenuity, and defends a view already suggested by Scheerer, that the laminated structure of these rocks may have been caused by currents in the molten mass of the globe. He further suggests that the first-formed crust may have had a different rate of rotation from the liquid below; ‡ from which also would result a stratiform arrangement in the elements of the solidifying layer, such as is seen in many slags, and in certain eruptive rocks. But while he applies this view to the primitive rocks, he proposes for the later crystalline schists one which is essentially the thermochaotic hypothesis of De la Beche and Daubrée, ascribing their origin to the action of a highly heated primeval ocean on the previously formed crust. The chief difficulties with which this endoplutonic hypothesis has to contend, according to Naumann, "arise from the structural relations of the primitive series, and the mineralogical characters of cer-

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* Bull. Soc. Géol. de France (3), xi., 30.

† Canadian Naturalist, vol. viii.

‡ It is worthy of note in this connection that Halley was long ago led, from the study of terrestrial magnetism, to adopt a similar hypothesis with regard to the earth's interior. "He supposed the existence of two magnetic poles situated in the earth's outer crust, and two others in an interior mass, separated from the solid envelope by a fluid medium, and revolving by a very small degree slower than the outer crust. The same conclusion was subsequently adopted by Hansteen." (Hunt, Chem. and Geol. Essays, p. 60.)

tain rocks belonging to it. Whether these difficulties can be explained away by the supposition of a hydro-pyrogenous development of the outside of the first solidified crust, as indicated by Angelot, Rozet, Fournet, Scheerer, and others, we must leave undecided in the meantime." Such a hydro-pyrogenous process is more clearly defined by Daubrée, when he refers the formation of granites and crystalline schists "to aqueous action intervening under extreme conditions which approach igneous action," as explained in § 14. Any modifications of the heated crust through the intervention of water must come under the categories of what we have called the thermochaotic and the metasomatic hypotheses, or else of that one which remains to be described in the present essay.

§ 24. In the paper already cited, Macfarlane has, moreover, discussed at length the probable condition of the earth's interior, beneath the crust of primitive stratiform rocks, with especial reference to the origin of the different types of eruptive rocks. Already in the last century we find Dolomieu maintaining the existence, beneath the granitic substratum, of a liquid layer from which come what he called basaltic lava-flows. A similar view was developed later by Phillips, Durocher, Bunsen, and Streng, who have imagined a separation of the liquid matter at the surface of the cooling globe into two layers, an upper, acidic one, corresponding to granites and trachytes, in which, besides alumina and an excess of silica, lime, magnesia, and iron-oxyd are present in very small quantities, and potash and soda abound; and a lower, basic one, corresponding to dolerite and basalt, in which lime, magnesia, and iron-oxyd abound, with an excess of alumina, and but little alkali. These two constitute the trachytic and pyroxenic magmas of Bunsen, who endeavored to determine what he conceived to be their normal composition, and, as is well known, sought to show that there exists such a relation between the proportions of these various bases and the silica, that it is possible to calculate the composition of any given eruptive rock from the amount of this element which it contains. He thence concluded that various intermediate rocks have been produced by a mingling or amalgamation, in different proportions, of these two separated magmas. For the composition of these, see farther a note to § 66. I have elsewhere discussed the history of this hypothesis, and have given reasons for its rejection.*

Sartorius von Waltershausen has also objected, from another point of view, to this hypothesis, and has maintained that while there is no such distinct separation of the liquid interior as was imagined by Phillips, Durocher, and Bunsen, there is nevertheless a gradual passage downward from a lighter, acidic to a denser and more basic liquid stratum; beneath which still heavier metallic minerals are supposed by him to be arranged in the order of their respective densities. This view has been adopted and extended by Mr. Macfarlane in his paper above cited. We shall however attempt to show in the second part of this memoir that the observed relations of acidic and basic eruptive rocks admit of a widely different interpretation to those above given, and one more in accordance with known chemical and mineralogical facts.†

§ 25. Returning from this digression on hypothetical notions of the earth's interior, we propose to consider the exoplutonic or volcanic hypothesis of the origin of the crystalline stratified rocks, according to which, as concisely stated by Naumann, the material composing them "has been projected from the interior, through the earth's crust, in an eruptive form." Inasmuch as the matter discharged in sub-aerial or submarine eruptions appears in part as flows of molten lava, and in part as disintegrated

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* On the Probable Seat of Volcanic Action, Geological Magazine, June, 1860, and Chem. and Geol. Essays, p. 66.

† For a discussion of the views of Phillips, Durocher, Bunsen, and Streng, see Hunt, Chem. and Geol. Essays, pp. 3-6, 66, and 284. See also farther Bunsen, Ann. de Chim. et de Phys., 1853 (3), vol. xxxviii., pp. 215-289.

solid materials which, like other detritus, may be arranged by water, it is evident that this hypothesis connects itself with that of the Huttonian school, to which, considering the mineralogical resemblances between volcanic and other crystalline rocks, it would make little difference whether the sediments required for the metamorphic process came from the disintegration of older crystalline strata, from a primeval granite, or from volcanic products. The volcanic hypothesis, except so far as consolidated lava-flows are concerned, thus becomes, as we shall see, a metamorphic or plutonic-detrital hypothesis.

As an illustration of this view, we find J. D. Dana in 1843 propounding a general theory of crystalline rocks, which is essentially volcanic. In this he endeavors to show (1) that the schistose structure of gneiss and mica-schist is not a satisfactory evidence of sedimentary origin, inasmuch as exotic or eruptive rocks may sometimes take on a laminated arrangement; (2) that granites without any trace of schistose structure may have had a sedimentary origin; and (3) that the heat producing metamorphic changes in sediments did not come from below, as supposed by the Huttonians, but through the waters of the ocean, heated by the same eruption which brought to the surface the materials of the metamorphic rocks, which were spread over the ocean's bottom in a disintegrated form. Their comminution was supposed by Dana to be effected in one of three ways: (1) they were ejected as pyroclastic material, in the form of a sand or ash-eruption, or (2) were disintegrated by coming in contact with water while in a fused condition, or (3) were broken by abrasion after consolidation. In any case, the detrital matter, as in the Huttonian hypothesis, was supposed to be transformed into a crystalline rock by the action of heated waters.

§ 26. After assigning such an origin to certain rocks called by him metamorphic porphyries and basalts, with regard to which he supposes "every eruption produced a heated sea around it, which hardened" the disintegrated porphyry, and recrystallized the comminuted materials, Dana proceeds to say that "granite, like porphyry, is an igneous rock. In its era, granite-sands were formed like porphyry-sands, and restored by heat to metamorphic granite, like metamorphic porphyry. . . . I use the word granite here as a general term for this and the associated rocks, mica-slate, syenite, and hornblende-slate, etc., which, I have shown, may also have an igneous origin. These granite-sands, like porphyry-sands, were formed about the regions of eruption, in one of the modes pointed out, and in all probability were never clays like the alluvial deposits of the present day. . . . With regard to primary limestones, a general survey of the facts seems to evince that some of these were of igneous origin like granite. If this were the case, there must have been others, formed at the same time with the deposits of granite-sand, and through the action of the same causes. These were recrystallized by the next discharge of heated waters." * Dana, forgetting the effects of the law of convection in liquids, here makes the suggestion that "at no great depth the waters might be raised to the heat of ignition before ebullition will begin, and if the leaden waters of a deep ocean . . . are for days in contact with the open fires of submarine volcanoes, we can scarcely fix a limit to the temperature which they would necessarily receive."

We have thus presented a complete exoplutonic or volcanic hypothesis, and at the same time a complete metamorphic or volcanic-detrital hypothesis, alike for porphyry, granite, syenite, gneiss, mica-schist, and crystalline limestone; each and all which are assumed to have a twofold origin, and to appear alike in an eruptive and in a secondary sedimentary form. A reference to the previous speculations of Scrope, already set forth in § 17, will show to what extent Dana was his disciple.

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* Dana, On the Analogies between the Modern Igneous Rocks and the so-called Primary Formations. Amer. Jour. Science, 1843, vol. xlv., pp. 104–129.

§ 27. Dana has since abandoned this hypothesis, so far as regards the eruptive origin of the detrital matters. In his later writings, he sets forth the familiar view of a liquid interior covered with a solid crust, which latter was the supposed source of the Archæan or primitive rocks. "These Archæan rocks are the only universal formation; they extend over the whole globe, and were the floor of the ocean, and the material of all the emerged land, when life first began to exist." These rocks of the first crust, disintegrated by submarine and sub-aerial agencies, yielded beds of detritus, which, being consolidated by the action of the heated waters, gave rise to new rocks, which would "be much like those that resulted from the original cooling, because chiefly made out of the latter by reconsolidation and recrystallization." "Igneous rocks have a close resemblance to granite, diorite, and other crystalline kinds, and hence may have proceeded from the fusion of older kinds. But these older kinds derived their material from an older source, and originally from the fused material of the globe, so that the proof of such an origin by refusion is not established beyond a doubt."

§ 28. It is not clear whether, according to Dana, we have anywhere this hypothetical primitive or truly Archæan rock exposed, since, speaking of the Laurentian series, which he also calls Archæan, he says at the same time: — "These Laurentian rocks are made out of the ruins of older Laurentian, or of still older Archæan rocks; that is to say, the sands, clays, and stones made and distributed by the ocean, as it washed over the earliest-formed crust of the globe. The loose material, transported by the currents and the waves, was piled into layers, as in the following ages, and vast accumulations were formed; for no one estimates the thickness of the recognized Laurentian beds as below thirty thousand feet." Lest he should be supposed to hold to his former theory of the volcanic origin of these supposed detrital matters, which formed the Laurentian, he now declares, "They have no resemblance to lavas or igneous ejections." * These crystalline stratified rocks are thus not that universal Archæan terrane which was the first-formed crust of the cooling globe. The imagination is at a loss, however, to understand the nature of the disintegrating process, or the source of the materials which in the Laurentian period were, according to this hypothesis, spread over vast areas to a depth of not less than thirty thousand feet, and seeks in vain for the site of the vanished Atlantis which furnished this enormous amount of mechanically disintegrated rock.

§ 29. Clarence King, in 1878, gave us a clear and admirable discussion of the same detrital metamorphic theory, and argued, as Dana had done before him, that the depression of sedimentary strata below the surface of the earth, even to great depths, is not sufficient to effect their crystallization; since basal paleozoic beds which have been buried beneath 30,000 feet or more of sediments are now seen, when exposed by great movements of elevation, and by erosion, to present no evidences of crystallization or so-called alteration. King, however, did not reject volcanic action as a source of detritus, for in discussing the origin of the great beds of serpentine and of olivine-rock which are often met with in the older crystalline schists, he says, "olivine-bearing rocks are among the oldest eruptive bodies," and then asks, "may not olivine-sands, like those now seen on the shores of the Hawaiian Islands, have been then, as now, accumulated by the mechanical separation of sea-currents, and subsequently buried by feldspathic and quartz-sands." He thus looks to volcanic eruptions for the source of olivine and serpentine beds, and adds, "I see no reason to ask for a different origin for the magnesian silicates than for the aluminous minerals," † the eruptive source of which is thus implied. A similar hypothesis of the for-

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* Dana, Manual of Geology, 3rd. ed., 1879, pp. 147, 154, 155, also 720.

† Geology of the Fortieth Parallel, vol. i., p. 117.

mation of beds of olivine-rock and serpentine from accumulations of volcanic olivine-sand, has since been maintained by Julien, whose paper is mentioned further on, § 37.

§ 30. Other geologists, besides King, have in later times advocated a similar volcanic hypothesis of the origin of crystalline rocks. A. Kopp, in 1872, taught that granite is an altered trachytic lava, and that gneiss may be derived from the detritus of trachyte or of granite, while doleritic lavas in like manner give rise to the various greenstones. The transformation of these is supposed to be effected through the intervention of heated waters, at great depths in the earth.* All this is but a repetition of the hypothesis put forward forty years since by Dana, and subsequently abandoned by him.

Törnebohm has also lately advanced a similar hypothesis to explain the origin of the primitive granite, and of the gneiss into which it seems to graduate. The material of these rocks came up as lava now does, and a portion of it, disintegrated, re-arranged by water and recrystallized, assumed the form of gneiss. Reusch, in like manner, according to Marr, supposes that the gabbros, diorites, and dioritic and hornblendic schists of the Bergen district, in Norway, are but altered tufas and erupted rocks.

§ 31. Mr. Marr, in a recent paper, urges the claims of the volcanic hypothesis to explain the origin of the ancient crystalline rocks, seemingly unaware of its earlier advocates. It is apparent that if we accept the doctrine of the permanence of continents and of oceanic depressions, the metamorphic-detrital theory of the Huttonians, which builds up series of crystalline rocks beneath the sea from the ruins of an older land, which had itself been formed beneath the sea, is no longer tenable. The difficulty of getting the thirty thousand feet of sediments required to spread over a continent, as in Dana's later hypothesis, is, as Marr perceives, overcome if we suppose

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* Neues Jahrbuch für Mineralogie, 1872, pp. 388 and 490.

this material to have been derived, not by the superficial waste and disintegration of former land, but by ejection from reservoirs beneath the earth's crust. Hence, with the advocates of the doctrine of the permanence of continents, the volcanic or exoplutonic hypothesis is again coming into favor.*

Similar considerations appear to have led C. H. Hitchcock, in 1883, to a like conclusion. The continents, in his scheme, are built up from beneath the waters of a universal ocean. He writes: — "We start with the earth in the condition of igneous fluidity. It cools so as to become encrusted and covered with an ocean. Numerous volcanoes discharge molten rock, building up ovoidal piles of granite [beneath the ocean], which change gradually into crystalline schists. When the hills are high enough to overlook the water, they constitute the beginnings of dry land." This is intelligible, but it seems strange to one familiar with the geological literature of the last forty years to read, in this connection, the remark of Hitchcock that few "have ventured to speak of anything like volcanic action, except as it has been manifested in the formation of dikes, in the early periods." †

To all of these speculations as to the exoplutonic or volcanic origin of the crystalline rocks, the language of Naumann, in criticising the original volcanic hypothesis of Dana, is applicable. "The perfect and thoroughly crystalline character of the gneiss, the enormous extent which the primitive formations occupy in so many districts, the architecture of these great gneissic regions, and their occurrence wholly independent of larger granitic masses, are all incompatible with this idea."

§ 32. The view of the igneous and eruptive origin of crystalline limestone, admitted in Dana's former scheme, was familiar to the geologists of forty years since. Em-

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* Marr, The Origin of Archæan Rocks; Geological Magazine, June, 1883.

† Hitchcock, The Early History of the North American Continent. — Proc. Amer. Assoc. Adv. Science, 1883.

mons and Mather in America, and Von Leonhard, Rozet, and Savi in Europe, among others, then held to the belief that many crystalline limestones were igneous, and Savi had even attempted to point out the centres of eruption of the Carrara marbles.* It is hardly necessary to recall the fact that serpentines, and great deposits of magnetite and specular iron, are still by some authorities considered as eruptive rocks, and that the hypothesis of the igneous origin of metalliferous lodes, taught by Hutton, is not yet wholly obsolete. In 1858, H. D. Rogers wrote of "the great dikes and veins of auriferous quartz" supposed to have issued "in a melted condition, through rents and fissures in the earth's crust. Outgushing bodies of this quartz," chilled by contact with the cold waters of the ocean, were supposed by him to have furnished the material for the Primal quartzites of Pennsylvania.† Still later, in 1874, we find Belt maintaining with learned ingenuity the igneous origin and the injection of auriferous quartz veins. He insists, as I have elsewhere done,‡ on the transition from veins of quartz, often metalliferous, to others containing feldspar, and thence to true granitic veins; but instead of regarding these as aqueous and concretionary, assumes them to be igneous, and thence concludes that the gold-bearing quartz lodes were filled with liquid quartz by "igneous injection," though admitting that in these, as in granites, water helped to impart liquidity.§

§ 33. In farther illustration of the extension of the plutonic doctrine to other rock-masses than those already mentioned, I quote from an essay by Daubrée, published

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* See for references, Hunt, Chem. and Geol. Essays, p. 218; also Boué, Guide du Géologue Voyageur, ii., 108.

† Geology of Pennsylvania, ii., 780.

‡ Chemical and Geological Essays, pp. 192–208, and *infra* § 58.

§ Belt, The Naturalist in Nicaragua, 1874, pp. 97–100. In the pages here referred to, my friend, whose premature death was a great loss to science, has set forth with clearness the Huttonian theory of metalliferous veins.

in 1871.* "The hypothesis advanced by Lazzaro Moro, in 1740, attributing an eruptive origin to rock-salt, as well as to sulphur and bitumen, was again taken up and applied by De Charpentier (1823) to the salt-mass at Bex, which is associated with anhydrite; and D'Alberti, in the classic study made by him of this terrane, maintained the same hypothesis for all the rock-salt found in the trias. Moreover, the examination of the deposits of pisolitic iron-ore had, in 1828, conducted Alexandre Brongniart to a similar conclusion, which was soon after applied to the siliceous deposits which constitute the buhrstone of the tertiary. A like origin was by D'Omalius (1841 and 1855) ascribed to other substances, particularly to certain clays and to certain sands, which, especially in Belgium, appear to be connected with the formation of calamine, and which Dumont in 1854 called geyserian deposits." "It was thus," adds Daubrée, "that various substances belonging to sedimentary strata were recognized as coming, or at least were supposed to come, from the lower regions (*étaient reconnues, ou au moins étaient supposées, provenir des régions profondes*)."

§ 34. The presence of water in ignited and molten rocks was shown by Poulett Scrope in 1825, in his studies of volcanoes.† Subsequently, Scheerer conceived that a small portion of water, probably five or ten hundredths, might, at a low red heat, give rise to a condition of imperfect liquidity such as he imagined for the material of eruptive granites. Similar ideas as to the aqueo-igneous fusion of granite were at the same time adopted by Élie de Beaumont, and are now generally admitted, the more so as they are in accordance with the results of microscopic study. From the presence in granitic rocks of what he called pyrognomic minerals, like allanite and

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* Daubrée, Des terrains stratifiés considérés au point de vue de l'origine des substances qui les constituent, etc. Bull. Soc. Géol. de France (2), xxviii., p. 307.

† Scrope, Considerations on Volcanoes, p. 25.

gadolinite, which, by exposure to ignition, undergo physical and chemical changes, Scheerer, moreover, argued that the temperature of formation of the granitic veins holding these minerals could not have been very high.*

This notion of hydroplutonic eruptions, thus set forth by Scrope, Scheerer, and Élie de Beaumont, has received a still further extension of late. The hydrated rock, serpentine, is supposed by some of those who maintain its exoplutonic derivation to have come up from below as an anhydrous silicate, and to have been subsequently hydrated. Daubrée, however, has suggested that it had already passed into the hydrated condition before its ejection.† Akin to this is the view of some modern Italian geologists, who explain the stratiform character of this rock by supposing that it was ejected from below as an aqueous magma, chiefly of hydrated silicates of magnesia and iron, mingled in some cases with feldspathic matter, from which, by crystallization and re-arrangement, the masses of serpentine and their associated euphotides have been formed, as well as the accompanying anhydrous silicates, olivine and enstatite. By this hypothesis "the serpentines are considered as eruptive without being truly igneous, inasmuch as they do not contain in their composition any mineral which has been submitted to igneous fusion," though "the magma may have had a temperature of several hundred degrees." ‡

The conception of hydroplutonic eruptions, whether applied by Scrope to lavas, by Scheerer to granites, by Belt to metalliferous quartz lodes, or by Daubrée and some Italian geologists to serpentines and euphotides, is instructive as a phase in the development of that geological hypothesis

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* For an analysis of these views of Scheerer and Élie de Beaumont, and references to the controversies to which they gave rise, see Hunt, Chemical and Geological Essays, pp. 5, 6, and 188, 189.

† Géologie Experimentale, p. 542.

‡ See, for an account of this hypothesis as maintained by Issel and Capacci, with much detail in their studies of Italian Serpentines, Essay X., § 90–93.

according to which a volcano is a *deus ex machina*, to be invoked for the solution of every knotty problem that presents itself in studying the origin of rock-masses.

§ 35. Writing in 1883 of the extravagances of the exoplutonic or volcanic doctrine, I spoke of it as "the belief in a subterranean providence which could send forth at will from its reservoirs" alike granite and basalt, olivine-rock and limestone, quartz-rock and magnetite.* An otherwise friendly critic † speaks of this language as "a kind of device for producing a false impression, by associating rocks for the most part of eruptive origin with others which are not so." This, however, is precisely what the plutonic school in question has done, and is still doing. Eminent teachers in geology of our time, some of them still living, have, as we have here shown, included with granites and basalt, not only serpentines, but limestones, magnetite, auriferous quartz, buhrstone, rock-salt, anhydrite, hydrous iron-ores, and even certain clays and sands, among the substances which have been thrown up from the depths of the earth.

The obvious question, as to the origin of these supposed accumulations of various and unlike substances in the underworld, has been one to perplex the thoughtful geologists of this school, and for those who did not admit that such might come from buried deposits, once superficial, presented difficulties which it was sought to overcome by a general theory of transmutation; by which it was imagined that a part or the whole of the original elements of a rock might be replaced, thus giving rise to new lithological species. Such a change has been appropriately named a metasomatosis or change of body. I have elsewhere pointed out that this view has been adopted by two distinct and, to a certain extent, opposed schools in geology, both of which, however, agree in admitting an almost unlimited capacity of change of substance, through aqueous

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* *Ibid.*, vol. i., part iv., p. 206.

† Geological Magazine for June, 1884, p. 278.

agencies, in previously solidified rocks. The first of these schools applies the doctrine of metasomatosis to silicated and aluminous rocks, either of plutonic or plutonic-detrital origin; the second to rocks of generally acknowledged aqueous origin, such as limestones.*

§ 36. As regards the metasomatosis of plutonic or plutonic-detrital rocks, such as the ordinary feldspathic types, — granites, gneisses, diabases, and diorites, — we are taught the conversion of any one or all of these into serpentine or into limestone. The integral change of each one of these into serpentine by the complete elimination of alumina, alkalies, and lime, and the replacement of these bases by magnesia and water, has, as is well known, been maintained by many writers of repute, including Müller and Bischof, and later, Dana and Delesse. Moreover, King and Rowney have, since 1874, taught the conversion into limestones of all the silicated rocks mentioned, and have assigned such an origin to the great interstratified masses of crystalline limestone which are found in the ancient gneisses, alike of North America and Europe. Not content with this, they have even maintained the conversion of serpentine itself into limestone, and have explained the existence of ophicalcites, and of serpentine masses in limestone, as evidences of the incomplete transformation of beds of serpentine, itself the product of a previous transformation of feldspathic rocks.† The older school of metasomatists regarded serpentine and other hydrated magnesian silicates, on account of their insolubility, as the last term in the metasomatic process; but King and Rowney contend that serpentine itself is not exempt from change.

§ 37. Among the gneisses and mica-schists of the Atlan-

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* See, in this connection, Hunt, Chem. and Geol. Essays, pp. 316, 320, 325; also preface to the second edition of the same, pp. xxvii.-xxxi.; and farther, Essay X., § 10 and § 108-110.

† Chem. and Geol. Essays, p. 324; also Trans. Roy. Soc. Can., I., part iv., p. 204; and W. King and T. H. Rowney, An old Chapter of the Geological Record, 1881, chaps. vii. and xii.

tic belt are found at many points, especially in Pennsylvania, and thence southward through the Carolinas into Alabama, important masses of a rock composed essentially of chrysolite or olivine, and referred to dunite or lherzolite. With these are associated not only serpentine, but various hornblendic and feldspathic rocks, together with much corundum—the latter alike in segregated veins and disseminated in the beds. These chrysolite rocks, which, as seen in North Carolina, were already described by the writer, in 1879, as indigenous stratified deposits in the Montalban series,* have been made the subject of detailed studies both by Genth and by Julien, whose published results are instructive examples of the application of the metasomatic doctrine in the hands of its disciples. Genth supposes that, at the time when these chrysolite rocks were deposited, vast amounts of alumina were set free by some unexplained process, and formed beds of corundum, and that this species, by subsequent hydration and metasomatosis, has been changed to bauxite, diaspore, spinel, opal, and a great number of aluminiferous silicates, including various micas, probably some feldspars, and also magnesian silicates of the chloritic group. The final result has been, "in many instances, a pretty thorough alteration of the original corundum into micaceous and chloritic schists or beds, or, as Prof. Dana would express it, 'a pseudomorphism on a broad scale.'" †

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* See James Macfarlane's Geological Handbook, 1879, p. 130; and, for some notes on the history of similar rocks, Essay X., § 123-125.

† Genth, Proc. Amer. Philos. Soc., September, 1873, and July, 1874; also Amer. Jour. Sci. (3), vi., 461, and viii., 221-223. Mr. Dana, in a notice of Dr. Genth's conclusions, in the last citation, denounces me severely for having, on a former occasion, cited from him the words above quoted by Genth, forgetting that it is Genth (whom he praises), and not myself, who is thus attributing them to him, and that Genth's conclusions, if admitted, form a striking exemplification of that doctrine, which Dana there repudiates. In the same note, after stating that I have declared that "the advocates of the doctrine of transmutation" have taught that "the greater part of all the so-called metamorphic or crystalline rocks are the result of an epigenic process," and that "the advocates of this doctrine maintain that a mass of granite or diorite may

§ 38. Julien, who has more recently studied these rocks, adopts with regard to the chrysolite-beds the view suggested by Clarence King, in 1878, that they were derived from the disintegration of chrysolitic eruptive rocks, and were originally chrysolite-sandstones. Chrysolite, according to him, and not corundum, has been the point of departure for the various changes which have given rise to the crystalline schists in question. Thus, while some of the chrysolite beds remain unchanged, others have been converted into strata of cellular chalcedonic quartz, of serpentine, of steatite, of talcose actinolite-schist, of tremolite-schist, and of a diorite or gabbro made of albite and smaragdite and including grains of red corundum, sometimes with margarite. Within these rocks are veins and fissures of various sizes and shapes, in which are found crystallized corundum, with enstatite, actinolite, talc, and ripidolite, among other species. Julien, who assigns a similar origin to the like crystalline schists found elsewhere throughout the Atlantic belt, concludes that all of these various rocks have been derived from chrysolite. As regards the hypothesis of Genth, he writes: " The view which has been suggested, founded on

be converted into serpentine or limestone, and that a limestone may be changed into granite or gneiss, which may in its turn become serpentine," Dana calls this an extravagant doctrine, and says, "I demonstrated that all writers on pseudomorphism, with but one or two exceptions, would repudiate it as strongly as myself." He farther asserts that the statements here quoted "have been shown by me to be untrue"; and, with regard to the transmutation of granite or gneiss into limestone, declares, in repeating his charges before the Boston Society of Natural History, that "he never knew any one ignorant enough or audacious enough to have suggested it." (Proc. Boston Soc. Nat. Hist., vol. xvii., p. 170.)

Those who read these pages, and will take the trouble to consult the authorities here cited, or given in more detail in my Chemical and Geological Essays, pp. 324–326, may satisfy themselves that I have not borne false witness in this matter, but that every one of the changes cited has been formally maintained by some one or more of the transmutationists. It is surely not more difficult to transform granite into limestone, than limestone to granite, as imagined by Volger, or corundum to opal with Genth, or chrysolite to corundum with Julien.

certain phenomena observed in the corundum-veins, that these secondary rocks, and many schists, have been derived from the alteration of corundum, finds not the least confirmation from my studies, and is indeed strongly contradicted by facts observed in the field. The corundum itself is, in all cases, both in the veins and in the particles found in the gabbro, a secondary or alteration-product. All the phenomena of alteration, both in the veins and rock-masses, absolutely require, and can be simply explained by, the introduction of a solution of soda and alumina into the fissures and interstices, during the period of alteration and metamorphism." * This solution he imagines to have come from some subterranean source in a heated condition. The applications of the doctrine of metasomatosis seem to be limited only by the imagination of its disciples.

§ 39. We now come to examine what we have called the second phase of the doctrine of metasomatism, which starts, not from silicated and aluminous rocks, but from limestones, and from these proceeds to silicated rocks. The resources of the chemist were severely taxed, when it was required by the metasomatist to change a sandstone or an argillite into a gneiss, a hornblende-schist, or a serpentine; but with a comparatively soluble rock, like limestone, the change was less difficult to conceive. Accordingly, we find Von Buch, Haidinger, and others, teaching the conversion of limestone into dolomite, and Gustaf Rose, and Dana, the further change of dolomite into serpentine; while Volger, and after him Bischof, maintained the transformation of limestone into gneiss and granite. The argument for this change, as stated by the latter, is instructive, as showing the ordinary mode of reasoning adopted by this school. The occurrence of feldspar in the form of calcite, according to him, "proves the possibility of carbonate of lime being replaced by a feldspathic substance." He elsewhere argues that since both quartz

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* Proc. Boston Soc. Nat. Hist. (1883) vol. xxiii., p. 147.

and feldspar may replace calcite, "if both changes take place together, the chief constituents of gneiss would be substituted for the limestone removed." "Volger also describes instances of the association of adularia and pericline with calcite, at St. Gothard, which shows that feldspar, quartz, and mica may be substituted for the carbonate of lime in calcite. Consequently, it may be inferred that granite or gneiss may be produced from limestone in the same manner." *

§ 40. Akin to this view of Volger is that suggested by Pumpelly with regard to the hälleflinta or bedded petrosilex-porphyry of Missouri (composed chiefly of quartz and orthoclase) — that this rock, as well as its included magnetic and specular iron and manganese ores, may have been derived by a metasomatic process from a limestone, parts of which were replaced by the oxyds of iron and manganese, "while the porphyry now surrounding the ores may be due to a previous, contemporaneous, or subsequent replacement of the lime-carbonate by silica and silicates." Portions of this petrosilex are, in fact, intimately mingled with calcite, and thin layers of crystalline limestone are also found interstratified with the petrosilex, which, in these associations, retains its normal composition of a mixture of orthoclase and quartz. †

The hypothesis of metasomatism as applied to silicated rocks, endeavors to account for the generation of different and unlike masses in a single crystalline terrane or series, and also for certain phenomena in the transformation of detrital rocks. As applied to limestones, however, by Rose, Volger, Bischof, and Pumpelly, it seeks to explain the conversion of a single widespread rock into granite, gneiss, serpentine, petrosilex, and crystalline iron ores. These transformations once established, we should have

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* Bischof; Chemical and Physical Geology, 1859, vol. iii., pp. 431, 432.

† Geological Survey of Missouri, 1873; Iron Ores, etc., pp. 25–27. Also Hunt, Azoic Rocks, Rep. E., Second Geological Survey of Penn., p. 194.

an intelligible hypothesis to account for the origin of the principal crystalline rocks.

§ 41. We have in the preceding historical sketch endeavored to show that the existing hypotheses regarding the origin of the stratiform crystalline rocks may be classed under six heads, which are as follows: —

I. ENDOPLUTONIC. This supposes the rocks in question to have been formed from the mass of the primeval globe as it congealed from igneous fusion, and, as Naumann remarks, implies a solidification from without inwards. The process beginning before the precipitation of water on the surface, this liquid took no part in their formation, and their stratiform structure and arrangement are to be ascribed to crystallization, or to the effect of currents set up in the congealing mass. (Naumann, T. Macfarlane, Hébert, *et al.*)

II. EXOPLUTONIC. This hypothesis conceives the crystalline stratiform rocks to have been built up out of matters ejected from beneath the superficial crust of the earth. Besides lavas and pyroclastic rocks, which are the ordinary products of volcanoes, the hypothesis of the Huttonians (in which the notion of metamorphism is carried back indefinitely, so that its products are confounded with the primeval crust) has apparently led the way to a belief in the eruption not only of re-fused sediments, but of hydrated serpentinic and feldspathic magmas, and even, as we have seen, of quartz, magnetite, limestone, rock-salt, anhydrite, and of clays and sands. It would not probably be maintained by its advocates that the eruption of all of these rocks was attended with volcanic phenomena, properly so called. Such extruded rocks, though not truly volcanic, would however, as coming up from the underworld, merit the more comprehensive designation of exoplutonic, already proposed.

III. METAMORPHIC or plutonic-detrital. This hypothesis conceives the crystalline rocks to have been formed by consolidation and recrystallization of sediments arranged beneath the sea, and derived (1) from the ruins of endoplutonic rocks resembling these, (Hutton, and his followers, Playfair, Scrope, Boué, Lyell, and Dana in 1863-1879); (2) from exoplutonic or volcanic rocks, broken up, for the most part, during the process of eruption, which was often submarine. With these materials may also be associated lava-flows. (Dana in 1843, Kopp, Reusch, Törnebohm, Marr, C. H. Hitchcock.) The heat, which was believed to effect the metamorphosis of these detrital materials beneath the sea into crystalline rocks, is supposed by the Huttonians to have come from the heated interior by conduction, but, according to the volcanic-detrital hypothesis of Dana, through the direct heating of the waters of the sea by contact with the eruptive matters.

IV. METASOMATIC. Although the crystalline rocks believed to be formed in each one of the preceding methods have been supposed to be occasionally the subject of wide-spread metasomatosis, we may properly restrict the title of a general metasomatic hypothesis to that which seeks to explain the derivation of the principal crystalline silicated rocks from limestones, as suggested by Rose, Volger, Bischof, and Pumpelly.

V. CHAOTIC. We have already suggested the name of the chaotic hypothesis for that which supposes the crystalline stratiform rocks, as well as the granites underlying them, to have been successively deposited by crystallization from a general chaotic ocean, by which their elements were originally held in solution. In this doctrine, which was taught by Werner and his immediate disciples, the conception of internal heat was not recognized, and there was no suggestion of an elevated temperature in the chaotic ocean.

VI. THERMOCHAOTIC. The history of the attempts to adapt the Wernerian hypothesis to the conception of a cooling globe has already been told in the preceding pages. It was supposed that the waters of the universal chaotic ocean were highly heated, and were thus enabled to exert a powerful solvent action upon the previously formed plutonic rocks of the primitive crust, transforming them into the present crystalline stratiform rocks; a hypothesis of their origin which may be appropriately designated as thermochaotic. According to this hypothesis, as set forth by Scrope, and afterwards by De la Beche and by Daubrée, the first water on the surface of the planet would be condensed under a pressure equal to 250 atmospheres, corresponding to a temperature near that of redness. We are reminded in this of Dana's earlier metamorphic theory, in which he also invoked the action of waters at a red heat. These, however, were supposed by him to be heated in the depths of the ocean by local volcanic eruptions, and the process, so far from being a universal one, belonging to a very early time in the history of our planet, was a partial one, repeated at different geological periods. According to Daubrée, the original plutonic rocks are not known, and the oldest crystalline schists are thermochaotic. Macfarlane, on the contrary, while adopting this hypothesis for the later crystalline or transition schists, maintains the endoplutonic origin of the primitive gneisses.

§ 42. Proceeding now to review briefly the claims of the above hypotheses, we remark with regard to the first, that multiplied observations in many parts of the world have established the existence of a regular succession in the crystalline rocks, which show by the greater corrugation of the lower members, by frequent discordances in stratification, and by the presence of fragments of the lower in the higher strata, that the order of generation was from below upwards. With this, moreover, corresponds the fact that the lower rocks are the more massive and more highly crystalline, while the upper ones present a gradual approximation in physical characters to the uncrystalline sedimentary or secondary strata; thus justifying the name of Transition, applied by Werner to these intermediate rocks. All of these facts are irreconcilable with the endoplutonic hypothesis.

The universal distribution, and the persistency of characters of these various groups of crystalline rocks, indicate moreover that they have been produced by a world-wide action, extending with great regularity through vast periods of time, and are incompatible with anything which we know of the phenomena of vulcanicity. The objections long since made by Naumann to the second or exoplutonic hypothesis are still as valid as ever, and there is no evidence in the lithological characters of these rocks of their volcanic origin. The argument derived from the similarity between their mineralogical composition and that of erupted rocks of paleozoic and more recent times, is equally strong in favor of the derivation of these latter from the primitive strata.

§ 43. The metamorphic hypothesis, which would derive the primitive strata from the consolidation and the recrystallization of detrital plutonic rocks, whether endoplutonic or volcanic, is for many reasons inadmissible. Without at present considering the later crystalline groups, which are also of vast extent, the ancient granitoid gneisses (originally called Laurentian and represented in Canada by the Ottawa and Grenville series) have an unknown volume, since their base has never been detected. It is, however, certain that they include, wherever studied in Europe or in America, a vast thickness, which, as Dana correctly says, cannot be assumed to be less than 30,000 feet. The detrital hypothesis demands an agency which shall create, transport, and lay down beneath the sea, over vast areas, now continental, this enormous thickness of sediment, not of mingled sands and clays, like those of later deposits (which are the results of a more or less complete sub-aerial chemical decomposition of primitive rocks), but in a chemically unchanged condition, and with the feldspar unaltered. It, moreover, demands a source for these enormous amounts of fresh detrital material, either in vanished pre-Laurentian continents, or in vast volcanic centres which have left behind them no traces of their existence.

This hypothesis further demands a consolidation and recrystallization of the elements of these recomposed rocks, so perfect that the microscope fails to detect the evidence of their detrital origin. The resemblance between the primitive crystalline rocks and what we know to be detrital rocks, compressed, recemented, and often exhibiting interstitial minerals of secondary origin, is too slight and superficial to deceive the critical student in lithology, and disappears under microscopical examination. The lessons taught by careful lithological and stratigraphical study have already led to the abandonment of the metamorphic hypothesis by the greater number of geologists; the more so since, as Bonney has well remarked, the long-quoted examples of metamorphic secondary and tertiary rocks in Europe have, without exception, been found to be mistaken, and to have been based either on false stratigraphy, on cases of recomposed crystalline rocks, or on a local development of crystalline minerals in the texture of clastic rocks.*

§ 44. The very ingenious metasomatic hypothesis, which would derive the crystalline stratified rocks from the transformation of limestones, is of course a gratuitous one, based on some observed cases of association of silicates with calcite, and the possible replacement of the one by the others, and deserves mention only as showing the greater difficulties of the previous hypothesis, which could lead to the adoption of that of general metasomatosis. It is possible, however, that its authors never imagined for it the rank of a universal hypothesis; the creation of continents of limestone, and their subsequent transformation into the vast masses of granitoid gneisses just referred to, would make as great demands on our credulity as the metamorphic hypothesis itself.

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* Geological Magazine, November, 1883, p. 507.

As regards the chaotic hypothesis of Werner, according to which the whole of the materials of the crystalline rocks were originally dissolved in a primeval sea, — its chemical difficulties are evident to the modern student. That the ocean could have ever held at one time in solution, under any conceivable conditions, the elements of the whole vast series of crystalline rocks, and could have deposited them successively, in that orderly manner which we observe in the earth's crust, was seen to be incredible. This argument, successfully urged by Playfair and his followers, contributed, with others, to the discredit which, as we have seen, soon fell upon the Wernerian hypothesis.

§ 45. Respecting what we have called the thermochaotic hypothesis, so ingeniously set forth by Daubrée, — while his conclusions as to the first precipitation of water on the globe at a very high temperature are not to be questioned, it can, we think, be shown that its direct action, under these conditions, upon the primitive crust could not have resulted in any such succession of deposits as those which make up the crystalline schists; these we are forced to assign to a later period in the history of the globe, for which the phase to which Daubrée has drawn attention was but a preparation.

The mineralogical characters and associations of the ancient crystalline rocks are, it is maintained, incompatible with the elevated temperature supposed in the hypothesis of Daubrée. The orderly interstratification with the ancient Laurentian gneisses of beds of limestone, and others of dolomite, not less than the presence in the one and the other of these of concretionary masses and beds of serpentine, after the manner of flint, and the inclusion in this of what so many regard as an organic form, the *Eozoon Canadense;* the presence, alike in the limestones, gneisses, and associated quartzites, of carbon in the form of graphite; and, finally, the occurrence of sulphids, testifying to a process of reduction of sulphates (which, not less than the graphite, suggests organic matter), all indicate chemical processes such as are now going on at the earth's surface, and have been in operation since the beginning of paleozoic time; but which are inconsistent with any considerable elevation of temperature above that now prevailing on the earth. They are, in short, evidences that the processes of vegetable and animal life were going on simultaneously with the deposition of the rocks of the Laurentian period. More than this, the presence of rounded masses of older gneisses in the younger crystalline schists, not less than the composition of these schists (as we shall hope to show in the sequel), are evidences that during the period in question a sub-aerial decay of the older crystalline rocks was already going on, giving rise to boulders of decomposition, to clays, and all the chemical reactions which that process implies, and which I have elsewhere set forth at length.*

§ 46. If we have correctly defined the conditions requisite for the production of the crystalline stratified rocks, they must have been separated from water by a process of crystallization or precipitation, at a temperature and a pressure not widely different from those now prevailing at the earth's surface. This process, in the earlier periods, must have been widely extended, and, so far as known continental areas were concerned, probably universal. A slowly progressive change meanwhile went on in the chemical conditions, indicated by a gradual modification in the composition of the rocks, and the areas of deposition, though still very great, became limited, leaving large surfaces, both of subsequently erupted rocks and of the precipitated stratified rocks, exposed to a process of sub-aerial decay, the soluble and insoluble products alike of which intervened in the rock-forming processes of this later or transition period. The conditions of the problem before us require moreover a source, neither detrital nor

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* The Decay of Rocks Geologically Considered, 1883. Amer. Jour. Sci., vol. xxvi., pp. 190–213, also, *post*, Essay VIII.

volcanic, for the immense mass of wholly crystalline material, chiefly quartz and feldspars, constituting the vast and as yet unfathomed primitive granitic and gneissic series; which only at a later time furnished its contingent of decayed and detrital matter to the crystalline transition rocks.

But there is still another condition imposed by the problem before us — that of a satisfactory explanation of the highly inclined and often nearly vertical attitude of the crystalline stratified rocks, which is most remarkable in those of the earliest periods. The ordinarily received explanation of this, as due to the contraction of a cooling globe, has seemed so inadequate to account for the great contortion, crushing, and folding of these older rocks, that some geologists, as Naumann tells us, have been led to regard the present as their original attitude, resulting from movements of the solidifying crust; in which connection he quotes with approval the language of Kittel, that "so long as a hypothesis is unable thoroughly to explain the almost vertical position of the primitive strata, it cannot be regarded as even approximately near the truth."

It will, we think, be apparent, in the light of the preceding review of existing hypotheses, that no explanation of the origin of the crystalline rocks which fails to meet all of the conditions just defined can hope for the approval of those who, after a careful survey of the whole field, seek for a new and more satisfactory hypothesis. It remains to be seen whether, with the help of modern physical and chemical science, and our present knowledge of geological facts, it is possible to devise such a one. After many years of reflection and study, the present writer ventures to propose a new hypothesis, believing that, while avoiding all the difficulties of those hitherto put forward, it will furnish an intelligible solution of a great number of hitherto unsolved problems in the physiology of the globe.

II.—THE DEVELOPMENT OF A NEW HYPOTHESIS.

§ 47. The history of the beginning and the growth of the new hypothesis here proposed to explain the origin of crystalline rocks is necessarily to a great extent personal, since it covers the work of many years of the author's life. The lines of investigation which have led to this hypothesis may be described as, first, that of the order and succession of the crystalline stratified rocks of the earth's crust; secondly, their mineralogy and lithology; thirdly, their history, considered in the light of physics and chemistry, involving an inquiry into all the chemical relations of existing rocks, waters, and gases, including the transformations and decay of rocks, and the artificial production of mineral species; and fourth and lastly, the probable condition of our planet before the creation of the present order. The adequate discussion of all these themes, which would include a complete system of mineral physiology, is impossible within the limits of the present essay, but a brief outline of some of the chief points necessary to the understanding of the hypothesis will here be attempted.

§ 48. As regards the order and succession of the crystalline rocks, the author's studies of them, begun in New England forty years since, and continued in Canada from 1847 onwards, were for many years perplexed with the difficulties of the Huttonian tradition (then and for many years generally accepted in America), that the mineral character of these rocks was in no obvious way related to their age and geological sequence, but that the strata of paleozoic and even of cenozoic times might take on the forms of the so-called azoic rocks. It was questioned by the partisans of the Huttonian school whether to the south and east of the azoic rocks of the Laurentides and the Adirondacks, in North America, there were any crystalline strata which were not of paleozoic or of mesozoic age, although many of these are undistinguishable from the rocks of the Laurentides.

As I have elsewhere said, the metamorphic and the metasomatic, not less than the exoplutonic hypothesis of the origin of the crystalline rocks, by failing to recognize the existence and the necessity of an orderly lithological development in time, have powerfully contributed to discourage intelligent geognostical study, and have directed attention rather to details of lithology and of mineralogy, often of secondary importance.* That a great law presided over the development of the crystalline rocks, was from the first my conviction; but until the confusion which a belief in the miracles of metamorphism, metasomatism, and vulcanism had introduced into geology was dispelled, the discovery of such a law was impossible.

§ 49. Convinced of the essential truth of the principles laid down by Werner, and embodied in his distinctions of Primitive, Transition, and Secondary rocks, I sought, during many years, to define and classify the rocks of the first two of these classes, and by extended studies in Europe, as well as in North America, succeeded in establishing an order, a succession, and a nomenclature, which are now beginning to find recognition on both continents. †

While the succession of the various groups of crystalline rocks was thus being established, not without the efficient aid and co-operation of other workers in late years, mineralogical and chemical studies were teaching us much of the true nature of the differences and resem-

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* Amer. Jour. Science, 1880, xix., 298.

† I have elsewhere given the history of the progress of inquiry in this direction in Report E of the Second Geological Survey of Pennsylvania (Azoic Rocks) 1878; in brief, in an essay on Pre-Cambrian Rocks, etc., in the Amer. Jour. Science, 1880 (xiv., 268); and later in a study of the Pre-Cambrian Rocks of the Alps, in the Trans. Roy. Soc.. Canada, *post*, Essays X and XI. See also in this connection the late address of Dr. Hicks, President of the British Geologists' Association, in its Proceedings, vol. viii., 1883, On the Succession of the Archæan Rocks, etc.; and the still more recent paper of Prof. Bonney, President of the Geological Society of London, on The Building of the Alps, in Nature for May 18 and 25, 1884; also the Geological Magazine for June, 1884, p. 280.

blances of these groups, as well as of the natural relations and modes of formation of various silicates and other mineral species which enter into the composition of the crystalline rocks. The investigations of physicists and astronomers had, moreover, given form and consistence to the ancient theory of the igneous origin of our planet, and the concurrent working in all of the lines of investigation above indicated was thus preparing the way for a new hypothesis of the origin of crystalline rocks — a hypothesis of which I shall endeavor to sketch the growth and the evolution.

§ 50. It was in January, 1858, more than a quarter of a century since, that I ventured to put forth a speculation as to the chemistry of a cooling and still molten globe. Considering only that crust with which geognosy makes us acquainted, it was maintained that at a very early period the whole of its non-volatile elements were united in a fused mass of silicates, which included the metallic bases of the salts now dissolved in the ocean's waters; while the dense atmosphere of that time was charged with all the carbon, sulphur, and chlorine, combined with oxygen or with hydrogen, besides which were present watery vapor, nitrogen, and a probable excess of oxygen. The first precipitated and acid waters from this atmosphere, falling on the hot earth's silicated crust, would, it was said, soon become neutralized by the protoxyd bases, giving rise to the chlorids and sulphates of the primeval sea; with the probable separation of the combined silica, at that high temperature, in the form of quartz. The suggestion as to the acid nature of the primitive atmosphere, and its first chemical action, which were obvious deductions from the igneous theory, had, as I afterwards learned, been anticipated by Quenstedt.*

§ 51. These views were reiterated in May, 1858, when they were coupled with the conception of a solid nucleus to the globe, as then taught by Poulett Scrope and by

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* Epochen der Natur, p. 20.

William Hopkins. The subsequent sub-aerial decay of exposed portions of the earth's primitive crust in a moist atmosphere, now purged of the acid compounds of chlorine and sulphur, but still holding carbonic acid, was then set forth as resulting in the transformation of feldspathic silicates into clays, and the transference to the sea of the lime, magnesia, and alkalies of the decayed rock in the form of carbonates, the latter of which, reacting on calcium-chlorid, would yield carbonate of lime and chlorids of sodium and magnesium. It was then said that by this hypothesis "we obtain a notion of the processes by which, from a primitive fused mass, may be generated the various silicious, argillaceous, and calcareous rocks which make up the greater part of the earth's crust." Of this it was declared, "the earth's solid crust of anhydrous and primitive igneous rock is everywhere deeply concealed beneath its own ruins, which form a great mass of sedimentary strata, permeated by water," and subjected to heat from below, changing them to crystalline metamorphic rocks, and at length reducing them to a state of igneo-aqueous fusion, through which they yield eruptive rocks. Of this primitive crust it was farther asserted that it "probably approached dolerite in composition."

The principal points in this hypothesis, as presented in 1858, were thus the solid condition of the earth's interior, and the derivation of the whole of the rocks of the known crust, by chemical transformations, from the original superficial and last-congealed layer of the cooling globe, which was considered to have been a basic rock, not unlike dolerite. All of these positions are fundamental to the present hypothesis.

§ 52. These views were again repeated in a paper read before the Geological Society of London in June, 1859, with some farther developments as to the origin of the various crystalline rocks derived from the primeval crust. This, it was claimed, was necessarily quartzless, and far removed in composition from the supposed granitic substratum, or the primitive gneiss. An attempt was, however, made to show that with the quartz, derived from the supposed first decomposition of the primitive igneous rock by acid waters, and the sediments resulting from subsequent disintegration and sub-aerial decay, coarser and finer sediments, more or less permeable, would result, which by the natural chemical action of infiltrating waters might, in accordance with known laws, divide themselves into two great classes, "the one characterized by an excess of silica, by the predominance of potash, and by small amounts of lime, magnesia, and soda, and represented by the granites and trachytes; while in the other silica and potash are less abundant, and soda, lime, and magnesia prevail, giving rise to pyroxene and triclinic feldspars. The metamorphism and displacement of such sediments may thus enable us to explain the origin of the different varieties of plutonic rocks without calling to our aid the ejections of the central fire."

§ 53. Such was the scheme put forward by the writer, in 1858 and 1859, to explain the generation from a homogeneous undifferentiated crust, without the intervention of plutonic matters from the earth's interior, of the two great types of acidic and basic crystalline rocks; gneisses, granites, and trachytes on the one hand, and doleritic rocks, greenstones, and basalts on the other.* Regarded as an attempt to adapt the Huttonian hypothesis to the growing demands of the science, and to give it what it had hitherto lacked, a starting-point in time, and a possible explanation of the two types of acidic and basic rocks, this scheme demands a place in the history of geology, although, in the judgment of its author, it must share the

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* See, for the references to this early statement, the American Journal Science for January, 1858 (vol. xxv., p. 102); also a Theory of Igneous Rocks and Volcanoes, Canadian Journal, Toronto, May, 1858; and Some Points in Chemical Geology, in abstract in Philos. Mag. for February, and in full in the Quarterly Geological Journal for November, 1859. The latter two papers are reprinted in the author's Chemical and Geological Essays, pp. 1-17.

fate of all other forms of the metamorphic hypothesis. In recognizing the adequacy of a primitive undifferentiated layer of igneous rock as the source of the materials of the future order it, however, effected a great step towards a more satisfactory hypothesis.

§ 54. The nature and history of this primitive layer were farther discussed by the author in a lecture on "The Chemistry of the Primeval Earth," given at the Royal Institution in London, in June, 1867.* Therein it was said: "It is with the superficial portions of the fused mineral mass of the globe that we have now to do, since there is no good reason for supposing that the deeply seated portions have intervened in any direct manner in the production of the rocks which form the superficial crust. This, at the time of its first solidification, presented probably an irregular diversified surface, from the result of contraction of the congealing mass, which at last formed a liquid bath of no great depth, surrounding the solid nucleus." It was further insisted that this material would contain all of the bases in the form of silicates, and must have much resembled in composition certain furnace-slags or volcanic products. Of this primary lava-like rock, it was said, that it is now everywhere concealed, and is not to be confounded with the granitic substratum. That granite was a secondary rock, formed through the intervention of water, was then argued from the presence therein, as a constituent element, of quartz, "which, so far as we know, can only be generated by aqueous agencies, and at comparatively low temperatures." The metamorphic hypothesis of the origin of granite was then maintained.

In 1869, in an essay on "The Probable Seat of Volcanic Action," † a further inquiry was made into the probable

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* Proceedings of the Royal Institution, and also Chemical and Geological Essays, pp. 35–45.

† Geological Magazine for June, 1869, and Amer. Jour. Science, for July, 1870 (vol. i., p. 21). See also Chemical and Geological Essays, pp. 59–67.

nature and condition of what had been spoken of in 1858 as "the ruins of the crust of anhydrous and primitive igneous rock." This, it was now said, "must by contraction in cooling have become porous and permeable, for a considerable depth, to the waters afterwards precipitated upon its surface. In this way it was prepared alike for mechanical disintegration and for the chemical action of the acids . . . present in the air and the waters of the time. . . . The earth, air, and water, thus made to react upon each other, constitute the first matters, from which, by mechanical and chemical transformations, the whole mineral world known to us has been produced." It was farther argued, from many geological phenomena, that we have evidence of the existence between the solid nucleus and the stratified rocks of "an interposed layer of partially fluid matter, which is not, however, a still unsolidified portion of the once liquid globe, but consists of the outer part of the congealed primitive mass, disintegrated and modified by chemical and mechanical agencies, impregnated with water, and in a state of igneo-aqueous fusion." *

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* Prestwich, in a memoir presented to the Royal Society of London, April 16, 1885, of which an abstract appears in *Nature* for April 23, after considering (1) the flexibility of the earth's crust as shown in foldings and corrugations, and in secular depressions and elevations of continental areas; (2) the increase of temperature in the depths, and (3) the volcanic phenomena of the present day, and the outpouring of vast sheets of trappean rocks during late geological periods, and after discussing the bearing of these upon various other geological hypotheses, enounces a similar view to that set forth above, and farther, in § 127. He concludes that all these phenomena "are most compatible with the movement of a thin crust on a slowly yielding viscid body or layer, also of no great thickness, and wrapping around a solid nucleus. The viscid magma is thus compressed between the two solids, and while yielding in places to compression, it, as a consequence of its narrow limits, expands in like proportion in conterminous areas." It would be difficult to express more concisely or more correctly the view of the earth's interior already set forth by the author in 1869, in his discussion of "The Probable Seat of Volcanic Action." The intervention of water in this primary plutonic magma, which Prestwich appears to reject, is, in the writer's opinion, inevitable.

§ 55. Although in 1858 I had, as already shown, sought to give a more rational basis to the metamorphic hypothesis of the origin of crystalline rocks, the traditions of which, as expounded by Lyell, weighed so heavily on the geologists of the time, other considerations soon afterwards led me to seek in another direction for the solution of the problem. The examination of the mineral silicates deposited during the evaporation of many natural waters, that of the Ottawa river among others, and the study which I had made of the hydrous magnesian silicate found in the tertiary strata of the Paris basin, induced me, as early as 1860, to inquire "to what extent rocks composed of calcareous and magnesian silicates may be directly formed in the moist way"; and again, in the same year, to declare with regard to the latter, "it is evident that such silicates could be formed in basins at the earth's surface, by reactions between magnesian solutions and dissolved silica"; a consideration which was then applied to the generation of serpentine and of talc. Again in 1863 and 1864, I ventured to conclude that "steatite, serpentine, pyroxene, hornblende, and, in many cases, garnet, epidote, and other silicated minerals, are formed by a crystallization or molecular re-arrangement of silicates generated by chemical processes in waters at the earth's surface." *

§ 56. While natural waters hold in abundance both lime and magnesia, alumina is, under ordinary conditions, insoluble in them, and, moreover, is not found uncombined with silica. The problem of the genesis of the aluminous double silicates, so abundant in the rocks, was therefore a more difficult one than that of the simple protoxyd-silicates, with which they are often intimately associated. Many facts in the history of zeolitic minerals, however, soon led me to recognize in the conditions under which these aluminous double silicates are formed, a clew

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* For citations and references see Chemical and Geological Essays, pp. 296, 297, and 300.

to the solution of the problem. Thus it was that, in an essay read before the Geological Society of Dublin, in April, 1863,* I called attention to the observations of Daubrée on the production, during the historic period, of the zeolites, chabazite and harmotome (phillipsite), by the action of thermal waters at a temperature not above 70° C., on the masonry of the ancient Roman baths at Plombières. The mode of the occurrence of these minerals showed that the aluminous silicate of the burned bricks had been changed into a temporarily soluble compound, which had crystallized in cavities as zeolites,—species which differ in composition from feldspars only by the presence of combined water. I also called attention, in this connection, to the experiments of Daubrée, who, by operating at higher temperatures in sealed tubes, had succeeded in producing crystallized quartz, pyroxene, and, apparently, feldspathic and micaceous minerals.

§ 57. The aqueous origin of feldspars, and their intimate relations to zeolites and other hydrous minerals, were farther noticed by the author, in the "Geology of Canada," in 1863, in which he cited the observations made by J. D. Whitney on the frequent occurrence of orthoclase in the copper-bearing veins in the melaphyres of Lake Superior. The crystals of this mineral, which had been mistaken for stilbite, are there found under conditions which show their formation contemporaneously with the zeolites, analcime and natrolite; while elsewhere in the same region, the associates of the orthoclase are epidote, calcite, native copper, and quartz, upon which, as well as upon saponite, the crystals of the feldspar were found implanted.† Whitney recalled in this connection the occurrence of a variety of orthoclase, the weissigite of Jenzsch, with chalcedony, in cavities of an amygdaloid.

[Mr. George F. Kunz has since discovered orthoclase in

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* The Chemistry of Metamorphic Rocks; Dublin Quarterly Journal for July, 1863; reprinted in Chemical and Geological Essays, pp. 18–34.

† Whitney, Amer. Jour. Science, 1869, vol. xxviii., p. 16.

the mesozoic diabase of New Jersey. The specimens lately shown to the New York Academy of Sciences are described by him as "compact veins and crystals of flesh-red primitive orthoclase, formed directly on the diabase," and sometimes in a granular form making up the chief part of veins traversing this rock. "The veins are usually perpendicular, running east and west, varying in thickness from half an inch to four inches, and were evidently formed by deposition directly on the walls of diabase. On each side of the orthoclase, milky quartz, either massive or at times in imperfect crystals, is implanted. On the orthoclase and quartz alike, calcite, massive and crystallized, and also apophyllite, datolite, pectolite, and the zeolitic minerals are often deposited. Scattered through the orthoclase and quartz are found pyrite, chalcopyrite, and occasionally galenite —all of these in perfect isolated crystals. The veins are frequently made up entirely of quartz, both massive and crystalline, neither calcite nor any zeolitic minerals having been deposited upon them. The zeolitic minerals are usually deposited directly upon the diabase." The careful observations by Mr. Kunz of these veins, which according to him are frequently found in the excavations in Bergen Hill, at Weehawken, throw much light on the relations of the zeolites to feldspathic and granitic aggregates.]

[Garnet is found in similar associations, Mr. Charles Robb, having, in 1882,* noticed its occurrence in a vein in the diabase of St. Ignace Island, Lake Superior, implanted in prehnite, with laumontite, quartz, calcite, barite, magnetite, native silver, copper-glance, and a chloritic matter. A specimen of this received from him shows dodecahedral garnets, reddish brown in color,† two or three millimetres in diameter, and small octohedrons of magnetite on prehnite with laumontite.]

§ 58. The facts noted by Whitney were insisted upon,

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* Communication to the New York Academy of Sciences, May 25, 1885.

† Canadian Naturalist, x., 176.

in connection with my own observations, to prove the aqueous origin of the feldspar found in veins among crystalline schists in the province of Quebec, where "a flesh-red orthoclase occurs so intermingled with white quartz and chlorite as to show the contemporaneous formation of the three species. The orthoclase generally predominates, often reposing upon or surrounded by chlorite, and at other times imbedded in quartz, which covers the latter. Drusy cavities are also lined with small crystals of the feldspar, and have been subsequently filled up by a cleavable bitter-spar," often with crystallized hematite, rutile, and copper-sulphids. It was shown that among these veins, then described as of aqueous origin, there was to be seen a transition, from those "containing only quartz and bitter-spar, with a little chlorite or talc, through others in which orthoclase appears, and gradually predominates, until we arrive at veins made up of quartz and feldspar, sometimes including mica, and having the character of a coarse-grained granite; the occasional presence of copper-sulphids and hematite characterizing all of them alike." There was also described the occurrence, in the same region, of a dark-colored argillaceous and schistose rock, having in parts the aspect of a chloritic greenstone, which is rendered amygdaloidal by the presence of numerous spherical or ovoidal masses of quartz, or more commonly of reddish orthoclase, often with a nucleus of quartz. In schistose varieties of this rock the feldspar extends from these centres in such a manner as to give a gneissoid aspect to the mass. All of these facts were regarded as showing the aqueous origin of orthoclase, and its secretion from the adjacent rock.*

§ 59. With the feldspar in the above-mentioned veins may be compared the similar occurrence, observed in 1872, in the great quartz lodes with chalcopyrite which traverse the Huronian greenstones at the Bruce Mines, on Lake Huron, of bands one or two inches wide of a brick-red

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* Geology of Canada, 1863; pp. 476 and 606.

orthoclase, mingled with a little quartz and a small amount of a greenish, apparently hornblendic element, forming an aggregate which can hardly be distinguished from some of the older granitic rocks, but is clearly interbanded with the metalliferous quartz and the bitter-spar of the lode. In this connection may also be quoted a description of the vertical parallel veins found cutting at right angles the Montalban gneisses in Northbridge, near Worcester, Massachusetts. These veins, as described by the writer, "may be traced for considerable distances, and are ordinarily but a few inches in thickness. The veinstone of these is generally a vitreous quartz, which in some parts exhibits selvages and in others bands of white orthoclase, by an admixture of which it passes elsewhere into a well characterized granitic vein. The quartz veins, in places, hold cubic crystals of pyrite, together with chalcopyrite and pyrrhotite, the latter in considerable masses, sometimes accompanied by crystals of greenish epidote imbedded in the quartz, and occasionally associated with red garnet. In one part there is found enclosed in the wider portion of a vein, between bands of vitreous quartz, a lenticular mass three inches thick, of coarsely granular pink calcite, with imbedded grains of dark green amphibole, and on one side small crystals of olive-green epidote and red garnet; the whole mass closely resembling some crystalline limestones from the Laurentian," and evidently endogenous.* I have also described remarkable examples of similar associations of zoisite, garnet, hornblende, pyroxene, and calcite in the metalliferous quartz-lodes in the Montalban series, at Ducktown, Tennessee.†

§ 60. The question of the aqueous origin of concretionary veins was resumed by the author in 1871, in an essay On Granites and Granitic Veinstones, when it was maintained that the relation of granitic veins with metalliferous

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* Azoic Rocks, Report E, Second Geological Survey of Pennsylvania, p. 247.

† Chemical and Geological Essays, p. 217.

quartz lodes, on the one hand, and with calcareous veins carrying the ordinary minerals of crystalline limestones, on the other, is such that to all these veins must be assigned a common aqueous origin. It was farther shown that the endogenous granitic masses or veinstones in the Montalban or younger gneissic series in New England often attain breadths of sixty feet or more, and that they present great varieties in texture, from coarse aggregates of banded orthoclase and quartz, often with muscovite (from which these various elements are mined for commercial purposes), to veins in which the concretionary character is not less marked, including beryl, tourmaline, garnet, cassiterite, and other rare minerals; while others still of these great veins are so fine-grained and homogeneous in character as to have been quarried as granites for architectural uses. These endogenous masses are included alike in the gneisses, the quartzites, the staurolitic mica-schists, and the indigenous crystalline limestones of the Montalban series, and, though generally transverse, are sometimes, for a portion of their course, coincident with the bedding of the enclosing rock.*

It was clear that these endogenous granitic veins of posterior origin were mineralogically very similar to the older gneisses and the erupted granites. From a prolonged study of all these phenomena, the conclusion was then reached that we have in the action which generated these endogenous granitic rocks a continuation of the same process which gave rise to the older or fundamental granitoid gneisses, which were hence of aqueous origin.

§ 61. This process of reasoning was in fact identical with that by which Werner, in the last century, was led to assign an aqueous origin to the primitive granite and the crystalline schists. In a description, in 1874, of some examples of these banded veinstones from Maine and Nova

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* Amer. Jour. Science (3), vol. i., pp. 88 and 182, and vol. iii., p. 115; also Chem. and Geol. Essays, pp. 183–209.

Scotia, it was said that their structure is "due to successive deposits from water of crystalline matter on the walls of the vein, and results from a process which, though operating in later times and in subterranean fissures, was probably not very much unlike that which gave rise to the indigenous granitic gneisses." * The same ideas as to the origin of the ancient crystalline rocks, and their relations to granitic and to zeolitic veins, were still farther defined by me, in 1874, when it was said: "The deposition of immense quantities alike of orthoclase, albite, and oligoclase in veins which are evidently of aqueous origin shows that conditions have existed in which the elements of these mineral species were abundant in solution. The relation between these endogenous deposits and the great beds of orthoclase and triclinic feldspar-rocks is similar to that between veins of calcite and of quartz, and beds of marble and of travertine, of quartzite and of hornstone. But while the conditions in which these latter mineral species are deposited from solution have been perpetuated to our own time, those of the deposition of feldspars and many other species, whether in veins or in beds, appear to belong only to remote geological ages, and, at best, are represented in more recent times only by the production of a few zeolitic minerals." †

§ 62. A farther and more particularized statement of the author's conclusions as to the origin of the crystalline rocks was embodied in a paper read before the American Association for the Advancement of Science at Saratoga, in August, 1879, containing the three following propositions: ‡—

"1. All gneisses, petrosilexes, hornblendic and micaceous schists, olivines, serpentines, and, in short, all silicated crystalline stratified rocks, are of neptunian origin,

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* Proc. Boston Society of Natural History, xvi., 237, p. 198.

† Chemical and Geological Essays, p. 298.

‡ The History of Some Pre-Cambrian Rocks, etc. Proc. A. A. A. S., for 1879, and Amer. Jour. Science (1880), xix., p. 270. Also farther on, Essay VIII.

and are not primarily due to metamorphosis or to metasomatosis, either of ordinary aqueous sediments or of volcanic materials.

"2. The chemical and mechanical conditions under which these rocks were deposited and crystallized, whether in shallow waters or in abyssal depths (where pressure greatly influences chemical affinities), have not been reproduced to any great extent since the beginning of paleozoic time.

"3. The eruptive rocks, or at least a large portion of them, are softened and displaced portions of these ancient neptunian rocks, of which they retain many of the mineralogical and lithological characters."

§ 63. In a subsequent paper, in 1880, it was said, with reference to the sub-aerial decay of rocks: "The aluminous silicates in the oldest crystalline rocks occur in the forms of feldspars, and related species, and are, so to speak, saturated with alkalies or with lime. It is only in more recent formations that we find aluminous silicates either free or with reduced amounts of alkali, as in the argillites and clays, in micaceous minerals like muscovite, margarodite, damourite, and pyrophyllite, and in kyanite, fibrolite, and andalusite; all of which we regard as derived indirectly from the more ancient feldspars." In connection with this important point, which I had already discussed elsewhere, I added the following note, referring at the same time to the propositions of the preceding paragraph:* "It is a question how far the origin of such crystalline aluminous silicates as muscovite, margarodite, damourite, pyrophyllite, kyanite, fibrolite, and andalusite, is to be sought in a process of diagenesis in ordinary aqueous sediments holding the ruins of more or less completely decayed feldspars. Other aluminous rock-forming

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* The Chemical and Geological Relations of the Atmosphere, *ante*, page 37. See farther, for the stratigraphical relations of the various aluminous silicates (which were first set forth by the author in 1863), Chem. and Geol. Essays, pp. 27 and 28; also Report E, Second Geological Survey of Pennsylvania (1878), p. 210.

silicates, such as chlorites and magnesian micas, are, however, connected, through aluminiferous amphiboles, with the non-aluminous magnesian silicates, and to all of these various magnesian minerals a very different origin must be ascribed."

In a farther discussion of this subject, in 1883, it was noted "that decayed feldspars, even when these are reduced to the condition of clays, have not, in most cases, lost the whole of their alkalies."* This was shown by the analyses made by Sweet of the kaolinized granitic gneisses of Wisconsin, from which it appears that "the levigated clays from these decayed rocks still hold, in repeated examples, from two to three hundredths or more of alkalies, the potash predominating."

§ 64. The question of the source of the matters in aqueous solution, which, according to the hypothesis before us, gave rise to granitic veinstones, naturally comes up at this stage of our inquiry. As we have seen, the granitic substratum of igneous origin, the existence of which is postulated by most modern geologists, is, since the time of Scrope, Scheerer, and Élie de Beaumont, generally conceived to be impregnated with a portion of water, conjectured by Scheerer to equal perhaps five or ten hundredths of its weight; and through the intervention of this to assume, at temperatures far below the point of liquefaction of the anhydrous rock, a condition which has been designated one of aqueo-igneous fusion. This interposed water, under the influence of great heat and pressure, we may suppose, with Scheerer, to constitute a sort of "granitic juice," which, exuding from the mass, might fill fissures or other cavities, alike in the granite and in the adjacent rocks, with the characteristic minerals of granitic veins. This seems to have been essentially the view of Élie de Beaumont, who described the elements of the pegmatites, the tourmaline-granites,

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* The Decay of Rocks Geologically Considered, Amer. Jour. Science (1883), xxvi., 194. Also *post*, Essay VII., § 16.

and the veins, often abounding in quartz, which carry cassiterite and columbite, as emanations from the adjacent granitic masses, or as a "granitic aura." Daubrée and Scheerer, in previously describing the similar granitic veins found in Scandinavia, conceived them to have been filled in like manner, not from an unstratified granitic substratum, but from the crystalline schists which enclose them.*

§ 65. In both of the above hypotheses, we note that the source of the orthoclase and the quartz of the veins is sought in the solutions derived from the granitic substratum or its closely related crystalline schists. If now we go farther back, and ask for the origin of this granitic substratum, with its constituent minerals, we have shown, in opposition to the view that it is the outer layer of a cooling globe, good reasons for maintaining, in the first place, that such a layer must have had a very different composition from that of granite, and in the second place that granite itself is a rock of secondary origin, in the formation of which water has in all cases intervened. We have, moreover, already sought to show that the attempt to derive this granitic rock, by any process of metamorphosis or metasomatosis, from sediments formed from the primitive quartzless rock, was untenable, and that the vast granitic substratum, so homogeneous and so widely spread, could not thus have originated. Already, in 1874, it had been declared that the process which generated the orthoclase and the quartz of the granitic rocks was represented in more recent times by the production of zeolites.

§ 66. The generation from basic rocks, by aqueous action, alike of orthoclase, of quartz, and of zeolites, is well known. These are often associated in such rocks under conditions which show them to be secretions from the surrounding mass. The substance named palagonite

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* For a general account of the views described in this paragraph, and for references to the somewhat extended literature of the subject, see Hunt, Chemical and Geological Essays, pp. 188–191; also *ibid.*, p. 6.

is an amorphous, apparently colloidal, hydrous silicate, the composition of which, deducting the water (about seventeen per cent on an average), is, according to Bunsen, identical with that of his normal pyroxenic or basaltic magma (§ 24), except that the iron in palagonite is in the state of peroxyd. This substance is changed by no great elevation of temperature into the zeolite, chabazite, a crystalline silicate of alumina and alkalies, rich in silica, but destitute of iron-oxyd and magnesia, and a more basic residuum, in which the latter two bases are retained. Basaltic rock is, according to Bunsen's observations in Iceland, changed through hydration into palagonite, "under the influence of a neptunian cause," and this, by the heat of contiguous eruptive masses, is subsequently transformed into a zeolitic amygdaloid. These operations, as he has shown, may be repeated in our laboratories. Fragments of amorphous native palagonite, when rapidly heated in the flame of a lamp, develop in their mass cavities filled with a white matter, recognized by the aid of a lens as crystalline chabazite; while the transformation of basaltic rock into palagonite itself may also be artificially effected.* Palagonite is not, apparently, a distinct min-

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* The following is the composition assigned by Bunsen to the typical trachytic and basaltic magmas, and to palagonite, as deduced from his studies of these rocks in Iceland; A, being the normal trachytic type, the mean of seven analyses of trachyte and obsidian; B, the normal basaltic type, from six analyses of basalt and lava; and C, the average of several palagonites of that region, deducting the water:—

	A.	B.	C.
Silica	76.67	48.47	49.15
Alumina	11.15	14.78	30.82
Ferrous oxyd	3.07	15.38	
Lime	1.45	11.87	9.73
Magnesia	0.28	6.89	7.97
Potash	3.20	0.65	0.90
Soda	4.18	1.96	1.34
	100.00	100.00	100.00

The ferrous oxyd in the six examples from which B was deduced varied from 11.69 to 19.43; while for the palagonite, the iron (which is not sepaeral species, but a colloidal hydrated mixture, interesting as marking a stage in the transformation of the vitreous form of certain basic silicated compounds. The crystalline forms of these by their decomposition may, however, yield zeolites without passing through this intermediate stage.

§ 67. That in these curious but neglected observations of Bunsen, we have reproduced in miniature not only the process which takes place on the large scale in masses of basic exoplutonic rock, but the process which must have gone on in the early ages, when the universal basic rock, which we have supposed to form the surface of the cooling globe, was heated from below, and penetrated by atmospheric waters — was a deduction which, although it seemed legitimate, was too vast and too far-reaching to be lightly accepted. It was therefore not until after many years of careful consideration, and the examination and rejection of all other conceivable hypotheses, that the conviction was acquired that in these reactions, which give rise to zeolitic minerals, we have the true solution of the problem of the genesis of crystalline rocks. This was formally enunciated in 1884, when, after considering the condition of a cooling earth, in accordance with the hypothesis defined in § 50, it was said: "The

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rated from the alumina in the above average, and is present as ferric oxyd) ranged from 11.85 to 21.30. The water therein varied from 16.0 to 24.0 per cent. The oxygen ratio for palagonite, taking the maximum of alumina, 18.97, and the ferric oxyd, 11.85, together, would be about 1 : 2 : 4; and excluding the latter from the calculation, very nearly 1 : 1⅜ : 4. Palagonite, according to Bunsen, is thus a hydrated basalt which has exchanged a portion of its lime for magnesia, with peroxydation of the contained iron. It "is the amorphous portion of basalt that gelatinizes with acids which is the part forming zeolites" (corresponding to the vitreous matter of the tachylite-basalts), and the hydration of this yields palagonite. Bunsen, by fusing a basalt with potassic hydrate, and treating the mass with water, got a material which differed from the basalt only in having lost a little silica and acquired 30.0 of water, and which had all the characters of palagonite. (Bunsen, Recherches sur la formation des roches volcaniques en Islande; Ann. de Chim. et de Phys. (1853) (3) xxxviii., 215-289.)

globe, consolidating at the centre, left a superficial layer of matter which has yielded all the elements of the earth's crust. This last-cooled layer, mechanically disintegrated, saturated with water, and heated by the central mass, furnished in aqueous solution the silicates which were the origin of the ancient gneisses and similar rocks." *

§ 68. The transformation of the primary basic layer, judging from the phenomena seen in basic exoplutonic rocks, would give rise not only to quartz, feldspars, and zeolites, but to such aluminous silicates as prehnite and epidote, and to non-aluminous silicates like pectolite, okenite, and apophyllite. These silicates are all non-magnesian, but the reactions of many of them, while in a soluble condition, with dissolved magnesian salts would give rise to various natural magnesian silicates, both aluminous and non-aluminous.

§ 69. The cooling of the surface of the earth by radiation, and the heating from below, would establish in the disintegrated, porous, and unstratified mass of the primary layer a system of aqueous circulation, by which the waters penetrating this permeable layer would be returned again to the surface as thermal springs, charged with various matters there to be deposited. The result of this process of upward lixiviation of the mass would be the gradual separation of the primary undifferentiated layer into an upper stratum, consisting chiefly of acidic silicates, such as feldspars with quartz, and a lower, more basic, and insoluble residual stratum, charged with iron-oxyd and magnesia; the two representing respectively the overlying granitic and the underlying basaltic layers, the presence of which beneath the earth's surface have generally been inferred from exoplutonic phenomena. The intervention of the argillaceous products of subaerial decay was considered, and the reactions between

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* From a report of a lecture by the author before the Lowell Institute, Boston, Mass., Feb. 29, 1884, in the Boston Daily Advertiser of March 1.

them and mineral solutions from below, it was conjectured, might give rise to certain micaceous minerals.

§ 70. That the great shrinking of the primary layer, consequent upon the removal from it, by solution, of the vast amount of matter which built up the overlying granitic and gneissic series, would result in a collapse and a general corrugation of this overlying deposit, and that this would probably be attended by outflows, through fissures, of the underlying basic magma, constituting *the first eruptive or exoplutonic rocks*, were among the most obvious deductions from this hypothesis. These various points were concisely set forth in notes read in April and May of 1884, with the suggestion that this newly proposed explanation of the origin of crystalline rocks, through the action of springs bringing up mineral matters from below, might be called the CRENITIC hypothesis, from the Greek κρήνη, a fountain or spring.[*]

§ 71. The steps in the chronological history of the new hypothesis, which we have sketched in the preceding pages, may be briefly resumed as follows: —

I. — 1858. An attempt to deduce from the doctrine of a solid incandescent nucleus, and a single primary igneous rock, supposed to be quartzless and basic, through mechanical and chemical agencies, two distinct and unlike classes of sedimentary deposits, which, when subsequently transformed by subterranean heat, should give the two types of acidic and basic crystalline rocks. This was an attempt to adapt the Huttonian metamorphic hypothesis to the conception of a cooling globe, and to give it, what it wanted, a point of departure.

II. — 1860. An attempt to explain the production, by aqueous action at the earth's surface, of various protoxyd-silicates.

III. — 1863. An attempt to extend this last conception

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[*] On the Origin of the Crystalline Rocks, National Academy of Sciences, Washington, April 15, 1884, in American Naturalist for June; also Royal Society of Canada, Ottawa, May 20, in Amer. Jour. Science, July, 1884, and Nature, July 3, p. 227.

to double aluminous silicates, by a consideration of the formation of zeolites at the earth's surface in rocks of secondary age, and also in more recent times, through the action of thermal waters; it being shown, from the association of zeolites with feldspar and quartz in nature, that all these are sometimes formed contemporaneously from aqueous solutions, and also that many feldspathic veins and masses have probably had a similar aqueous origin.

IV. — 1871. The subject of granitc veins farther discussed, and the mineralogical similarity between these endogenous masses and the indigenous gneissic and granitic rocks insisted upon.

V. — 1874. The argument reiterated that the conditions under which the primitive granitic and gneissic rocks had been produced were essentially similar to those of the granitic veins of the later crystalline schists, and that these conditions are reproduced to a smaller extent, in later times, in the formation of zeolitic minerals: finally, that the gneisses and bedded granites are to granitic veins what beds of chemically-deposited limestone and travertine are to calcareous veins.

VI. — 1880. The definite assertion of the aqueous origin of stratified crystalline rocks, coupled with the rejection of the doctrines of metamorphism and metasomatism in explaining their origin, and the assertion of their pre-paleozoic age. At the same time, the probable intervention of clays from the sub-aerial decay of feldspars, as a source of certain crystalline aluminous silicates is suggested.

VII. — 1884. The definite assertion is made that the ancient crystalline rocks were generated either directly from materials brought to the surface by subterranean springs from the primary igneous rock, or, as was the case in later times, by the reactions of these materials with the products of sub-aerial decay. These latter included clays from feldspars, and dissolved magnesian salts formed by the action upon sea-water of magnesian carbonate set free in the atmospheric decomposition of basic rock erupted from the primary stratum. Thus, while what may be called the Primitive crystalline rocks were wholly crenitic in their origin, the soluble and insoluble results of the sub-aerial decay, alike of basic exoplutonic matter and of the older crenitic rocks, contributed to the formation of the later or Transition crystalline schists.

III. — ILLUSTRATIONS OF THE CRENITIC HYPOTHESIS.

§ 72. The crenitic hypothesis, which has been proposed in the second part of this essay to account for the origin of the granites and crystalline schists, conceives them to have been derived, directly or indirectly, by solution from a primary stratum of basic rock, the last congealed and superficial portion of the cooling globe, through the intervention of circulating subterranean waters, by which the mineral elements were brought to the surface. This view not only compares the generation of the constituent minerals of the primitive rocks with that of the minerals formed in the basic eruptive rocks of later times, but supposes these latter rocks to be extruded portions of the primary plutonic stratum which, though more or less modified by secular changes, still exhibit after eruption, though on a limited scale, the phenomena presented by that stratum in remoter ages. The study of these rocks, and of their accompanying secondary minerals, which may be properly described as the secretions of these rocks, will therefore be found very important as illustrations of the crenitic hypothesis.

§ 73. Without here entering into the details of their geognosy or their lithology, it is sufficient to recall the fact that such basic eruptive rocks abounding in zeolitic minerals are found, with many characters in common, from the time of the Cambrian or pre-Cambrian Keweenian series of Lake Superior to that of the trias of eastern North America, the tertiary of Colorado and the British Islands, and the recent lavas of Iceland. The secreted minerals of these rocks often occur in closed cavities in tufaceous beds, constituting amygdaloids, and, at other times, in veins or fissures of considerable size. They are not, however, confined to the tufaceous or recomposed detrital exoplutonic rocks (which are sometimes themselves hydrated and transformed into palagonite, as described by Bunsen in Iceland), but occur in veins and cavities in massive rocks, as is well seen in the diabase of Bergen Hill, New Jersey, and the massive basalt of Table Mountain, near Denver, Colorado, both remarkable for their zeolitic minerals.

§ 74. The accumulations of secreted minerals in these conditions are often considerable in amount. Among other examples, it may be noticed that the zeolitic masses in the amygdaloids of the Faroë Islands are sometimes three or four feet in diameter, and constitute a large portion of the rock. Veins of laumontite in Nova Scotia attain breadths of a foot or more, while some veins on Lake Superior, which are made up to a great extent of zeolitic and related species, are two and three feet or more in breadth, and often of considerable extent. The history of the chemical composition of the zeolite-bearing rocks of Lake Superior, and of the changes which have taken place in their degradation from the original eruptive mass, have been studied in detail by Pumpelly, with the help of the previous analyses of Macfarlane, but cannot here be discussed.*

§ 75. We may here notice the modes of occurrence of the zeolites of Table Mountain, Colorado, as described in 1882 by Messrs. Cross and Hildebrand.† The upper forty feet of a great flow of basalt, one hundred feet or more in thickness, show many cavities, large and small, de-

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* T. Macfarlane, Geological Survey of Canada, 1866, pp. 149-164; Pumpelly, Geology of Michigan, 1872, part 2; also the same, on The Metasomatic Development of the Copper-bearing Rocks of Lake Superior, Proc. Amer. Acad., Boston (1876), vol. xiii., pp. 253-309.

† Cross and Hildebrand, American Journal of Science, xxiii., 452, and xxiv., 129.

scribed as more or less flattened and drawn out. Some of these cavities are empty, while others are more or less completely filled by various zeolites, which are also found in fissures in the mass and, in the case of analcite, in a conglomerate made up of pebbles of basic eruptive rocks, underlying the bed of basalt. The zeolitic deposit often appears as "a reddish-yellow sandstone-like material, which occurs in many of the cavities. In the larger ones it takes the form of a floor, the upper surface being horizontal, and the deposit may be several inches in thickness. Small cavities have been completely filled with it, and it is clear that the deposition has taken place from the bottom of each cavity, upward. In parts of South Table Mountain, especially, the same material has filled fissures. Usually the lower part of such masses is composed of a reddish-yellow mineral in irregular grains, which form a compact aggregate, in which lie isolated spherules of a similarly colored radiated mineral. These spherules are seldom more than two millimetres in diameter, and are very perfect spheres. They increase in number upwards, and finally form the greater part of the deposit. In one cavity, six or eight feet in horizontal diameter and about two feet high, the deposit is quite different. Here the main mass is loosely granular, and is formed chiefly by a bright greenish-yellow mineral, while a stratified appearance is produced by layers of a white or colorless mineral. Some of the white layers are chiefly made up of easily recognized stilbite, and the same mineral, in distinct tablets, forms the upper layer of the whole deposit. There are also irregular seams of white running through the yellow mineral."

The greenish-yellow crystalline mineral was found to consist of laumontite, and the other layers were mixtures of stilbite and laumontite, with some of which were found spherules of thomsonite. This, in other cavities, formed layers by itself, without admixture of the other zeolites mentioned. The presence of these zeolites in cavities side by side with other cavities which were entirely empty, is, according to the writers whom we have quoted, apparently due to the fact that the former communicated with fissures which were channels for the percolating waters that deposited the zeolites. Such fissures, filled up with similar zeolites, were in many cases found leading to these cavities.

§ 76. The eruptive rocks which break through the Trenton (Ordovician) limestone at and near Montreal, in Canada, are of various ages and unlike composition. Some of these are highly basic, and have been described as dolerites and diorites, while some have been found to contain analcite, and others again much nephelite, and have been referred to teschenite and nepheline-syenite. In some fine-grained amygdaloidal varieties of these basic rocks, which have been designated dolerites, I long since described the occurrence of heulandite, chabazite, analcite, and natrolite, with quartz and epidote.* These zeolites are not abundant, but in certain of the basic doleritic rocks on Mount Royal I have found remarkable veins of orthoclase with quartz and other minerals, which merit a notice in this connection. Included in vertical dikes of these rocks, themselves cutting the horizontal limestones which appear at the base of the mountain, are frequent granitic veins, sometimes twelve inches or more in breadth, parallel with the walls of the inclosing dike, often distinctly banded, and exhibiting a bilateral symmetry which, together with their drusy structure, shows them to be endogenous. The most characteristic of these veins are made up of white, coarsely crystalline orthoclase with a little quartz which, in druses, presents pyramidal forms. In some of the veins, Dr. Harrington has since detected, besides orthoclase and quartz, nephelite, sodalite, cancrinite, amphibole, acmite, biotite, and magnetite. All of these minerals are seemingly secretions from the enclosing basic exotic rock.

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* Hunt, in Geology of Canada, 1863, pp. 441, 655, and 668; also Harrington, Report Geol. Survey of Canada, 1877-78, p. 43, G.

§ 77. The mineral secretions of the basic eruptive rocks may be conveniently grouped under seven heads, as follows: —

1. The aluminous silicates, including the zeolites properly so called, to which we append the related hydrous species, prehnite, and the associated species, orthoclase, garnet, and epidote, which are found in the amygdaloidal rocks of Lake Superior. To these we must add albite, axinite, tourmaline, and sphene, observed by Emerson, in 1882, in a diabase dike in the trias at Deerfield, Massachusetts,* and also the various anhydrous aluminous silicates found with orthoclase in the veins on Mount Royal, just described.

2. The group of hydrous protoxyd-silicates, the bases of which are lime and alkalies, and of which pectolite may be taken as the type. These species are sometimes wrongly spoken of as belonging to the class of zeolites. As an appendage to this group, we note the hydrous borosilicate of lime, datolite, frequently found in these rocks. Mention should here also be made of the anhydrous protoxyd-silicates, amphibole and acmite, in the feldspathic veins of Mount Royal. We have already called attention to the occurrence of amphibole and pyroxene in granitic veins under other conditions (§ 57).

3. Quartz in its various crystalline and cryptocrystalline forms, as rock-crystal, amethyst, chalcedony, agate, and jaspery varieties, is found both alone and associated with the minerals of the preceding groups. Hyalite of very recent origin has also been observed by Emerson at Deerfield.

4. The oxyds, magnetite and hematite, are frequent in the zeolite-bearing rocks of Nova Scotia, where both of these species form veins in amygdaloid, and where magnetite moreover occurs in drusy cavities with quartz, lau-

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* Emerson, Amer. Jour. Science, xxiv., pp. 195, 270, and 329. We reserve for another occasion the discussion of the paragenesis of the minerals of this locality, so carefully studied by Emerson.

montite, and calcite. Hematite, in the form of plates of specular ore, is also found there in veins with laumontite, and manganese-oxyd is sometimes associated with these iron-oxyds. Small crystals of hematite on prehnite, with a little manganese-oxyd, have been observed by Emerson at the Deerfield locality, as also cuprite on datolite, and malachite on prehnite. In similar associations he found moreover small portions of various sulphids, such as chalcopyrite, pyrite, sphalerite, and galenite. (*Ante*, page 121.)

5. The presence of native copper, and occasionally of native silver, associated with the various silicates already named, should also be noticed. The former metal is common to the zeolitic rocks of Lake Superior and Nova Scotia.

6. Mention should here be made of the saponite often found in amygdaloidal rocks, which, in its purer form, is a hydrous silicate of magnesia with but little alumina or iron-oxyd. Matters, apparently of this class, fill, or more frequently line, amygdaloidal cavities which are filled with other species. This magnesian hydrous silicate is perhaps distinct in origin from the delessite or iron-chlorite which is a frequent constituent of many basic rocks, such as the melaphyres of Lake Superior, and is probably not a secretion but a residual product of the transformation of the rock.

7. Calcite in various forms is a common species in the rocks in question, and fluorite and barytine may also be mentioned as accidental minerals therein.

It is principally with the first two classes of minerals, the zeolitic group with its appendages, and the pectolitic group that we have to do. These two, as is well known, though chiefly found in the eruptive rocks already noticed, are not confined to them. Some species of zeolites occur occasionally in veins in gneiss and other crystalline rocks, and even in limestones and other sedimentary deposits. These occurrences are the more readily understood when we consider that the same minerals have in various localities been recently formed by the action of thermal waters, and are even generated in submarine ooze. Many of the species of these two groups have also been formed artificially in the chemist's laboratory.

§ 78. It is our present purpose to consider, first, the zeolitic, and secondly, the pectolitic group, both as regards their chemical composition and their relations to various anhydrous silicates. We shall then proceed to notice the action of water at high temperatures on glass and similar bodies, in giving rise to various crystalline species, including quartz. In this connection will also be discussed some facts relating to the chemistry of the alkaline silicates. We shall next notice the action of thermal waters in historic times, and the occurrence of zeolites in the clays of the deep sea, and then pass to the experiments on the artificial reproduction of zeolitic species in the laboratory of the chemist, and discuss the relations of hydrous and anhydrous species. From this, we shall proceed to a consideration of the reactions of the hydrous species of the two groups with magnesian salts. The origin of these salts through sub-aerial decay of exoplutonic magnesia-bearing silicates, and their relation to the primeval sea, will then claim our notice; after which will be considered the probable relations of the clays from the sub-aerial decay of feldspathic rocks to other classes of rock-making silicates. The conditions of crystallization of mineral matter will next be considered in relation to the formation of rocks, after which the conclusions of our present study will be briefly summed up in the fourth and last part of this essay.

§ 79. In the accompanying table of zeolites and related species, are placed, in the first column, the names of hydrous species, and in the second column the oxygen-ratios between the protoxyd-bases, the alumina, the silica, and the water, represented respectively under R, r, Si, and H. In the fourth column are given the names of corresponding anhydrous species. In this and the succeeding

TABLE OF ZEOLITES AND RELATED SPECIES.

HYDROUS.	R : r : Si : H	R	ANHYDROUS.
Thomsonite	1 : 3 : 4 : 2	Ca, Na.	Anorthite, etc.
Gismondite	1 : 3 : 4½ : 4½	Ca.	Nephelite.
Esmarkite	1 : 3 : 5 : 1	Mg.	Barsowite, Iolite, etc.
Fahlunite	1 : 3 : 5 : 2	Mg.	
Natrolite	1 : 3 : 6 : 2	Na.	Labradorite.
Scolecite	1 : 3 : 6 : 3	Ca.	
Mesolite	1 : 3 : 6 : 3	Ca, Na.	
Levynite	1 : 3 : 6 : 4	Ca, Na.	
Analcite	1 : 3 : 8 : 2	Na, Ca, K.	Andesite, Hyalophane, Leucite.
Eudnophite	1 : 3 : 8 : 2	Na.	
Laumontite	1 : 3 : 8 : 4	Ca.	
Herschelite	1 : 3 : 8 : 5	Na, K.	
Phillipsite	1 : 3 : 8 : 5	Ca, K.	
Chabazite	1 : 3 : 8 : 6	Ca, Na, K.	
Gmelinite	1 : 3 : 8 : 6	Ca, Na.	
Faujasite	1 : 3 : 9 : 5	Ca, Na.	Oligoclase.
Hypostilbite	1 : 3 : 9 : 6	Ca, Na.	
Puflerite	1 : 3 : 9 : 6	Ca.	
Harmotome	1 : 3 : 10 : 5	Ba.	——?
Heulandite	1 : 3 : 12 : 5	Ca.	Orthoclase, Microcline, Albite.
Epistilbite	1 : 3 : 12 : 5	Ca.	
Brewsterite	1 : 3 : 12 : 5	Ba, Sr.	
Stilbite	1 : 3 : 12 : 6	Ca.	
Prehnite	2 : 3 : 6 : 1	Ca.	——?
Jollyte	1 : 2 : 3 : 2	Mg, Fe.	Zoisite, etc.

tables I have generally followed the terminology and adopted the formulas given in the fifth edition of Dana's "System of Mineralogy."

In the line with the most basic zeolite known, thomsonite, is placed the feldspar, anorthite, and with nephelite is coupled the hydrous species gismondite, a true zeolite. The recent analyses, by Cross and Hildebrand, of the zeolites of Table Mountain, Colorado, give for the zeolites having the characters of thomsonite a proportion of silica greater than corresponds to the formula of that mineral given by Rammelsberg, which we have placed in the table. Some of their analyses, while yielding almost exactly the other ratios of the formula, give for silica, instead of 4.00 the numbers, 4.65, 4.76, and even 5.17; showing a composition more silicious than that of gismondite, and approaching that of a zeolite corresponding to fahlunite, barsowite, and bytownite. These chemists, while believing the specimens analyzed by them to represent a pure and unmixed mineral, leave undecided the question of its real composition.

§ 80. The feldspar which has been called barsowite and bytownite, according to several concordant analyses is as distinct from anorthite as it is from labradorite, and apparently as much entitled to form a distinct species as the latter feldspar, or as andesite or oligoclase. The composition of a lime-barsowite, with the ratios, 1 : 3 : 5, would be silica 48.54, alumina 33.33, and lime 18.13 = 100.00. With barsowite has been placed iolite, which is a magnesia-iron silicate, giving the above ratios, and, as I long since pointed out, is from its atomic volume entitled to be regarded as a feldspathide. These various anhydrous species would appear to correspond very nearly with the so-called thomsonite of Cross and Hildebrand. With this anhydrous group we have placed two hydrous magnesian species, the one, esmarkite, also called praseolite and aspasiolite, and the other fahlunite, which includes what have been called auralite and bonsdorffite.

These species are often associated in nature with iolite, from which they differ only in the presence of water, and they have been by most mineralogists regarded as formed by subsequent hydration from this mineral. This view, however, was contested by Scheerer, who regarded the association of the hydrous and anhydrous minerals as due to a simultaneous crystallization of two isomorphous species.*

The relations of the silicates of the natrolite section to labradorite are obvious from the table. The same may be said of the relations of the numerous silicates of the analcite section to andesite, hyalophane, and leucite, and of the faujasite section to oligoclase. It is to be noted that the well-defined zeolite, harmotome, has as yet no corresponding anhydrous silicate. Of the heulandite section, and the corresponding feldspars, orthoclase and albite, it is to be remarked that orthoclase and albite are the only feldspars hitherto found associated with zeolites, and the only feldspars as yet artificially produced in the wet way. The observations of Whitney already noticed (§ 57) have since been fully confirmed by Pumpelly, who finds orthoclase very common with the zeolitic minerals on Lake Superior, where its deposition is shown to be posterior to laumontite, prehnite, analcite, apophyllite, quartz, calcite, copper, and datolite; the only species superimposed upon it being calcite, chlorite, and epidote, which latter also occasionally occurs between laumontite and prehnite in order of superposition.†

§ 81. We have placed at the end of the table the two hydrous silicates, prehnite and jollyte, though neither of them presents the ratios for protoxyds and alumina which characterize the zeolites. Prehnite has no known corresponding anhydrous silicate, while jollyte, though a less common species, is interesting inasmuch as it affords the

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* Amer. Jour. Science (1848), v. 385, from Pogg. Annalen, lxviii., 319.

† See Pumpelly, Geology of Michigan, already cited, § 74; also Amer. Journal Science (1871), iii., 254.

oxygen-ratios of the anhydrous zoisite and the nearly anhydrous species epidote. It has also the oxygen-ratios of meionite of the scapolite group, an anhydrous silicate, which, however, belongs to a much less condensed type than zoisite, as is indicated by its inferior density and hardness, and its ready decomposition by acids. I have elsewhere discussed the relations of these two silicates, and have shown that the density, hardness, and chemical indifference of epidote and saussurite assign them a place with garnet and idocrase, in the grenatide group; while meionite, though lacking the proper feldspar-ratio between protoxyds and alumina, belongs to the feldspathides.* [The recent conclusions of Tschermak as to the oxygen-ratios of the scapolites are set forth in Essay VIII., on "A Natural System in Mineralogy, etc.," § 75–78, in which essay, under Tribes 6, 7, and 8, will be found discussed at length the chemical constitution and history of the principal aluminous double silicates here noticed.]

§ 82. It is to be noted that the protoxyd-bases of the zeolites and their related feldspathides are either alkalies or lime, baryta or strontia, if we except the partially magnesian zeolite, picrothomsonite, and iolite and some related hydrous species, which, besides magnesia, include ferrous oxyd. The latter base enters also to some extent into epidote and prehnite. It should also be remarked that small portions of ferric oxyd are frequently found in the analyses of zeolites, amounting, in the red varieties of laumontite to three or four, and in some natrolites to one and two hundredths. Some part of this, however, is disseminated in the form of hematite, giving color to the zeolites, and recalling the association alike of hematite and magnetite with zeolites, as already noticed, as also a similar occurrence of these oxyds crystallized in many granitic veins.

§ 83. We next come to the hydrous silicates of lime and alkalies, which we have called, for convenience, the

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* Chemical and Geological Essays, pp. 445–447.

pectolitic group, and which are correlated in the accompanying table with other protoxyd-silicates having similar oxygen-ratios, chiefly magnesian, and partly hydrated and partly anhydrous. We have indicated in the second column, for the known silicates of the pectolitic group, the oxygen-ratios of R, Si, and H, as in the former table, and have left a blank under H, where, as in the first three terms, for example, no non-magnesian species is known.

TABLE OF PROTOXYD SILICATES.

PECTOLITIC.	R : Si : H	
——? . . .	4 : 3 : —	Chondrodite, Humite, etc.
——? . . .	1 : 1 : —	Chrysolite, Monticellite, Phenacite, etc.
——? . . .	3 : 4 : —	Serpentines, Leucophanite.
Gyrolite, etc. .	2 : 3 : 1	Deweylite, Genthite.
Xonaltite . .	1 : 2 : ½	Wollastonite, Amphibole, Rhodonite, Pyroxene, Enstatite, Cerolite.
Plombierite .	1 : 2 : 2	
Pectolite . . .	5 : 12 : 1	Amphibole in part, Spadaite.
——? . . .	2 : 5 : —	Talc in pa.
——? . . .	1 : 3 : —	Sepiolite, Talc in part.
(Unnamed) . .	1 : 4 : ½	Titanite, Guarinite.
Okenite . . .	1 : 4 : 2	
Apophyllite .	1 : 4 : 2	

The first place in the table is given to chondrodite, with its sub-species, the most basic natural protoxyd-silicates known, and remarkable for the replacement of a small and variable proportion of oxygen by fluorine. In the second line, besides the chrysolites (including the pure magnesian species, forsterite) monticellite, and phenacite, there named, belong the hydrous glucinic species, bertrandite, the hydrous magnesian species, villarsite, the anhydrous zincic and manganesian species, willemite and tephroite, with many others. In the third line are to be placed the various hydrous magnesian silicates generally known as serpentine; we have discussed further on, in Essay VIII., the history of these species, including the prismatic chrysolite and picrolite, the foliated thermophyllite and marmolite, and the amorphous colloid species, retinalite, and that for which we retain the name of serpentine. The anhydrous species, leucophanite, presents the same atomic ratios for protoxyds and silica as the serpentine group, for which there is no corresponding anhydrous magnesian species. It is worthy of note that, as Daubrée has shown, serpentine, when dehydrated and fused, breaks up into a mixture of crystalline chrysolite and enstatite, between which, excluding water, it is intermediate in composition.* With the hydrous lime-silicate, gyrolite, may be placed the manganesian species, friedelite, and the chloriferous ferrous silicate pyrosmalite, both also hydrous, and properly classed with the tribe of pectolitoids. To these correspond the hydrous magnesian silicate, deweylite, and the niccolic species, genthite.

§ 84. We come next to the great section of bisilicates, represented among anhydrous species by wollastonite, enstatite, pyroxene, many amphiboles, and the manganesian species rhodonite, with related species and sub-species. With these are the hydrous magnesian bisilicates, picrosmine, aphrodite, and cerolite, together with hydrorhodonite, dioptase, and chrysocolla. These various bisilicates are represented among the pectolitic group by plombierite and xonaltite; the former a lime-silicate found by Daubrée in the process of formation at the hot spring of Plombières in France, and having the oxygen-ratio, 1:2:2. Of the less hydrated xonaltite, it is worthy of remark that,

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* Comptes Rendus de l'Acad. des Sciences, lxii., le 19 mars, 1866.

as observed by Rammelsberg, it occurs in concentric layers with the anhydrous species, rhodonite (bustamite), and the hydrous quadrisilicate, apophyllite.

While many amphiboles have the ratio of a bisilicate, others are believed to have a ratio (excluding a little water) of 4:9, not far from that of pectolite, with which we have placed them. Here also comes the hydrous magnesian species, spadaite. Different analyses have assigned to talc the ratios for the fixed bases of 2:5 and 1:3 (the water being variable), — the latter corresponding to sepiolite, 1:3:1. For neither of these do we know any corresponding pectolitic silicate.

§ 85. We come, in the last place, to the quadrisilicates, which have no known representatives among hydrous magnesian species, or among anhydrous silicates, if we except the titanosilicates, titanite, and guarinite. They are, however, represented in the pectolitic group by no less than three species, okenite, apophyllite, and an unnamed species got artificially by Daubrée. It is fibrous, like okenite, is decomposed by acids, and is a hydrous silicate of lime, with six per cent of soda, giving the ratios, $1:4:\frac{1}{2}$. Pectolite, it will be recollected, contains in like manner about nine per cent of soda, while apophyllite contains five per cent of potash and a little fluorine.

§ 86. The process by which this unnamed pectolitic silicate was obtained by Daubrée is very instructive, as showing, in many ways, the action of heated water on an undifferentiated silicate of igneous origin. He took for the subject of his experiments a common glass, the analysis of which gave silica 68.4, alumina 4.9, lime 12.0, magnesia 0.5, and soda 14.7 = 100.5. Tubes of this glass were sealed up, with many precautions, in tubes of iron, with about one-third their weight of pure water, and exposed during several weeks to a temperature not less than 400° C. At the end of this time the glass was found to be completely disaggregated and changed into a white fibrous or lamellar substance, composed in great part of the fusible pectolitic quadrisilicate of lime and soda in question. With this were found abundant crystals of quartz, and a few crystals having the form of diopside and the composition of a lime-iron pyroxene. In certain of the crystals of this latter mineral were also included microscopic grains of a black matter resembling magnetite or picotite, probably the former. The iron of these minerals was perhaps derived from the metal tube.

§ 87. The net result of the prolonged action of heated water on the glass was that the vitreous silicate gave up 44.0 per cent of its silica, 64.0 per cent of its soda, and 85.0 per cent of its alumina; the lime, with the remaining silica and soda and alumina (equal to 1.4 hundredths) forming the pectolitic silicate. Of the separated silica, the larger part separated in the form of well crystallized quartz, with globules of chalcedony, and the few crystals of pyroxene mentioned above. The soluble matter, got by treating the decomposed glass with boiling water, was a silicate of soda with some dissolved alumina, neglecting which, the proportions of soda and silica in the liquid were found, in one instance, to be as 63 to 37, by weight, corresponding to an oxygen-ratio for R:Si of about 3:4. But as, according to Daubrée's analysis, 85.0 per cent of the alumina had passed into the solution, this would make for 63 parts of soda not less than 9.7 parts of alumina, which should give for the silico-aluminate in solution a ratio of R:r:Si of nearly 3:1:4; a result of much significance which it would be very desirable to verify by further trials.

§ 88. Daubrée has recorded experiments like that above made to determine the solvent action of heated water upon vitreous volcanic rocks, such as obsidian and perlite, which gave similar results to glass, though, according to him, not so well defined. Fragments of sanidin, of oligoclase, of potash-mica, and of pyroxene, in these tubes, suffered no apparent change, though incrusted with crystals of quartz derived from the glass.

This stability was to have been expected from the fact that crystals of pyroxene are formed under similar conditions, and, as we shall see, both albite and orthoclase have since been crystallized at high temperatures in presence of solutions of alkaline silicates. Another experiment, mentioned by Daubrée in this connection, is important. By heating in a glass tube with water a refractory clay (probably under similar conditions to the preceding experiments), this became filled with white pearly hexagonal scales, resembling a mica. They were fusible, attacked by hydrochloric acid, and contained both silica and alumina, being seemingly a product of the action of the alkaline silicate from the glass upon the infusible kaolin.*

Daubrée recalls in this connection the observations of Frémy, who found that colloidal silicates of soda (water-glass), made at low temperatures, and containing a large excess of silica, give up, when heated, a portion of their silica, which separates in a form having the insolubility of quartz.† Daubrée well remarks that we appear to have, in his own experiments at high temperatures with water, a similar breaking-up of the silicate of soda, which had separated from the glass, into quartz and a more basic silicate.

§ 89. In connection with this apparent solubility of alumina, under certain conditions, in watery solutions of alkaline silicates, the observations of Ordway are very important. In his extended studies of the alkaline silicates in 1861, he notes that Bolley had shown that magnesia and lime are slightly soluble in solutions of water-glass, and that Kuhlmann had obtained a double silicate of potash and manganese as a violet-colored vitreous mass, giving a brown solution with water, and had also observed a similar combination of cobalt. Ord-

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* Daubrée, Géologie Expérimentale, pp. 159–179.

† Frémy, Comptes Rendus de l'Académie des Sciences (1856), xliii., p. 1146.

way found in the manufacture of water-glass, that if care be not taken, a portion of iron passes into the compound, which is not separated from the solution by peroxydation, and but imperfectly by sulphids. The solvent power of the water-glass is diminished by dilution, but the liquid, thus rendered turbid, becomes clear again on concentration. He observed that when a few drops of a weak solution of a metallic salt are added to a solution of water-glass, the precipitate at first formed is redissolved by agitation. "A liquid silicate thus takes up no inconsiderable amount of the oxyds of iron, zinc, manganese, tin, antimony, copper, and mercury." By agitating a solution of ferrous sulphate with one of water-glass in a vessel partly filled with air, a liquid is got which, after filtration, has a very deep blue color.* This solubility of metallic oxyds in aqueous solutions of alkaline silicates will help to a rational explanation of many obscure facts in mineralogical chemistry, as, for example, the presence of iron, manganese, and copper-oxyds, and of metallic copper, with the zeolites and other minerals secreted from basic rocks.

§ 90. We may now consider the observations of Daubrée and others on the contemporaneous formation of crystalline zeolites, and many other mineral species, by the slow action of various thermal waters on the bricks and mortar of ancient Roman masonry in France and Algeria. It was at Plombières, in the Vosges, that his first observations were made. The hot water, here rising from a fissure in a granitic rock, penetrates a layer of gravel, and to protect it from the superficial waters, the Romans had capped the spring with a mass of concrete, resting partly upon the granite and partly upon the gravel. From beneath this concrete, extending over a length of more than a hundred metres, and in parts three metres in thickness, the waters were led to the surface through vertical channels of cut stone. The water, hav-

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* Ordway, Amer. Journal Science (1861), xxxii., 338.

ing at its outlet a temperature of 70° C., fills the gravel beneath the roof of concrete, and a portion filters slowly upward through this. The concrete itself was made of fragments of burnt red brick, with others of sandstone and of a friable granite, the whole in a calcareous cement. Repairs having required cuttings to be made in this mass, it was found to contain numerous crystallized mineral species, formed through the action of the water, which were examined by Daubrée, with the aid of De Senarmont for the crystallographic determinations, and first described in 1858.

§ 91. The substance of the fragments of brick was found to be altered to some depth, while the numerous cavities therein were lined or filled with various matters, often distinctly crystallized. Among these were identified chabazite and phillipsite (christianite), gismondite, implanted on the chabazite, scolecite, and what is designated by Daubrée as mesotype (thomsonite or natrolite). In the calcareous cement were well defined crystals of apophyllite, containing, as usual, a little fluorine; while in cavities in the lower part of the concrete, near the gravel, was found an abundant gelatinous matter, which was detected in the act of deposition in recent cuttings in the mass through which the water was still oozing. This matter elsewhere had consolidated into a white mammillary concretionary fibrous substance, which was found to be a hydrous silicate of lime, with but 1.3 hundredths of alumina, and constitutes the pectolitic species, plombierite, already noticed (§ 84). With the various minerals in the concrete were also found an abundant deposit of silica in the form of hyalite, and, more rarely, crystals of tridymite, and globules of chalcedony, together with calcite in well defined crystals, arragonite, and fluorite. The chabazite was often found adherent to fragments of wood enclosed in the concrete, recalling, as observed by Daubrée, the similar occurrence of zeolites with fossil wood in lacustrine limestone in Auvergne.

The various minerals named were absent from the fragments of friable granite, while in the underlying gravels the only matter deposited was an amorphous aluminous silicate, compared to halloysite, and found also in the concrete.

§ 92. The fragments of red burnt brick in the cement had undergone an alteration from their surface, marked by concentric lines of changed color, as well as by the development of zeolites, and also of an amorphous matter compared by Daubrée to palagonite. In these fragments, the amount of combined water had increased from two or three hundredths in the centre, to eight hundredths in the outer infiltrated portion, in which the amount of matter soluble in nitric acid was equal to fourteen or fifteen hundredths, including a notable proportion of potash, supposed by Daubrée to have been taken up from the waters. The silica, alumina, and lime of the new mineral species were derived from the cement and the bricks, the calcination of which had probably rendered them more susceptible to chemical change. As has been pointed out by Daubrée, the resemblance between these species and the similar ones found in many rocks extends even to minor details of crystalline form and association. The small geodes lined with crystals, in the bricks, as the writer can testify, cannot be distinguished by inspection from many similar cavities in certain amygdaloids.

§ 93. Similar phenomena have since been noticed in the ancient constructions around the thermal waters of Luxeil, Bourbonne, and others in France, and at Oran in Algeria. These localities have added little more to our knowledge of the production of silicates, though at some of them, and notably at Bourbonne, besides zeolites, have been found various crystalline metallic sulphides derived from the transformation of metallic objects enclosed in the concrete. The water of the last named locality, which, unlike that of Plombières, rises from the muschelkalk, has a temperature of about 60° C., and is a neutral saline containing seven or eight thousandths of mineral matters, chiefly sulphates and chlorids of alkalies, and of lime and magnesia; while that of Plombières contains only about three ten-thousandths, and is also said to be neutral. As remarked by Daubrée, it is probable that the action of the water in the formation of these mineral silicates is, to a great extent, independent of its composition, since pure water, in acting upon finely divided alkaliferous materials, soon becomes itself alkaline.

As regards other silicated deposits from thermal waters, we may notice the case of the baths of St. Honoré (Nièvre), the waters of which, having a temperature of 31° C., yield a finely laminated white translucent substance in concentric layers, which appears from analysis to be a hydrous silicate of alumina, with a large excess of silica, but is probably a mixture. Mention is also made of a similar deposit from a mineral spring at Cauterets, which is talcose in aspect, and, according to qualitative analysis, is a silicate of alumina, with magnesia and alkalies.* In this connection mention should be made of the occurrence at the thermal spring of Olette (Pyrennées Orientales) of a crystalline silicate, having, according to Descloizeaux, the crystalline form of stilbite, of which it has also the composition.†

§ 94. As an example of a zeolite apparently in process of formation, may be mentioned the observations of R. Hermann, who found in the crevices of a columnar basalt at Stolpenau, in Saxony, an amorphous white plastic substance, which after some time changed into acicular crystals of scolecite.‡ More recently, Renevier has described the occurrence of a white subtranslucent matter, unctuous to the touch, gelatinous at first, but becoming a

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* For a summary of the observations of Daubrée, the details of which are found in several papers, see his Géologie Expérimentale, 1879, pp. 179–207.

† Cited by Dana, System of Mineralogy, 5th ed., p. 443.

‡ Jour. für Prakt. Chemie, lxxii. Cited by Dana, System of Mineralogy, *sub voce* Scolecite.

plastic mass, and called by the quarrymen "mineral lard," found in constructing a tunnel in the molasse or tertiary sandstone near Lausanne, in Switzerland, in 1876. This substance, which formed layers of from one to three centimetres on the walls of fissures, was said by observers to have, in some cases, taken on a crystalline form, a fact, however, which Renevier was not able to verify. When dried at 100° C., it was found to be a hydrated double aluminous silicate, giving the oxygen-ratios of chabazite, 1 : 3 : 8 : 6; the bases being lime and potash, with 3.14 per cent of magnesia.[*]

§ 95. A remarkable fact in the history of zeolites is that lately made known by the researches of Murray and Rénard, that a decomposition of volcanic detrital material goes on at low temperatures in the depths of the ocean, transforming basic silicates, "represented by volcanic glasses such as hyalomelane and tachylite," into a crystalline zeolite on the one hand, and the characteristic red clay of deep-sea deposits on the other. To quote the language of the authors, this process, "in spite of the temperature approximating to 0° C., gives rise, as an ultimate product, to clearly crystallized minerals, which may be considered the most remarkable products of the chemical action of the sea upon the volcanic matters undergoing decomposition. These microscopic crystals are zeolites, lying free in the deposit, and are met with in greatest abundance in the typical red-clay areas of the central Pacific. They are simple, twinned, or spheroidal groups, which scarcely exceed half a millimetre in diameter. The crystallographic and chemical study of them shows that they must be referred to christianite,"[†] which is but another name for phillipsite. We have here, as in the case of palagonite, and in ordinary zeolitic rocks, the breaking-up of a basic igneous silicate into an acidic crystalline aluminous silicate of lime and alkalies, and a more basic insolu-

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[*] Bull. de la Soc. Vaudoise des Sci. Naturelles, x [illegible], 15.

[†] Lecture, in Nature, June 5, 1884, p. 133.

ble residue, rich in iron-oxyd; a portion of which, as is well known, separates from these red clays in the form of concretions, often with oxyd of manganese.

§ 96. We have next to examine the conditions under which zeolites, feldspars, and related silicates have been artificially produced in the chemist's laboratory. When, according to Berzelius, three parts of silica and two of alumina are fused with fifteen parts or more of potassic carbonate, and the cooled and pulverized mass is exhausted with water, there remains a double silicate, which has the composition of a potash-anorthite, with the ratios, 1 : 3 : 4, corresponding to potash 28.68, alumina 32.04, and silica 39.31; the excess of silica being dissolved as an alkaline silicate.* The analogous soda-compound may be produced in like manner. A similar silicate, according to Ammon, is obtained when recently precipitated alumina is added to a moderately concentrated and boiling solution of caustic soda, mixed with silicate of soda. The alumina is at first completely dissolved, but a white pulverulent precipitate soon separates, which is a hydrous silicate of soda and alumina, having for the fixed bases the same ratio as before, 1: 3: 4; corresponding to anorthite and to thomsonite.†

§ 97. C. J. Way, in his studies on the absorption of bases by soils, prepared artificial aluminous silicates by dissolving alumina in soda-lye, and adding thereto a solution of silicate of soda containing not more than one equivalent of silica to one of alkali (R : Si = 1 : 3), to which any convenient excess of soda might be added. A precipitate was thus obtained, which, when washed and dried at 100° C., was a white pulverulent silicate of alumina and soda, holding twelve hundredths of water, and having almost exactly the oxygen-ratios, 1 : 3 : 6 : 2; being a true soda-mesolite. This artificial silicate, when digested with lime-water, or with any neutral salt of lime,

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* Cited in Gmelin's Handbook, iii., 431.

† Jahresbericht der Chemie, 1862, p. 128.

exchanged its soda for lime. It was difficult thus to separate the whole of the soda, but in some cases the replacement was almost complete, and a scolecite was formed. Either of these compounds, when digested with sulphate or nitrate of potassium, was converted into a potash-mesolite. With a solution of a magnesian salt, these compounds gave a magnesian double silicate, which was not particularly examined.* Berzelius, by adding a solution of silica to one of alumina in potash, in proportions which are not indicated, found the mixture to solidify in a few minutes to an opaque jelly in consequence of the separation of a silicate of alumina and potash having the oxygen-ratios, 1 : 3 : 8, which are those of analcite.† Farther investigations are required to make known the precise conditions for the production of these different silicates, which give for their fixed elements the ratios respectively of thomsonite, mesolite, and analcite. The most basic of these, according to Berzelius, is formed in the presence of an excess of a soda-silicate.

§ 98. Henri Ste.-Claire Deville, by mingling solutions of silicate of potash and aluminate of soda in such proportions as gave for the oxygen-ratios, al : Si = 3 : 6, obtained a gelatinous precipitate, which in sealed tubes, at temperatures of from 150° to 200° C., was gradually changed into hexagonal plates of a potash-soda zeolite with the oxygen-ratios, 1 : 3 : 6 : 2, having the physical characters of levynite. The residual liquid was nearly free from both silica and alumina. On repeating this experiment at a higher temperature, a very different result was obtained. There was an abundant separation of silica in crystalline grains, with a little levynite, while an alkaline aluminate remained in solution. This remarkable dissociation of the first-formed aluminous silicate into free silica and soluble alumina recalls the conditions of the separation of quartz,

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* Way, On the Power of Soils to absorb Manures, Trans. Royal Soc. Agriculture, 1852, xiii., 123–143.

† Cited in Gmelin's Handbook, iii., 439.

already noticed in § 87. The crystalline silica produced in this reaction may be either quartz or tridymite, which latter form of silica, mingled with quartz, was obtained in 1879 by Friedel and Sarrasin by heating gelatinous silica with an alkaline solution to about 400° C. The dissociation of alumina from silica, observed in this experiment, serves to throw light on the origin of corundum and spinel. In other experiments with mixtures of solutions of silicate and aluminate of potash in sealed tubes at 200° C., Deville got a crystalline compound with the formula of phillipsite, 1 : 3 : 8 : 5. Subsequently, De Schulten, in similar experiments, at 180° C., with silicate and aluminate of soda, obtained crystals of analcite, with the ratios, 1 : 3 : 8 : 2.*

§ 99. More recent investigations in the same direction by Friedel and Sarrasin are very instructive, as showing not only the generation of feldspars in the wet way, but the production at will, under similar conditions, of a feldspar or a zeolite. These chemists had already, by heating a mixture of silicate of alumina (precipitated from a solution of chloride of aluminium by silicate of potash) with an excess of a solution of silicate of potash, obtained crystals of orthoclase, mingled with crystals of quartz or, at a more elevated temperature, of tridymite. In subsequent experiments, undertaken for the production of albite, a similar hydrous silicate of alumina was mingled with a solution of silicate of soda (the silica and alumina in the proportions of the soda-feldspar), and heated to from 400° to 500° C. Instead of the anhydrous albite, however, were obtained crystals of analcite, 1 : 3 : 8 : 2; the excess of silica, with soda and some alumina, remaining in solution. When, however, an excess of silicate of soda was employed, the whole of the silicate of alumina was transformed into albite.† Thus analcite, which is

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* The results of Deville, Friedel and Sarrasin, and De Schulten in the preceding paragraphs are cited from Michel Levy and Fouqué, Synthèse des Minéraux et des Roches, Paris, 1882, pp. 87–134 and 161–164.

† Compte Rendu de l'Acad. des Sciences, le 30 Juillet, 1883.

formed by the action of thermal springs below 70° C., is equally produced at 180° C., as in the experiments of De Schulten, and at 400° C. and upwards.

§ 100. We have thus far considered among aluminous double silicates those which present the oxygen-ratio of $R : al = 1 : 3$, and have only mentioned incidentally the epidote and meionite groups. The numerous experiments already detailed suffice to show that the double silicates of alumina and alkalies, formed under very varied conditions in the wet way, in the presence of an excess of alkali, always present this ratio, of $1 : 3$. When, however, we pass to aluminous double silicates with other protoxyd-bases, we find many with the ratio, $1 : 2$, as in the epidote and meionite groups; with $1 : 1$, as in the alumina-garnets, gehlenite, and biotite; or even $2 : 1$, as in melilite, phlogopite, and many hydrated alumino-magnesian species of the chlorite group. The genesis of these various calcareous and magnesian alumina-silicates, so conspicuous in the rocks, is an important and unsolved problem.

Artificial zeolitic compounds, like the soda-mesolite formed by Way, with the ratio, $R : al = 1 : 3$, may, as we have seen, exchange their alkaline base for lime or magnesia, but for the silicates in question, in which this ratio is $1 : 2$, or $1 : 1$, or $2 : 1$, the corresponding silicates of alumina and alkalies are as yet unknown to chemistry, being soluble, and probably unstable and uncrystallizable. Analogy, however, as well as the modes of occurrence of these calcareous and magnesian silicates, would lead us to expect the production of such alkaline double silicates, under certain conditions, in solution, and we are not without evidence of the occurrence of such compounds. The soluble alkaline extract from the decomposition of an aluminous glass, in Daubrée's experiment (§ 87), holding in solution both silica and alumina, gave, if the data are exact, the oxygen-ratio for $R : al : Si = 3 : 1 : 4$. We have also, in Friedel and Sarrasin's experiment (§ 99), the separation of analcite from a like solution, which retained both silica and alumina in solution. Researches in this direction will probably make known to us the conditions under which such residual solutions may be produced, containing alkalino-aluminous silicates with the ratios corresponding to epidote, garnet, biotite, phlogopite, and the chlorites.

§ 101. Magnesian silicates corresponding to the zeolitic and feldspar group are rare, and known to us only through the artificial compound of Way, the species iolite, esmarkite, and fahlunite, and certain partially magnesian zeolites. Chabazite, when finely pulverized, according to Eichhorn, exchanges a portion of its lime for potash when digested with a potassium salt, but is very slightly attacked by a solution of magnesian chlorid.* The more silicic of these zeolites are apparently indifferent to such substitutions and, as we have seen, phillipsite is formed in sea-water. We should, however, expect the more basic of the calcareo-aluminous silicates, with the ratios, R : al = 1 : 1 or 2 : 1, to be very susceptible to replacement by magnesia. Bunsen has shown that palagonite, a hydrous silicate of this class (§ 67, footnote), with a large proportion of calcareous base, decomposes even a solution of ferrous sulphate, which removes its lime, and it would doubtless decompose in a like manner magnesian salts. I have long since shown that an artificial hydrous silicate of lime readily decomposes a solution of magnesium-chlorid, with the production of calcium-chlorid and a magnesian silicate; a result in accordance with the earlier observations of Bischof on the power of solutions of silicate of lime to decompose magnesian salts.†

§ 102. While on one side of what we may call the normal type of alumina-protoxyd silicates, with the ratio, R : al = 1 : 3, as seen in the group of the feldspars and the zeolites, we have those with an excess of protoxyds (including scapolites, epidote, garnet, idocrase, melilite,

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* Cited by S. W. Johnson, Amer. Jour. Sci., 1859, xxviii., 74.

† Hunt, Chem. and Geol. Essays, p. 122.

gehlenite, biotite, phlogopite, and the chlorites), there is another series of aluminous silicates in which the proportion of protoxyds falls below this normal ratio, and still another series in which protoxyd-bases are absent. Of the latter we need only name the anhydrous species, andalusite, fibrolite, and cyanite, and the hydrous species, pyrophyllite, pholerite, and kaolinite, with the amorphous halloysite, a more highly hydrated and colloidal form of the kaolin-silicate, and others. The aluminous protoxyd-silicates with a diminished proportion of alkali, constitute an important group, including most of the tourmalines and the principal non-magnesian micas, muscovite, margarodite, euphyllite, damourite or sericite, and paragonite, but excluding the rarer lepidolite of veinstones, which is more highly alkaliferous. In the following list, the formulas for the last four species named have been taken from Dana's "System of Mineralogy," while the three given for different varieties of muscovite have been devised so as to facilitate comparison with the latter, and at the same time to represent, as near as may be, the variable composition of the anhydrous mica.

NON-MAGNESIAN OR MUSCOVITIC MICAS.

	R : r : Si : H
Muscovite (*a*)	½ : 6 : 9
Muscovite (*b*)	⅔ : 6 : 9
Muscovite (*c*)	1 : 6 : 9
Margarodite	1 : 6 : 9 : 2
Euphyllite	1 : 8 : 9 : 2
Damourite	1 : 9 : 12 : 2
Paragonite	1 : 9 : 12 : 2

§ 108. The frequent occurrence of muscovite in endogenous granitic veins with orthoclase and albite, shows that this species, like the feldspars, may be crystallized from solutions. At the same time, their composition and their geological relations suggest that this and the related micas have more generally been derived, directly or indirectly, from the sub-aerial decay of the feldspar of granitic rocks. While these micas are rare, or altogether absent from the oldest granitoid gneisses, they become comparatively abundant in the younger gneisses and their associated mica-schists, and, finally, in the forms of damourite, sericite, and paragonite-schists, characterize great masses of strata among the still younger Transition strata. We have called attention to the fact that decayed feldspars, already changed to the form of clay, and approaching to the kaolin-ratio, in which al : Si = 3 : 4, still retain, in many cases, a few hundredths of alkali (§ 63); while the three anhydrous silicates of alumina, — andalusite, fibrolite, and cyanite, — which are frequently found crystallized in certain mica-schists, have each the ratio, 3 : 2. It will be readily seen that the separation of these highly aluminous silicates from clays still holding a little alkali would leave residues having essentially the composition of the micas given in the above table. There are, however, other mica-schists which are not accompanied by such anhydrous aluminous silicates, but on the contrary are associated with serpentines and chloritic minerals, indicating in the waters of the time a very different condition from that which we have first supposed, and pointing to the intervention of soluble silicates. That these, by their union with the kaolin from decayed feldspars, might yield muscovitic micas, will be evident, when we note that the elements of one equivalent of kaolinite united with one of thomsonite, or of natrolite, would give essentially the oxygen-ratio of muscovite or margarodite, and two of kaolinite with one of thomsonite that of damourite or paragonite.

§ 103 A. [The tourmalines constitute an important group of double aluminous silicates, which, though very unlike the muscovitic micas in physical characters, are nevertheless, as long since pointed out by Rammelsberg, closely related to them in chemical composition, and present similar varying relations between the alumina and the protoxyd-bases. The exhaustive study of the tourmalines by that chemist in 1850, based on the analyses of specimens from thirty localities, gave him the data for a satisfactory classification of these minerals in five divisions, to which the red tourmaline of Rozena may be added as a sixth. All of these contain, as is well known, a considerable though varying amount of boric oxyd, rightly regarded by Rammelsberg as replacing a portion of silica. These five divisions are distinguished alike by the nature of their protoxyd-bases, and by the different atomic ratios of protoxyd, sesquioxyd, and silica. The white, yellow, or brown magnesian tourmaline, which we have designated coronite, has the ratios, 1 : 3 : 5, which are those of iolite. The black ferro-magnesian species which may be called schorlite, gives 1 : 4 : 6, the black ferrous species, aphrizite, 1:6:8; indicolite, 1:9:12; and rubellite, 1:12:15. The protoxyd-bases in the last two species are chiefly alkalies, in large part lithia, the presence of which connects these tourmalines with the lithia-bearing micas of the granitic veins in which they occur.

In all of these tourmalines a portion of ferric oxyd replaces alumina. The determinations of Mitscherlich, making a larger amount of the iron in schorlite and aphrizite in the ferrous state than supposed by Rammelsberg, will, if admitted, bring the ratios of these species nearer to that of coronite. The oxygen-ratios of indicolite, as pointed out by Rammelsberg, are the same with those of the micas designated above as damourite and paragonite, while intermediate between those of rubellite and the Rozena tourmaline already mentioned (which are 1 : 15 : 21) are the ratios of the muscovite (*a*) of the preceding table, which equal 1 : 12 : 18. It is evident that all that has been said about the genesis of these micas is equally applicable to the tourmalines. The constitution and the atomic volume of the various tourmalines will be found discussed at length in Essay VIII., §§ 85, 86.]

§ 104. There exists an important class of hydrous alkaline aluminous silicates, related to the muscovitic micas in composition, but differing widely from them in structure and physical characters. It includes what has been variously designated as pinite, gieseckite, agalmatolite, and dysyntribite, which sometimes occur in crystalline forms in other rocks, and at other times themselves constitute rock-masses. Amorphous, and granular or compact in texture, its hardness and general aspect have often led observers to compare it to serpentine. The many varieties of this substance, as Dana has remarked, agree closely in physical characters, as well as in composition, and he has deduced from their analyses a formula corresponding to a hydrous silicate of potash and alumina, with the ratios, 1 : 8 : 12 : 3, which requires potash 12.0, alumina 35.1, silica 46.0, water 6.9 = 100; in which the potash may be partially replaced by soda, lime, or magnesia. Dysyntribite, as first described by C. U. Shepard, forms rock-masses, associated with specular hematite, in St. Lawrence county, New York; and similar deposits, often of considerable extent, occur in the crystalline schists of the Green Mountain range, both in Vermont and Quebec. In the latter province, a bed of it in Stanstead, interstratified with chloritic schists, is one hundred and fifty feet wide, schistose, and often with an admixture of quartz. Layers of the pure pinite from this deposit, formerly described by the writer under the synonym of agalmatolite, have a banded structure, a ligneous aspect, and a satiny lustre. The mineral is translucent, soft, unctuous, and somewhat resembles steatite. A similar deposit occurs in argillite, among the crystalline schists of St. Francis, Beauce, which is honey-yellow in color, and granular in texture. The pinites from these two localities agree closely in composition. That of the latter contained silica 50.50, alumina 33.40, magnesia 1.00, potash

8.10, soda 0.63, water 5.36 (with traces of lime and iron-oxyd) = 98.99. These elements give almost exactly the oxygen-ratio of 1 : 8 : $13\frac{3}{4}$: $2\frac{1}{2}$, closely agreeing with Dana's formula, except in an excess of silica, perhaps due to an admixture of quartz, which is apparent in the deposit at Stanstead.* The variety of pinite formerly described by the writer as parophite, from its resemblance to serpentine, occurs in uncrystalline Cambrian shales at St. Nicholas, near Quebec.† Related to pinite are the minerals which have been called onkosine and oösite.

The name of cossaite has been given to a similar mineral having the physical characters of pinite, from which it differs in containing soda instead of potash. The formula which has been deduced from its analysis, is identical with that of the soda-mica, paragonite. We cannot be certain, in the case of massive minerals like these, whether this same general formula is not as well adapted to pinite as that proposed above. In any case, it is evident that we have in the pinitic group a widely distributed class of natural silicates, not less important than the muscovitic group, and probably similar in origin.

§ 105. The constancy in composition and the wide

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* See, for an account of these various forms of pinite, there described as agalmatolite, the Geology of Canada, 1863, pp. 484, 485.

† There are several other hydrous silicates of alumina, sometimes with alkali, which, like pinite, are sometimes found among uncrystalline strata, showing that the conditions of their deposition have been continued down to comparatively recent times. Such is the bravaisite described by Mallard, a soft unctuous matter, with a fibrous texture, occurring in layers in shales of the coal-measures in France. It is a hydrous silicate of potash and alumina, with a little lime and magnesia, and according to its author, after deducting impurities, gives essentially the ratios, 1:3:9:4. The hygrophilite of Laspeyres is also a soft, unctuous, cryptocrystalline matter, found in sandstone, which somewhat resembles bravaisite, and is compared to pinite. It contains potash and some soda, and gives the ratios, 1:5:9:3. A somewhat similar substance, found replacing coal-plants in the Tarentaise, has been also referred to pinite or to the so-called gümbellite. Genth, on the other hand, found pyrophyllite replacing the substance of coal-plants in Pennsylvania. (See Dana's System of Mineralogy, Supplements, I., 6; II., 29, 63; and III., 18, 54). Also farther, Essay VI., respecting hamelite, glauconite, and related silicates.

distribution of pinite show it to be a compound readily formed and of great stability. Such being its character, it might be expected to occur as a frequent product of the aqueous changes of other and less stable silicates. It is met with in veinstones, in the shape of crystals of nephelite, iolite, scapolite, feldspars, and spodumene, from each of which it is supposed to have been formed by epigenesis. Its frequent occurrence as an epigenic product is one of the many examples to be met with in the mineral kingdom of the law of "the survival of the fittest." It is, however, difficult to assign such an origin to beds of this mineral like those which have been above described, which are probably the results of original deposition or of diagenesis. It is a characteristic of our present unnatural system of mineralogy to banish to the category of doubtful species most of the substances which are supposed to be of epigenic origin, and which do not ordinarily present a definite crystalline structure. Several mineral compounds are apparently indisposed to assume a crystalline condition, and among these are pinite and serpentine. The latter is probably, like pinite, in certain cases, a product of epigenesis; but few, we think, who have studied the mode of its occurrence and distribution in crystalline limestones, will ascribe to it, in such conditions, an epigenic origin.

§ 106. Dana has compared serpentine and pinite on the ground of their physical resemblances, and has said that pinite is "an alkali-alumina-serpentine, as pyrophyllite is an alumina-talc." * The relations between the minerals thus compared are, however, mimetic only and not genetic. A true system of mineralogical classification must not be based on analogies such as these, nor on assumptions regarding water as replacing fixed bases, or alumina as taking the place on the one hand of silica or on the other of protoxyd-bases. Some of the relations suggested by formulas constructed in accordance with

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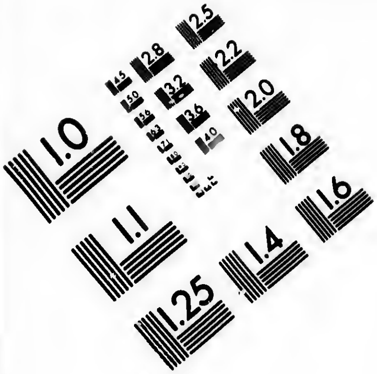
* Dana's System of Mineralogy, 5th ed., p. 479.



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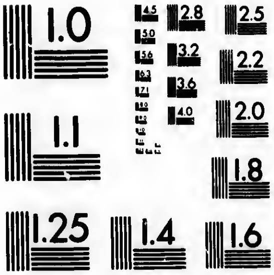

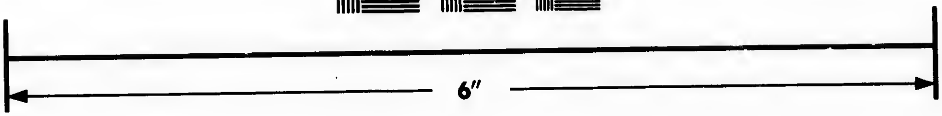

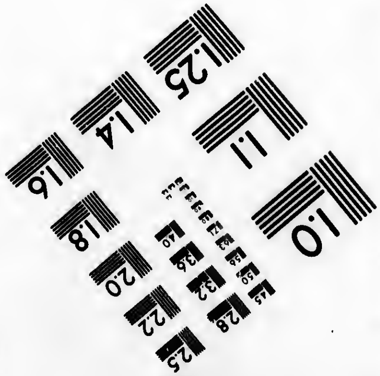

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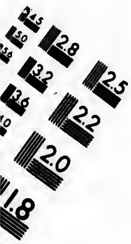
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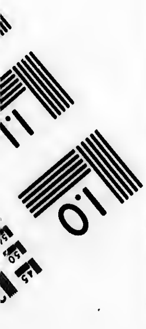
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such assumptions, are not without interest from the point of view of theoretical chemistry, but serve only to mislead the mineralogist who seeks for a fundamental and genetic system of classification of mineral silicates.

§ 107. The cardinal distinction is that between protoxyd-silicates and aluminous silicates, based on their origin and on the chemical relations of their respective bases. For the latter class there comes, in the next place, the consideration of the proportions between the protoxyd-bases and the alumina, and the departures on either side from the ratio, $R : al = 1 : 3$, as seen in the relations of those aluminous silicates with an excess of R, on the one hand, and, on the other, those with a deficiency of R, which are connected with the simple aluminous silicates. The above ratio of $1 : 3$, which we have called the normal ratio of protoxyd to alumina, is that not only of the feldspars and the zeolites, but of diaspore, of the spinels, and of the crystalline aluminate of potash. The chemist will not need to be reminded that this stable group is the simplest possible compound which the hexatomic element, aluminium, can form with a monatomic or a diatomic element like sodium or calcium, corresponding to a condensed molecule the water-type of which will be H_8O_4.

§ 108. The point of next importance, which is of special significance in the aluminous double silicates, is that of their greater or less condensation, or, in other words, the relation of their density to their empirical equivalent weight, as already pointed out in the case of the scapolite and epidote groups (§ 81).* The greater stability of those which belong to the more condensed types is shown in their superior resistance to decay, and is thus of geological significance. The relations of anhydrous to hydrous species of aluminous double silicates appear to be of less importance when we consider what secondary causes will

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* See, in this connection, the author On the Objects and Method of Mineralogy, Chem. and Geol. Essays, pp. 452–458; also the same, pp. 445–447, and farther in Essay VIII., *passim*.

determine the formation either of a hydrous or an anhydrous species, of a zeolite or a feldspar.† The relations of the bases, potash, soda, and lime, to each other, and to magnesia and other protoxyd-bases, are next to be considered, alike for the double aluminous silicates and for simple silicates of protoxyds.

A system of classification, constructed in accordance with these principles, has already been indicated in the preceding illustrations of the crenitic hypothesis, and will, it is believed, be found of fundamental importance for the student of mineral physiology; since it is based on the genetic processes by which the species of the mineral kingdom have in most cases been formed. The principles which it embodies will be found not less applicable to compounds of igneous origin than to those formed by aqueous processes. Such a system of classification is developed farther on, in Essay VIII.

§ 109. In considering the origin of crystalline stratified rocks formed, in accordance with our hypothesis, in all cases with the concurrence of water, questions connected with the process of crystallization of mineral species, and of their condition when first deposited, are of much importance. The most familiar case is that of the direct separation of matters in a crystalline condition, as happens from the evaporation or the change of temperature of the solvent, or from the generation of new and less soluble compounds, as in many cases of chemical precipitation. In this connection, it should be noted "that many such compounds, when first generated by double decomposition in watery solutions, remain dissolved for a greater or less length of time before separating in an insoluble condition. . . . There is reason to believe that silicates of insoluble bases may assume a similar state, and it will probably be shown one day that for the greater number of those oxygenized compounds, which we call insoluble, there exists

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† On the relations of hydrous to anhydrous species, see farther the author in Essay X., § 117-118.

a modification soluble in water. In this connection also may be recalled the great solubility in water of silicic, titanic, stannic, ferric, aluminic, and chromic oxyds, when in what Graham has called the colloidal state."* In writing the above, in 1874, reference was also made to my own earlier observations on the solubility, under certain conditions, of carbonate of lime, which are subjoined.

§ 110. "The recent precipitate produced by a solution of carbonate of soda in chlorid of calcium is readily soluble in an excess of the latter salt, or in a solution of sulphate of magnesia. The transparent, almost gelatinous magma, which results when solutions of carbonate of soda and chlorid of calcium are first mingled, is immediately dissolved by a solution of sulphate of magnesia, and by operating with solutions of known strength [titrated solutions] it is easy to obtain transparent liquids holding in a litre, besides three or four hundredths of hydrated sulphate of magnesia, 0.80 gramme, and even 1.20 grammes, of carbonate of lime, together with 1.00 gramme of carbonate of magnesia; the only other substance present in the water being the chlorid of sodium equivalent to these carbonates. A solution of chlorid of magnesium, holding some chlorid of sodium and sulphate of magnesia, in like manner dissolved 1.00 gramme of carbonate of lime to the litre. Such solutions have an alkaline reaction."

These solutions, which contained in all cases neutral carbonates with no excess of carbonic acid, possessed a considerable degree of stability. One prepared with 0.80 gramme of carbonate of lime and 1.00 gramme of carbonate of magnesia, when filtered after standing eighteen hours at 10° C., still retained 0.72 gramme of carbonate of lime to the litre, but, after some days, deposited the whole of this in transparent crystals of hydrous carbonate of lime, all of the carbonate of magnesia remaining dissolved. This hydrous carbonate, stable at low temperatures, is at once decomposed, with loss of its water, at

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* Hunt, Chem. and Geol. Essays, p. 223.

30° C. "The solubility of the yet uncondensed carbonate of lime in neutral solutions, which are without action upon it in another state of aggregation, is a good example of the modified relations presented by bodies in the so-called nascent state, which probably, as in this case, consists of a simpler and a less condensed molecule. At the same time, the gradual spontaneous decomposition of the solutions thus obtained affords an instructive instance of the influence of time on chemical changes." *

[Another instructive instance of an isomeric modification of a carbonate is afforded by the late discovery by Engel of an anhydrous magnesian carbonate having the same centesimal composition as the dense insoluble natural (and artificial) rhombohedral carbonate, but unlike it slowly absorbing water to form crystalline hydrates, and even soluble in water, giving a solution from which such a hydrated carbonate crystallizes; recalling in these respects the soluble lime-carbonate just described. It is got by decomposing, between 70° and 150° C., the crystalline hydrous compound of magnesian carbonate and potassic acid-carbonate, the water and one-fourth the carbonic acid being expelled. The new carbonate remains mingled with potassium carbonate, which is removed by water. †]

§ 111. The spontaneous conversion of uncrystalline precipitates into crystalline aggregations may next be noticed. Instances of this are well known to chemists, but a remarkable and hitherto undescribed example is afforded in the case of the mixed oxalates of the cerium-metals, got by precipitating their nitric solution with oxalic acid in the cold. A tough pitchy mass was thus repeatedly obtained which, in a few minutes, changed into incoherent crystalline grains, the conversion being attended with a notable evolution of heat. Another example of a some-

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* Hunt, Contributions to the History of Lime and Magnesia Salts; Part II., 1866. Amer. Jour. Science, vol. xlii., pp. 58, 59.

† Compte Rendu de l'Acad. des Sciences, October 26, 1885, p. 814.

what similar phenomenon is presented in the case of the amorphous insoluble malate of lead, which, as is well known, spontaneously changes into crystals beneath the liquid in which it has been precipitated.

§ 112. In the paper above quoted on the salts of lime and magnesia, I have described not less remarkable examples of similar transformations in the case of the carbonates of lime and magnesia. A paste of hydrous carbonate of magnesia precipitated in the cold, slowly changes under water, at ordinary temperatures, into a crystalline mass made up of prisms, grouped in spherical aggregations, of the well-known terhydrated magnesian carbonate. In like manner, the amorphous paste got by triturating in a mortar a solution of chlorids of calcium and magnesium, in equivalent proportions, with the requisite amount of a solution of neutral carbonate of soda, is, at a temperature of from 65° to 80° C., changed, after a few hours, into an aggregate of translucent crystalline spheres of a hydrous double carbonate, resembling the hydrodolomite of Von Kobell. At temperatures of from 15° to 18° C., the same magma changes slowly into a more highly hydrated compound. The process of change, which requires from twelve to twenty-five days, appeared "to consist in the formation of nuclei from which crystallization proceeded until every particle of the once voluminous, opaque, and amorphous precipitate had become translucent, dense, and crystalline." The product is made up of brilliant prisms, apparently oblique, grouped around centres, and sometimes forming spheres five or six millimetres in diameter. The hydrated double carbonate of lime and magnesia, thus formed in presence of a slight excess of carbonate of soda, was found to contain more than two per cent of the latter, but it was not certain whether this did not proceed from an admixture of the hydrous double carbonate of lime and soda, gaylussite. The new combination itself was described as having the composition of a gaylussite in which magnesium replaces sodium. The production of crystals of true gaylussite, as observed by Fritzsche, by the slow crystallization of the gelatinous precipitate got when a strong solution of carbonate of soda in excess is mingled with one of calcium-chlorid, is another remarkable example of the phenomenon under consideration.

Fritzsche moreover observed that it is not necessary that the lime-carbonate should be in its gelatinous form in order to produce this compound, since the previously precipitated carbonate, when digested with a solution of carbonate of soda, slowly combines with it to form the crystalline hydrous double salt. More remarkable still is the observation of H. Ste.-Claire Deville, which I have repeatedly verified, that a paste of magnesia alba and bicarbonate of soda, with water, is slowly changed, at a temperature of from 60° to 70° C., into a transparent crystalline anhydrous double carbonate of lime and soda, rhombohedral in form, and called by its discoverer a soda-dolomite.*

§ 113. In this connection, it should be said that we have here an explanation of the formation of the double carbonate of lime and magnesia which constitutes ordinary dolomite. The origin of this mineral species, which so often constitutes rock-masses, is still generally misunderstood. The baseless notion of its production by a metasomatosis or partial replacement of the lime in ordinary limestone, imagined by the older geologists, is still repeated, and holds its place in the literature of the science despite the facts of geognosy and of chemistry. I have long since shown, by multiplied examples, that the ordinary mode of the occurrence of dolomite in nature is not in accordance with this hypothesis of its origin, since beds of dolomite, or more or less magnesian limestone, are found alternating, sometimes in thin and repeated layers, with beds of non-magnesian carbonate of lime. Moreover, beds of crystalline dolomite, conglomerate in

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* Hunt, Contributions to the History of Lime and Magnesia Salts; Part II., 1866. Amer. Jour. Science, vol. xlii., pp. 54–57.

character, are found to enclose pebbles and fragments of pure non-magnesian carbonate of lime. I have also explained at length the natural reactions by which precipitates consisting of a greater or less proportion of hydrous carbonate of magnesia, mixed with carbonate of lime, must, in past ages, have been laid down in the waters of lakes and inland seas, in some cases with, and in others without, the simultaneous formation of sulphate of lime.

It was, moreover, found that the reaction at an elevated temperature in presence of water, between sulphate of magnesia and an excess of carbonate of lime, supposed by Haidinger and Von Morlot to explain the frequent association of gypsum and dolomite, does not yield the double carbonate, since the carbonate of magnesia separates in an anhydrous form, and does not combine with the carbonate of lime. Finally, it was shown that mixtures of hydrous carbonate of magnesia and carbonate of lime, when heated together in presence of water, unite to form the anhydrous double carbonate which constitutes dolomite. In my experiments, their combination, with the formation of dolomite, was effected rapidly, at 120° C., but many considerations lead to the conclusion that its production in nature is effected slowly at much lower temperatures, and that the formation of the hydrous double carbonate already described is, perhaps, an intermediate stage in the process.* The existence of a soluble and active form of magnesian carbonate, as described in § 110, throws an additional light upon the formation of dolomite.

§ 114. The reactions described in the preceding paragraphs between the elements of comparatively insoluble substances in the presence of water, resulting not only in the conversion of amorphous into crystalline bodies, but in the breaking-up of old combinations, as well as in the union of unlike matters mechanically mingled to form

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* Hunt, Contributions to the Chemistry of Lime and Magnesia, part i., 1859, Amer. Jour. Sci., xxviii., pp. 170, 365; and part ii., 1866, *ibid.*, vol. xii., p. 49; also in abstract in Chem. and Geol. Essays, pp. 80–92.

new crystalline species, are instructive examples of what Gümbel has termed DIAGENESIS. The changes in the masonry of the old Roman baths in contact with thermal waters, resulting in the hydration of the substance of the bricks, and its conversion into zeolitic minerals; the hydration of volcanic glasses with similar results, going on, even at low temperatures, in the deep sea; the decomposition of common glass by heated water; the conversion of basaltic rock into palagonite, and the production therefrom of zeolites; the similar changes seen elsewhere in amygdaloids, and even in massive basic plutonic rocks, are also examples of this process of diagenesis, and serve to show its great geological significance. We have already suggested the intervention of similar reactions in past ages among the sediments from the sub-aerial decay of feldspathic rocks, in some cases with the concurrence of the secretions from the primary basic stratum, which, in accordance with the crenitic hypothesis, we suppose to have been the source of soluble mineral silicates. In the diagenesis of these early argillaceous sediments, aided by crenitic action, will, it is believed, be found the origin of many of the crystalline schists of the Transition rocks.

§ 115. An instructive phase in this diagenetic process is that of the gradual conversion of smaller crystalline grains or crystals into larger ones, which is familiar to chemists. This action is in fact nearly akin to that which takes place in the transformation of amorphous into crystalline precipitates, since in both cases a partial solution precedes the crystallization. It is well known that, as a result of successive solution and redeposition, large crystals may be built up at the expense of smaller ones. To quote the author's language of fifteen years since, this process, as H. Deville has shown, "suffices, under the influence of the changing temperature of the seasons, to convert many fine precipitates into crystalline aggregates, by the aid of liquids of slight solvent powers. A similar agency may be supposed to have effected the crystallization of buried sediments, and changes in the solvent power of the permeating water might be due either to variations of temperature or of pressure. Simultaneously with this process, one of chemical union of heterogeneous elements may go on, and in this way, for example, we may suppose that the carbonates of lime and magnesia become united to form dolomite or magnesian limestone." *

§ 116. The tendency of the dissolved material in this process to crystallize around nuclei of its own kind, rather than on foreign particles, is a familiar fact, and its geological importance, to which I first called attention, as above, in 1869, was again pointed out by Sorby in 1880, when he showed that dissolved quartz might be deposited upon clastic grains of this mineral in perfect optical and crystallographic continuity, so that each broken fragment of quartz is changed into a definite crystal, as was seen in his microscopic studies of various sandstones.† This fact has been confirmed by the observations of Young, Irving, and Wadsworth in the United States; ‡ and Bonney has suggested the possible extension of such a process to feldspar, hornblende, and other minerals. §

Vanhise has very recently announced that his microscopical examinations of certain sandstones of the Keweenian series, from Lake Superior, afford evidence of the secondary deposition of both orthoclase and plagioclase feldspar, in crystallographic continuity, upon broken feldspathic grains, in one case uniting the two parts of a broken feldspar-crystal. The sandstones which have yielded these examples are made up in part of feldspathic fragments, and in part of fragments of "some altered basic rocks." They are, moreover, interstratified with and, in

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* Hunt, The Chemistry of the Earth, Report of Smithsonian Institution, 1869; also Chem. and Geol. Essays, p. 305.

† Sorby, Presidential Address, Quar. Jour. Geo. Soc. London, xxxvi., 83.

‡ Young, Amer. Jour. Sci., xxiv., 47. Irving, *ibid.*, xxv., 401. Wadsworth, Proc. Boston Soc. Natural History, Feb. 7, 1883.

§ Bonney, Quar. Jour. Geol. Soc., xxxix., 19.

some cases at least, immediately underlie the basic plutonic rocks of the same Keweenian series.* When we consider that orthoclase is a common secretion of these basic rocks, as is shown by its frequent occurrence in them with zeolites and epidote, it may perhaps be questioned whether the secondary feldspar in the sandstone has been derived from the adjacent grains of this mineral, or has come into solution from the transformation of the basic rocks. The apparent stability and insolubility of orthoclase and oligoclase at high temperatures in the presence of water, as observed by Daubrée, would seem to favor the latter view. In any case, it is a striking illustration of the tendency of mineral species to crystallize around nuclei of their own kind, which is so marked a factor in the development of the crystalline rocks.

IV. — CONCLUSIONS.

§ 117. We reviewed in the first part of this essay the history of the different hypotheses hitherto proposed to explain the origin of the crystalline rocks, and, in doing so, reached the conclusion that not one of them affords an adequate solution of the various problems presented by the chemical, mineralogical, and geognostical characters of the rocks in question; at the same time, we endeavored to show succinctly what are the principal conditions to which a satisfactory hypothesis must conform. In the second part, we sketched the growth and development, during the last quarter of a century, of what we believe to be such a hypothesis. In the third part, we sought to bring together a great number of facts, both new and old, which serve to illustrate the new hypothesis; according to which the crystalline stratiform rocks, as well as many erupted rocks, are supposed to have been derived by the action of waters from a primary superficial layer, regarded as the last portion of the globe solidified in cooling from a state of igneous fluidity. This, which we have described

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* Vanhise, Amer. Jour. Sci., 1884, xxvii., 399.

as a basic, quartzless rock, is conceived to have been fissured and rendered porous during crystallization and refrigeration, and thereby made permeable, to considerable depths, to the waters subsequently precipitated upon it. Its surface being cooled by radiation while its base reposed upon a heated solid interior, upward and downward currents would establish a system of aqueous circulation in the mass, to which its porous but unstratified condition would be very favorable. The materials which heated subterraneous waters would bring to the surface, there to be deposited, would be not unlike those which have been removed by infiltrating waters in various subsequent geological ages, from erupted masses of similar basic rock; which, we have reason to believe, are but displaced portions of this same primary layer. The mineral species removed from these latter rocks, or segregated in their cavities, are, as is well known, chiefly silica in the form of quartz, silicates of lime and alkalies, and certain double silicates of these bases with alumina, including zeolites and feldspars, besides oxyds of iron and carbonate of lime; the latter species being due to the intervention of atmospheric carbonic acid. The absence from these minerals of any considerable proportion of iron-silicate, and, save in rare and exceptional conditions, of magnesia, is a significant fact in the history of the secretions from basic rocks, the transformation of which, under the action of permeating waters, has resulted in the conversion of the dissolved portion of the material into quartz and various silicates of alumina, lime, and alkalies, while leaving behind a more basic and insoluble residue abounding in silicated compounds of magnesia and iron-oxyd with alumina.

§ 118. The peculiarities resulting from this comparative insolubility of magnesian silicates long ago attracted the attention of the writer. The addition to solutions like sea-water, of bicarbonate of magnesia, which is a product of the sub-aerial decay of basic rocks, would, it was shown, effect a separation of dissolved lime-salts in the form of carbonate, leaving the magnesia in solution as chlorid or as sulphate; while on the contrary the reaction of such a natural water with certain silicates, whether solid or in solution, containing lime or alkalies, would effect a removal of the dissolved magnesia. At the same time it was shown that "by digestion at ordinary temperatures with an excess of freshly precipitated silicate of lime, chlorid of magnesium is completely decomposed, an insoluble silicate of magnesia being formed, while nothing but chlorid of calcium remains in solution. It is clear that the greater insolubility of the magnesian silicate, as compared with silicate of lime, determines a reaction the very reverse of that produced by carbonates with solutions of the two earthy bases. In the one case, the lime is separated as carbonate, the magnesia remaining in solution, while in the other, by the action of silicate of soda, or of lime, the magnesia is removed and the lime remains. Hence carbonate of lime and silicate of magnesia are found abundantly in nature, while carbonate of magnesia and silicate of lime are produced only under local and exceptional circumstances. It is evident that the production from the waters of the early seas of beds of sepiolite, talc, serpentine, and other rocks in which a magnesian silicate abounds, must, in closed basins, have given rise to waters in which chlorid of calcium would predominate."*

§ 119. From this reaction it would follow that the magnesian salts formed when the first acid waters from the atmosphere fell upon the primary stratum, would be removed from solution, either by the direct action of the solid rock, or by that of the pectolitic secretions derived therefrom in the earliest ages. The primeval ocean, if, as we suppose, a universal one, would soon be deprived of magnesian salts, and henceforth the early-deposited rocks would be essentially granitic in composition, and non-

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* Amer. Jour. Sci., 1865, vol. xl., p. 49; also Chem. and Geol. Essays, p. 122.

magnesian, until the introduction of magnesia into its waters from an exterior source.

The pectolitic silicates themselves, which, in the cavities of exotic basic rocks, are deposited in crystalline forms, would, if set free in a sea deprived of magnesian salts, be readily decomposed by the carbonic acid everywhere present, with separation of free silica and carbonate of lime. From this would be formed the first deposits of limestone, which make their appearance in the old gneissic rocks and become mingled with magnesian carbonate and silicates from the introduction of magnesian salts into the waters. The comparative instability of the lime-silicate is seen when wollastonite is compared with the corresponding silicates, pyroxene and enstatite. It is possible, notwithstanding the absence of magnesian species from zeolitic secretions, that, under certain conditions, small portions of magnesian silicate may have been included in the early crenitic deposits, but the rarity of such magnesian silicates in these, and their abundance in parts of the later Laurentian and in younger deposits, point to a new source of the magnesian element, namely, the extrusion of portions of the underlying plutonic mass, and its sub-aerial decay.

It would be instructive to consider in this relation the gradual removal of a large proportion of silica from the primary plutonic stratum in the forms of orthoclase, albite, and quartz, and the consequent partial exhaustion of portions of this underlying mass, so that its succeeding secretions should consist chiefly of less silicic silicates, such as labradorite and andesite, without quartz, as in the Norian series.

§ 120. The conditions of this first exoplutonic action cannot be fully understood until we have settled the question of the permanence of continental and oceanic areas, and the extent of the early crenitic rocks which constitute the fundamental granites and the granitoid gneisses. Whether these are spread, with their vast thickness, alike underneath the great areas of the paleozoic series and our modern oceanic basins,—in brief, whether or not they are universal, as supposed by Werner, is a question which cannot here be discussed. There is, however, nothing incompatible with what we know of the chemistry of the early rocks and the early ocean in the supposition that they were universal, since there is apparently no evidence that the products of sub-aerial decay of exposed rocks intervened in their production. Such a condition of things was, however, necessarily self-limited; the progressive diminution in volume of the primary plutonic stratum from the constant removal of portions of it in a state of solution, and the weight of the superincumbent accumulated granitic and gneissic material, could not fail to result in widely spread and repeated corrugations and foldings of the overlying mass, the effects of which are seen in the universally wrinkled and frequently vertical attitude of the oldest gneissic rocks. Such a process, like the similar though less considerable movements in later times, would probably be attended with outflows, in the form of fissure-eruptions, of the underlying basic stratum, which, in accordance with our hypothesis, was permeated with water under conditions of temperature and pressure that must have given to it a partial liquidity. Such a process of collapse and corrugation of the crenitic deposits, attended with extravasation of the underlying plutonic stratum, would doubtless be often repeated in these early periods, resulting in frequent stratigraphical discordances, which are, however, in all cases to be looked upon as local accidents, and not as wide-spread catastrophes. Hence the appearance, from time to time, of exoplutonic masses, with upliftings and depressions of the crenitic rocks, which caused the exposure of both alike to the action of the atmosphere.

§ 121. The consequent sub-aerial decay of these two types henceforth introduced new factors into the rock-forming processes of the time, and made the beginning of what Werner called the Transition period. The decomposition of these, under the influence of a moist atmosphere holding carbonic acid, resulted in the more or less complete removal of the alkali from the feldspars of crenitic rocks, and their conversion into kaolin, while the corresponding changes in the basic exoplutonic rocks were still more noteworthy. These rocks, while containing feldspars, consisted in large part of silicates of lime and magnesia, presumably pyroxene and chrysolite, which, as we are aware, yield to the action of the atmosphere the whole of their lime and magnesia. These, in the form of carbonates, passed into solution, together with a large proportion of silica, leaving behind the remaining portion, together with iron-oxyd and the kaolin from the feldspars. The carbonates of alkalies, of lime, and of magnesia, resulting from the sub-aerial decay of the exposed exoplutonic and the crenitic rocks alike, were carried to the sea, there to play an important part. Besides the direct influx of carbonate of lime into the waters of that time, it is evident that both the alkaline and the magnesian bicarbonates would react upon the calcium-chlorid of the primeval sea, with the production of a farther amount of lime-carbonate, and the generation of alkaline and magnesian chlorids. In this way, the sea becoming magnesian, a new order of things was established. Henceforth, the pectolitic matters brought up from the primary layer would at once react upon the dissolved magnesian salts, and the production of such compounds as chondrodite, chrysolite, serpentine, and talc would commence. No one who has studied the mode of occurrence of these silicates in the upper part of the Laurentian series, where serpentine not only forms layers, but frequent concretions like flints, often around nuclei of white pyroxene, can fail to recognize the process which then came into play, resulting later in the production of abundance of pyroxene, amphibole, and enstatite, and apparently reaching its culmination in the vast amount of magnesian silicates found in the deposits of the Huronian age.

§ 122. The solutions of simple silicates of alkalies, which by heat had deposited their excess of silica in the form of quartz, as in the case of the soluble matter from glass, probably gave rise by their reaction with magnesian solutions to the basic protoxyd-silicates, like chondrodite, chrysolite, serpentine, and pyroxene. That we have no anhydrous quadrisilicates corresponding to apophyllite and okenite is apparently due to the fact that such silicates, in contact with water at elevated temperatures, break up into anhydrous bisilicates and quartz; as is seen in the artificial association of pyroxene and quartz in the experiments of Daubrée, and the frequent occurrence of admixtures of the two in beds among the ancient gneissic rocks. A noticeable fact in the history of the surbasic silicates of magnesia and related protoxyd-bases, mentioned above, is their frequent association with non-silicated oxyds. Examples of this familiar to mineralogists are the occurrence of aggregates of chondrodite and magnetite; of chromite, picotite, ilmenite, and corundum, with chrysolite and serpentine; and of franklinite and zincite with tephroite and willemite. These collocations are probably connected with the solvent power of solutions of alkaline silicates, already insisted upon (§ 89), and also with the dissociation of silicate of alumina in heated alkaline solutions, noticed by H. Deville (§ 98).

The separation, by the alternate action of decaying organic matters and of atmospheric oxygen, of iron-oxyd, which readily passes from a soluble ferrous to an insoluble ferric condition, and conversely, has probably played an important part in the formation of deposits of iron-oxyds, which are much more general in their associations than corundum, or the compounds of chromic, titanic, aluminic, manganic, and zincic oxyds mentioned above, to which we have assigned a very different origin. It will remain for the mineralogist to determine what deposits of magnetite and of hematite are to be ascribed to the one and what to the other origin.

§ 123. We have seen, among the secretions of basic rocks, lime-alumina silicates, like epidote and prehnite, in which the ratio of the protoxyd-bases to alumina, instead of being 1 : 3, as in the feldspars and the zeolites, is 1½ : 3 or even 2 : 3. Although, probably on account of their solubility and their instability, we do not know of any natural silicates with a still larger proportion of lime to the alumina, we have indirect evidence of their former existence in solution, in the frequent occurrence of double silicates of magnesia and alumina, in which the oxygen-ratio of R, al, instead of being 1 : 3, as in the feldspars, or 2 : 3, as in prehnite, becomes 3 : 3 and even 6 : 3, as seen in the magnesian micas and in the chlorites. Such silicates, often with epidote, abound in the rocks of Huronian age.

This process by which, through the intervention of silicated secretions from the substratum, the magnesian salts are removed from the sea-water, is, as we have shown, the reverse of that which takes place through the action of the carbonates from the sub-aerial decay of silicated rocks precipitating lime-salts and giving rise to magnesian waters, if not over oceanic areas, at least in inland basins of greater or less extent. Alternations of this kind must have been frequent in geological history, and we have evidence of a widespread phenomenon of this kind following the Huronian age, when in seas from which magnesian salts were apparently for the most part excluded, were deposited the gneisses and mica-schists of the Montalban series. These, in very many places, are found resting directly, often in unconformable superposition, upon the older or Laurentian gneisses, but elsewhere upon the Huronian, showing the intervention of extensive movements of elevation and subsidence, and probably of denudation, subsequent to the Huronian time.

§ 124. The introduction on a limited scale, into the sea-basins of the Montalban time, of magnesian salts is evident from the occasional appearance of magnesian silicates in the Montalban rocks. The most noteworthy fact in their history is, however, the appearance in this series, with gneisses which differ from those of older times in being finer grained and less granitoid, of deposits containing aluminous silicates characterized by a diminished proportion of protoxyd-bases. Such as these are the beds of quartzose schists holding non-magnesian micas and the simple silicates, andalusite, fibrolite, and cyanite. It has already been mentioned that in the formation of these rocks the more or less completely decomposed feldspar from the sub-aerial decay of older crenitic rocks may have been brought into the areas of deposition. Either such clays, still retaining a portion of alkali from undecayed feldspar, or else admixtures of kaolin with the elements of a feldspar or a zeolite might, as has been suggested, yield, by diagenesis, muscovite and quartz, with one of the simple aluminous silicates just named. That a process of sub-aerial decay was in progress in the Montalban time is shown by the presence in the mica-schists of this series, at several localities in Saxony and elsewhere, as described by Sauer and subsequently noticed by the present writer, of "boulders of decay," having all the appearance of those formed during the atmospheric decay of the older gneisses.* The intervention in the deposits of that period of somewhat basic zeolitic minerals, is shown by the presence in the younger gneissic series of Germany of large masses of so-called dichroite-gneiss or iolite-gneiss, and the occasional occurrence of iolite in the younger or Montalban gneisses of New England.

§ 125. The predominance of micaceous schists of the muscovitic type in the upper portions of the Montalban, marks the growing change in the conditions of the process which gave rise to the indigenous crystalline rocks; a process continued with many modifications, and with diminished energy, through the subsequent period of the

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* Sauer, in 1879, Zeitschrift f. d. ges. Naturwiss, Band lii; also Hunt, Amer. Jour. Sci., 1883, vol. xxvi., p. 197, and Essay X., § 80.

Taconian. This was marked by the deposit of quartzites, limestones, and argillites, and also by the intercalation of schistose beds characterized by an abundance of damourite or related micaceous minerals, as well as by the presence of matters apparently feldspathic, which seldom take upon themselves the characters of well defined species, though found transformed by sub-aerial decay into a form of kaolin, and in some instances apparently assuming the state of an imperfect gneiss. These Taconian schists, which require careful chemical and microscopic study, also include serpentine, talc, pyroxene, epidote, and garnet. The appearance in paleozoic argillites of crystals of rutile, of tourmaline, and of staurolite, indicates a later stage of that condition of things which marked the crenitic process in pre-paleozoic times, and made possible the formation of the vast series of Primitive and Transition crystalline schists which we have sought to include under the names of Laurentian, Norian, Arvonian, Huronian, Montalban, and Taconian — designating in their order the upward succession of these great groups from the fundamental granitoid gneisses (here included in the Laurentian) to the dawn of paleozoic time. The Arvonian or petrosilex group intervenes between the Laurentian and the Huronian. The peculiar characters of the Norian, and its localization to some few limited areas in Europe and North America, make it difficult for us, as yet, to define its precise relations to the Arvonian. The Norian, however, like the Arvonian, probably occupies a horizon between Laurentian and Huronian. Much time may pass, and many stratigraphical studies must be made, before the precise relations of the Huronian and the succeeding Montalban can be defined. It seems probable, in the present state of our knowledge, that the Montalban series, though of great thickness, was, in many cases, deposited over areas where the Huronian had never been laid down. Notwithstanding the great geographical extent and the importance of these two series, neither can claim that universality which apparently belonged to the primitive granitic stratum; a universality soon interrupted by the uplifting of portions of dry land, an event which preceded Huronian time.

§ 126. That the production of large quantities of similar pectolitic silicates, in regions remote from exotic rocks, was continued from the pre-Cambrian to far more recent times is evident, from the presence of a considerable deposit of serpentine among the horizontal Silurian dolomites of Syracuse, New York, of which the writer has elsewhere recorded the history,[*] and also from the well known beds of sepiolite found with opal in the tertiary dolomites of the Paris basin.[†] The recent amorphous zeolitic deposits in tertiary sandstone in Switzerland (§ 94), and the compounds referred to on page 164, should not be forgotten in this connection. .

Whether the silicates brought from below by crenitic action were directly separated as feldspars, as crystalline zeolites, or as gelatinous precipitates to be subsequently changed by diagenesis into crystalline hydrous or anhydrous species, are questions for farther discussion. The range of temperature through which we have noted the crystallization of chabazite, and the association of orthoclase by contemporaneous or subsequent crystallization with hydrous species like zeolites and chlorite, lead us to conclude that for the hydrous and anhydrous aluminous double silicates alike, a considerable range of temperature is permissible. In any case, we find nothing in the conditions of the formation of zeolitic minerals in the past, any more than in modern times, incompatible with the existence of organic life.

§ 127. The phenomena of exoplutonic action, or so-called vulcanicity, though relegated to a secondary place in the crenitic hypothesis, are yet, as we have said, of

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[*] See farther, Essay X., §§ 27-34.

[†] Hunt, on the Dolomites of the Paris Basin, 1860. Amer. Jour. Science, xxix., p. 284.

great importance and significance, and are by no means simple. They were, according to our hypothesis, confined in early times to fissure-eruptions of the underlying plutonic stratum. This, although in the course of ages it has suffered a gradual change from the ceaseless crenitic action, which has removed from it the elements of the various series of crystalline rocks, including the primitive granitic and gneissic series, probably still retains in the lower portions somewhat of its original constitution.

A second phase in the history of exoplutonic rocks, already foreseen by the Huttonians, here presents itself for our consideration. The more deeply buried portions of the primitive crenitic deposit must themselves have been brought within the influence of the central heat, and, permeated as they were by water, would have suffered a softening which permitted them, as a result of subsequent movements of the crust, to appear again at the earth's surface as exoplutonic or exotic rocks of the trachytic or granitic type.

We can hardly suppose the displacement, either of the plutonic stratum, or of the early granitic deposits, to have been attended with the evolution of permanent gases, such as attend modern volcanic eruptions and are to be ascribed to the action of subterranean heat on more recent deposits, including carbonates, sulphates, chlorids, and organic matters. Such materials, when mingled with silicious and argillaceous sediments, and brought by local accumulation and depression within the heated zone, would give rise to the various gases which characterize the volcanic eruptions of recent periods, in which, however, the materials of the underlying plutonic and crenitic layers also apparently intervene.

By thus ascribing a threefold origin to the products of exoplutonic action, it becomes possible to classify and harmonize the apparently discordant phenomena of eruptive rocks. While the typical basalts and related basic rocks would be derived from the primary plutonic or igneous stratum, and the trachytic and granitic rocks from the earlier crenitic deposits, the more fusible portions of the later Transition and Secondary strata may have furnished their contingent, not only of gases and vapors, but of lavas and volcanic dust.

§ 128. The history of the origin of crystalline rocks is the history of the origin of the mineral species which compose them. The crystalline masses are essentially made up of a few groups of species. Various feldspars, and occasional zeolites, some of which apparently occur as integral parts of rocks chiefly feldspathic, form a great central group. On one side of these are the aluminous double silicates, represented by basic species like garnet, epidote, magnesian micas and chlorites, all with an excess of protoxyd-bases; while on the other hand are the aluminous double silicates of the muscovitic and pinitic groups, in which the diminished proportion of the protoxyd-bases prepares the way to the associated simple aluminous silicates, pyrophyllite, andalusite, cyanite, etc. To these groups must be added the non-aluminous silicates, including amphibole, pyroxene, enstatite, and chrysolite, and the hydrous magnesian species, serpentine and talc. Besides these are free silica, generally as quartz, free oxyds, including the spinel and corundum groups, which, together with the carbonates, make up the essential parts of the crystalline rocks.

§ 129. Rock-masses, and the mineral species which compose them, present variations in time, as we find in tracing the history of the great successive groups of crystalline strata; and they moreover show local changes, as seen in different parts of their distribution in the same geological group. As regards the causes of these variations, very much remains to be discovered by the patient collection and recording of facts concerning the associations of mineral species, their artificial production, and their transformations under the influences of fire and water, and of solutions of potassic, sodic, calcareous, and magnesian salts. The instability of silicated compounds of igneous origin in the presence of water and watery solutions, so widely diffused through nature, is the warrant for a general aqueous hypothesis; while, on the other hand, the derivation of stable mineral species, under such influences, from matters of igneous origin justifies us in assuming for these species an igneous starting-point.

Igneous fusion destroys the mineral species of the crystalline stratified rocks, and brings them back as nearly as possible to the primary undifferentiated material. Fire is the great destroyer and disorganizer of mineral as well as of organic matter. Subterranean heat in our time, acting upon buried aqueous sediments, destroys carbonates, sulphates, and chlorids, with the evolution of acidic gases and the generation of basic silicates, and thus repeats in miniature the conditions of the ante-neptunian chaos, with its surrounding acidic atmosphere. On the other hand, each mass of cooling igneous rock in contact with water begins anew the formative process. The hydrated amorphous product, palagonite, is, if we may be allowed the expression, a sort of silicated protoplasm, and by its differentiation yields to the solvent action of water the crystalline silicates which are the constituent elements of the crenitic rocks, leaving, at the same time, a more basic residuum, abounding in magnesia and iron-oxyd, and soluble, not by crenitic, but by subaerial action. Palagonite, or some amorphous matter resembling it, probably marks a stage in the sub-aqueous transformation of all igneous rocks, though only under special conditions does this unstable, hydrous substance form appreciable masses. In all cases, igneous matter, of primary or of secondary origin, serves as the point of departure.

According to the proposed hypothesis, which derives rocks of the granitic type, composed essentially of quartz and feldspars, by aqueous secretion from a primary igneous and quartzless mass, it would follow that the highly basic compound, assumed by Bunsen to represent the typical pyroxenic or basaltic rock (§ 24), would be the above mentioned insoluble residuum; and that less basic varieties of similar rocks would correspond to portions of the same primary plutonic mass, less completely exhausted by lixiviation, or modified by partial separation through crystallization and eliquation, as will be explained in Essay VI., and consequently approaching in composition to admixtures of the basaltic and granitic types, as maintained on other grounds by Bunsen himself.

§ 130. The principles which have been enumerated in the preceding pages, will, it is believed, lead the way, not only to a natural system of mineralogy, but to a natural system of classification of crystalline rocks, considered with regard alike to their chemical composition, their genesis, and their geological succession. A valid hypothesis for the crystalline rocks must seek to connect all the known facts of their history, by alleging a true and sufficient cause for the production of their various constituent mineral species. Such a hypothesis will violate no established principles in chemistry or in physics, but will show itself to be in accord with them all, and will commend itself to the acceptance of those who take the pains to understand it.

The crenitic hypothesis set forth in these pages is the result of many years of patient study applied to the elucidation of a great problem; and as such is offered to chemists and mineralogists as a first attempt at a rational explanation of the fundamental questions presented by the history of the crystalline rocks of the earth's crust.

VI.

THE GENETIC HISTORY OF CRYSTALLINE ROCKS.

This Essay was presented to the Royal Society of Canada at its meeting in Ottawa, May, 1886, and will appear in its Transactions, vol. iv., with the above title. In May, 1885, there was read before the same society a paper in which the phenomena of stratification in endogenous veinstones and in erupted rocks were discussed in relation to the crenitic process, and to the hypothesis of eliquation. Of this paper, which was published only in abstract in the Canadian Record of Science, under the title of The Geognosy of Crystalline Rocks, the present essay is but an extension and a development.

I.

§ 1. In a preceeding essay on The Origin of Crystalline Rocks, we have considered at length the different views hitherto maintained as to the mode of their production, and have set forth what we have called the crenitic hypothesis. It is proposed in the following pages to examine still farther the new hypothesis in some of its aspects, to show how far the conception of a single consolidated igneous mass under the combined action of water and heat may be made to explain satisfactorily the various facts in the history of the earth's crystalline crust, and thus to reconcile many of the contradictions which still divide the geological world as to the relations of stratified and massive crystalline rocks. Hence the title of the present essay.

Of the great divisions adopted by the Wernerian school in geology, those of Primary and Secondary correspond respectively to Original and Derived rocks, and were supposed to represent earlier and later periods in geologic time; the name of Transition being applied to the rocks of an intermediate period, believed to mark the passage from the conditions of the primary to those of the secondary age. The name of Tertiary given to the rocks of a still later age and, marking a subsequent period in the process of derivation, needs no explanation. By the geologists of the Huttonian school the rocks called primary or original by the Wernerians were imagined to be in many, if not in all cases, secondary or derived rocks, the materials of which, got from the disintegration of preexisting masses, had been arranged by water, and subsequently transformed by combined mechanical and chemical agencies into their present crystalline condition; in accordance with which hypothesis they have been called Metamorphic rocks. By rejecting, as their master Hutton had done, all "inquiry into the first origin of things," or "the commencement or termination of the present order," and by teaching that the rocks called by Wernerians primary and transition, were for the most part, if not wholly, metamorphosed portions of derived rocks which, themselves, in their prolongation into other regions, could be recognized as secondary or as tertiary strata, the Huttonians have sought to destroy the chronological value of the Wernerian terminology. With the abandonment of the Huttonian or so-called metamorphic doctrine, now shown to be false, so far at least as regards the secondary or tertiary age of crystalline stratified rocks, we are naturally led back to the nomenclature of Werner and his school, which should be equally acceptable to endoplutonists and to neptunists, whether the latter adopt the chaotic hypothesis of Werner, the modified or thermochaotic hypothesis set forth by De la Beche and Daubrée, or the crenitic hypothesis more recently maintained by the present writer in the essay just cited.

§ 2. The term "crystalline rocks" is conventionally used in geology to designate those original aggregates of which crystalline silicates make an essential part. Such silicates may however be associated in these aggregates with quartz, or with oxyds like magnetite, with carbonates, as in limestones and dolomite, and even with phosphates, as apatite, or with sulphates, as karstenite and gypsum. By a certain license the term may also be extended to masses of definite hydrous silicates, such as serpentine and pinite, which are in great part amorphous and colloidal, and also to uncrystalline silicates, often hydrated, and of indefinite composition, such as palagonite, tachylite, pitchstone, and obsidian. The silicates having the composition of serpentine and of pinite assume, in some cases, proper crystalline forms; palagonite is by heat readily changed in large part into a crystalline zeolite; while glassy silicates, such as obsidian, by devitrification are in like manner resolved more or less completely into crystalline species. Hence rock-masses, including or even made up of these various uncrystalline materials, may all be regarded as inchoately crystalline, and for geognostical purposes may be conveniently classed with the crystalline rocks into which they graduate.

§ 3. When stratified masses of quartz, calcite, dolomite, and karstenite are found among contemporaneous crystalline silicated rocks, they generally enclose indigenous crystalline silicates, which give them a title to be regarded as parts of the accompanying crystalline series. The mineral species just named have, however, in other cases become aggregated in crystalline rock-masses in times and under conditions which did not permit the genesis of such species as feldspars, micas, amphibole, and pyroxene, which are the most characteristic silicates of the crystalline rocks. Hence we find beds of crystalline quartz, limestone, dolomite, karstenite, and gypsum interstratified with uncrystalline rocks of detrital origin, and of secondary or tertiary age. It is worthy of note, however, that the conditions for the production of certain mineral silicates have continued in later ages, as is shown by the frequent formation of zeolitic, pectolitic, and other crystalline silicates in younger and uncrystalline rocks, and even down to our own time, and, moreover, by the occurrence among uncrystalline sediments of later geological periods, of deposits of serpentine, sepiolite, and glauconite. The history of both zeolitic and pectolitic silicates as formed by secretions in basic rocks, and as generated in deep-sea ooze, and in the channels of thermal waters, has been discussed at some length in the preceding essay, but there are facts in relation to the other silicates just mentioned which are of such importance in connection with the origin of crystalline rocks as to merit consideration in this place.

§ 4. Two examples of crystalline silicates related to zeolites in composition, which are found injecting organic remains in paleozoic limestones, have been observed by Sir J. W. Dawson, and were farther described and analyzed by the present writer in 1871. The first of these is from a Silurian limestone which is found near Woodstock, in the province of New Brunswick, and consists almost wholly of comminuted organic remains, including fragments of trilobites, gasteropods, brachiopods, and joints and plates of small encrinites, the whole cemented by calcite. The pores of the crinoidal remains are filled by a peculiar silicate, seen in sections or on surfaces etched by an acid. Surfaces thus treated show a congeries of curved, branching, and anastomosing cylindrical rods of the injecting mineral, sometimes forming a complete network, and exhibiting under a microscope coralloidal forms, with a white, frost-like, crystalline aspect resembling the variety of aragonite known as *flos ferri*. The same crystalline mineral, as observed by Dawson, occasionally fills the interstices between the larger fragments of organic forms in the limestone, and, as he observes, "was evidently deposited before the calcite which cements the whole mass."

§ 5. The limestone in question is nearly pure, containing very little magnesia or iron-oxyd, and leaves, after the action of cold dilute chlorhydric acid, five or six hundredths of insoluble residue which is the mineral in question with about one fourth its weight of silicious sand. The silicate is of a pale grayish-green color when seen in mass, and, losing water, becomes bright reddish-brown by calcination. It is partially decomposed by strong heated chlorhydric acid, and completely by hot sulphuric acid, which dissolves alumina, ferrous oxyd, magnesia, and small portions of alkalies, leaving flocculent silica, which is readily separated by a solution of carbonate of soda from the accompanying quartz-grains. Thus analyzed, the mineral, which under a lens appeared wholly crystalline and homogeneous, save the accompanying quartz, yielded silica 38.93, alumina 28.88, ferrous oxyd 18.86, magnesia 4.25, potash 1.69, soda 0.48, water 6.91. The atomic ratio of this for protoxyds, alumina, silica, and water is very nearly 1:2:3:1, which, abstracting the water, is that of zoisite; the hydrous silicate jollyte being 1:2:3:2. I have given to this crystalline silicate, which is of curious interest alike for its composition and the mode of its occurrence, the name of hamelite, for the Rev. Dr. Hamel, rector of Laval University, Quebec.*

§ 6. The second silicate above referred to is not unlike hamelite in its characters and manner of occurrence, though differing somewhat in atomic ratios. It was found in a mass of fossiliferous limestone said to be from a locality in the island of Anglesey, and including, "besides a small coral-like body referred to the genus Verticillopora, joints and plates of crinoids, small spiral gasteropod shells, with fragments of brachiopods, and a sponge-like organism with square meshes." All of these organic forms are more or less penetrated with a greenish silicate, which fills the cavities of the gasteropods, the central canal of the crinoids, and the pores of the Verticillopora. It has also replaced, or filled, the spongy fibres, and injected the minute cells of some of the crinoidal fragments, though many of these are solid throughout, in which respect the specimen differs from that from New Bruns-

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* Amer. Jour. Science, 1871, i., 379; also J. W. Dawson. The Dawn of Life, pp. 120-123, with figure of a portion of infiltrated crinoid on p. 103.

wick described above, where the infiltration of the crinoidal remains is much more complete and perfect. Sir J. W. Dawson, to whom we owe these observations, supposes that in both cases the infiltration took place while the remains were still recent.

§ 7. Decalcified surfaces of this limestone from Anglesea show similar appearances to those presented by the New Brunswick specimen, and the casts of the gasteropodous shells, two millimetres in length, are in some cases perfect. The limestone is nearly pure with the exception of a little fine yellow ochreous matter which is insoluble in the dilute chlorhydric acid, and remains suspended in the solution, but is easily separated by washing from the pale grayish-green silicate. This equals about three hundredths of the weight of the limestone. When ignited in the air it assumes a bright fawn color, and under a lens contrasts strongly with the colorless grains of quartz with which it is mixed. Its chemical characters were like those of hamelite, and analyzed in the same manner it gave, after deducting 21.0 per cent of insoluble sand, the following composition: Silica 35.72, alumina 22.26, ferrous oxyd 21.42, magnesia 6.98, potash 1.49, soda 0.67, water 11.46 = 100.00.* This gives for protoxyds alumina, silica, and water very nearly the atomic ratios 3 : 4 : 7 : 4; but we are not sure of its homogeneous character. A silicate very like this in aspect and mode of occurrence has been found in a band of fossiliferous limestone near the base of the coal-measures in southern Ohio, but has not yet been chemically examined.

§ 8. In connection with these minerals should be noticed a greenish fibrous asbestiform silicate, elsewhere described by the writer, which occurs in veins traversing the anthracite and the carbonaceous shales of the coal-measures at Portsmouth, Rhode Island, either without admixture, or mingled with pyrites, or penetrating white quartz, and also coating the fragments of the crumbling

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* Amer. Jour. Science, 1871, ii., 57.

disintegrated anthracite. It is a hydrous silicate of alumina, ferrous oxyd, magnesia, and alkalies, more basic than those above described, yielding the atomic ratios 4 : 4 : 6 : 3, and, though differing in structure, is near to prochlorite or voigtite in composition.*

§ 9. We have elsewhere explained (*ante*, page 159) how solutions which would otherwise have yielded zeolitic minerals or epidote may, by exchanging their lime and alkalies for magnesia and ferrous oxyd, have given rise to aluminous double silicates like those just described. In like manner non-aluminous solutions which might have yielded pectolite, apophyllite, or related silicates, by exchange with magnesian or ferrous solutions, may give origin to silicates like serpentine, sepiolite, and probably to glauconite. The magnesian silicates just named occur, as is well known, in aqueous deposits, by themselves or mingled with carbonate of lime, in strata of paleozoic or even of cenozoic age, while serpentine fills the Eozoön of more ancient times.

§ 10. The probable relations between the protoxyd-silicates and glauconite are worthy of notice. By the latter name is designated a soft greenish amorphous mineral sometimes found in the cavities in basic amygdaloidal rocks, but more abundantly in sandstones and marls, among which it often forms beds with but little admixture, and is commonly called green-sand. It is well known that glauconite is met with filling the shells of foraminifera and other marine organisms, from early geological times, and even occurs in the same manner in recent foraminifera in various seas. The mode of its occurrence in these cases is similar to that of the aluminous double silicates in organic forms from limestones, as described above. The composition of glauconite is very variable; and, while essentially a hydrous silicate of potash and iron-oxyd, it may contain of alumina from one or two up to twelve hundredths or more, and of magnesia from traces up to six hundredths.

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* See farther, Essay VIII., A Natural System of Mineralogy, etc., § 91.

Indeed, a so-called green-sand from the calcaire grossier, according to Berthier, is rather a highly ferrous serpentine, containing, silica 40.0, ferrous oxyd 24.7, magnesia 16.6, lime 3.3, alumina 1.7, water 12.6 = 98.9.*

§ 11. These variations show that the material in question is a mixture, and render it difficult to fix its real constitution. According to the multiplied analyses of Haushofer, the iron present in glauconite is for the most part in the ferric condition, the ferrous oxyd in various examples ranging from three to seven hundredths. The formula proposed by him represents glauconite as containing 6.3 of ferrous oxyd, 8.3 of potash, and 9.6 of water, with 22.7 of ferric oxyd and 3.6 of alumina, giving for the atomic ratios of protoxyds, sesquioxyds, silica, and water, 1 : 3 : 9 : 3.† The very variable quantity of alumina found in glauconites may, however, well be owing to a zeolitic admixture; and, if we hazard the conjecture that the large proportion of ferric oxyd therein is due to a partial oxydation of what was originally a ferro-potassic silicate, we should have for its composition before peroxydation (deducting the alumina as a zeolite with the above atomic ratios, like faujasite) a silicate with the ratios for protoxyds, silica, and water, of 3 : 9 : 3; corresponding to sepiolite, and to an unknown pectolitic silicate intermediate between pectolite and apophyllite, which may be supposed to have given rise alike to talc, to sepiolite, and to glauconite. The variable amounts of magnesia in glauconite itself would thus be due to an admixture of sepiolite. The reaction of such a soluble pectolitic compound, having a lime-potash base like apophyllite, with the dissolved magnesian salts in sea-water would generate a magnesian silicate having the ratio of talc and sepiolite (which latter forms beds in tertiary sediments), and with ferrous solutions by a similar double decomposition might

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* Beudant, Traité de Minéralogie, ii., 178. See also Report Geol. Survey of Canada, 1866, p. 231.

† Cited in Dana's System of Mineralogy, 5th ed., p. 462.

yield a ferro-potassic silicate like glauconite. It is well known that under proper conditions decaying organic matters acting upon sediments containing ferric oxyd reduce this and give rise to such solutions, in which ferrous carbonate is often associated with a proportion of an organic acid. Such a solution and redeposition in the forms of siderite and pyrite goes on in sedimentary deposits through this agency (Essay VII., § 35), and this would permit the conditions necessary to produce glauconite with the pectolitic silicate, which in the absence of the iron-solution would generate sepiolite by reaction with magnesian salts.

§ 12. The variations in the composition of glauconite-like minerals, and the existence in silicates similar to it in their mode of occurrence of more or less alumina and magnesia, probably corresponding, as suggested above, to admixtures of zeolite and sepiolite, are farther illustrated by the following analyses by the writer. I. is a typical glauconite from the green-sand beds of the cretaceous series in New Jersey; II. a glauconite, remarkable for its fine green color, which forms layers in the Cambrian (Potsdam) sandstone at Red Bird, Minnesota; III. a similar material found in a Cambrian sandstone on the island of Orleans, near Quebec. The results, after deducting silicious sand, are calculated for one hundred parts, and the whole of the iron is represented as ferrous.*

	I.	II.	III.
Silica	50.70	46.58	50.7
Ferrous oxyd .	22.50	20.61	8.6
Magnesia . . .	2.16	1.27	3.7
Lime	1.11	2.49	—
Alumina . . .	8.03	11.45	19.8
Potash	5.80	6.96	8.2
Soda	.75	.98	.5
Water	8.95	9.66	8.5
	100.00	100.00	100.00

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* Geology of Canada in 1863, p. 486; also Rep. Geol. Survey of Canada 1863–69, p. 232.

§ 13. The crenitic hypothesis advanced by the present writer in the preceding essay to explain the aqueous origin of the mineral species which make up alike the granites and the crystalline stratified rocks, supposes that from an early period watery solutions analogous to those which in later times have given rise to zeolitic and pectolitic minerals, played an important part in the chemistry of the earth. The double silicates of alumina and lime or alkalies then dissolved, are conceived to have been the source not only of the feldspars and the zeolites, but of epidote, garnet, muscovitic micas, and tourmalines, and, by their reactions with magnesian and ferrous solutions, of the chlorites and the highly protobasic micas. At the same time the dissolved protoxyd-silicates not only gave rise to species like pectolite and apophyllite, but, by similar reactions, to pyroxene, amphibole, chrysolite, serpentine, talc, sepiolite, and glauconite, and, by decomposition through carbonic dioxyd, to carbonate of lime. In both cases the solutions, like those in later zeolite-bearing rocks, carried free silica and iron-oxyd, which were deposited as quartz and magnetite and hematite. These silicated solutions, according to this hypothesis, resulted primarily from the action of permeating waters at high temperatures, under pressure, upon the universal stratum of basic plutonic rock; and secondarily from their action upon the displaced portions of this stratum, which, in a more or less modified form, have appeared in all geological periods as erupted basic rocks. These, in their secreted minerals, show us in later times, and on a smaller scale, the process which in previous ages built up great masses of indigenous and endogenous crystalline rocks. To what extent these deposits, more or less concretionary in their origin and their arrangement, were laid down horizontally, and to what extent in inclined or vertical layers, as in many veinstones, is a question which will be discussed farther on in this essay.

§ 14. Having thus briefly restated the crenitic hypothesis so far as it is related to the classes of rocks already noticed, we have to consider in the next place the question of exoplutonic or eruptive rocks. It will be remembered that the existence of such rocks, having an igneous origin, was not admitted by the Wernerians, who conceived not only all endogenous rocks, but also all exotic masses, except modern lavas, to be of aqueous origin. By the earlier Huttonians, who understood better the geological importance of the eruptive rocks, these were looked upon as results of the fusion of deeply buried detrital materials, themselves derived from similar rocks of higher antiquity. The hypothesis of great chemical changes to explain the genesis of many crystalline rocks from such material by what was comprehensively designated as "metamorphism," and generally involved a supposed metasomatic process, was devised at a later day by the disciples of Hutton. Haidinger and Bischof may be looked upon as the originators of that view of metasomatic changes in rock-masses by aqueous action which, from its supposed analogy with the phenomena giving rise to what are called pseudomorphous shapes or pseudo-crystals, has been infelicitously described as "pseudomorphism on a broad scale." *

§ 15. The stratiform arrangement, which extends to the intimate structure of crystalline masses such as gneisses and mica-schists, is by endoplutonists supposed to be due to movements in an imperfectly homogeneous semi-fluid material dependent on unequal cooling and the rotation of the globe, and to be analogous to the banded structure apparent in lavas and furnace-slags. In the exoplutonic hypothesis, on the contrary, it is maintained that the internal movements in such material, when forced outwards and upwards through the earth's superficial crust, have given to the masses that laminated structure and that arrangement of the constituent elements which, alike by Wernerians and Huttonians, are regarded as evidences of deposition from water. This latter or exoplutonic view

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* Ante, page 100.

was clearly expressed by Poulett Scrope, sixty years since, in his "New Theory of the Earth," published in 1825 (*ante*, page 81), wherein he imagines the granite to have formed the original surface of the globe, and supposes that movements in extruded portions of the mass compressed beneath overlying sediments gave to it the gneissic structure. He insists upon the friction of its elements "as they were urged forward in the direction of their plane surfaces towards the orifice of protrusion, along the expanding granite beneath, the laminæ being elongated and the crystals forced to arrange themselves in the direction of the movement." This view was adopted, though without acknowledgment, by J. D. Dana in 1843, when he argued that the schistose structure of gneiss and mica-schist is not a satisfactory evidence of sedimentary origin, since erupted rocks may assume a laminated arrangement.*

§ 16. The same notion has continued to find favor among geologists of the plutonist school up to the present time. Poulett Scrope himself, in rewriting his famous treatise on Volcanoes, after a lapse of thirty-seven years, restates his argument with great precision. He therein supposes that the primitive material of the globe, so far as known, was an aggregate consisting essentially of feldspar, quartz, and mica, in a crystalline or granular condition. This material, which was impregnated with water and highly heated, possessed a certain plasticity, and when extruded by pressure took upon itself a stratiform structure, being "bodily forced up the axial fissure of dislocation in crumpled zigzag folds or upright walls of vertical laminated rock." To show to what extent this view had met the approval of other geologists, Scrope farther observed, "The late Mr. Sharpe and Mr. Darwin, as is well

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* Scrope, Considerations on Volcanoes, etc., 1825, p. 22. See also J. D. Dana, On the Analogies Between Modern Igneous Rocks and the so-called Primary Formations, 1843; Amer. Jour. Science, 1843, xlv., 104–129; and *ante*, pages 89, 90.

known, concurred in the opinion here given, that at least as respects the oldest or fundamental gneiss, its foliated structure is due not to original sedimentary deposition, but to the movement of the particles under great pressure while the mass was in a condition of imperfect igneous fluidity. Prof. Naumann has still more recently advocated the same view, which is, however, resisted by Lyell, Murchison, Geikie, and others." *

§ 17. The same view has very recently been brought forward by Joh. Lehmann, who maintains, with Scrope, that the schistose structure in crystalline rocks is no evidence of aqueous deposition, but is imposed upon them by the process of extrusion. The Saxon granulites, according to Lehmann, were intrusive masses which consolidated among sedimentary strata far below the surface, and, being afterwards forced up by great pressure, took upon themselves a banded schistose arrangement, the adjacent strata, more or less impregnated by the granulitic material. appearing as micaceous gneisses and mica-schists.† This whole granulitic series of Saxony may be described as made up of fine-grained binary gneisses (granulites), passing into micaceous gneisses and mica-schists, and has been by the present writer elsewhere referred to the younger gneissic or Montalban series of crystalline rocks.‡

§ 18. An example of the resuscitation of the views of Poulett Scrope in North America is found in a recent note by Prof. H. Carvill Lewis on the crystalline schists of eastern Pennsylvania. A belt of these which crosses the Schuylkill near Philadelphia, long ago described by H. D. Rogers, and since by the present writer,§ includes a band of granitoid gneiss succeeded by micaceous gneisses and

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* Scrope, on Volcanoes, 2d ed., 1862, as revised in 1872, pp. 300–305.

† Joh. Lehmann; Untersuchungen über die Enstehung der Altkrystallinen Schiefergesteine, 1884. Not having been able to consult this work, I am indebted for a notice of its argument to a review in the Amer. Jour. Science, xxviii., p. 39.

‡ See Essay X., §§ 79, 80.

§ See Hunt, Azoic Rocks, pp. 10–15 and 200; also Essay X., § 18.

micaceous schists, often garnetiferous, comprising a layer of serpentine with steatite and dioritic rocks, the whole representing both the older and the younger gneissic series so well known in eastern North America as Laurentian and Montalban. The rocks in this belt, notwithstanding their stratiform character, are, in the opinion of Lewis, "of purely eruptive origin, consisting of syenites, acid gabbros, trap-granulites, and other igneous rocks, often highly metamorphosed. It is the outer peripheral portions of this zone to which attention is here directed. While the rocks are massive in the centre, this outer portion has been enormously compressed, folded, and faulted, with the result of producing a tough banded porphyritic fluxion-gneiss." Lewis supposes "a recrystallization of the old material under the influence of pressure-fluxion," by which he conceives the feldspar to have been recrystallized. "In similar manner the biotite has been made out of the old hornblende, garnets have been developed, and the quartz has been granulated and optically distorted by the pressure." In another example mentioned by him, a belt of sphene-bearing amphibolite schist, described as included unconformably in the mica-schists of Philadelphia, is supposed by Lewis to be "a highly metamorphosed intrusive dike of Lower Silurian age. The original augite or diallage has been completely converted into fibrous hornblende, and the influence of pressure is shown in the perfectly laminated character of the schist, in the close foldings produced, and in the minute structure of the rock." "The chemical changes and interchanges of elements which might result from a loosening of molecular combinations under extreme pressure," and their subsequent re-arrangement to form new compounds, suggest to Lewis great possibilities in the so-called "mechanical metamorphism" now advocated by some to replace the discredited dogma of chemical metamorphism, which has hitherto played such an important part among a school of geologists.*

* H. C. Lewis, Proc. British Association, in Nature, Oct. 8, 1885, p. 560.

§ 19. Thus, while the ancient Wernerians maintained the direct deposition of granite from aqueous solutions in a chaotic ocean, the plutonists, from Poulett Scrope in 1825 to Darwin, Naumann, Lehmann, and Lewis, assert the igneous origin not only of granites but of gneisses and micaceous and amphibolic schists, and the followers of the Huttonian or metamorphic school hold an untenable and an illogical position between the two, — deriving the materials of both of these rocks from a primary granitic mass, whose origin is unaccounted for, and whose supposed transformations chemistry cannot explain.

§ 20. It remains to notice, in connection with the neptunian, the plutonic, and the metamorphic hypotheses, regarding the sources and the geognostic relations of the crystalline rocks, a view which has been proposed to explain the attitude of certain apparently exotic masses: which is that their present position is due neither to deposition from solution nor to intrusion in a fluid or plastic condition, but to local movements which have permitted portions of rigid rock to displace and even penetrate softer and more yielding materials in their vicinity. Examples of this are described by Stapff as seen in the St. Gothard tunnel in the Alps, where great masses of serpentine have been caused to traverse adjacent schistose strata; the solid condition of the intruding rock being made evident by the accompanying breccia, consisting of its fragments.* There is reason to believe that such instances are not uncommon, and that in many cases the phenomenon of intrusion is due to the superior hardness of the intruding rock, broken beds or masses of which are forced through softer strata; the conditions being the reverse of those which attend plutonic or volcanic injections. The notion that rocks when in a solid condition may be intruded among others, is found in the pages of more than one writer on geological questions, but, so far as the writer is aware, is for the first time clearly and satisfactorily de-

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* See farther, Essay X., §§ 128–130, where details and references are given.

fined in the description of Stapff, which is an important conception gained for the student of geognosy.

§ 21. The endoplutonists, as we have seen, have sought to explain the laminated structure of certain crystalline rocks, not, like the exoplutonists, by the pressure attendant on extrusion, but by movements in an imperfectly fluid material in which, during refrigeration, a separation of solid matters and a process of eliquation were going on. The possible production in this manner alike of unstratified and stratiform crystalline rocks from an igneous mass is ingeniously set forth by Thomas Macfarlane in his studies of the geology of Lake Superior.* He notes first the occurrence of fragments of denser and more basic hornblendic aggregates enclosed in lighter and less basic granitoid masses, and, from these facts, and the composition and specific gravity of granitic veins penetrating the masses, conjectures that these various products represent different stages in crystallization from a primitive magma, the first separated portions from which were more basic and the later more silicious.

If this took place when the mass was undisturbed, a granitoid rock would be formed; but if while it was in motion, "hornblendic and micaceous schists and gneisses were most probably the results of this process, and the strike of these would indicate the direction of the current at the time of their formation." The material thus separated, notwithstanding its greater specific gravity, is supposed to have formed at the surface of the molten mass, as a result of cooling; but in Macfarlane's view "there arrived a time when, from some cause or other, these first rocks were rent or broken up and the crevices or interstices became filled with the still fluid and more silicious material which existed beneath them. This gradually solidified in the cracks, or in the spaces surrounding the fragments, and the whole became again a consolidated crust above a

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* Geological Features of Lake Superior, Canadian Naturalist, May, 1867.

fluid mass of still more silicious material," which by subsequent movements would again be intruded in the form of veins in the broken crust. This restatement of the hypothesis of the solidification of a molten globe from above downwards, already taught by Naumann,* serves to show how the endoplutonist school explains the origin alike of massive and of stratiform crystalline rocks, and may be compared with the detailed statement of the exoplutonist view as set forth by Poulett Scrope.

§ 22. The broad distinction sometimes drawn between stratified crystalline rocks as of indigenous and aqueous origin, and unstratified rocks as intruded or exotic masses of igneous origin, thus finds no place in the hypotheses of the plutonic schools, according to both of which these two classes of rocks have come directly from a primitive fused mass, which was either simple or had become complex through differentiation. The Huttonian school also, which teaches that eruptive rocks, in many if not in all cases, were originally sediments which, as a result of profound alteration, have lost their bedded structure, arrives by a different route to a conclusion not unlike that of the plutonists; namely, that the differences between stratified and unstratified rocks are due solely to superinduced structure and geognostic relations. Those who, for the most part unfamiliar with any other view, acquiesce in the metamorphic hypothesis of Hutton and his followers, now so popular with a school of writers on geology, are scarcely prepared, without farther study, to criticise intelligently either the plutonic or the crenitic hypothesis of the origin of crystalline rocks. The latter, as set forth in the preceding essay, and concisely resumed on page 199 of the present, supposes that the source of all crystalline rocks is to be sought in a previously solidified primary plutonic material. The elements of these rocks have been derived in part indirectly, by aqueous solution, and in part directly from this original mass, more or less profoundly

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* See *ante*, page 85.

altered alike by previous aqueous action and by differentiation through crystallization and eliquation. By this hypothesis, as we have elsewhere attempted to show, we may hope to lay the foundation of a rational geogeny and geognosy.

§ 23. We have already, in the preceding essay, considered at some length the views of those who, noting the existence of predominant types of crystalline rocks, have sought to explain their origin by supposing the presence beneath the earth's solid crust of two distinct layers of molten rock: an upper, lighter, and more viscous silicious or so-called acidic stratum, the material of trachytes, granites, and gneiss; and a lower, heavier, and more fluid basic layer, the source of doleritic and basaltic rocks,— a view which was put forth by John Phillips, defended by Bunsen, and elaborated and more definitely formulated by Durocher. To this are opposed the modified view of Von Waltershausen, of a gradual passage downward in a liquid mass from a more acidic to a more basic portion, and the entirely distinct view held and defended by the present writer as the basis of the crenitic hypothesis. According to this the plutonic underworld, so far as it intervenes directly in geologic phenomena, is an essentially homogeneous basic rock, not in a state of simple and original igneous fusion, but solidified and subsequently impregnated with water, which communicates a certain plasticity to the highly heated mass, and, moreover, dissolves and removes therefrom the materials of the trachytic and granitic rock, — which are thus primarily of aqueous origin.

§ 24. This process implies secular changes in the composition of the plutonic stratum, which are moreover local, since the conditions of solution and upward percolation will vary in different areas, and during different periods in the same area. It involves also a corresponding change in the nature of the materials dissolved, so that differences greater or less are to be looked for in the composition alike of eruptive plutonic and of crenitic rocks, when those of different areas and different ages are compared. The evidence of some such changes, even independent of aqueous action, in the composition of the plutonic mass did not escape the acute observation of Durocher, and was in 1857 discussed by him in his remarkable essay on Comparative Petrology.* To this I called attention in 1858, stating that in Durocher's view the two strata of molten mineral matter imagined by him, "occasionally more or less modified by a partial crystallization and eliquation, or by refusion," give rise to the principal varieties of acidic and basic crystalline rocks.†

§ 25. This view was stated with great clearness by Durocher, who declared, "The magmas which have produced the igneous rocks are to be compared to metallic baths, which, holding many metals in a state of fusion, separate in solidifying into different alloys, according to the circumstances of their solidification,"—these circumstances being "conditions of an exterior rather than of an interior order." Subsequently, in comparing a basic and highly aluminous phonolite with a trachytic porphyry, more silicious and less aluminous, he remarks that an admixture of these in equal proportions would give the composition of a normal trachyte, and expresses the opinion that the rocks thus compared are probably "the two opposite products of an eliquation which took place in the midst of the liquid mass, as in the formation of two opposite alloys, into which a metallic bath is so often seen to separate." These phenomena of eliquation he conceived to be very general in nature: "They must have taken place beneath the surface of the earth, and in its caverns and crevices, as well as at the surface."

§ 26. The probability of this view is apparent to all chemists who have studied the phenomena due to the crystallization and different melting and solidifying points

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* Annales des Mines, xi., 217. A translation of this into English by Haughton was separately published in Dublin, in 1859.

† Chemical and Geological Essays, page 3.

of metallic alloys, as, for example, the separation of lead from its silver-bearing alloy in the Pattinson process, and the eliquation of this metal from its alloy with copper. It was adopted by Macfarlane in 1867, in explanation of the relations of more or less basic hornblendic and granitic rocks, already cited in § 21, and finds a striking illustration in the late experiments of Fouqué and Michel Lévy on the artificial production of crystalline mineral species from fused vitreous mixtures. From such a mixture, containing the elements of six parts of chrysolite, two of pyroxene, and six of labradorite, kept at a heat near whiteness for forty-eight hours, there separated crystals of chrysolite, 0.5 millimetre in diameter, together with magnetite and spinel (picotite); a vitreous magma still remaining, from which crystallized, at a lower temperature, macled crystals of labradorite, with pyroxene, magnetite, and spinel, as before. It is apparent that with a greater lapse of time, and the formation of larger crystals of chrysolite, which has a specific gravity of about 3.4, these would, under the influence of gravity, subside, together with magnetite and spinel, from a fused glass holding the elements of pyroxene and feldspar, the more so as the density of fused doleritic and basaltic material is less than 2.8. From such a slowly cooling mixture the process of eliquation would, under favorable conditions, give rise to a highly chrysolitic aggregate on the one hand and to a dolerite with little or no chrysolite on the other. Moreover, if, as is probable, there are conditions under which pyroxene may be separated in a similar manner from the feldspathic element, we should have a farther differentiation, giving rise to heavier and highly pyroxenic portions on the one hand and to lighter and more feldspathic portions on the other.

§ 27. The careful student of crystalline rocks will have noticed many examples in nature of variations in different portions of eruptive masses, which find a ready explanation in a process of partial solidification and eliquation, as suggested by Durocher and illustrated by the experiments of Fouqué and Michel Lévy. This is well displayed in certain rocks intruded among the Ordovician strata of the St. Lawrence valley, near Montreal, and forming the hills known as Rougemont, Montarville, and Mount Royal. These, as I have long since described them, are essentially doleritic, but present very great differences in the proportions of their mineralogical elements in contiguous parts. Thus in some portions of these masses we have a pyroxene and labradorite rock in which these two elements are pretty equally distributed, while in other portions the rock is almost wholly a black, coarsely crystalline pyroxene, with but an insignificant proportion of the feldspathic element. Elsewhere the arrangement of these two species gives rise to a stratiform structure.

§ 28. As described by me in 1863,* for Mount Royal, "mixtures of augite and feldspar are met with, constituting a granitoid dolerite, in parts of which the feldspar predominates, giving rise to a light grayish rock. Portions of this character are sometimes found limited on either side by bands of nearly pure black pyroxenite, giving at first sight the aspect of stratification. The bands of these two varieties are found curiously contorted, and . . . seem to have resulted from movements in a heterogeneous pasty mass, which have effected a partial blending of an augitic magma with one more feldspathic in nature." In the doleritic mass of Montarville the alternation of a coarse-grained variety of dolerite, porphyritic from the presence of large crystals of pyroxene, with a finer-grained and whiter variety is noticed, the two "being arranged in bands whose varying thickness and curving lines suggest the notion that they have been produced by the flow and the partial commingling of two fluid masses." Of this stratiform structure it was then said, it seems to be due to "the arrangement of crystals during the movement of the

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* Geology of Canada, 1863, pp. 665, 667, and Amer. Jour. Science, 1864, xxxviii., 175–178.

half-liquid crystalline mass, but it may in some instances arise from the subsequent formation of crystals arranged in parallel planes." *

§ 29. The feldspars mentioned, as shown by the published analyses by the writer, are near in composition to labradorite. The composite rocks described also contain, besides pyroxene, more or less magnetite and menacanite, with chrysolite. This last species is for the most part distributed sparsely through these rocks, but occasionally, like the pyroxenic element, occurs in predominant quantity. An example of this is seen in a coarsely granitoid chrysolitic aggregate, exposed with the same characters, over an area of many hundred square feet, on Montarville. The chrysolite in this rock is in irregular crystalline masses from five to ten millimetres in diameter, and was separately analyzed, as was the black pyroxene, in still larger and well defined crystals from the mass, and also the feldspathic element, selected as carefully as possible. For an analysis of the rock as a whole, it was attacked in fine powder successively by dilute sulphuric acid and by a weak solution of soda, the portions thus dissolved being analyzed separately, as well as the insoluble residue. The relative proportions of these being 55.0 per cent of the former and 45.0 of the latter, it became possible to calculate the composition of the rock as a whole.

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* Farther illustrations of this are given by the author in a communication to the Boston Society of Natural History, January 7, 1874: "Among these was a specimen shown from Groton, Connecticut, in which a large angular fragment of strongly banded micaceous gneiss is enclosed in a fine-grained eruptive granite, the mica plates in which are so arranged as to show a beautiful and even stratification in contact with the broken edges of the gneiss, but at right angles to the strata of the latter. Another example is afforded by the eruptive diabase from the mesozoic sandstone of Lambertville, New Jersey, which is conspicuously marked by light and dark bands, due to the alternate predominance of one or the other of the constituent minerals; and still another is a fine-grained dark micaceous dolerite dike from the Trenton limestone at Montreal, in which the abundant laminæ of mica (probably biotite) are arranged parallel to the walls of the dike." Chem. and Geol. Essays, p. 186.

§ 30. In the following table, I. is the composition of the feldspar; II the pyroxene; and III. the chrysolite; IV. the soluble portion (55.0 per cent), chiefly chrysolite; V. the insoluble portion (45.0 per cent); VI. the rock as a whole, including an undetermined amount of titanic oxyd with the iron-oxyd. For the purposes of comparison we give under VII. the composition of the supposed basic magma of the earth's interior, as deduced by Bunsen from the mean of several analyses of basic eruptive rocks, and under VIII. the composition of the same as calculated by Durocher, who, however, admits a range in proportions through geologic time which includes the figures adopted by Bunsen. The last five analyses are necessarily calculated for one hundred parts, and the whole of the iron is represented as ferrous oxyd, although an unknown proportion exists in a higher state of oxydation.

	I.	II.	III.	IV.
Silica . . .	53.10	49.40	37.17	37.30
Alumina . .	26.80	6.70	—	3.00
Lime . . .	11.48	21.88	—	—
Magnesia . .	.72	13.06	39.68	33.50
Ferrous oxyd .	1.35	7.83	22.54	26.20
Soda	4.24	.74	—	—
Potash . . .	.71	—	—	—
Volatile . .	.60	.50	—	—
	99.00	100.11	99.39	100.00

	V.	VI.	VII.	VIII.
Silica	49.35	42.70	48.47	51.5
Alumina . . .	18.92	10.16	14.78	16.0
Lime	18.36	8.27	11.87	8.0
Magnesia . .	6.36	21.29	6.89	6.0
Ferrous oxyd .	4.51	16.45	15.38	13.0
Alkalies . . .	2.50	1.13	2.61	4.0
	100.00	100.00	100.00	—

§ 31. The process which has thus given rise in parts of a mountain mass of dolerite to considerable areas of a rock containing over 21.0 of magnesia, and more than one half its weight of chrysolite, and in other parts of the same mass to an aggregate of pyroxene and labradorite almost, and in some cases wholly, destitute of chrysolite, is readily explained if we admit a separation from a still fluid mass of the previously crystallized and heavier chrysolite by a process like that imagined by Durocher. It will be noticed that the insoluble and non-chrysolitic portion separated from the Montarville rock, V., is near in composition to an ordinary dolerite, or to the normal basic types of Bunsen and Durocher. We may conjecture that dolerites of average composition are, perhaps, themselves products separated by eliquation from a more chrysolitic aggregate.

§ 32. The segregation of groups of crystals, which takes place in the devitrification of glasses, shows, within narrow limits, the process of differentiation through crystallization in a homogeneous mass. The operation of this process on a larger scale, giving rise to remarkable mineralogical differences, is well shown in the careful studies by Fouqué, in 1873, on the recent eruptive rocks from Santorin. The ordinary type of these lavas examined by him was a vitreous mass enclosing crystals of feldspars, with pyroxene, chrysolite, and magnetite. The feldspar was chiefly labradorite, but its association with crystals of albite, and with some anorthite, was established. Druses in this same rock were, however, filled with anorthite, associated with a pyroxene and a chrysolite, both differing from those contained in the paste in being less dense and in containing less ferrous oxyd. In an obsidian-like rock from the same region were rounded masses, sometimes a metre in diameter, gray in color, and made up of crystalline anorthite, with pyroxene, chrysolite, sphene, and magnetite, with very little paste. The small portions of alumina found in the analyses of these pyroxenes were apparently, according to Fouqué, derived from adherent anorthite, but another variety of pyroxene, seemingly very pure, and freed from anorthite, contained 12.4 per cent of alumina, which he regards as an integral part of the mineral,—a true aluminous pyroxene. Fouqué made use in these investigations of concentrated fluorhydric acid, which readily attacks the coarsely powdered rock, dissolving alike the vitreous paste, albite, labradorite, and anorthite, but leaving behind the pyroxene and chrysolite, which, like amphibole, are but slightly attacked by the acid,* or, like staurolite and zircon, resist its action.

§ 33. Durocher, in his statement of the hypothesis of eliquation as applied to eruptive rocks, of which this process of segregation just noticed is but an illustration, raises, in connection with the question of differentiation, another not less important. He concludes from his comparative studies that, "in the long course of the ages which divide the primary and the tertiary periods from each other," there have been changes "in the composition of the fluid mass which nourished the eruptions"; and, moreover, that in the case of the acidic layer — the source of the granitic and trachytic rocks — "there was a diminution of eight or nine hundredths in the proportion of silica, and of one-fifth in the potash, while the proportions of lime and iron-oxyd were almost doubled, and that of the soda tripled. Similar changes, according to him, have taken place in the basic layer, represented by dolerites, basalts, melaphyres, from the comparative study of which he concludes that "in the ferro-calciferous layer

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* Fouqué, Nouveau procédé pour l'analyse médiate et son application aux laves de la dernière eruption de Santorin; in abstract, Comptes Rendus de l'Académie des Sciences, June, 1873, lxxvi., 1181. Also, in extenso, Mem. des Savants Étrangers, de l'Acad. des Sciences, xxii., no. 11. For farther details of this use of fluorhydric acid, see Fouqué and Michel Lévy, Minéralogie Micrographique, p. 116.

Crystals of zircon from different localities, according to the late observations of Ed. Linnemann, when exposed for ten days to the vapors of fluorhydric acid, crumble to a white powder, which is not attacked by fluorhydric acid nor by aqua regia, and is pure silicate of zirconia, equal to 93 and 94 per cent of the crystals. The matters attacked are silicates of various bases, including alkalies, lime, magnesia, iron, zinc, and alumina. (Sitz. Berichte Kais. Acad. Wissenschaft, 11, 1885, in Chem. News, Nov. 6, 1885.)

from the primary to the tertiary period . . . there was a sensible diminution of silica and potash, and a notable augmentation of soda and lime." Of these changes "the diminution of silica and potash in the modern rocks, both of the acidic and basic groups," was by Durocher explained by supposing that while these imaginary igneous layers remain distinct from each other, there is, nevertheless, in each a partial separation of these elements by gravity, resulting in an accumulation of silica and potash in their upper portions, and of lime in their lower portions. The augmentation in the proportion of soda was by him referred to a special and independent cause, the supposed "intervention of sea-water in the formation of igneous products during the later geological periods," which, as he writes, would explain "the considerable increase of soda in the more modern of the igneous rocks, whether they be derived from the acidic or the basic layer."

§ 34. While Durocher included in the category of eruptive rocks certain masses, such as those of magnetite, serpentine, and various amphibolic rocks, for which an igneous origin is not admissible (so that some of his data may be questioned), the correctness of his important generalizations, which suggest a vast geogenic problem, cannot be contested. As regards his proposed explanation, it is easy to conceive that a separation by specific gravity might possibly cause such variations, alike in the acidic and the basic layer, that the ejections in the course of ages from successively lower portions of each of these would show the gradual diminution observed in the proportions of silica and potash, as well as the augmentation of lime. To this ingenious explanation, however, it is to be objected that it is based upon the unproved and, in the opinion of many modern philosophers, the untenable hypothesis of a molten substratum, and, moreover, one divided into two distinct zones. The whole of the phenomena in question, moreover, admit of a simpler and, it is believed, a more probable explanation by the crenitic hypothesis. This, as we have seen, supposes a constant and progressive differentiation of an original basic plutonic mass through the action of water, which removes therefrom in the elements of orthoclase and quartz, — the chief constituents of granitic rocks, — preponderant proportions of silica and potash; an action which would result at last in the partial exhaustion of the lixiviated portion of the basic rock, which, with the diminution of the amount of available silica and potash, would finally yield to the solvent action of the waters only the elements of the more basic feldspars. As a result of this continued process, the crenitic products themselves will naturally show a diminution in the proportions of silica and potash, by reason of the progressive exhaustion of the source of these, while this residual portion of basic rock will not only exhibit a reduction in the proportions of silica and potash, but a relative increase in the proportion of lime. Moreover, the sodium and magnesium-chlorids which, from the results of sub-aerial decay, find their way into the surface-waters, which subsequently pass downwards in the process of lixiviation, may by double exchange effect the displacement of potash and the fixation of soda and magnesia in the basic mass, as explained farther on.

§ 35. This hypothesis thus explains at the same time the origin of the highly silicic and potassic rocks, represented by the granites, and the conversion of the original plutonic stratum into a more and more basic material, progressively richer in alumina, soda, lime, and magnesia. It moreover requires that the long-continued lixiviation of a given area of plutonic rock should at length reach a point at which water could no longer remove from it the elements of orthoclase and quartz. With the disappearance of the latter would come the elements of the more basic feldspars, such as andesite and labradorite, as well as protoxyd-silicates, which together predominate in the norites and the diorites, characteristic crenitic rocks of the later crystalline series, as the Norian and Huronian, which succeed the granites and the granitoid gneisses of the earlier periods.

The crenitic hypothesis, as we have elsewhere seen, involves the conception that all trachytic and granitic rocks are primarily of crenitic origin, and that penetrating granitic masses, when not, as is the case with most granitic veins, directly crenitic or endogenous masses, are displaced portions of older crenitic deposits. The first-formed granitic layer itself, it is held, may become softened under the combined influences of water and internal heat, and, being then displaced, may appear in an eruptive form.

§ 36. The question here arises as to the respective parts which crenitic action, on the one hand, and crystallization and eliquation, on the other, may play in the genesis of various types of crystalline rocks. It is apparent, from the illustrations which we have given, that by the latter process aggregates could, in paleozoic times, be formed in which chrysolite makes more than one half the weight of the mass, and others in which either pyroxene or labradorite may largely predominate. The texture and the general facies of these different mineral aggregates, not less than their geognostic relations, however, suffice to distinguish them from crenitic deposits of somewhat similar composition. It was from a failure to recognize these differences that the original Wernerians denied or minimized the significance of igneous rocks, on the one hand, and that the later plutonists of both schools, on the other hand, have argued the igneous origin of rocks of manifestly crenitic origin. The Wernerians, from the stratiform structure of gneiss, which they ascribed to its aqueous origin, argued for a similar origin for the granite into which it appears to graduate, while the plutonists from an analogous structure in undoubtedly igneous rocks conclude to the igneous origin of gneiss. We have already noticed this laminated or stratiform character in plutonic rocks, the true significance of which as evidences of igneous flow should not be lost sight of (page 210).

§ 37. It must be kept in mind that the crenitic process, unlike eliquation, modifies the primary mass not only by abstraction but by addition, since the surface-water, which, by the hypothesis, is the dissolving agent, will bring with it in solution, in varying proportions, salts of calcium and magnesium, of potassium and of sodium, the action of all which upon the heated plutonic mass will effect certain interchanges, resulting in the fixation of bases like magnesia, whose silicated compounds are comparatively insoluble in the circulating waters, and perhaps in a substitution of soda for lime. It is not improbable that potassic solutions from some local source * could thus be introduced, and give rise by their action upon a doleritic mass, either integral or partially differentiated by eliquation, to a material so rich in potash as to furnish the elements of leucite, — which has the oxygen-ratios of andesite.

§ 38. The genesis of rocks like phonolite, which are essentially made up of a feldspar having the orthoclase-ratios, with an admixture with a more basic silicate, as nephelite or a zeolite, can, however, hardly be explained save as an educt of crenitic action, like trachyte and granite. It represents, however, a period in the history of the plutonic mass when, from a diminution of silica, the production of quartz ceases, and more basic feldspathic or zeolitic compounds begin to replace the orthoclase. When from compounds like these, in which the proportion of protoxyds to alumina falls below the normal oxygen-ratio of 1 : 3, we pass to others, like the muscovitic micas, most tourmalines, and the pinite-like minerals, with a diminished proportion of protoxyds, we have probably in all

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* While in ordinary spring-waters the proportion of potassium to sodium salts is small, seldom exceeding two or three hundredths of these bases, calculated as chlorids, I have shown that in an alkaline spring-water from paleozoic shales at St. Ours, Quebec, containing in a litre about 0.3 gramme of alkalies, chiefly as carbonates and chlorids, the potassium thus calculated equalled 25 per cent. In the case of the water of the St. Lawrence River it equals 16 per cent, and of the Ottawa River 32 per cent. See for a discussion of the question of potassium in natural waters the writer's Chem. and Geol. Essays, pp. 135–137.

cases to do either with crenitic products or with the direct results of sub-aerial decay.

§ 39. Fouqué and Michel Lévy, in their recent experiments, have shown us how to form artificially, from mixtures in igneous fusion, in which the proportions of elements were pre-arranged, crystalline aggregates containing leucite with labradorite, pyroxene, magnetite, and spinel, and others holding chrysolite in similar associations. The problem which lies behind their discovery is to determine how the materials are so grouped in nature's laboratory as to yield the mixtures necessary, in the one case, for the production of a leucitophyre and, in the other, for a chrysolitic dolerite. The research of the natural processes by which these combinations are reached has been the object of the preceding inquiry into the results of eliquation, on the one hand, and of the solvent and replacing action of percolating waters, on the other.

§ 40. It is farther to be noted that the experiments of Fouqué and Michel Lévy were made by the slow cooling of mixtures from simple igneous fusion, and the question must here be raised how far these reactions would be affected by the intervention of water; in other words, whether, as maintained by Poulett Scrope, Scheerer, Élie de Beaumont, and many others, water is not always present in the mass of igneous rocks. So far as experiments go, the process of cooling from simple igneous fusion would seem to be inadequate to account for the origin of many of the minerals of eruptive rocks. Fouqué and Michel Lévy inform us that they "have vainly sought to produce by igneous fusion rocks with quartz, orthoclase, albite, white or black mica, or amphibole," * although the occasional accidental production of orthoclase as a furnace-product has been noticed. The presence of albite in the recent lavas of Santorin in association with labradorite, pyroxene, and chrysolite has been shown by Fouqué (§ 32), and its probable occurrence in a diabase has been

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* Synthèse des Mineraux et des Roches, p. 75.

pointed out by Hawes.* Both orthoclase and albite have, however, been formed in the wet way, at elevated temperatures, under pressure (*ante*, page 157); and pyroxene, while readily generated from the products of igneous fusion, was got by Daubrée by the action of superheated water on glass at the same time with crystallized quartz and magnetite or spinel (*ibid.*, page 148). The frequent occurrence of pyroxene in veinstones, in intimate association with orthoclase, quartz, apatite, and calcite, suffices to show its aqueous origin, in common with all of these species. In like manner, magnetite, which is readily formed in fused basic mixtures, is found crystallized with orthoclase and quartz, with apatite and pyrite, in granitic veinstones. Moreover, the fact of its association with garnet, and with zeolitic minerals, in the secretions of basic rocks suffices to prove that magnetite, as well as hematite, may be formed by aqueous action. Chrysolite, also, is produced by igneous fusion, but its presence in crystalline limestone in the form of forsterite, and in massive magnetite as hortonolite, shows that, like the related and similarly associated species, chondrodite, it may be formed in the presence of water (Essay X., § 122–124).

§ 41. The evidences of the intervention of water in eruptive rocks have since the time of Scrope been too often pointed out to need repetition here. Its elements may even be retained in fused compounds at the temperature of ignition, under the ordinary atmospheric pressure, as seen not only in the hydrate and the acid-sulphate of potassium, but in certain vitreous borates of sodium and potassium, long since described by Laurent, which at a red heat and in tranquil fusion hold an amount of hydrogen equal to 1.2 and 1.3 hundredths of water, and are, under these conditions, slowly decomposed by metallic iron, with abundant disengagement of hydrogen gas, which burns with a green flame from the presence of combined

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* See Essay VIII., § 75.

boron.* That, under greater pressure, water may be held by other compounds, such as silicates, is undoubted. Hydrous glasses like pitchstone and perlite are examples of these, and differ from obsidian in containing three or four hundredths of water.

§ 42. The late researches of Tilden and Shenstone on The Solubility of Salts in Water at High Temperatures throw much light on the geological relations of water. While the solvent power of this liquid rapidly increases, when under pressure, at temperatures above 100° C., they have shown that "the increase of solubility follows the order of the fusing-point of the solid." Thus, of potassium-iodid, which melts at 634°, 100 parts of water at 180° dissolve 327 parts, while of barium-chlorate, melting at 400°, 100 parts of water at 180° dissolve 526 parts. Of potassium-nitrate, melting at 339°, 100 parts of water at 120° dissolve 495 parts, or nearly five times its weight; while of silver-nitrate, whose fusing-point is 217°, 100 parts of water at 125° dissolve 1622.5 parts, and at 133° 1941.4 parts, or nearly twenty times its own weight. Of certain substances it can be said that they are infinitely soluble at certain temperatures. This is true of the decahydrated sodium-sulphate, which melts at 34°, and nearly true for benzoic acid. This substance, which melts at 120°, requires for its solution 600 parts of water at 0° and 25 parts at 100°; but when heated in a sealed tube to a few degrees above its fusing-point it is miscible with water in all proportions. These heated solutions, in the case at least of barium-chlorate and potassium-nitrate, are described as notably viscous, a condition which indicates that they are perhaps colloidal.†

§ 43. From these results it is easy to conceive what might be expected at elevated temperatures with mate-

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* The potassium-borate in question, apart from combined water, contained boric oxyd 58.6, potash 16.3, giving the oxygen-ratio 72:5, and the sodium-borate had the same atomic ratios. Aug. Laurent, Compte Rendu des Travaux de Chimie, 1850, pp. 36–42.

† Philos. Trans., 1884, part 1, pp. 23–36.

rials as insoluble at ordinary temperatures as quartz or the natural silicates. A few hundredths of water at several hundred degrees Centigrade would probably convert these into a viscid fluid, from which, as from an anhydrous magma, by rest or by partial cooling, definite compounds might successively crystallize; — the mixture becoming, to use the simile of Poulett Scrope in speaking of lavas, like a syrup holding grains of sugar. From such mixtures partially cooled, or from a heterogeneous plutonic mass impregnated with water and not yet raised to the full temperature of solution, or what has been aptly termed "igneo-aqueous fusion," the more soluble portions, removed by percolation or by diffusion, we conceive to have constituted the liquids which in earlier times produced the various crenitic rocks. The fact that, as shown by Sorby,* pressure augments the solvent power of water, irrespective of temperature, should not be lost sight of in this connection. The remarkable observations of Tilden and Shenstone serve to explain and to justify the view of the intervention of water in giving liquidity to various eruptive rocks, originally put forward by Poulett Scrope, and afterwards ably maintained, among others, by Scheerer and Élie de Beaumont.†

§ 44. We have already noticed the banded structure (p. 210) which often results from movement in the extrusion of more or less differentiated masses of eruptive rocks, simulating that produced by the separation from water either of mechanical sediments or of crystalline deposits. It is important in this connection to distinguish between the latter two processes, and to insist upon the more or less concretionary character of the matters separated from solution, often shown in the lenticular shape of beds of this character, and well displayed in the crystalline schists.

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* Proc. Roy. Soc. London, xii., 538.

† Scrope, Jour. Geol. Soc. London, xii., 326. Scheerer, Bull. Soc. Géol. de France, 1845, iv., 468, and Élie de Beaumont, *ibid.*, 1249 *et seq.* See farther the author's Chem. and Geol. Essays, 188–191, and also 5, 6, for farther references to the literature of the subject.

The conditions under which these were laid down from water were less like those of ordinary sediments than of the accumulations of crystalline matter in geodes and in veins. Many facts with regard to the banded character of mineral veins are familiar to geologists, and the stratiform character of such deposits has often been remarked in smaller vein-like masses. I have elsewhere called attention to the fact that crystalline masses having the relations of veinstones may assume great proportions, and that much granitic rock often regarded as eruptive is really of concretionary and endogenous origin, and discussed the question at some length in 1871.* Veins of this kind were then described, sixty feet in breadth, traversing the gneisses and mica-schists of the younger gneissic or Montalban series in New England, often coarsely crystalline and banded, and evidently concretionary, but sometimes so finely granular and homogeneous in portions as to be quarried for architectural purposes, like the indigenous gneisses of the series, which they often closely resemble. Remarkable examples of the same phenomenon are to be met with in the older gneissic or Laurentian series, some of which are conspicuous in the sections of these rocks visible in the cañon of the Arkansas River and elsewhere in Colorado. Still more striking examples are met with in the similar gneisses in parts of Canada, and are well displayed in Ottawa County, in the province of Quebec, where, in the township of Buckingham, veins eighty feet in breadth, and made up almost wholly of orthoclase and crystalline cleavable magnetite, traverse for considerable distances the stratified gneiss of the region.†

§ 45. In the same County, and near the Rivière aux Lièvres, are the great veins which have lately been extensively mined for apatite in what is known as the Lièvres district. Very similar veins also occur a short distance

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* Granites and Granitic Veinstones, Amer. Jour. Science, 1871. Granites, Chem. and Geol. Essays, pp. 191–202.

† Geol. Report of Canada, 1863–66, pp. 20, 215.

to the southwest, along the Rideau canal, in the province of Ontario, in what may be called the Rideau district. The veins in this latter area were first described by the writer as early as 1848, and subsequently in 1863, in 1866, and in 1884.* The history of these apatite deposits in the two districts, which may be considered together, will serve to illustrate some important facts in the theory of crystalline rocks. The principal associates of the apatite in these districts are pyroxene, phlogopite, orthoclase, quartz, calcite, and pyrite. It was said of the localities in the Rideau district, in 1863, that careful examination in each case shows that "the deposit occurs in a fissure in the stratification, and has well defined walls," while "a banded arrangement of the mineral contents is often very well marked;" — the various minerals named sometimes occurring in alternate layers, of which the calcite, often with included apatite crystals, has "the aspect of a coarsely crystalline lamellar limestone." Farther examples were then given showing the bilateral symmetry of many of the veins, and the occasional presence in them of drusy cavities. Moreover, although small portions of apatite were observed in what were regarded as the limestone beds of the enclosing gneiss, it was said that "the workable deposits of apatite, with few if any exceptions, are confined to the veinstones." Such were the conclusions announced by the writer as late as 1866. Subsequently, in 1884, after farther studies of the Rideau district, he was led to write that although the deposits of apatite are in great part in true veins cutting the strata, and sometimes including angular fragments of the wall-rock,— which is the characteristic red or gray gneiss of the region,— they are "in part bedded or interstratified

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* Geol. Survey of Canada, Report for 1848, p. 132, and for 1863–66, pp. 224–229; also Geology of Canada, 1863, pp. 461, 592, 761, and Trans. Amer. Inst. Mining Engineers, 1884, vol. xii., pp. 459–468. See farther, B. J. Harrington, Report Geol. Survey of Canada, 1877–78, G., pp. 1–36, and J. Fraser Torrance, *ibid.*, 1882–83–84, J., pp. 3–30, for valuable contributions to our knowledge of the Canadian apatite deposits.

in the pyroxene-rock of the region." With regard to certain apparently bedded deposits of apatite it was farther said, "I am disposed to look upon [them] as true beds deposited at the same time with the enclosing rocks," which were described as "chiefly beds of pyroxene-rock, generally pale green or grayish-green in color, with mixtures containing quartz and orthoclase, and distinctly gneissoid in structure."

§ 46. I am careful to emphasize this apparent contradiction between the assertion of the truly endogenous character of the deposits in which apatite occurs with pyroxene, phlogophite, orthoclase, quartz, and calcite, and that of the interstratification of the same apatite in contemporaneous layers with a gneissoid pyroxenic rock, for the reason that both statements are strictly true, and that in their reconciliation light will be thrown on the great problem of the genesis of these crystalline aggregates. The mining operations on a large scale in these apatite deposits in the Lièvres district, especially in the years 1883–1885, have in fact shown that the stratiform pyroxenic masses are, like the associated orthoclase-rock, the apatite, and the calcite, subordinate parts of veins, which assume in many cases vast proportions, and at the same time have in parts of their mass a banded structure much resembling that of the enclosing gneiss. Illustrations of this condition of things abound at the great open cuttings for exploration and for mining which have been made at the High Rock, the Union, and the Emerald mines, in Portland and Buckingham townships, on the Lièvres River.* At the first-named locality the nearly vertical

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* The workings at each of the three mines named have yielded five thousand tons or more of commercial apatite annually for three or four years, and consist for the most part of open cuttings, in some cases to depths of over one hundred feet, causing the uncovering or displacement of great portions of the accompanying rock-masses. In other mines in this region, also very productive, shafts have been sunk on apatite bands in these veins to depths of one hundred and fifty and two hundred feet.

gray hornblendic gneiss, running northeast and southwest, is traversed by venous masses, sometimes with the strike, but at other times oblique or even at a right angle.

§ 47. A study of some of the smaller veins of the region (which are not mined) will help to an understanding of the nature and relations of those which are exploited for apatite. As seen at the High Rock mine, these lesser veins are from a few inches to several feet in width, and are chiefly of a binary granite or pegmatite, often including portions of the wall-rock, and sometimes near their borders presenting, for a breadth of two or three feet, a veritable breccia of angular fragments of gneiss from one to six inches in diameter. The granitic veinstone includes two feldspars, one weathering white and the other reddish, the latter forming considerable cleavable masses. A little white mica is also sometimes met with in these veins, which, in parts of their extension, hold portions of green cleavable pyroxene, sometimes in slender strings running with the strike, but in other cases filling the greater part of the vein, and including little seams of white feldspar, and small masses of greenish apatite, — fine and large crystals of which, and others of pyroxene, are, moreover, occasionally found directly imbedded in the granitic veinstone.

§ 48. Veins of vitreous quartz a foot or more in breadth are met with in the immediate vicinity, and also sometimes enclose crystals of apatite, or portions of feldspar, by an admixture of which they graduate into the binary granite or pegmatite. There is thus apparent a transition from pure quartz to a granitic rock, and to one essentially pyroxenic, each occasionally bearing apatite, which of itself also forms rock-masses. All of these are associated in the larger veins, sometimes in alternating bands or irregular lenticular masses a few inches in thickness, but at other times attaining breadths of many feet each. A frequent intermediate type of rock in these veinstones consists of a granular or coarsely cleavable green pyroxene with an admixture of quartz and a feldspar, generally white in color, but occasionally bluish, and with cleavage-planes an inch in breadth. The quartz and feldspar in this aggregate sometimes predominate, offering a transition into the granitic rock already noticed, which frequently includes crystals of pyroxene, apple-green or grass-green in color, and then sometimes holds clove-brown titanite, brown tourmaline, and, more rarely, zircon.

§ 49. These rocks, essentially made up of feldspar, quartz, and pyroxene, were long since noticed by the writer as occurring among the Laurentian gneisses in the Rideau district, and at various points in the province of Quebec, and were described in 1866 as generally "granitoid or gneissoid in structure, sometimes fine-grained, and at other times made up of crystalline elements from two tenths to five tenths of an inch in diameter. . . . They are often interstratified with beds of granitoid orthoclase gneiss, into which the quartzo-feldspathic pyroxenites pass by a gradual disappearance of the pyroxene." The occasional presence in them not only of titanite, but of mica, amphibole, epidote, magnetite, and graphite, was then noticed, and attention was called to the fact that these mineral species are common to the pyroxenite rocks and to associated crystalline limestones. The feldspar of these intermediate rocks was described as having generally the characters of orthoclase, as was shown by the analysis of a specimen from Chatham, Quebec, but as in some cases triclinic and resembling oligoclase.* Dr. Harrington has since found for one of these the composition of albite.

As will appear from the language just cited, these aggregates were then regarded as portions of the country-rock. The pyroxenite seen in North Burgess, in the Rideau district, was described as sometimes granitoid and at other times micaceous and schistose, interstratified with what was then called a binary granitoid gneiss, and also

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* Geology of Canada, 1863, p. 475; also Report Geol. Survey of Canada, 1863-66, pp. 185 and 224-228.

with layers of crystalline limestone, some of them holding serpentine, and others including pyroxene, mica, and crystals of apatite. Both varieties of the pyroxenic rock were then said to contain small grains and masses of apatite, in one case forming an interrupted bed, which was traced two hundred and fifty feet with the strike, and was in parts two feet in thickness.

§ 50. While apatite was thus found in crystals, in lenticular masses, and in layers, alike in the calcareous and the pyroxenic stratiform rocks, these same rocks were described as traversed at right angles by veins, the banded and symmetrical character of which was insisted upon, carrying not only apatite but calcite, quartz, orthoclase, scapolite, pyroxene, amphibole, and wollastonite. While the venous character of these secondary deposits (which also intersect the red and gray gneissic country-rock) was thus recognized, it was not until a later period that it became apparent that the same view was to be extended to the greater stratiform masses in which these veins were enclosed; in fact that the process of depositing these mineral species had been repeated in these localities, and that the pyroxenic and granitic rocks, not less than the interstratified limestone masses, were portions of great endogenous masses or lodes.*

§ 51. At this stage of the inquiry the writer found himself face to face with the exoplutonists. Emmons, who, in 1842, first described the geological characters of the similar crystalline rocks in northern New York, regarded the whole of them — gneisses, granites, iron-ores, and crystalline limestones included — as of plutonic origin, a view which was supported by the evident geognostic relations of the calcareous veins. This was in accordance with the views of Von Leonhard, Savi, and others in Europe who taught the igneous origin of certain limestones; an opinion afterwards adopted by J. D. Dana,

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* For an analysis of the argument, and many references, see Amer. Jour. Science, 1872, iii., 125, and Chem. and Geol. Essays, 208.

who supposed that some of the so-called primary limestones "were of igneous origin, like granite." The aqueous origin of similar calcareous masses in Scandinavia had, however, been recognized by Scheerer and by Daubrée, and in Germany by Bischof, while the vein-like character of certain aggregates of this kind in which various silicates and other mineral species are associated with carbonate of lime, in the ancient gneisses of North America, had been noticed by C. U. Shepard, H. D. Rogers, and W. P. Blake, among others, as was shown by the writer in some detail, in 1866. In a paper then read before the American Association for the Advancement of Science, it was said that deposits of carbonate of lime, sometimes of great dimensions, and holding the characteristic minerals of the crystalline limestones, are found filling fissures and veins in the Laurentian gneisses. These were then designated endogenous rocks, regarded as of aqueous origin, and to be carefully distinguished from intrusive or exotic rocks.*

The subject was discussed in the same year in an account of the mineralogy of the Laurentian rocks, when it was said, in commenting upon the view of Emmons that such masses, and in fact all of the crystalline limestones of the series, are eruptive: — "The greater part of the calcareous rocks in the Laurentian system in North America are stratified, and the so-called eruptive limestones are really calcareous veinstones or endogenous rocks, generally including foreign minerals, such as pyroxene, scapolite, orthoclase, quartz, etc."† I had not at that time as yet discovered that these same endogenous masses may include, besides calcareous bands, others essentially quartzose, pyroxenic, and feldspathic, resembling more or less the strata of the enclosing gneissic series, nor con-

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* Proc. Amer. Assoc. Adv. Science, 1866, p. 54; also Can. Naturalist (II.), iii., 123.

† Report Geol. Survey of Canada, 1863–66, p. 194. See also the facts resumed in Chem. and Geol. Essays, p. 218.

sidered that these same calcareous bands might sometimes be found in fissures coincident with the bedding of the latter.

§ 52. In 1869 I visited with the late L. S. Burbank a locality at Chelmsford, Massachusetts, where limestone has been quarried from interrupted masses, sometimes two hundred feet in length, enclosed in gneisses of the ordinary Laurentian type, to which I then referred them.* I failed to recognize in the quarries then examined the endogenous character which doubtless belongs to some of the limestone-masses of this region, where they have been traced at intervals for twenty-five miles, through Chelmsford, Boxborough, and Bolton; but at the same time I called the attention of Mr. Burbank to the question of these vein-like masses, placing in his hands my publications of 1866. He, as a result of farther observations, had, in 1871, persuaded himself that all of the limestones of the region were newer than the enclosing rocks, not eruptive, but "of a vein-like character," occupying fissures in the gneiss, of which character his descriptions, in certain cases, give evidence.† He noted the banded structure visible in the arrangement of the various enclosed minerals, as I had described them in 1866 in the similar limestone-masses in Canada, and enumerated in the region under consideration; amphibole, pyroxene, chrysolite (forsterite or so-called boltonite), phlogopite, scapolite, and garnet, besides serpentine in grains or in irregular bands or layers, sometimes traversed by veins of chrysotile. To this list may be added spinel, chondrodite, petalite, and titanite.

§ 53. The late J. B. Perry at the same time and place‡ announced a similar conclusion, to which he had arrived; namely that these limestones in eastern Massachusetts, as well as others elsewhere in New England and in northern

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* Amer. Jour. Science, 1870, xlix., 75.

† Burbank. Proc. Amer. Assoc. Adv. Science, 1871, pp. 263–266.

‡ Perry. *Ibid.*, pp. 270–276.

New York, though possessing "the form of dikes," "have a vein-like structure, and should be regarded as true vein stones." He farther says of these deposits: "The foliated structure, with its accompanying series of mineral substances, each occurring in a determinate order, evinces that the process of deposition was gradual and probably long continued." Thus these observers, in 1871, had, although without acknowledgment, confirmed my observations, and adopted my conclusions of 1866, as to these endogenous calcareous masses of the ancient gneissic series. J. W. Dawson had in 1869 recognized *Eozoön Canadense* in a serpentinic limestone from Chelmsford, and both Burbank and Perry maintained that all of the limestone masses of the region were veinstones, as an argument against the organic nature of Eozoön.

§ 54. The mineralogy of these endogenous, more or less calcareous masses, has been the subject of much study. While sometimes having the aspect of a coarsely crystalline limestone, and nearly pure, they may include apatite, fluorite, chondrodite, wollastonite, amphibole, pyroxene, danburite, serpentine, phlogopite, gieseckite, orthoclase, scapolites, brown tourmaline, idocrase, epidote, allanite, garnet (sometimes chromiferous), titanite, zircon, rutile, spinel, völcknerite, corundum, menaccanite, magnetite, hematite, pyrite, and, more rarely, pyrrhotite, chalcopyrite, sphalerite, molybdenite, and galenite. To these must be added prehnite, stilbite, chabazite, and barite. All of these species have been met with in the deposits studied in Canada and New York, while in the similar calcareous masses in eastern Massachusetts chrysolite and petalite occur. Exceptionally, as in Franklin and Stirling, New Jersey, there are found in this connection zinciferous and manganiferous minerals, as willemite, tephroite, spartalite and franklinite.*

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* For farther and more detailed accounts of the occurrence of the mineral species already mentioned, and many others which are found with the calcareous masses of the Laurentian rocks, see Report Geol.

The various associations of apatite in these aggregates are worthy of notice. Crystals of this species have been observed by the writer directly imbedded in the quartzo-feldspathic veinstone, in vitreous quartz, in calcite and dolomite, in pyroxene, in crystals of phlogopite, in pyrite, in magnetite, in spinel, and in foliated graphite, as well as in a massive granular apatite, which sometimes surrounds large and well defined crystals of the same species. Dr. Harrington has farther noted its inclusion in amphibole, in orthoclase, in scapolite, in steatite, and in fluorite. On the other hand, apatite crystals have been found to enclose quartz, calcite, fluorite, phlogopite, pyroxene, zircon, titanite, and pyrite. The apatite of these deposits, so far as known, is essentially a fluor-apatite, containing in one case, by the writer's analysis, 0.5 hundredths of chlorine. From these facts it is evident that the succession of species in these veins is by no means invariable. Mention should here be made of the apatite occurring in disseminated grains in the great deposit of magnetite so extensively mined at Mount Moriah, New York. The banded arrangement of the crystalline apatite, generally reddish in color and, in thin layers, occasionally predominating, gives a stratified aspect to the iron ore. A similar aggregate is found in the Rideau district, in Ontario.

§ 55. The stratiform character of these endogenous deposits, as seen alike in the individual portions, and in the arrangement of these as constituent parts of a vein, is well shown at the Union mine, in the Lièvres district. Here the great mass or lode is seen to be bounded on the west by a dark-colored amphibolic gneiss, nearly vertical in attitude, and with a northwest strike. Within the vein, and near its western border, is enclosed a fragment of the

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Survey of Canada, 1863–66, pp. 181–229, which was reprinted, with the exception of the last six pages, in the Report of the Regents of the University of New York, for 1867, Appendix E. See also, in abstract, Chem. and Geol. Essays, pp. 208–217, and farther the reports of Dr. Harrington and Mr. J. Fraser Torrance, cited on page 224.

gneiss, about twenty feet in width, which is traced some yards along the strike of the vein, to a cliff, where it is lost from sight, its breadth being previously much diminished. It is a sharply broken mass of gray banded gneiss, with a re-entering angle, and its close contact with the surrounding and adherent coarsely granular pyroxenic veinstone is very distinct. Smaller masses of the same gneiss are also seen in the vein, which was observed for a breadth of about 150 feet across its strike, — nearly coincident with that of the adjacent gneiss, — and beyond was limited to the northeast by a considerable breadth of the same country-rock.

§ 56. In one opening on this lode there are seen, in a section of forty feet of the banded veinstone, repeated layers of apatite, pyroxenite, and a granitoid quartzo-feldspathic rock, including portions of dark brown foliated pyroxene, all three of these being unlike anything in the enclosing gneiss, but so distinctly banded as to be readily taken for country-rock by those not apprised of the venous character of the mass. A fracture, with a lateral displacement of two or three feet, is occupied by a granitic vein twelve inches wide, made up of quartz with two feldspars and black amphibole, which themselves present a distinctly banded arrangement. This same granitic vein is traced for fifty feet, cutting obliquely across both the pyroxenite and the older granitoid rock, and at length spreads out, and is confounded with a granitic mass interbedded in the greater vein. It is thus posterior alike to the older quartzo-feldspathic rock, the pyroxenite, and the apatite, — as are also many smaller quartzo-feldspathic veins, which, both here and in other localities in this region, intersect at various angles the apatite, the pyroxenite, and the granitoid rock into which the latter graduates. We have thus included in these great apatite-bearing lodes, quartzo-feldspathic rocks of at least two ages, both younger than the enclosing gneiss. A small vertical vein of fine-grained black diabase-like rock intersects the whole. No one looking for the first time at this section of forty feet, as exposed in the quarry, with its distinctly banded and alternating layers of pyroxenite and granitoid quartzo-feldspathic rock, including two larger and several smaller layers of crystalline apatite, would question the stratiform character of the mass, whose venous and endogenous nature is, nevertheless, distinctly apparent on farther study.

In other portions of the same great vein, which has been quarried at many points, this regularity of arrangement is less evident. Occasionally masses are met with presenting a concretionary structure, and consisting of rounded or oval aggregates of orthoclase and quartz, with small crystals of pyroxene around and between them; the arrangement of the elements presenting a radiated and zone-like structure, and recalling the orbicular diorite of Corsica. The diameter of these granitic concretions varies from half an inch to one and two inches, and they have been seen in several localities in the veins of this region, over areas of many square feet.

§ 57. In the Emerald mine the stratiform arrangement in the vein is remarkably displayed. Here, in the midst of a great breadth of apatite, were seen two parallel bands (since removed in mining) of pyroxenic rock, several yards in length, running with the strike of the vein, and in their broadest parts three and eight feet wide respectively, but becoming attenuated at either end, and disappearing, one after the other, in length, as they did also in depth. These included vertical layers, evidently of contemporaneous origin with the enclosing apatite, were themselves banded with green and white from alternations of pyroxene and of feldspar with quartz. Accompanying the apatite in this mine are also bands and irregular masses of flesh-red calcite, sometimes two or three feet in breadth, including crystals of apatite, and others of dark green amphibole. Elsewhere, as at the High Rock mine, tremolite is met with. In portions of the vein at the

Emerald mine pyrite is found in considerable quantity, and occasionally forms layers many inches in thickness. Several large parallel bands of apatite occur here, with intervening layers of pyroxenic and feldspathic rock, across a breadth of at least 250 feet of veinstone, besides numerous small, irregular, lenticular masses of apatite. The pyroxenite in this lode, as elsewhere, includes in places large crystals of phlogopite, and also presents in drusy cavities crystals of a scapolite, and occasionally small, brilliant crystals of colorless chabazite, which are implanted on quartz.

At the Little Rapids mine, not far from the last, where well defined bands or layers of apatite, often eight or ten feet wide, have been followed for considerable distances along the strike, and in one place to about 200 feet in depth, these are, nevertheless, seen to be subordinate to one great vein, similar in composition to those just described, and including bands of granular quartz. In some portions of this lode the alternations of granular pyroxenite, quartzite, and a quartzo-feldspathic rock, with little lenticular masses of apatite, are repeated two or three times in a breadth of twelve inches.

§ 58. The whole of the observations thus set forth in detail above serve to show the existence in the midst of a more ancient gneissic series, of great deposits, stratiform in character, complex and varied in composition, and, though distinct therefrom, lithologically somewhat similar to the enclosing gneiss. Their relation to the latter, however, as shown by the outlines at the surfaces of contact, by the included masses of the wall-rock, the alternations of unlike mineral aggregates, the evidences of successive and alternate deposition of mineral species, and the occasional unfilled cavities lined with crystals, forbid us to entertain the notion that they have been filled by igneous injection, as conceived by plutonists, and lead to the conclusion that they have been gradually deposited from aqueous solutions. This conclusion is made more apparent when we compare these immense banded lodes with the many small veins from a foot in breadth upwards, also banded, and lithologically similar to the great lodes, which intersect not only these but the ancient gneisses, as already described at the High Rock mine, and also in many other localities, especially in parts of the Rideau district.

It may here be noticed that the very similar banded and vein-like deposits now largely mined for apatite in Norway, are regarded by Brögger and Reusch, who have lately studied them, as igneous masses erupted in a liquid condition, and slowly cooled from fusion, a hypothesis by which they endeavor to explain many of the phenomena of these deposits. For an analysis of their argument and a forcible statement of the objections thereto, the reader may consult Dr. Harrington's report on the apatite region of the Lièvres.*

§ 59. These various endogenous deposits are instructive illustrations of the crenitic process. The alternations of stratiform layers of quartz, of calcite, and of feldspathic and pyroxenic aggregates, with included layers of apatite, pyrite, etc., show that a process closely analogous to that which formed the older gneissic series was in operation and gave rise to these banded mineral masses in the midst of rifted and broken strata of the older rocks after these had assumed their present attitude. The lithological resemblances between the older and the younger deposits are not less remarkable than their differences, and suffice to show the great similarity between the conditions which produced the veinstones and their enclosing rocks. The latter, however, appear, in the present state of our knowledge, to have been deposited not only on a vaster scale, but apparently in a horizontal or nearly horizontal attitude.

§ 60. What are regarded as examples of calcareous deposits of the two ages were described by the writer, in

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* Brögger and Reusch; Zeitschrift d. deutsch. Geol. Gesell. Heft III., pp. 640–702. Report Geol. Survey Canada, 1877–78, G., pp. 11–12.

1878, as occurring at Port Henry, on Lake Champlain, in the State of New York. Near the town is a quarry whence limestone has been got for the blast-furnaces of the locality. "Here elongated, irregular fragments of dark hornblendic gneiss, from two inches to a foot in thickness, were found completely enveloped in crystalline carbonate of lime. In 1877, five such masses of gneiss were exposed in an area of a few square yards. One of these, a thin plate of the gneiss, having been broken in two, the enclosing calcareous matter had filled the little crevice, keeping the fragments very nearly in their place. The carbonate of lime, which is coarsely granular, and contains some graphite and pyrite, is banded with lighter and darker shades of color, and one of its layers was marked by the presence of crystals of green pyroxene and of brown sphene. The contact of this mass with the surrounding gneiss, which is near by, is concealed. No serpentine was found in this limestone, though it abounds in a limestone quarried in the vicinity. About half a mile to the north is still another quarry, opened in a great and unknown breadth of more finely granular and somewhat graphitic limestone, which near its border presents three beds of two or three feet each, interstratified with the enclosing gneiss." Of this it was said that "it presents alternations of lighter feldspathic and darker hornblendic beds with others highly quartzose, and includes layers of a sulphurous magnetite, which are, however, insignificant when compared with the great deposit of this ore mined at Mount Moriah, in the vicinity."

§ 61. While the great breadth of limestone interstratified with the gneiss was regarded as belonging to the ancient series, it was said of the limestone of the first-described quarry that it "seems clearly to be a brecciated calcareous vein enclosing fragments of the gneiss wall-rock." * Reference was then made to similar observations

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* Azoic Rocks, etc., pp. 166–167; also The Geology of Port Henry, Canadian Naturalist, X., No. 7.

in this vicinity, described by Prof. James Hall in 1876, who, from this breccia of gneiss-fragments in an exposure to crystalline limestone, rightly inferred the posterior deposition of the latter, and was led to conjecture that it might belong to a newer geological series. The only evidence of this, however, was the enclosed fragments of the gneiss, which, in similar cases, had led Emmons and Mather to infer the eruptive character of these same limestones, regarded by the writer as endogenous masses or veinstones. The great thickness of the interstratified limestone-masses which form, according to Logan, integral parts of the vast Laurentian series, and their geographical extent, were described in detail in the publications of the geological survey of Canada, in 1863, and farther in 1866. A summary of these results will be found in the writer's volume on Azoic Rocks,* and farther on in Essay IX. of this volume.

§ 62. As regards the genesis, according to the crenitic hypothesis, of the various mineral species found in this vast crystalline series, alike in the more ancient strata and in their included endogenous masses, we have already considered the formation of the double silicates of alumina with alkalies and lime, represented by the various feldspars, and more rarely by the scapolites, epidote, garnet, and the muscovitic or non-magnesian micas. These latter, though abundant, with garnet and black tourmaline, in some granitic veins in this geological series, are rare in those portions in which the protoxyd-silicates abound,—while the silicates of alumina without protoxyd-bases, such as are andalusite, fibrolite, cyanite, topaz, and pyrophyllite, are unknown. On the other hand, aluminous double silicates with magnesia are abundantly represented by phlogopite, and protoxyd-silicates with magnesia, such as chondrodite, pyroxene, and amphibole, are abundant; the simple calcareous silicate, wollastonite, being more rarely met with. The genesis of all these we have sup-

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* Azoic Rocks, p. 154.

posed to be by the reaction of soluble calcareous silicates with magnesian and ferrous solutions. The magnesia required may be found either in salts like those of sea-water, or in solutions of magnesian bicarbonate from sub-aerial decay of plutonic rocks, which solutions, by reaction with lime-silicates, would give rise to insoluble magnesian compounds and soluble lime-carbonate. A similar reaction, with liberation of silica, would result from the direct operation of carbonic dioxyd upon the lime-silicate. The intervention of ferrous solutions in similar reactions has already been discussed, in considering the origin of glauconite, on page 197.

§ 63. As regards the presence in these, and similar crystalline rocks, of basic oxyds uncombined with silica or with carbonic acid, such as alumina and magnesia in corundum, spinel, and some chromites, chromic oxyd in the latter and in some spinels, glucina and magnesia in chrysoberyl and periclase, together with zinc, manganese and iron-oxyds in spartalite, franklinite, magnetite, and hematite, not to mention titanic oxyd in rutile and in menaccanite and other titanates, it should be noticed that these various compounds, for the most part, occur in such intimate association with certain silicates as to suggest their contemporaneous production. Thus corundum and spinel are found crystallized with certain micas, with chlorites, or with feldspars, pyroxene or chrysolite, in which latter, or in serpentine, chromite is generally met with. Spartalite and franklinite are associated with silicates of zinc and manganese, and magnetite with quartz, with orthoclase, with pyroxene, with chondrodite, or with chrysolite, while rutile and menaccanite are found in like manner with feldspars, with phlogopite, or with serpentine. The intimate association of magnetite with calcite, with apatite, with pyrite, and with graphite, in these deposits, may also be noticed. We must conclude that all these simple and compound oxyds have been in solution, and have crystallized in the presence of the various silicates, etc., and in many cases with quartz. It is evident that the partial reduction and solution of ferrous oxyd by the intervention of the products of organic decay, and its subsequent precipitation, which in later times, has played so large a part in the genesis of iron-oxyds and carbonate, is not the sole agency. A process which separates not only iron-oxyd, but chrome-oxyd, alumina, glucina, magnesia, and zinc and manganese-oxyds, from their silicated combinations, and has permitted them to crystallize side by side with silicates, and even with free silica, has intervened in the genesis of these ancient crenitic deposits. The solvent action exerted by solutions of alkaline silicates on oxyds of iron, manganese, zinc, magnesium, and calcium, as well as upon those of tin, antimony, copper, and mercury, throws, as elsewhere pointed out, an important light on this problem (pages 150, 181).

To this we must add the dissociation of silicate of alumina at elevated temperatures, under pressure, in presence of alkaline solutions, with separation of silica in the form of quartz, as observed both by Daubrée and Henri Sainte-Claire Deville (pages 148, 156). These experimenters obtained at the same time zeolites, and one of them pyroxene, apparently with magnetite, while Friedel and Sarrasin, under similar conditions, got orthoclase and albite, quartz and analcite. We are as yet ignorant under what circumstances the liberated alumina might be separated from these solutions as corundum or diaspore. The conditions of temperature, and the presence of alkaline solutions in these experiments, approach very closely to those which we have supposed to concur in the formation of mineral species by the crenitic process.

§ 64. The geognostic and genetic history of the great endogenous crystalline masses which we have now discussed in some detail is important for several reasons: 1. It brings before us the views of the plutonists, who see in great bodies of crystalline limestone, and of magnetite, as well as in granitic veins and in metalliferous quartz-lodes, the evidences of igneous eruption. 2. It shows the differences, alike mineralogic and geognostic, between true exotic rocks (which, with small differences in composition, have been erupted through widely separated geologic ages up to the present) and those endogenous deposits which are found only in eozoic rocks, and were formed in eozoic time, since their fragments are met with in the oldest overlying paleozoic sediments. 3. It makes evident the close mineralogic resemblances between these endogenous crystalline masses and the more ancient enclosing rocks, and thus helps us to a clearer conception of the conditions under which these ancient gneissic strata, and the pre-gneissic granite itself, were generated.

§ 65. The crenitic hypothesis, as we have seen, supposes that the granite, and the succeeding crystalline schists, have been built up by matters dissolved from a primary plutonic substratum, upon which, as upon a floor, through successive ages, was laid down the enormous thickness of crenitic rocks which, with small exceptions, make up the pre-Cambrian terranes. The bearing of this hypothesis upon the great problem presented by the corrugated condition of the older crystalline schists has already been noticed on page 179. The contraction of a cooling globe, which is often cited in explanation of this phenomenon, is clearly inadequate to account for this great and general corrugation of the strata, and the present writer in 1860 * suggested, as a farther element in explanation thereof, the condensation during crystallization of the mechanical sediments from which, in accordance with the Huttonian hypothesis, the crystalline schists were supposed to be derived. This explanation, based on an untenable hypothesis, must, however, be rejected. The endoplutonist must appeal to contraction in the igneous mass of the globe as the only explanation of the corrugations of its outer envelope, while the exoplutonist adds

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* **Amer. Jour. Science, xxx., 138, and Chem. and Geol. Essays, pp. 56, 71.**

thereto the diminution of the liquid interior as the result of successive transfers of portions of its mass by ejections of igneous material from beneath a first-formed crust. Against this latter explanation it is to be urged that, as we have endeavored to show, the successive groups of stratiform crystalline rocks which have been laid down on the pre-gneissic granite, and even this primeval granite itself, are not igneous but aqueous in origin, so that the exoplutonic hypothesis itself is untenable. The amount of plutonic extravasation in pre-Cambrian times was apparently small.

§ 66. The crenitic hypothesis, however, admits a transfer of matters from below upwards, in a state of solution, and the building-up from them, upon the solid floor of igneous rock, of the granite and all the succeeding crystalline schists, as in the scheme of the exoplutonists. This new aqueous hypothesis thus offers, it is believed, for the first time, a reasonable and tenable explanation of the universal corrugation of the oldest crystalline strata. The earth, according to this hypothesis, although intensely heated, had not, even at the early time when the waters were first condensed on its surface, a liquid interior, but was solid; and its crust is supposed to have presented no variations in composition, except such as might result from crystallization and eliquation in a purely igneous congealing mass. The superficial quartzo-feldspathic or granitic layer, which is believed to overlie everywhere the quartzless basic doleritic rock, did not then exist, but has since been derived by crenitic action from the primary plutonic layer. This granitic stratum is, however, itself still subject, like the basic stratum beneath, to softening under the combined influences of water and heat, and to extrusion in the forms of eruptive granite and trachyte; although it is less fusible, and, consequently, less susceptible of differentiation by eliquation. It is, moreover, at the same time, less liable to alteration by lixiviation, from the fact that it is not a mass cooled from igneous fusion, but one deposited from water at comparatively low temperatures, and thus lacks the porosity which belongs to the original plutonic stratum.

§ 67. The upward transference of the vast and unknown quantity of material constituting the ancient granitic and gneissic rocks, which are at least many miles in thickness, and the contraction of the plutonic substratum, diminished by the removal of this great mass, would necessarily result in great movements of subsidence, with plications and fractures of the gneissic strata. We are, of course, ignorant whether these processes went on to a uniform degree over the whole surface of the earth, and whether similar conditions of thickness, and similar corrugations, exist in those great portions of the eozoic crust which are concealed beneath the ocean's waters, and beneath accumulations of newer strata. It may well be that the plication of the ancient granitic crust was, as in the case of younger stratified rocks, limited to certain areas. It can only be affirmed, in the present state of our knowledge, that in the relatively very small areas of the oldest gneissic rocks known to us, this plication is great and apparently universal, diminishing, however, materially in degree, in the younger gneissic series.

§ 68. Within the fractures and rifts of the ancient gneissic strata resulting from these great movements, the products of the uninterrupted crenitic process would henceforth be deposited, filling them with masses closely resembling those of the enclosing strata. Repetitions on a smaller scale of these movements would give rise to newer fissures intersecting alike these strata and the first-deposited veinstones, in the manner shown in our studies of the Laurentian rocks, where the process which produced the original quartzose, feldspathic, and calcareous deposits of the series was repeated at least twice, giving rise to primary and to secondary veinstones mineralogically very similar to the first-formed or country-rock, and thereby showing the survival of the original chemical conditions of solution and deposition after one, and even after two movements of displacement and disruption in the region.

§ 69. We have thus endeavored in the present essay to bring together, in the first place, a number of facts which serve to throw light upon the generation of mineral silicates by aqueous processes, especially in later times, subsequent to the formation of the great series of crystalline schists, and thereby help to a better understanding of the crenitic hypothesis. We have next considered the two plutonic hypotheses as to the origin of crystalline rocks, and have discussed the question of stratiform structure in rocks whose eruptive character is undisputed. This has led us to consider the process of differentiation in such masses through partial crystallization and eliquation, and, farther, to a discussion of the possible relations of water to the process. The secular changes which may be wrought in igneous masses by aqueous percolation are next discussed, with reference at the same time to the crenitic process. From this we are led to a discussion of the stratiform structure seen in vein-like masses for which an igneous origin is inadmissible, and which, it is maintained, are endogenous deposits of crenitic origin. An account of these, as they have been observed in the ancient gneissic rocks of North America, leads to a farther consideration of the crenitic hypothesis, alike in relation to the genesis of the silicates, carbonates, and non-silicated oxides of the crystalline rocks, and also to the general plication of the ancient crystalline strata.

§ 70. The conclusions from this extended study are, briefly, as follows. The quartzless basic material which is supposed to have constituted the primary plutonic mass, and is the direct source of basaltic and doleritic rocks, has been subject to modifications from three agencies: —

1. The solvent action of permeating and circulating waters, which, from parts of it, have removed alumina, with preponderating proportions of silica and potash, — the ele-

ments of granitic, trachytic, and gneissic rocks,—and also silicates of alumina and other protoxyds, which have been more or less directly the source of the other silicated species, of the oxyds, and in part also of the carbonates of the crystalline schists and veinstones:—

2. The farther action of the same circulating waters in carrying down from the surface, alike in the condition of carbonates, formed by sub-aerial action, and of sulphates and chlorids, large portions of calcium, magnesium, sodium, and potassium,—all of which, by interchange and replacement, have variously modified the composition of the plutonic material:—

3. The process of differentiation in portions of the plutonic mass by partial crystallization and eliquation, thereby giving rise to more chrysolitic and more pyroxenic aggregates on the one hand, and to more feldspathic aggregates on the other,—a process in which it is conceived water may intervene, giving to the material an igneo-aqueous fluidity. All of these agencies, it is believed, have, from the earlier ages, been at work on the plutonic substratum, causing secular changes alike in the crenitic products derived therefrom, and in the residual portion, from which have come, and are still derived, the basic eruptive rocks.

APPENDIX.

The genesis of dense crystalline species in less dense colloidal fused magmas, whether hydrous or anhydrous (pp. 209, 222), not only involves the disengagement of heat, but, as Becker has shown (Amer. Jour. Science, xxxi., 120), its disengagement at the maximum rate, thus maintaining the liquidity of the crystallizing magma. The passage of certain dense species, when fused *per se* (*post*, pp. 299, 300), into vitreous or crystalline forms of less specific gravity is no exception to the law of condensation, since the chemical and physical conditions are unlike those of the more complex magma. When such a magma, holding combined a portion of water, is changed into anhydrous species, this will be liberated, as appears in the often observed disengagement from solidifying lavas of aqueous vapor, sometimes with boric oxyd, fluorhydric and chlorhydric acids, and various chlorids. Hence silicates like epidote, tourmalines, and micas, which contain such volatile elements, will only be generated under conditions which prevent their liberation.

VII.

THE DECAY OF CRYSTALLINE ROCKS.

This essay, presented and read in abstract to the National Academy of Sciences at Washington, April 17, 1883, was published under the title of "The Decay of Rocks Geologically Considered" in September of the same year, in the American Journal of Science, [III.], xxvi., 190–213.

§ 1. THE subject of the decay of rocks has not yet received from geologists all the attention which it merits, and there still appear to be misconceptions with regard to it which warrant us in reviewing some points in its history. F. H. Storer,* in a recent notice of a suggestion of Nordenskiöld as to the liberation of gems through the decay of the feldspathic rocks in which they are often contained, cites with approval the opinion of Professor Stubbs of Alabama that "the decomposition of these rocks in southern latitudes has proceeded much faster than with the same rocks in higher latitudes," a "condition which can be accounted for, to a large extent, by climatic influences." The cold and frost now prevailing in northern regions are supposed by him to retard the action of atmospheric waters, regarded as the chemical agent of this process of decay.† These views, implying that the process is one belonging to the present time, are accepted by Storer, who writes of the "more active and thoroughgoing disintegration which occurs" in these southern regions.

§ 2. That the presence in the northern hemisphere of a mantle of softened material, from the decay *in situ* of

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* Science, for Feb. 16, 1883, p. 29.

† Bernay's Hand-book of Alabama, 1878, p. 199.

crystalline rocks, is more common at the outcrops of these in low than in high latitudes, where it is often entirely absent, is a familiar fact; but it will, I think, be made evident that present climatic differences have nothing to do with the fact that similar rocks are in one area covered with a thick layer of the products of decay, and in another are wholly destitute of it.

§ 3. The decay in question is well known to be due to a chemical change of which the predominant mineral silicates of the rock, chiefly feldspars and amphibole, are the subjects, and which results in the removal by solution of the protoxyd-bases, together with a great proportion of the combined silica, leaving a residue essentially of clay, mingled with quartz, garnet, magnetite, and such other mineral species as resist the process of decomposition.

§ 4. A memoir, by Fournet, published in 1834,* gives many facts regarding the early observations on rock-decay. Its author there describes the wide-spread decomposition of the granites near Pont-Gibaud in Auvergne, a change which Deribier dè Cheissac had already shown to be anterior to the deposition of the tertiary rocks. Fournet, moreover, noticed the similar decay of basalts, phonolites, trachytes, and even obsidians, and described the process of exfoliation, by which rounded masses of undecayed rock are left. He cites in this connection the observations of Pallas, who, in his travels in Siberia (1768–1774), noticed hills "that seemed composed of masses heaped together, as it were rounded by decomposition." The view of Werner, that the rounded form of masses such as these was due to original concentric structure, was rejected by Fournet.

§ 5. In 1818, Messrs. J. F. and S. L. Dana described a similar phenomenon in the decaying greenstones at Somerville, near Boston, Massachusetts, where the rock was found to be converted by decay *in situ* into nodular masses presenting exfoliating concentric layers of differing degrees

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* Ann. de Ch. et de Phys., [2], v., 225–256.

of decomposition. These masses rest upon each other, the decayed material filling the interstices.[*] In 1825, J. W. Webster noticed the same example, and explained the formation of boulders by the exfoliation of the decayed greenstone.[†] Again, in 1858, W. P. Blake described the production of rounded masses both of sandstone and of granite through disintegration. He explains how angular blocks, separated by joints admitting water to all sides, would be "attacked most rapidly on the angles, thus producing a succession of curved faces gradually approaching a sphere," and illustrates the process by figures. He described, moreover, the boulder-like masses of granite in Placer County, California, lying on an uneven surface of the same rock, "as due to the manner in which the rock decomposes, and not to abrasion." Like Fournet, he rejects the notion of an original concentric structure in the rock.[‡]

§ 6. Hartt, in 1870, discussed the well known examples of rock-decay found in Brazil, and called such rounded masses of rock as we have just described "boulders of decomposition." He moreover noted that the process of decay was there anterior to the supposed glacial action, which had worked over the material of the previously decomposed rocks.[§] Lyell already, in 1849, had pointed out that the tertiary clays and sands of the southern United States have been derived from the waste of the previously decayed crystalline rocks of the region; [||] and, as we have seen, the ante-tertiary age of the decay in Auvergne had long before been recognized.

§ 7. The account given by Charles Upham Shepard, in 1837, of the origin and mode of occurrence of the porcelain-clays of western Connecticut is remarkable for its exactness and perspicuity. That at New Milford is de-

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[*] Mem. Amer. Acad. Sciences, 1st Series, iv., 201.

[†] Boston Jour. Philos. and Arts, ii., 285.

[‡] Geol. Recon. of California, pp. 146, 286.

[§] Scientific Results of a Journey in Brazil, pp. 28, 573.

[||] Lyell, A Second Visit to the United States, ii., 28.

scribed as occurring "upon the western slope of an elevated range of granitic gneiss. . . . In many places the decomposition of the parent rock is so complete as to present the aspect of a secondary deposit; but the prevailing appearance is that of the rock altered in place through the decay of the feldspar and mica. Indeed, the same relative arrangement of the quartz and the altered feldspar is observed in the bed as is presented by these materials in the undecomposed rock. Veins and seams of a perfectly impalpable white clay traverse the rock in various directions, analogous to the veins of feldspar in the granite of the neighborhood." Of a pure white clay in the town of Kent, our author says, "It forms a vein many feet in width, cutting through quartz rock. It owes its origin to a graphic granite, which must have been free from mica." A similar vein of clay is described as occurring in the town of Cornwall, and as including frequent crystals of black tourmaline; the feldspar also being incompletely decomposed.*

§ 8. As showing that the process of sub-aerial decay is not confined to silicated rocks, it may be noted that J. D. Whitney described, in 1862, the existence, in the lead-region of Wisconsin, of a layer of red clay and sand, mixed with chert, sometimes thirty feet in thickness, which he showed to be a residuum from the secular decay of several hundred feet of the impure paleozoic limestones of the region.† A like occurrence was afterwards, in 1873, described by Pumpelly, in southern Missouri, where such residuary deposits sometimes attain a thickness of 120 feet.‡ This process is evidently due to a simple solution of the carbonates of lime and magnesia in meteoric waters.

§ 9. A similar decay is conspicuous along the outcrop of the Taconian limestones and their associated schists in

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* Shepard : Geological Survey of Connecticut (1837), pp. 73–75.

† Geology of Wisconsin, i., 121.

‡ Geological Survey of Missouri : Iron Ores and Coal Fields, p. 8.

the Appalachian valley, as will be noticed farther on, in § 25, and may also be seen at several points in the Trenton limestone and the Utica shale of the St. Lawrence valley. One of these localities, described by J. W. Dawson, is at Les Eboulemens, on the north shore of the St. Lawrence, below Quebec. Here, at the southwest base of the high Laurentide hills, the post-pliocene clays, enclosing marine shells and large gneiss boulders, are found resting upon a mass of Utica shale, deprived of its calcareous matter, and so soft as to be readily mistaken for the newer clays of the region, but for its stratification and its organic remains. This, according to Dawson, had been changed to a great depth by sub-aerial action previous to the period of submergence, during which it was covered with the boulder-clay.[*] Some facts connected with the decay of the Trenton limestone near Montreal will be mentioned in § 40.

§ 10. It may be said that, with the exception of Darwin, who had observed the decay of rocks in Brazil, and conjectured that the process might have been submarine, all observers have correctly regarded it as sub-aerial. The chemistry of the process was discussed, among others, by Fournet, in the paper already cited, and later by Delesse, in 1853;[†] also very fully by Ebelmen, who considered the question of rock-decay in its relations to the atmosphere, in two memoirs, in 1845 and 1847.[‡] The same subject was further considered at some length by the present writer, in 1880.[§]

§ 11. Having thus briefly indicated some of the points in its history during the past century, we are prepared to notice in more detail the contributions made to the subject, regarded in its geological bearings, during the last ten years. Previous to this, as we have seen, it had been

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[*] Dawson: Post-Pliocene Geology of Canada; Can. Naturalist, vi., 1872.

[†] Bull. Soc. Géol. de France, x., 256.

[‡] Annales des Mines [4], vii. and xiii.

[§] *Ante*, pp. 30–34; also Chem. and Geol. Essays, p. 100.

already recognized that the process of rock-decay was in operation not only in pre-glacial but in pre-tertiary times, and that the resulting material was the source of the tertiary clays and sands, and even, in certain cases, of glacial drift and boulders.

§ 12. In a review of Hartt's volume on Brazil, in 1870, the present writer said: "The great wasting and wearing away of crystalline rocks in former geological periods, of which we have abundant evidence, is less difficult to understand when we learn that rocks as hard as those of our New York Highlands become [are] even in our own time, under certain conditions, so softened as to offer little more resistance to the eroding action of a torrent than an ordinary gravel-bed."* Subsequently, in an account of some observations made in North Carolina, among the rocks of the Blue Ridge, and presented to the Boston Society of Natural History, October 15, 1873, he expressed the belief that the decay of crystalline rocks was a process of great antiquity; that it had been universal; that the covering of decayed material now seen in the south, at one time extended to the rocks of northern regions, from which it had been removed by erosion during successive ages, culminating in the glacial period at the close of the pliocene, since which time the chemical decomposition of the surface has been insignificant. From the products of this subaerial decay, it was then maintained, has been derived a great part of the sediments alike of paleozoic, mesozoic, and cenozoic times. The permeable nature of the surface-soil, formed of highly inclined strata of decayed rocks, affording a natural subterranean drainage, explains, it was said, both the absence of lakes, and the comparative permanency of the surface to be remarked in uneroded regions; showing that something more than ordinary aqueous agencies must have effected the removal of the decayed material.†

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* The Nation, New York, Dec. 1, 1870.

† Proc. Boston Soc. Nat. History, Oct. 15, 1873, and Amer. Jour. Science, vii., 60; also Proc. Amer. Assoc. Adv. Science for 1874, p. 39; and Hunt, Chem. and Geol. Essays, pp. 10, 250.

§ 13. This communication of mine was speedily followed by a paper published in the Proceedings of the Boston Society of Natural History for November 19, 1873, by the late Mr. L. S. Burbank, repeating and insisting upon the same conclusions, and, moreover, dwelling especially upon the process of decay (which he also had studied in North Carolina) as a preliminary to the formation of boulders and glacial drift.

In accordance with the views thus expressed in 1870 and 1873, it was conceived that the power of the usual eroding agents, ice and water, would be inadequate to the removal of great areas of rock unless this had been previously softened by decay, and in a review of the subject by the present writer, in 1873, the conclusion was reached that the decomposition of rocks has been "*a necessary preliminary to glacial and erosive action, which removed already softened materials.*"* Such erosion and denudation would, in accordance with this view, consist in the removal of previously decayed rocks, and the forms and outlines of the sculptured surface thereby exposed would be determined by the varying depths to which the process of sub-aerial decomposition had already penetrated the once firm and solid rock. The basin-like depressions and the hillocks of the eroded surface, not less than the detached rounded masses or boulders, were thus, as the writer has ever since taught, the results of the previous process of rock-decay.

§ 14. I had long before this time been led to insist upon the evidences of a widely spread decomposition of crystalline rocks in very early periods of geological history. In an essay, entitled Some Points in Chemical Geology, published in 1859,† and another, on the Chemistry of Metamorphic Rocks, in 1863,‡ both reprinted in my volume of Chemical and Geological Essays, I have

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* Harper's Annual Record of Science, etc., for 1873, p. xlvii.

† Geol. Jour., London, xv., 488–496.

‡ Geol. Soc. Jour., Dublin, x., 85–95.

pointed out the important part played by the protoxyd-bases liberated by the sub-aerial decay of feldspathic and hornblendic rocks. Starting from the conception of a primitive terrestrial crust consisting wholly of crystalline silicated rocks, we are forced to find in such a process of decay the source of all limestones and dolomites. These are derived from the carbonates of lime and magnesia generated either directly, during the process, from the bases previously existing in the state of silicates, or indirectly, by reactions between magnesian and alkaline carbonates formed during the decay, and the calcic salts of the early ocean. The chemical genesis of the lime-carbonate must evidently precede its assimilation by organisms. It was, in fact, thus shown, as the result of a great number of observations, that fossil sea-waters (mineral waters), representing the ocean of paleozoic and even of mesozoic times, contained large proportions of calcic chloride, such as are required by this theory.* The relations of these reactions when "this decay of alkaliferous silicates is sub-aerial," as set forth in 1859 and 1863, will be found discussed at length in the volume above named, on pages 23–31, and page 108. [See, for a certain extension and modification of this view of the source of lime-carbonate, *ante*, pp. 178, 239.]

§ 15. I farther proceeded at that time to consider the proportions between the alkalies and the alumina in the various characteristic minerals of crystalline rocks, noting the decrease in the former which is seen when silicates like orthoclase and albite are compared with micas like muscovite, and with silicates like andalusite, cyanite, pyrophyllite, and staurolite. The conclusion was then reached that "the chemical and mineralogical constitution of different systems of rocks must vary with their antiquity," and that "it now remains to find in their comparative study a guide to their respective ages"; in which connection a comparison was then attempted between the older

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* Hunt, Chem. and Geol. Essays, pp. 41, 108, 117–121.

gneisses and the newer crystalline schists. A further application of this principle was essayed in 1878, when the progressive elimination of the alkalies from the aluminiferous rocks of the eozoic groups was shown by comparing the mineralogical composition of the Laurentian with the Huronian, Montalban, and Taconian crystalline schists.*

It should here be noticed that the decayed feldspars, even when these are reduced to the condition of clays, have not, in most cases, lost the whole of their alkalies. This is well illustrated in a series of analyses, by Mr. E. T. Sweet, of the kaolinized granitic gneisses of Wisconsin, to be noticed farther on (§ 38). From these analyses it appears that the levigated clays from these decayed rocks still hold, in repeated examples, from two to three hundredths or more of alkalies, the potash predominating.†

§ 16. The existence, in the Laurentian series, of limestones, not less than that of sulphuretted iron-ores and of graphite, pointing to the existence of land and of vegetation during the deposition of the Laurentian, leads us to conclude to a process of sub-aerial decay of the more ancient gneisses in that far-off period. Such a process must have been continued in later times to give the materials for the aluminiferous sediments of the newer eozoic groups, and we might therefore hope to find in the latter boulders or pebbles of more ancient gneisses, such as are met with among the products of sub-aerial decay in later deposits. Remarkable examples of such rounded masses, alike of Montalban, Huronian, and Laurentian or pre-Laurentian types, are found abundantly in the very ancient pre-Cambrian (Keweenian) conglomerates on Lake Superior, as I have elsewhere described.‡ Not less striking examples of rounded masses of older gneisses occur in the Huronian series in many localities, particularly on Lake

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* Second Geological Survey of Penn.; Azoic Rocks, Rep. E., p. 210.

† See for these, Irving on the Mineral Resources of Wisconsin, Proc. Amer. Inst. Mining Engineers, vol. viii., p. 305. For other analyses, see Geo. H. Cook, Geol. Survey of New Jersey, Report on Clays, 1878.

‡ Hunt, Azoic Rocks, pp. 78, 230.

Temiscaming, where are great beds of conglomerate made up chiefly of gneiss boulders.* I have elsewhere noticed a specimen in my possession which shows a perfectly well defined and rounded pebble of finely granular white limestone, measuring an inch in its greatest diameter, enclosed in a laminated hornblendic gneiss, from Grafton County, New Hampshire. Slices cut from the specimen for the microscope show a strong adhesion between the limestone and the quartz and feldspar of the matrix, without, however, any evidence of chemical change at the contact.†

§ 17. The rounded masses and pebbles of gneiss found abundantly in several localities imbedded in the pre-Cambrian micaceous schists of the Saxon Erzgebirge are not less remarkable examples of the same kind. I had in 1881 the opportunity of examining with Dr. Credner at Leipsic a large collection of these, which consist chiefly of types of various kinds of gneiss resembling those of the Laurentian series as seen in North America and in the Alps. These Saxon mica-schists, with their associated gneisses passing into granulites or leptynites, have all the characteristics of the Montalban or newer gneissic series of North America and of the Alps, to which I have elsewhere compared them in two communications,‡ wherein are noticed the above-mentioned conglomerates, which had been previously studied in much detail by Sauer,§ in 1879. No one who sees these accumulations of rounded masses of gneiss and other crystalline rocks entering into conglomerates at the various horizons above named, can fail to be struck with their close resemblance to those which are to be found either in the glacial or other modern deposits, or lying *in situ* as undecayed rounded masses in the midst of decomposed rocks. It is difficult to resist the conclusion that these rounded masses of the eozoic ages

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* Geology of Canada, 1863, p. 50.

† Bull. Soc. Géol. de France, [3], x., 27.

‡ Geol. Magazine, January, 1882, p. 30, and Bull. Soc. Géol. de France, x., 26.

§ Zeitschrift f. d. ges. Naturwiss, Band lii.

must have been formed under conditions not unlike those which gave rise to their more modern representatives.

§ 18. The various considerations above presented thus led the writer, in 1873, to assign to the beginning of the process of rock-decay an antiquity compared with which the time that has elapsed since the drift-period is to be regarded as of short duration. It was, however, then suggested by him that a climate and atmospheric conditions unlike those of modern times might have favored the process in the earlier ages. Further evidence was soon forthcoming both of the former spread of this decay over northern regions, and of its great antiquity.

In 1874 I was called to examine the condition of the great tunnel then recently opened through the Hoosac Mountain in western Massachusetts, my report on which was published by the General Court of the State;* while a note on the observations therein made which have a bearing on the present inquiry, was presented to the American Institute of Mining Engineers in October, 1874.†

§ 19. As there explained, the gneissic rock of Hoosac Mountain, at the west end of the tunnel, 700 feet above the sea, is completely decayed, the feldspar being converted into kaolin for a distance of several hundred feet eastward, along the line of the tunnel. The gneiss on the crest of the mountain, 2000 feet above the sea, and on the eastern slope, on the contrary, wherever exposed, presents the rounded surfaces common throughout the region, often marked by glacial striæ, and without any appearance of decay. The softening and decomposition of the highly inclined strata of gneiss in the tunnel were described as complete for a distance of 600 feet from the west portal, where the floor of the tunnel is 200 feet from the surface, and were partial at 1000 feet, where it is 230 feet below; while farther in, at 1200 feet, an included bed of

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* House Document No. 9, 1875.

† Trans. Amer. Inst. Mining Engineers, iii., 187.

limonite, doubtless of epigenic origin, showed that the solvent and oxydizing action of atmospheric waters had penetrated to a depth of more than 300 feet from the present surface. At the western entrance to the tunnel the gneiss is immediately succeeded by the crystalline limestone and quartzite of the Taconian (Lower Taconic) series, the decayed rocks apparently coming from beneath the limestone. It was evident that this great mass of decayed gneiss at the western base of Hoosac Mountain is but a portion of a once widely spread mantle of similar materials, which has escaped the action that denuded and striated the surface of the other parts of the mountain.

§ 20. Numerous examples of similar remaining portions of decayed feldspathic rock have been observed farther southward, as in northwestern Connecticut (described in § 7), and among the Laurentian rocks of the South Mountain, in Pennsylvania, north of the Schuylkill. One of these decayed portions, at Siesholtzville, was seen in 1875, where a bed of magnetite, at that time mined, was found to overlie at a high angle a mass of granitoid gneiss completely kaolinized, but apparently protected from erosion by the incumbent iron-ore.

In another example in the same region, about two miles south of Allentown, the Primal or Taconian sandstone was found resting for a little distance on the Laurentian gneiss, here much decayed. Where this had been exposed in a recent cutting (in 1875) the reddish feldspathic rock, still retaining its color and its gneissic structure, though kaolinized, contained numerous "boulders of decomposition," from three to twelve inches in diameter, consisting of undecayed gneiss, the laminated structure of which was clearly continuous with that seen in the enclosing decayed mass. These boulders, still *in situ*, spheroidal in form, and often with pitted surfaces, are identical with those found in the drift near by, on the southeast slope of the hill, and are very different in outline from the half-angular forms of adjacent sandstone blocks. This gneiss rock, lying decayed in place, would, unless examined in fresh cuttings, which show its highly inclined foliation, be readily mistaken for the drift of the vicinity, which has evidently been derived from it.

§ 21. In my earlier notices of the decayed Montalban rocks of the Blue Ridge in North Carolina, I had described a mantle of from fifty to one hundred feet or more of decayed material, but this, according to the late William B. Rogers, sometimes exceeds two hundred feet, a thickness approaching to that observed at the western base of Hoosac Mountain. I have since noticed the decay of the Montalban rocks near Atlanta, in Georgia, where, with local exceptions of undecayed areas (as in Stone Mountain), the decomposition is more or less complete, in many places, to a depth of fifty feet. Here, as elsewhere, the more massive rocks include nuclear masses of undecayed material. The decayed highly hornblendic gneiss of Atlanta, though still retaining considerable coherence, has lost about two thirds of its weight, the specific gravity of unchanged portions being 2.97–3.08, while that of the decayed material is reduced to 1.20, and even, for some specimens, to less than 1.0.* The decomposed gneiss in this region is, in some cases, sufficiently coherent to furnish blocks for certain purposes of construction, such as the walls of rude chimneys, but at the surface it readily disintegrates, yielding a strong red soil, often used as a brick-clay. The decayed mica-schists of the Montalban series, which still retain their micaceous aspect, have been called hydro-mica schists, though distinct from those of the Taconian, with which they have been confounded.

§ 22. The relations to the general process of decay, of the large deposits of cupriferous iron-pyrites found in the rocks of the Blue Ridge, were discussed by the writer in 1873,* after a study of the copper-mines opened in Carroll County, Virginia, in Ashe County, North Carolina, and in

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* Azoic Rocks, p. 250.

Polk County, Tennessee.* These ore-deposits were described as in each case in rocks of the Montalban group — the newer gneisses and mica-schists — and as constituting veins or lenticular masses of posterior origin, consisting essentially of pyrite, pyrrhotite, and chalcopyrite. The agent which kaolinized the enclosing rocks also oxydized the sulphurets, removing the sulphur and the copper, and converting the residue into limonite, which, in a vertical lode in Ashe County, was found to extend to depths of from forty to seventy feet. Beneath the oxydized portion is found in all cases the unchanged pyritous mass, seldom carrying more than four or five hundredths of copper. The limonites thus generated were for some years smelted for iron, both in Virginia and in Tennessee, before they were discovered to be the oxydized outcrops of cupriferous pyrites-lodes. Between the unchanged pyrites and the limonite there is often found, in favorable conditions, an accumulation known as black ore, consisting of imperfectly crystalline sulphurets, rich in copper, and sometimes approaching to bornite in composition, occasionally with red oxyd and native copper; the whole, doubtless, reduced from the oxydized and dissolved copper brought from above.

§ 23. The crystalline eozoic rocks of various ages, in the more northern parts of the continent, contain, as is well known, many deposits of cupriferous pyritous ores, both in veins and beds which, like the enclosing strata, are undecayed, showing that the process of oxydation, like that of kaolinization, has been a very gradual one, going back to remote ages. We have seen, from the observations in the southern United States, that the oxydation of the sulphids, their conversion into limonite, and the removal therefrom of the copper by solution, went on *pari passu* with the decay of the including rocks, and hence preceded their erosion. The copper thus dissolved was, as I have suggested, again deposited in rocks at the time in process

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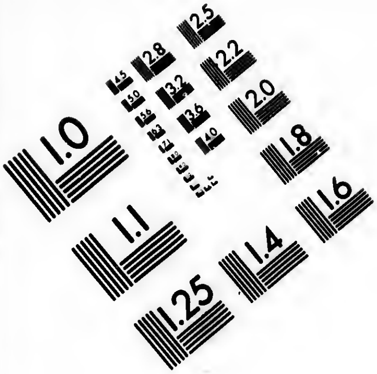
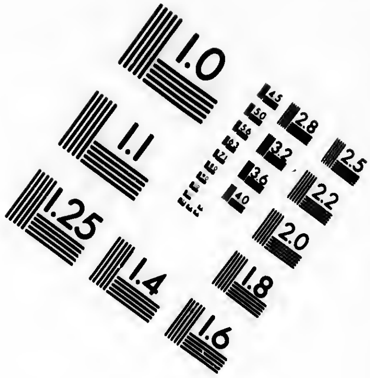
* Proc. Amer. Inst. Mining Engineers, ii., 123, and Amer. Jour. Science, vi., 305; see also Chem. and Geol. Essays, pp. 217, 250.





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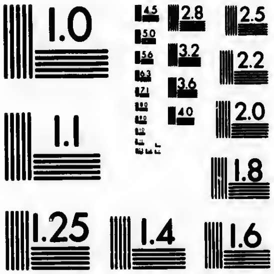

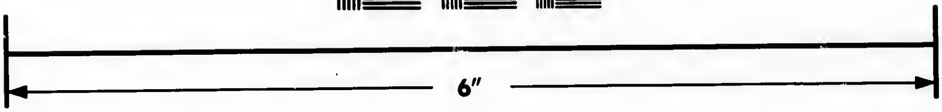

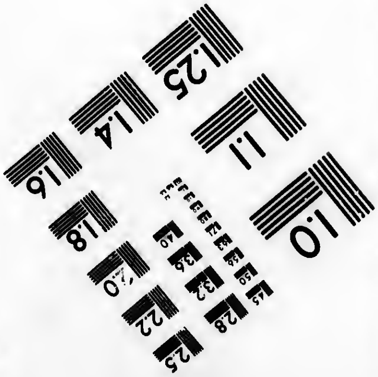

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of formation. The chief part of the iron being left behind, a veritable concentration of the copper would thereby be effected, and we should expect to find it separated on reduction as a rich sulphide, or as native copper. In accordance with this view, it was said, in an essay on The Geognostical Relations of the Metals, in February, 1873,* that certain deposits of such copper-sulphids, found chiefly in limestones, probably of Cambrian age, which, in the province of Quebec, as at Acton and Durham, lie along the northwest border of the crystalline Huronian belt, might be formed from "the results of oxydation of the cupriferous beds which abound in the crystalline schists of these mountains, from which the dissolved metal accumulated in basins at their foot," as suggested by Murchison with regard to the cupriferous Permian strata near the crystalline schists of the Ural Mountains. "To a like process," it was said, "we may perhaps ascribe the rich deposits of native copper in the Keweenaw amygdaloids and conglomerates, which rest upon the ancient Huronian schists."

§ 24. The farther extension of this view to the mesozoic sandstones of Connecticut, New Jersey, and Pennsylvania, well known to be very often impregnated with copper disseminated in the form of sulphids, sometimes associated with organic remains, is obvious. It is to be noticed that the strata in question are generally deposited directly upon eozoic rocks, from the ruins of which they were formed, and that these, in our hypothesis, furnished the dissolved copper from which the disseminated ores were derived. If this view be admitted, we have farther and independent evidence that the decay of the eozoic rocks, with that of their contained cupriferous sulphurets, was going on in that pre-Cambrian period in which the Keweenian series was accumulated, and was still active in mesozoic time.

§ 25. Not less striking examples of rock-decay are seen

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* Proc. Amer. Inst. Mining Engineers, i., 341.

in the great Appalachian valley, of which the Hoosac Mountain, the South Mountain, and the Blue Ridge form parts of the eastern rim. Therein, as is well known, large quantities of limonite are mined, from New England to Alabama. This ore, as well as its accompanying manganese-oxyd, is clearly of epigenic origin, and is, in most cases, still imbedded in ancient and highly inclined clayey strata derived from the sub-aerial decay *in situ* of the schists which accompany the dolomites and quartzites of the Primal and Auroral (Taconian) series. These oxydized ores have been formed by the transformation of included masses of pyrites and of carbonates of iron and manganese.* The evidences of the pyritic origin of many of these limonites is similar to that for those of the Blue Ridge (§ 22), namely, their association with unchanged pyrites. An example of this is seen in the so-called Copperas mine at Breinigsville, near Trexlertown, Pennsylvania, long ago described by H. D. Rogers,† where large quantities of pyrites have been mined from the same openings which yield limonite. Some of this I found still retaining the imitative forms of the adjacent pyrites (from which Rogers had inferred a conversion of limonite into pyrites), while the waters of the mine, like those of others in the region, were charged with sulphuric acid and with iron-sulphate. Another remarkable locality, where pyrites replaces the limonite in depth, was visible in 1875 at Seitzinger's mine, near Reading, Pennsylvania, and other similar cases are reported in the vicinity; while at Salona, in the Nittany valley, the association of pyrites with limonite at this same geological horizon has also been noticed.

§ 26. The association of siderite or iron-carbonate with the limonites of the Appalachian valley is well known east of the Hudson, in New York and Massachusetts. This mineral is often manganesian, and passes into nearly pure rhodocrosite. Examples of the association of siderite

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* Azoic Rocks, pp. 201-203.

† Geology of Pennsylvania, i., 265.

with limonite are also seen, among other localities, near Hackettstown, New Jersey, and near Hanover, York County, Pennsylvania. These carbonates, or at least the limonite and manganese-oxyd derived from them, are found in close association with pyritous deposits, as we have seen near Trexlertown. In like manner, pyrites and siderite, as is well known, often occur side by side in the coal-measures.

§ 27. I have elsewhere considered the change in siderite under the action of oxydizing atmospheric waters, which proceeds like that in feldspathic rocks, from without inwards, and is necessarily accompanied with considerable diminution of volume, which, in the conversion of a siderite of specific gravity 3.6 into a limonite of the same density, would equal 19.5 per cent.

"The evidences of this contraction may be seen in the structure of the limonite derived from siderite, which often forms a porous or spongy mass. In the case, however, of nodules or blocks of solid ore, the conversion beginning at the outside of the mass, an external layer of compact limonite is formed, and then another within this, and still another, till the change is complete. The void space resulting from contraction is then found between the layers, which are arranged like the coats of an onion, or sometimes wholly at the centre, where a cavity will be formed, holding in many cases more or less clay or sand, the impurities of the carbonate, which have been separated in the process of conversion into limonite. In this way are formed the hollow masses sometimes known as bombshell ore, which occasionally include nuclei of unchanged siderite. Their structure will generally serve to distinguish the sideritic from the pyritic limonites." *

In the paper just quoted I have also considered the change of volume which should accompany the conversion of pyrites into limonite, a process generally com-

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* The Genesis of Certain Iron Ores; read before the Amer. Assoc. Adv. Science, 1880: Canadian Naturalist for December, 1880, ix., 434.

plicated by the loss of a part of the iron as a soluble sulphate.

§ 28. Portions of the contorted and often highly inclined schistose strata enclosing the limonite ores in the Appalachian valley, are still found but partially decayed, and while some are converted, to depths of 100 feet or more, into white or variously colored clays, others retain more or less of their original texture. From the presence in some of these of considerable quantities of a hydrous micaceous mineral, having the composition of damourite, they have been called damourite-slates. There are many reasons for believing that these ancient rocks were thus folded, and were decomposed, before the deposition of the Trenton and Chazy limestones, which rest upon them in the outlying or western valleys of the Appalachian region, alike in Pennsylvania and in Alabama.*

§ 29. Professor Lesley, in discussing the history of the limonites of the Appalachian valley, has fallen into an error with regard to my view of their origin. Referring, in 1876, to the opinions expressed in my paper of 1873 (already noticed in § 13) touching the decayed crystalline rocks of the Blue Ridge, that "the iron-oxyd from these has been in great part dissolved out by subsequent processes, and was the source of the immense deposits of hydrous iron-ores" in question, he supposes me to "conjecture that the ores lying along the eastern edge of the Shenandoah valley had been washed into it from or across the Blue Ridge." This Lesley properly qualifies as an

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* The fact of the existence at various points in the Appalachian valley of beds of limonite interstratified in tertiary clays with lignite, as at Brandon, Vermont, must not be overlooked. First recognized by Edward Hitchcock, and subsequently noticed by Lesley, in 1864, the later observations of Prime, Lewis, and others, show the presence of these ores and clays, with lignites, at various points in Pennsylvania and in Alabama, as well as in Vermont. These are but fragments of what were probably once extended deposits, and although of geological interest as resulting from re-solution and re-arrangement, in tertiary time, of a portion of the ancient decayed strata of the valley, are of comparatively little economic importance. (H. C. Lewis, Proc. Acad. Nat. Sci. Phila., Oct. 27, 1879.)

"absurd conclusion," since it does not explain the origin of the limonites found in the back or central valleys, a hundred miles or more to the west of the Blue Ridge; and declares that had R. S. M. Jackson continued his geological studies, "he would have published a satisfactory refutation of this surface-drainage theory of the brown hematites." *

§ 30. Those who have read what I had written on the subject previous to 1876, and especially my discussion of the origin of these ores in 1874,† are aware that I have never advocated any such theory. I have, it is true, endeavored to find in the insoluble products of decay of these ancient crystalline rocks, the source not only of the clays and sands of the succeeding sediments, but of their contained iron, whether diffused, or accumulated in ore-masses. I have, however, at the same time, always maintained that the ores associated with the so-called Primal and Auroral rocks of the Appalachian basin, like those of the higher horizons, up to the coal-measures inclusive, were deposits contemporaneous with the strata in which the valleys were subsequently excavated; and that, save in some cases where, as mentioned below, it was apparently deposited as peroxyd, the iron was accumulated in the form of carbonate, and more rarely of sulphid; from the alteration of both of which, *in situ*, the limonites have been formed. This view, which, as I then showed, was that advocated by Charles Upham Shepard, in 1837, for the limonites of western New England, was the same as that put forward, in 1838, by R. S. M. Jackson himself, who maintained, as stated in the language of Professor Lesley, "that the ore belonged to the stratified limestone beds themselves, and had been set free from them by chemical and mechanical decomposition." This history was clear to Dr. Persifor Frazer, who, having remarked that "the theory of alteration *in situ* of various iron-minerals result-

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* Second Geol. Survey of Penn., Report A, p. 83.

† Trans. Amer. Institute Mining Engineers, iii., pp. 418–421.

ing in the formation of many of these limonites, advanced by C. U. Shepard, and ably discussed and adopted by Dr. T. Sterry Hunt, cannot be disregarded in seeking the cause which produced these limonites," adds, "In 1838, and independently of Prof. Shepard's observations, Dr. R. S. M. Jackson reported to Prof. H. D. Rogers substantially the same conclusion, from the study of the limonites of Centre and Huntingdon Counties." *

§ 31. This same view was in fact well stated by Lesley himself in 1864, when he said, "The brown-hematite ore-deposits of Mount Alto follow the edge of the slates and sandy limestones," and are "but the residues of these beds after decomposition and dissolution, the honey-combed and altered edges" of the slates and limestones themselves, "after the lime has been washed out of them, and their carbonated and sulphuretted iron has been hydrated and peroxydized; the slates having formed the red and white clays." He farther described at one locality of the region in question "an outcrop of almost unchanged blue carbonate of iron and lime, several feet thick. . . . and evidently in part changing into honeycombed brown hematite ore." †

§ 32. In 1867, Mr. Benjamin Smith Lyman expressed similar views in his account of the limonites of Smyth County, Virginia, found lying below the limestones of No. II. (Taconian), where many localities "show the ore unmistakably in regular beds conformable to the other rocks." He at the same time supposed that some of these ore-deposits are, like one noticed in Wythe County, Virginia, due to "the weathering of the upper part of a fissure-vein of iron-pyrites," but maintains that the ores, with such exceptions as this, were "deposited in regular beds, of greater or less extent and thickness, at the same time with the other rocks," and from the presence in the limonite of occasional masses of carbonate of iron,

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* Second Geological Survey of Penn., Report C, p. 143.

† Amer. Philos. Soc. Proc., ix., pp. 471–475.

concludes that it was originally deposited in this condition.*

§ 33. But while it is apparent that the ores in question, now found imbedded in clays resulting from the decomposition *in situ* of ancient schists, were, previous to that decay, enclosed therein as massive siderite or pyrites, we must not overlook the evidences that in certain cases a process of segregation of diffused iron-oxyd has played an important part, alike in ancient and in modern times, in the genesis of limonites. Setting aside, as not relevant to our present inquiry, the formation of bog iron-ores and ochres, which are directly deposited from ferrous solutions by peroxydation and precipitation, we here recall the contribution to the theory of the origin of imbedded iron-ores made by the late William B. Rogers. The ferrous carbonate found in the rocks of the coal-measures has, as he has endeavored to show, been generated from diffused ferric oxyd by a process of reduction, carbonation, and solution, through waters charged with organic matters from vegetable decay; the carbonate of iron thus formed remaining in some cases diffused through the sediments, and in others becoming concentrated by accretion.†

§ 34. This view is to be supplemented by the consideration that carbonated solutions of ferrous oxyd formed as above (and often containing organic acids) may, by reacting with beds of carbonate of lime, effect a gradual replacement of the latter by carbonate of iron.‡ The

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* Proc. Amer. Assoc. Adv. Science, 1867, p. 114.

† Geological Survey of Penn., 1858, ii., 757.

‡ J. Ville found one litre of carbonated water at the ordinary pressure to hold in solution at 20° C. 1.142 grammes of ferrous carbonate, and at 115° C. 1.390 grammes. From these solutions neutral alkaline carbonates readily throw down the ferrous carbonate, themselves passing to the state of bicarbonates; and carbonates of lime and magnesia produce the same effect, though more slowly. (Comptes Rendus de l'Acad. des Sciences, October, 1881, vol. xciii., p. 443.) The present writer found recently precipitated ferrous carbonate to be temporarily much more soluble, under the above conditions, yielding supersaturated solutions, which in close vessels spontaneously deposit, after many hours, a large part of the carbonate in a crystalline condition.

transformation of diffused ferric oxyd in sediments into massive limonite, imbedded therein, is thus a twofold process, involving, first, the intervention of reducing solutions converting the peroxyd into ferrous carbonate, and the concentration of the latter; and second, the change of this latter, through peroxydation and hydration, into limonite.

[Dr. N. S. Shaler has shown the important bearing of the reaction just pointed out (by which beds of carbonate of lime are gradually changed, through replacement, into carbonate of iron) upon the production of beds of ferriferous limestone, and of iron-ores, at various geological horizons. This he especially notes in the many limestone layers found in Kentucky and Ohio, in the great mass of sandstones and shales of the carboniferous series, where he points out that the fact that the iron is confined to the upper part of the limestone layers shows their transformation by the action of ferrous solutions from above. He farther adduces the iron-ore beds at different horizons between the base of the Devonian shales and the great sandstone (Oneida-Medina), which in the Appalachian basin forms the basal member of the Silurian. These include, besides iron-carbonate superficially changed into limonite, the widely spread deposit of so-called fossil ore, or Clinton ore, evidently a changed marine limestone, in which the iron is now in the form of scaly red hematite. The genesis of this anhydrous peroxyd is not yet clearly explained, but it is to be remarked that concretions of similar hematite are found, instead of siderite, in certain shales in the coal-measures in Ohio. Shaler is careful to distinguish between ore-beds from replaced limestone and the concretionary carbonate ores which are found in shales, where there is no evidence of the previous accumulation of calcareous masses.]*

§ 35. It is evident that the first stage of the process indicated by Rogers as taking place in sediments as yet

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* Geol. Survey of Kentucky, 1877, iii., 163–167.

unconsolidated, may also be set up in the disintegrated ferriferous materials resulting from the sub-aerial decay of rocks, and still undisturbed; that is to say, that the infiltration of waters holding dissolved organic matter may give rise in the decomposed mass to concretions of ferrous carbonate, which are subsequently changed into limonite. In this way, a concentration may be effected, through which rocks originally containing a small portion of diffused iron-oxyd come to include masses of limonite. Illustrations of this process are sometimes seen in the decay of ferriferous limestones or dolomites, in the residuum of which we find the iron accumulated in the shape of crusts or layers of limonite.

An instructive example of an analogous process is seen in the limonite which on Staten Island, New York, is found imbedded in a layer of brownish earthy material, sometimes attaining a thickness of twelve feet. This rests immediately upon the serpentine-rock of the region, into which it graduates, and from the sub-aerial decay of which it has evidently been derived; the lower portion of the earthy matrix still preserving the peculiar jointed structure of the underlying serpentine. This decomposed material, though including botryoidal crusts, geodes, and concretionary grains of limonite, with occasional druses of chalcedony and of quartz crystals, retains considerable coherence.

The source of this limonite seems to have been the iron-oxyd liberated by the decay of the ferriferous serpentine, and the proportion of ore in the superjacent mass shows a direct relation to the color and apparent proportion of iron-silicate in the serpentine beneath. This limonite, which is now mined to a considerable extent, contains, as several analyses have shown, from one to two hundredths of chromic oxyd, which is also known to be present in small amount in the serpentine. An impure argillaceous specimen, containing only 59.63 of ferric oxyd, yielded the writer 2.81 of chromic oxyd in a condition readily soluble in chlorhydric acid.

§ 36. Dr. N. L. Britton, of the School of Mines of Columbia College, New York, in whose company I lately had an opportunity of visiting this interesting locality, published, in 1880, a geological map, with sections, and a description of Staten Island.* He therein shows that the earthy material in which the limonite is imbedded is confined to the tops of certain hills of serpentine, being absent alike from other similar hills adjacent, and from intervening valleys cut into the serpentine, and he has connected this distribution of the ore-bearing stratum with the facts of the local glaciation of the region, to which he has devoted much attention. It is, I think, evident that the decay of the serpentine, and the concentration, in the residuum, of its iron in the form of limonite, was a process anterior to the glacial erosion, and that the ore-banks are areas of the decayed material which escaped this action.

§ 37. Turning now to the valley of the Mississippi, we find that Pumpelly, in his geological survey of Missouri, showed, in 1873, that the decay *in situ* of granitic rocks, and of quartziferous porphyry, has left great rounded blocks of these crystalline rocks; while the conversion of the porphyry into clay, and its subsequent removal, have liberated included veins or masses of crystalline hematite, giving rise to an accumulation of detrital iron-ore, such as, at the well known Iron Mountain, forms a covering over the surface of the hill of porphyry. From the presence of stratified deposits of this detrital ore in the ancient Cambrian strata around the base of the hill, Pumpelly inferred that the decay of the porphyry was already complete to a considerable depth, at this early period.† His observations and deductions were not known to me when, in the same year, I published my conclusions as to the great antiquity and the universality of the process of rock-decay.

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* Annals New York Acad. Sciences, vol. ii., part 6.

† Geology of Missouri; Report on Iron Ores and Coal Fields, pp. 8–12.

§ 38. Proceeding from Missouri northward, we find that in Minnesota, as shown by C. A. White,* in 1870, and by N. H. Winchell, in 1874, the ancient granitoid rocks, when protected by cretaceous strata, support a kaolinized layer of considerable thickness.† In Wisconsin a similar condition of things is found beneath the Potsdam sandstone in the central part of the State, as described by Irving, in 1876,‡ in an essay which is a valuable contribution to the literature of kaolin, and contains many analyses of the decayed rocks of the region, by Mr. E. T. Sweet, which have been already referred to (§ 16). Further details of the same region and its kaolins, with analyses, as before, were given by Irving in an essay, in 1880, on the Mineral Resources of Wisconsin.§ In Jackson and Wood Counties, where the crystalline (Laurentian) rocks are covered by a thin sheet of Potsdam sandstone, the river-valleys, cutting through this, expose the kaolin, which "occupies its original position, retaining sometimes the structure of the unaltered rock." This is derived from the decay *in situ* of certain bands, which, passing downward, graduate into unaltered feldspathic rock. Save where this mantle of decayed material has been protected by the paleozoic sandstone, the crystalline rocks are there seen for the most part in an undecayed condition, evidently, as Irving remarks, from the removal of the decayed material by "the denuding action of the drift." In some portions of the driftless area of this region the unprotected gneisses still retain their mantle of kaolinized material.

§ 39. From the facts before us, it is clear that the decay of the eozoic crystalline rocks was already far advanced in pre-Cambrian times. I am informed that similar evidence is afforded in Sweden by the presence of decom-

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* Geology of Iowa, i., 124.

† Second Annual Rep. Geol. Minnesota, pp. 162, 166, 207; also Hunt, Chem. and Geol. Essays, p. 250.

‡ Trans. Wisconsin Academy, etc., iii., 13.

§ Trans. Amer. Inst. Mining Engineers, viii., 103.

posed rock beneath Cambrian strata. Prof. A. Geikie has moreover shown that the sculpturing of the gneiss rocks of western Scotland, a process which I have maintained to be dependent on previous sub-aerial decay, was effected before the deposition of the Cambrian sandstones, which there rest upon ancient *roches moutonnées.*[*]

§ 40. It might be supposed, from their stability under ordinary atmospheric influences in regions protected by vegetation, that all such portions of decayed eozoic rocks as still exist in driftless or in protected areas date from the dawn of paleozoic time, did we not know that the same processes of decay have been active in subsequent ages, as is shown by the decay of eruptive rocks of later periods. An example of this, which shows at the same time the little progress made in the process of decay since the drift-period, is seen in Canada, at Montreal, where, to the south of Mount Royal, the nearly horizontal beds of the impure Trenton limestone are found, in sheltered places, deeply decayed, and porous from the removal of their carbonate of lime, and are moreover traversed by dikes of dolerite and other feldspathic rocks, themselves decayed to considerable depths; while near by, and especially to the north of the mountain, where glaciation did its work of removing alike decayed aqueous and igneous rocks, the eroded surfaces of both of these are found to be hard and comparatively unchanged, beneath a thin layer of soil and vegetation, as described by J. W. Dawson.

Another instance is afforded by a dike intersecting the Potsdam sandstone in this vicinity, which is found to be converted, to a depth of twenty feet or more, into a plastic, highly aluminous clay, which, from the presence of portions of titanium and chromium, is, we may conjecture, derived from a doleritic rock.[†]

§ 41. Rigaud Mountain, an igneous mass rising through the Potsdam sandstone, and occupying several square

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[*] Nature, August 26, 1880, p. 403.

[†] Report Geol. Survey of Canada, 1878–79, H., p. 7.

miles on the south side of the Ottawa, near its confluence with the St. Lawrence, is probably of paleozoic age, and consists in large part of a reddish granitoid orthoclase rock. Considerable areas of its surface, lying lower than the surrounding crests of the mountain, are covered to a depth of seven feet or more, in places, with well rounded boulders from three to eighteen inches in diameter, consisting wholly of the rock of the mountain, with the exception of a few masses of sandstone. The areas so covered attain, in their higher parts, an elevation of about 280 feet above the Ottawa, but slope gently both to the south and the north. The boulders are very rare on the north slope of the mountain and at its northern base, but are abundant on the southern slope and in the low-lying clay-covered plains to the southward.* These well rounded masses, spread over so much of the mountain, are apparently boulders of decomposition, still *in situ*, having escaped the denuding agents of the drift-period.

§ 42. Examples of more recent sub-aerial decay of crystalline rocks, under peculiarly favorable conditions, were in 1880 described independently by Jos. LeConte and myself, in the auriferous pliocene gravel of California. The pebbles of feldspathic and hornblendic rocks occurring in the portions below drainage-level — the so-called *blue gravel* — are unaltered, while above that level the similar pebbles, exposed to the action of meteoric waters, are more or less completely kaolinized, exfoliating, becoming earthy in texture, rusty in color, and in some cases converted into a clayey mass. The pyrites, so abundant in the blue gravel, has, in these upper portions, or so-called *red gravel*, been oxydized, and the accompanying lignites have been silicified, and often incrusted with crystallized quartz, from silica liberated in the process of rock-decay through the infiltration of surface-waters.†

§ 43. To the porosity of the gravel, and the great

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* Geology of Canada, p. 896.

† LeConte, Amer. Jour. Science, xix., 177; Hunt, *ibid.*, xix., 371.

amount of surface thus exposed, is to be added the influence of carbonic acid from the decaying lignite, the carbon of which is oxydized as the process of silicification goes on. The amount of carbonic dioxyd in the air of certain drift-mines in these auriferous gravels is so great that candles will not burn therein. Mr. D. T. Hughes of San Francisco, a well known mining engineer, to whose careful scientific observations I have been much indebted, informs me that in the case of a drift-mine 300 feet below the surface, in Table Mountain, Tuolumne County, California, where the foulness of the air was especially remarked, he satisfied himself, by appropriate tests, of the presence in the air of a large proportion of carbonic dioxyd. If, as there is reason to suppose, the amount of this element in our atmosphere was somewhat greater in former ages than at present, we have in these gravels an illustration of its influence in promoting the decay of silicated rocks. It is not improbable that the sulphuric acid generated by the oxydation of the pyrites present in these gravels may also have aided in the process.

§ 44. The slight evidences of decomposition to be seen in the crystalline rocks of thoroughly glaciated regions, as well as in transported boulders, make it probable that the seemingly rapid progress of decay, occasionally observed on exposure, of similar rocks in other regions, sometimes appealed to as evidence of a decomposition now going on, is really but the mechanical disintegration of masses already partially kaolinized in former ages. The crumbling of certain apparently unaltered granitoid rocks, in which the feldspar remains bright and hard, should be distinguished from that which follows chemical decomposition. Such disintegration, due apparently to changes of temperature * and the action of frost, is, how-

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* In this connection I venture to recall the attention of geologists to a phenomenon already described both by Dr. Shaler and myself, apparently due to superficial alternations of temperature on certain crystalline rocks, which have resulted in establishing in them, to a considerable depth, a

ever, important, and deserves farther study from the fact that materials apparently of similar origin enter into the composition of many derived rocks. Lava-flows are, it has been observed, subject to comparatively rapid subaerial decay, but these rock-surfaces differ widely in texture, as well as in composition, from most crystalline rocks.

§ 45. An essay by Professor Pumpelly on Secular Rock-Disintegration, read before the National Academy of Sciences, in April, 1878,* is a very valuable contribution to the subject before us. He cites therein my conclusions as to the great antiquity and the universality of the process of rock-decay (to which his own observations in Missouri have contributed important data), and also as to the final removal of decomposed material from northeastern America in the time of the glacial drift. He further notes the little attention hitherto given to the subject of sub-aerial decay, and points out its importance in connection with great problems in dynamical geology. The view that this process of rock-decay is "a necessary preliminary to glacial and erosive action, which removed already softened materials," receives from Professor Pumpelly an extended discussion and application. He proceeds to consider the removal and the re-arrangement of these softened materials by three different agencies. First, the encroachment of the sea upon a subsiding region of decayed rocks; second the action of land-glaciers, in which he points out that the great mass of disintegrated and water-impregnated rock would become frozen, and

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series of rifts or divisional planes parallel to the present surface, which are well known to quarrymen. Instances of this abound; besides those noticed by me in the Amer. Jour. Science for July, 1870 (vol. i., p. 89), may be mentioned the gneiss on the opposite slopes of Rolleston Hill, Fitchburg, Massachusetts, and that of Stone Mountain, near Atlanta, Georgia; also a remarkable example of comparatively thin horizontal plates at the outcrop of beds of nearly vertical micaceous gneiss in the vicinity of Worcester, Massachusetts.

* Amer. Jour. Science, xvii., 133–144.

included, as it were, in the glacier, sharing in its movements and forming thus a ground-moraine.*

§ 46. To these modes, with which are to be included the ordinary action of rivers and floods, all acting on the peripheral areas of continents, he adds, for the central areas, removed from these agencies, and rendered desert by geographical conditions, the action of the winds. By these the decayed rock, according to Pumpelly's extension of the ingenious hypothesis of Richthofen, will be separated into the fine material of the lœss, on the one hand, and the sand and gravel of the desert steppes on the other. He thus explains the condition of the crystalline rocks in northern Asia, from which the decayed mantle has been removed not by glacial but by aerial agencies; while the similar rocks in southern Asia, as in Brazil and the southern United States, are still deeply covered with the products of their own decomposition.

§ 47. Pumpelly farther remarks that the surface of the undecayed rock to be laid bare by erosion is necessarily an irregular one, the inequalities depending not upon its original differences in hardness, but upon its resistance to decay under the influence of atmospheric waters. The effect of fractures, joints, veins, and dikes in the rock, in favoring or retarding the action of this agent, would be manifested by still further irregularities of the plane limiting the decomposition of the rock in depth. Thus the

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* Other agencies than ice may produce a similar displacement of decayed material. Belt, in 1874, in his Naturalist in Nicaragua (page 94), describes a movement of the mantle of decayed crystalline rock on hillsides, in that country, as due to land-slides in wet weather. The layer of ground and "reworked" decayed material resting on the gneiss, found by Hartt in Brazil (Scientific Results of a Journey, etc., pp. 28, 573), and referred by him to glaciation, may perhaps be a similar phenomenon. More recently, Kerr, in 1870, has described the results of a slow downward motion of the decomposed surface on mountain-sides in North Carolina as due to the alternate freezing and thawing of the contained water. To this displaced and modified layer, which resembles that produced by glacial action, he gives the name of *frost-drift*. (Proc. Amer. Inst. Mining Engineers, viii., 462.)

rounded surfaces, and the closed rock-basins, so often observed in glaciated regions of crystalline rocks, are seen to be but the natural results of the process of rock-decay, which preceded and prepared the way for denudation.

§ 48. Similar views as to glacial erosion have since been advocated by Nathorst, and more lately by Reusch, who, in a memoir on the geology of Corsica, presented to the Geological Society of France, in November, 1882,* has described the disintegration of the granitic region of Corsica to a depth of several metres, giving to the surface smooth slopes, instead of the bold escarpments seen in like rocks in Scandinavia. He notes in these disintegrated rocks in Corsica, enclosed balls or ellipsoidal masses, fresh in appearance, but like in composition and in structure to the enclosing rock, which, when detached, have been taken for erratic blocks. With this region he contrasts the similar rocks near Christiania, in Norway, with hard, rounded surfaces, marked by glacial scratches, where it is difficult to find any trace of superficial decay. He does not believe that the ice of the glacial period removed any considerable portion of the hard rock, to form fiords, valleys, etc., but supposes "a profound disintegration of the Scandinavian rocks before the glacial period," and conceives the present relief to "represent the surface of the unaltered syenite after the removal by the glaciers of all the decomposed part."

The salient rock-masses of the Norwegian coast are, like the fiords, arranged in a north and south direction, and this, according to Reusch, corresponds with that of fissures, more or less nearly vertical, which traverse the rock, and, as he well remarks, prepared the way for its disintegration in depth, the extent of which would depend upon differences in the nature of the rock. Many of the lake-basins of this region were, in his opinion, formed through the removal by glaciers of the decayed material

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* Bull. Soc. Géol. de France, xi., 62–67.

from depressions, while others are due to the action of moraines, serving as dikes.

§ 49. It is difficult to state more clearly the consequences which follow from the conception that the decomposition of rocks is "a necessary preliminary to glacial action and erosion, which removed previously softened materials." Reusch, however, seems, from some misconception, to regard this pre-glacial disintegration of the rocks as distinct from kaolinization, of which the crumbling of the granites in Corsica, as in other regions, doubtless represents an incipient stage, such as we meet with in regions where the superficial, and more completely decayed portions, have been removed (§ 44).

§ 50. The points insisted upon in this essay may be thus briefly resumed: —

1. The evidence afforded by recent geological studies in America, and elsewhere, of the universality and antiquity of the sub-aerial decay both of silicated crystalline rocks and of calcareous rocks, and of its great extent in pre-Cambrian times.

2. The fact that the materials resulting from this decay are preserved *in situ* in regions where they have been protected from denudation by overlying strata, alike of Cambrian and of more recent periods; or, in the absence of these coverings, by the position of the decayed materials with reference to denuding agents, as in driftless regions, or in places sheltered from erosion, as in the Appalachian and St. Lawrence valleys.

3. That this process of decay, though continuous through later geological ages, has, under ordinary conditions, been insignificant in amount since the glacial period, for the reason that the time which has since elapsed is small when compared with previous periods, and also, probably, on account of changed atmospheric conditions in the later time.

4. That this process of decay has furnished the materials not only for the clays, sands, and iron-oxyds from the

beginning of paleozoic time to the present, but also for the corresponding rocks of eozoic time, which have been formed from the older feldspathic rocks by the partial loss of protoxyd-bases. The bases thus separated from crystalline silicated rocks have been the source, directly and indirectly, of most limestones and carbonated rocks, and have, moreover, caused profound secular changes in the constitution of the ocean's waters. The decay of sulphuretted ores in the eozoic rocks has given rise to oxydized iron-ores, and also to deposits of rich copper-ores, in various geological horizons.

5. That the rounded masses of crystalline rock left in the process of decay constitute not only the boulders of the drift, but, judging from analogy, the similar masses in conglomerates of various ages, going back to eozoic time; and that not only the forms of these detached masses, but the outlines of eroded regions of crystalline rocks, were determined by the preceding process of sub-aerial decay of these rocks.

VIII.

A NATURAL SYSTEM IN MINERALOGY.

This essay was presented in abstract to the National Academy of Sciences, in Washington, April 23, 1885, and subsequently to the Royal Society of Canada, in Ottawa, May 27, 1885. It is published in full in the Transactions of the latter society, vol. III., sec. iii.; in abstract in the American Naturalist for July, 1885; and also, with some farther additions, in the Canadian Record of Science, i., 129-135 and 244-247.

I. — HISTORICAL INTRODUCTION.

§ 1. THE examination of the various species of the inorganic kingdom which constitute the crust of the earth has long occupied the attention of students of natural history, and has given rise to descriptive and systematic mineralogy. Botanists and zoölogists, by making known the structure, growth, and development of organic species, have meanwhile performed a similar task for the vegetable and animal kingdoms, and have, moreover, arranged organic species in genera, families, orders, and classes, in such manner as to show more or less perfectly their origin and affinities, so that to-day the received classifications of plants and animals merit the name of natural systems.

§ 2. Without adverting to the work of earlier students, it should be said that Werner, about a century since, proposed for the mineral kingdom a classification which makes an epoch in the history of mineralogy. His system was based on "the natural alliances and differences which exist between minerals," and of him it is said that he "established and arranged the greater number of species in the mineral kingdom solely by agreements and differences in external characters;" grouping the various minerals in classes, families, genera, species, sub-species, and kinds. While chemical considerations were not overlooked in the larger divisions, Werner, according to Jameson, regarded the intervention of chemistry as but a provisional expedient, and doubted the possibility of constructing a philosophical system in which the external and the chemical characters should be conjoined.

§ 3. Werner died in 1817, and was succeeded at Freiberg by Frederick Mohs, who sought to complete the work of his great predecessor in mineralogy. His early publications on mineral classification go back to 1805, but it was not till 1822–24 that he gave to the world his "Grundriss der Mineralogie," in two volumes. This was translated into English, with additions, by one afterwards famous in science, William Haidinger, who declared, in the preface to that translation, published in Edinburgh in 1825, that he had been a student in mineralogy with Mohs since 1812.

Previous to 1820, however, Mohs had visited Edinburgh, and had there aided Jameson, then preparing the third edition of his "System of Mineralogy," which appeared in three volumes in Edinburgh in 1820. In his preface to this edition, Jameson gratefully acknowledges his aid, and says that the arrangement adopted "is nearly that of my celebrated friend, Mohs, who now fills the mineralogical chair of the illustrious Werner." He adds, "The mineral system, as it appears in this work, is to be considered as realizing those views which Werner entertained in regard to the mode of arranging and determining minerals." This system, which was designated by Jameson the Natural History Method, is, according to him, "founded on what are popularly called external characters, and is totally independent of any aid from chemistry." It was, moreover, in his opinion, the only method "by which minerals would be scientifically arranged and rightly determined." *

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* For a further notice of Werner's views of mineral classification, the reader is referred to the preface to Jameson's work, already cited, and also to Cleveland's Treatise on Mineralogy and Geology, in 1822, where, in vol. i., pp. 77–83, will be found an excellent analysis of Werner's mineralogical system, as put forth by him at Freiberg in 1816.

§ 4. The system of Mohs at once found favor with naturalists, and was adopted by many (notably by his successor, Breithaupt), not, however, without certain modifications as to the divisions, some of which may here be noticed, in order to give a general idea of the plan of classification.* In the order SPAR, as defined by Mohs, were included not only all zeolites, scapolites, and feldspars, with sodalite, nephelite, and leucite, but petalite, spodumène, and cyanite, as well as pyroxene, amphibole, wollastonite, and epidote, the latter four being made species of one genus, *Augite-Spar* (§ 48). Again, in the order GEM of Mohs we find garnet, idocrase, and staurolite grouped together as species of the genus *Garnet;* chrysolite, axinite, emerald, tourmaline, topaz, andalusite, and zircon, types of as many genera; together with the genus *Quartz*, including the species iolite, quartz, and opal. Corundum, chrysoberyl, and spinel are also united in one genus, and boracite and diamond constitute other genera under this order.

§ 5. In adopting the system of Mohs, Charles Upham Shepard sub-divided the order SPAR, and established a new order, ZEOLITE, in which were included with the zeolites, sodalite, nepheline, and leucite, the other genera in the order SPAR of Mohs being left as before. J. D. Dana, on the contrary, enlarged this order, renamed by him CHALCINEA, by adding to it a large part of the order MICA of Mohs, including all the true micas then known. He, on the other hand, removed epidote from the alliance with pyroxene, made by Mohs, and placed it in its proper position, with garnet and idocrase, in the order GEM, called by Dana HYALINEA. This, for the rest, embraced all the species which had been therein included by Mohs, whom Dana followed by placing cyanite and fibrolite with the Spars, while andalusite was arranged with the Gems.

§ 6. Bearing in mind the changes just noted, we have

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* See, for the system as modified by Weisbach and Breithaupt, § 111, note.

to record that in 1835 the classification and the nomenclature of Mohs, as translated into English by Haidinger, were adopted by Shepard in the first edition of his "Treatise on Mineralogy." In the second and third editions of this work, however, in 1844 and 1852, Shepard, while retaining with slight modifications the classes and orders of Mohs, abandoned the characteristic specific names of the latter for the trivial names generally accepted. The natural-history system of Mohs was also adopted, in the first and second editions of his "System of Mineralogy," by J. D. Dana, in 1837 and 1844. He, however, devised a Latin terminology for the orders, as well as a binomial Latin nomenclature for the genera and species.

§ 7. In abandoning the natural-history system in his third edition, in 1850, Dana returned to the trivial nomenclature. Referring to these changes, its author declared in the preface to a fourth edition of his System, in 1854, his opinion that "the system of Mohs, valuable in its day, had subserved its end, and that, in throwing off its shackles for the more consistent principles flowing from recent views on chemistry, the many difficulties in the way of perfecting a new classification led the author to an arrangement which should serve the convenience of the student, without pretending to strict science."

A so-called "purely chemical mineral system" had been proposed by Berzelius as early as 1815,* and had meanwhile found favor with chemists. Towards this, the difficulties of the natural-history method in mineralogy directed Dana, who, in the preface to his second edition, in 1844, gave, "besides the natural classification, another, placing the minerals under the principal element in their composition," adding that "various improvements on the usual chemical methods have been introduced, which may render it acceptable to those who prefer that mode of arrangement." The chemical scheme then given by him was, as he informs us, taken almost entirely from Rammels-

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* Berzelius, Nouveau Système de Mineralogie, Paris, 1819.

berg's treatise on Chemical Mineralogy, then recently published. In 1850, in the latter part of his third edition, Dana put forth a new chemical classification, "in which the Berzelian method was coupled with crystallography"; while in his fourth edition, in 1854, he maintained that "the classification of minerals must flow directly from the principles of chemistry," and accepted what he now called the Berzelian system, which, as his readers are aware, is retained in his fifth and last edition, that of 1868. It is also followed in the "Text-Book of Mineralogy" of his son, E. S. Dana, in 1883.

§ 8. The views of Berzelius, as adopted and modified by Rammelsberg, Naumann, Dana, and others, now prevail among students of mineralogy, with whom the results of the chemical analysis of species are generally considered as of paramount significance; while hardness, specific gravity, crystalline form, and optical characters assume a secondary value in classification, and are regarded as important chiefly in connection with determinative mineralogy. The conception of a true natural method, which, although but partially understood, was at the basis of the system of Mohs, has been lost sight of; the order which the naturalist finds in the organic is no longer apparent in the inorganic world, as presented in modern mineralogical text-books; and this state of things has contributed not a little to the comparative neglect into which systematic mineralogy has of late years fallen.

As to the complete divorce between physical and chemical characters in the study of mineral species, maintained by Werner, Mohs, and his followers, there seems to have underlaid it the notion of framing a system which, as in botany and zoölogy, shall be available for the purposes of determination without the destruction of the individual. It is to be noted, however, that characters dependent upon chemical differences, such as the presence or absence of certain acids, alkaloids, and groups of essential oils, are not without significance in determining the natural affinities of plants, and, moreover, that as we descend the scale of being, from the highly organized forms of the animal and vegetable world to the simple crystal or the amorphous colloid mass, the external characters which serve to show likeness and difference become fewer, and are often obscure and ill-defined. Again, a natural system is not one subordinate to the end of identifying species, but should consider objects in all their alliances and relations. Such a system, as long since defined by John Ray, is one which neither brings together dissimilar species nor separates those which are nearly allied, and the most important resemblances and differences in the mineral kingdom are, in many cases, those which can only be determined by chemical investigation.

§ 9. If, however, we regard as mistaken those who in their search after a natural system in mineralogy have rejected the aid of chemistry, it must be said, on the other hand, that the chemical mineralogists who, disregarding the relations of density and hardness, or relegating them to a secondary rank, build systems on the results of chemical analysis, are false to chemical science itself. There exist, in fact, inherent and necessary relations between the physical characters and the chemical constitution of inorganic bodies which serve to unite and reconcile the natural-historical and the chemical methods in mineralogy. A physico-chemical study of the mineral kingdom, having in view these relations, will enable us, while remaining faithful to the great traditions of Werner and of Mohs, to frame a classification which it is believed will merit the title of a Natural System in Mineralogy.

II.—AN ATTEMPT AT A NATURAL SYSTEM.

§ 10. That such a system is possible was maintained by the present writer in a series of papers published in 1853, 1854, and 1855, to be noticed in detail farther on. In putting forth, in the first-named year, my conclusions as to the extension of chemical homology, and the similarity of volume in isomorphous species, it was said that "these views will be found to enlarge and simplify the plan of chemical science, and lead to a correct mineralogical system." This aim was again clearly defined in a communication to the French Academy of Sciences in 1863, published in the Compte Rendu, and also, in a translation by the author, in the American Journal of Science, in the same year.* Therein, while adverting to an earlier note on the same subject, which appeared in the Compte Rendu for July 9, 1855, it was said that the views of polymerism in mineral species, and of the connection between relative condensation or specific gravity, hardness, and chemical characters are, "as I have already elsewhere shown, of great importance in mineralogy, and will form the basis of a new system of classification, which will be at the same time chemical and natural-historical." These early papers, however, perhaps from the general and abstract manner in which the subjects were then treated, have hitherto received but little attention either from chemists or from mineralogists.

§ 11. The whole subject was again discussed in 1867, in an essay entitled "The Objects and Method of Mineralogy," in which the argument of the preceding papers was resumed. It was therein maintained that chemistry is to mineralogy what biotics is to organography; that both physics (or dynamics) and chemistry, which together preside over the genesis of inorganic species, must be taken into account in their study, and that chemical characters must be greatly depended upon in mineralogical classification; while it was added that "in its wider sense the chemical history of bodies takes into consideration all those characters" upon which the natural-history system is based.†

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* Compte Rendu de l'Acad., June 29, 1863, and Amer. Jour. Science, xxxvi., 426–428.

† Read before the American Academy of Sciences, January, 1867, and published in the Amer. Jour. Science of the same year, xliii. 203–206; also in the author's Chemical and Geological Essays, pp. 453–458.

§ 12. After discussing in this connection the question of the densities of certain substances of high equivalent, or molecular weight, alike in vapor and in liquid and solid forms, it was said: "Starting from these high equivalent weights of liquid and solid hydrocarbonaceous species, and their correspondingly complex formulas, we are prepared to admit that other orders of mineral species, such as oxyds, silicates, carbonates, and sulphids, have formulas and equivalent weights corresponding to their still higher densities; and we proceed to apply to these bodies the laws of substitution, homology, and polymerism, which have so long been recognized in the chemical study of the members of the hydrocarbon series. The formulas thus deduced for the native silicates and carbon-spars show that these polybasic salts may contain many atoms of different bases, and their frequently complex and varying constitution is thus rendered intelligible. In the application of the principle of chemical homology we find a ready and natural explanation of those variations, within certain limits, occasionally met with in the composition of certain crystalline silicates, sulphids, etc.; from which some have conjectured the existence of a deviation from the law of definite proportions in what is only an expression of that law in a higher form. The principle of polymerism is exemplified in related mineral species, such as meionite and zoisite, dipyre and jadeite, hornblende and pyroxene, calcite and aragonite, opal and quartz, in the zircons of different densities, and in the various forms of titanic oxyd and of carbon, whose relations become at once intelligible if we adopt for these species high equivalent weights and complex molecules. The hardness of these isomeric or allotropic species, and their indifference to chemical reagents, increase with their condensation or, in other words, vary inversely as their empirical equivalent volumes; so that we here find a direct relation between chemical and physical properties. . . .

§ 13. "Chemical change implies disorganization, and all so-called chemical species are inorganic, that is to say, unorganized, and hence really belong to the mineral kingdom. In this extended sense, mineralogy takes in not only the few metals, oxyds, sulphids, silicates, and other salts which are found in nature, but also all those which are the products of the chemist's skill. It embraces not only the few native resins and hydrocarbons, but all the bodies of the carbon series made known by the researches of modern chemistry. The primary object of a natural classification, it must be remembered, is not, like that of an artificial system, to serve the purpose of determining species, or the convenience of the student; but so to arrange bodies in orders, genera, and species, as to satisfy most thoroughly natural affinities. Such a classification in mineralogy will be based upon a consideration of all the physical and chemical relations of bodies, and will enable us to see that the various properties of a species are not so many arbitrary signs, but the necessary results of its constitution. It will give for the mineral kingdom what the labors of great naturalists have already nearly attained for the vegetable and animal kingdoms.

§ 14. "In approaching this great problem of classification, we have to examine, first, the physical conditions and relations of each species, considered with relation to gravity, cohesion, light, heat, electricity, and magnetism; secondly, the chemical history of the species, in which are to be considered its nature, as elemental or compound, its chemical relations to other species, and these relations as modified by physical conditions and forces. The quantitative relation of one mineral (chemical) species to another is its equivalent weight, and the chemical species, until it attains to individuality in the crystal, is essentially quantitative. It is from all the above data, which would include the whole physical and chemical history of inorganic bodies, that a natural system of mineralogical classification is to be built up. . . . The variable relations to space of the empirical equivalents of non-gaseous species, or, in other words, the varying equivalent volumes (obtained by dividing their empirical equivalent weights by the specific gravity), show that there exist in different species very unlike degrees of condensation. At the same time, we are led to the conclusion that the molecular constitution of gems, spars, and ores, is such that those bodies must be represented by formulæ not less complex, and with equivalent weights far more elevated than those usually assigned to the polycyanids, the alkaloids, and the proximate principles of plants. To similar conclusions conduce also the researches on the specific heat of compounds." In the paper, published in 1867, from which the above extracts are taken, it was farther said that the views there set forth as "the basis of a true mineralogical classification" were not new, but had been brought forward and maintained by the author in various publications from 1853.

§ 15. The starting-point in this inquiry was the study of the chemistry of carbon. It was in 1852 that I wrote, "We may define organic chemistry as the chemistry of the compounds of carbon,"* a statement which, though a common-place to-day, was then perhaps made for the first time. I then insisted upon what I called "the carbon series" and "the silicon series," the latter including all the known silicon compounds. This was followed in 1853 by an essay on "The Theory of Chemical Changes and Equivalent Volumes,"† wherein the question of equivalent or so-called atomic volumes was discussed with relation to the investigations of Playfair and Joule, and the speculations of Dana. It was then and there suggested that "all species crystallizing in the same shape have the same equivalent volume, so that their equivalent weights

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* Essay on Organic Chemistry, forming part iv. of the Principles of Chemistry by B. Silliman; 3rd revised edition, 1852, p. 378.

† Amer. Jour. Science, March, 1853 (xv., 226–234); L., E. & D. Philos. Mag. (4), v., 526, and in a German translation in the Chemisches Centralblatt of Leipsic for the same year (p. 849); also in the author's Chem. and Geol. Essays, pp. 427–437.

(as in the case of vapors) are directly as their densities, and the equivalents of mineral species are as much more elevated than those of the carbon series as the specific gravities are higher."

§ 16. Another principle there set forth was the general application of the law of progressive or homologous series, first enunciated in 1842 by James Schiel of St. Louis, and soon afterwards adopted by Ch. Gerhardt, but hitherto applied only to hydrocarbonaceous or so-called organic species. It was now said that "it may be expected that mineral species will exhibit the same relations as those of the carbon series, and the principle of homology be greatly extended in its application. The history of mineral species affords many instances of isomorphous silicates whose formulas differ by nO_2M_2, as the tourmalines, and the silicates of alumina and magnesia; while the latter, with many zeolites, exhibit a similar difference of nO_2H_2 [O in these formulas = 8]. The relation is in fact that which exists between neutral, surbasic, and hydrated salts." It was further declared that the carbon-spars must be represented as polycarbonates, having not less than from "twelve to eighteen equivalents of base replaceable so as to give rise to a great number of species"; while the variations in the calculated atomic volumes of these carbonates were said to "indicate the existence of several homologous genera, which are isomorphous."

§ 17. These conceptions of progressive series of more or less highly condensed molecules of polycarbonates and polysilicates, and of similarity of volume for isomorphous species, were developed more at length in a second paper published in the same year, 1853, on "The Constitution and Equivalent Volume of Mineral Species."* It was therein explained that the formulas of homologous bodies may be represented as series in arithmetical progression, in which the first term may be either like or unlike the

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* Amer. Jour. Science, 1853 (xvi., 203–218), and, in abstract, in the author's Chem. and Geol. Essays, p. 438, etc.

common difference; both cases being, it was shown, illustrated in the chemical history of mineral species, including carbonates, silicates, and oxyds. Similar views were also then extended to nitrates and sulphates, as well as to chlorids and to sulphids.

The simplest atomic formula of the carbonates being CMO_3 ($C=6$ and $O=8$, according to the molecular weights then in use), the rhombohedral carbon-spars were referred to three genera represented by $n(CMO_3)$, namely: (1) calcite, $n=30$; (2) dolomite, siderite, and diallogite, $n=36$; and (3) smithsonite and magnesite, $n=40$. For the prismatic species, aragonite, like calcite, belonged to a genus with $n=30$; while for strontianite, cerusite, and bromlite, $n=25$; and for witherite $n=22$. The volumes of the rhombohedral species deduced from these formulas were from 550 to 560, and for the prismatic species from 500 to 510. These arbitrary molecular weights and volumes were, at the time, supported by comparisons with those deduced from the formulas of the rhombohedral red-silver ores and the prismatic bournonite, and farther by the volume of the compound of glucose and sodium-chlorid, regarded as homœomorphous with calcite, with a density of 1.563, which, doubling its empirical formula, gave a volume of 558.5. The various alums, if their formulas be doubled, give in like manner, as was shown, volumes of from 543 to 561.

§ 13. Extending to the silicates the same notion of polymerism which had just been applied to the carbonates, the existence of various polysilicates was admitted. Thus the formulas of spodumene, diopside, hudsonite, and wollastonite were described as presenting a homologous series of the first kind, in which the first term is the same as the common difference, "represented by $n(Si_2MO_3)$, the respective values of n being 30, 26, 24, and 22." Spodumene was then, chiefly on crystallographic grounds, compared with the pyroxenes. The excess of silica above the bisilicate ratio, met with in some amphiboles, was referred to as an example of a homology of the second kind, in which the common difference is unlike the first term. To these species there was assigned an equivalent volume approximating to 460. In support of this volume it was noted that the various orthophosphates and ortharseniates of sodium, with $12H_2O$ have, according to Playfair and Joule, equivalent volumes of from 233 to 235, while ferrocyanid of potassium gives 230, lactose 234, and piperine (with a density of 1.244) 476, or about double these numbers. Other species, as it was pointed out, have apparently an equivalent volume of 430, and still others about 200, or some multiple of this number. Whether the weights thus assigned to various silicates and carbon-spars might represent their chemical equivalents, or some portion thereof, they in any case served to show the relative condensation of matter in the different species compared.

§ 19. This subject was continued a few months later, in a paper read at Washington in May, 1854, before the American Association for the Advancement of Science, entitled "Illustrations of Chemical Homology."* Therein were reviewed and re-affirmed the teachings of the two papers of 1853, while the principles of homology were farther exemplified, and it was maintained that homologies may exist alike between species differing by $n(M_2O_2)$ and $n(H_2O_2)$, and even between those related species which differ in the proportion of silica, so that the ratio between silica and bases has but a specific value. It was farther contended that the water contained in a great many hydrated species often described as altered silicates, was to be regarded as not of subsequent introduction, but an original and essential element of the species, as is admitted to be the case in the zeolites.

§ 20. In the second paper for 1853 was considered the

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* Proc. Amer. Assoc. Adv. Science, 1854, pp. 237–247; also, in abstract, Amer. Jour. Science for September of the same year, and noticed, with extracts, in the author's Chem. and Geol. Essays, p. 438, *et seq.*

question of chemical notation and formulas, which was farther illustrated in the paper of 1854. At this time the question of the atomicities of the elements had not yet been discussed, and the distinction between univalent and bivalent metals, suggested by Cannizaro in 1858, was unrecognized. The symbols then used for both of these stood for one atom, or for the proportion which in the so-called protoxyds is united with eight parts by weight of oxygen. In sesquioxyds like alumina, however, recognizing the trivalent character of Al_2O_3 $(27+24)$, it was by the writer regarded as corresponding to three atoms of oxyd of aluminium $=3alO$. Silica, which, following Berzelius, was then generally written SiO_3 $(21+24)$, became $3siO$. With this notation were constructed atomic formulas, the elements now regarded as diatomic being confounded with monatomic elements, and, like these, represented by capital letters. Thus the common atomic formula for bisilicates, as given above, was written $n(si_2MO_3)$, and spodumene, $n=30$, was made $si_{60}O_{60}(al_{24}Li_4Na_2)O_{30}$. Similar atomic formulas are still employed in these pages, using, however, small letters to represent an atom of any element, whether univalent, like sodium or chlorine; bivalvent, like calcium or oxygen; trivalent, like boron; quadrivalent, like silicon, titanium, and carbon; or sexvalent, like the double molecule of aluminium. The above general formula is thus now written $n(si_2m_1o_3)$, and that given for spodumene $(si_{60}al_{24}li_4na_2)o_{90}$. In order to distinguish the atom of ferrosum $=\frac{1}{2}Fe$, from that of ferricum $=\frac{1}{3}Fe$, the former is written fe, and the latter fi, while manganicum, corresponding to manganic sesquioxyd, is mni.

§ 21. The M in the general formula M_2O_2, employed in 1853, was thus made to represent an atom either of protoxyd or sesquioxyd, and in 1854 a farther generalization was attempted. The boric, titanic, tantalic, and niobic anhydrids were reduced to the same atomic formula as silica, and, moreover, in view of the variations in the silica-ratio in related silicates, like feldspars, scapolites, and micas, and the supposed replacement of silica by alumina in certain amphiboles, it was suggested that the old distinction of acid and base, recognized in the dualistic hypothesis, might be set aside. M, in the generalized formula as then written, $n(MO_2)$, would then represent not only Na and Ca, but al, si, b, ti, and ta, as well, and "to this type, which is also that of the spinels, all silicates may be referred, except a certain number which, like eudialyte, sodalite, and pyrosmalite, contain metallic chlorids; hauÿne, nosite, and lapis-lazuli, which contain sulphates; and cancrinite, which holds a portion of carbonate. These are respectively basic chlorids, sulphates, and carbonates, and are represented by $(M_2O_2)n.\ MCl$, by $(M_2O_2)n.\ S_2M_2O_8$," etc. To these should of course be added the basic fluorids, or oxyfluorids, like chondrodite and topaz; and oxysulphids like helvite and danalite. It was then said, "The above formulas are intended to involve no hypothesis as to the arrangement of the elements, for in the author's view each species is an individual, in which the pre-existence of different species that may be obtained by its decomposition cannot be asserted." The importance of this notation, proposed in 1854, will be apparent when we come to consider farther the question of atomic volume in its relation to mineralogical classification.

§ 22. Another and an important question, connected with the complex constitution which had been assumed for silicates and carbonates, was considered in the paper now under review. The high molecular weight assigned to the polysilicates admitted the presence therein of many atoms of base, and of partial replacements; while the existence in crystalline species of visible mixtures of foreign matters also served to explain the presence of small portions of many elements detected therein by chemical analysis. It had, however, become apparent that there are variations in composition which can scarcely be explained in either of these ways. Delesse had already noticed that in the homœomorphous triclinic feldspars the silica-ratio appears to vary continuously between albite and anorthite, and was disposed to regard the feldspars intermediate in composition between these two as varieties only.* Scheerer, also, had in like manner expressed the opinion that the various feldspars were to be regarded as combinations of anorthite with labradorite, albite or orthoclase, or of labradorite with albite. Von Waltershausen had, however, given a more definite shape to the notion already in the minds of chemists, when, in 1853, he proposed to admit three typical triclinic feldspars, anorthite, albite, and krablite; the latter a supposed highly silicious species with the atomic ratios, 1 : 3 : 24, since generally regarded as a mixture of albite with quartz. These three feldspars, according to him, "alone have the right to be regarded as species in mineralogy. . . . All other feldspars, labradorite, andesine, oligoclase, etc., are merely mixtures of these," and were conceived by him to be built up "of infinitely small crystals of anorthite and krablite, or of anorthite and albite." †

§ 23. At the time of writing, in 1854, I was ignorant of the lately published conclusions of Von Waltershausen. I had then made an extended series of analyses of these feldspars, from the Norian rocks, and, rejecting the hypothesis of Scheerer, to which I referred, attempted to give the matter a more definite form by pointing out that anorthite and albite might be represented by a common formula, which, if a molecular volume of about 402 were assigned, would be $32(M_2O_2)$; the two polysilicates being respectively, in the atomic notation adopted, $(si_{32}al_{24}Ca_8)$

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* Delesse, Ann. des Mines, 1853 (5) iii., 376. Scheerer, Pogg. Ann. lxxxix., 19, cited in L. and K. Jahresbericht for 1853, p. 105.

† Sartorius von Waltershausen, Uber die Vulkanischen Gesteine in Sicilien und Island, Göttingen, 1853. For this reference, and for other notes on the literature of this question, I am indebted to my friend, Dr. G. F. Becker.

O_{64} and $(si_{48}al_{12}Na_4)O_{64}$. Petalite having the volume of these, and its composition not being then definitely settled, was referred to the same general formula, while orthoclase, from its less density, was conjectured to be $30(M_2O_2)$. As regards the homœomorphous triclinic feldspars, it was then said that "between anorthite and albite may be placed vosgite, labradorite, andesine, and oligoclase, whose composition and densities are such that they all enter into the same general formula with them, and have the same equivalent volume. The results of their analyses are by no means constant, and it is probable that many, if not all of them, may be variable mixtures of albite and anorthite. Such crystalline mixtures are very common; thus in the alums, aluminium, iron and chromium, and potassium and ammonium, may replace one another in indefinite proportions. . . . Heintz has shown by fractional precipitation that there are mixtures of homologous fatty acids, which cannot be separated by crystallization, and have hitherto been regarded as distinct acids. The author insists that the possibility of such mixtures of related species should be constantly kept in view in the study of mineral chemistry. The small portions of lime and potash in many albites, and of soda in anorthite, petalite, and orthoclase, are to be ascribed to mixtures of other feldspar-species."

§ 24. These conclusions were reiterated, in 1855, in a paper giving the results of my chemical studies of these feldspars (when Scheerer's hypothesis was noticed), and it was said that similar views "must also be extended to the scapolites." * Some years later, in 1864, Tschermak † put forth a view similar to that advocated by Von Waltershausen and myself, and maintained that the feldspars proper were reducible to three species, adularia or ortho-

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* Examinations of Some Feldspathic Rocks; L., E. & D. Philos. Mag., May, 1855.

† Tschermak, 1864, K. K. Academie Wissenschaft, Wien, and Pogg. Ann., 1865, v., 139. See also the author's Chem. and Geol. Essays, p. 444.

clase, albite, and anorthite. While recognizing the fact that certain potash-soda feldspars (such as perthite) are made up of alternations of orthoclase and albite, he further concluded, as I had already done, "that oligoclase, andesine, and labradorite appear to be members of a great series, with many transitional forms, and may be regarded as isomorphous mixtures of albite with anorthite, sometimes with small admixtures of orthoclase."

§ 25. With regard to this conception of the nature of these intermediate feldspars, it should be noted that the chemical difficulties in the way of verifying it are much greater than in the case of soluble compounds, where, as in the case of the fatty acids just mentioned, solution and separation by fractional precipitation are possible, or where differences in volatility may be appealed to. While a definite feldspar-species having the composition assigned to labradorite doubtless exists in nature, it is nevertheless true that a mixture of proportions of anorthite and albite containing equal parts of alumina would give a centesimal composition identical with that assigned to labradorite, just as the composition of a fatty acid may be simulated by a mixture of its higher and lower homologues. In so far as the view of Von Waltershausen and myself, since adopted by Tschermak, is true, the action of acids capable of attacking the basic feldspars will enable us to discriminate between admixtures and definite intermediate species. That the latter should occur in nature is, *a priori*, probable from the composition of the parallel series of the zeolites, in which appear well crystallized species, having the atomic ratios (excluding the water) of the intermediate feldspars, and also from the evidences of species like hyalophane and leucite. The late observations by Tschermak as to the action of acids on various intermediate scapolites, to be noticed farther on (§ 75), go far to show that these are not admixtures but integral compounds.

§ 26. In concluding the paper of 1854, which I have here reviewed, it was said with reference to the problem of a natural system in mineralogy, then, as now, before the writer: —

"No mineralogical classification can be complete which does not take into account both the chemical and the physical characters of species; and the connection between these, which is shown in the relation of equivalent weight to specific gravity, must constitute an important element in a natural system. Guided by their physical characters and composition, we bring together such homœomorphous species as belong to one chemical subtype, and from the densities fix their formulas and comparative equivalent weights. From the comparison of the formulas, and the associations of these different minerals, we must also decide which are to be considered as mixtures and which are true species. Until we shall have determined with certainty the comparative volumes of dissimilar crystalline forms, the relations of species differing in this respect must be decided by their affinities, and their places in a homologous series must remain undetermined. In this way we may hope to arrive at a mineralogical classification which shall satisfy alike the chemist and the naturalist."

§ 27. Before going farther, it seems proper to advert to the history of the notion of polymerism in silicates and carbonates, which enters into the views maintained in the author's papers of 1853 and 1854; and to show its relation to the views previously put forward by Auguste Laurent. He had already, in 1847, proposed to reduce all natural silicates to a small number of types, corresponding to the observed atomic ratios. These yield both neutral and basic salts, according to Laurent, who, moreover, in his notation, admitted, in order to explain the complex results of chemical analysis, a divisibility of molecules to which he assigned no limit, and supposed that protoxyds and sesquioxyds might, within certain limits, replace each other indefinitely. He also extended a similar view to the borates.* In a subsequent memoir, in 1849, Laurent criticised the arbitrary formulas proposed by chemical mineralogists, and showed that the relations therein set forth were often but approximations. It was pointed out by him that in many related species, as for example in the various micas, the atomic relations between sesquioxyds and protoxyds were not constant, and it was argued that these two classes of bases, and water, were capable of replacing each other mutually, within certain limits, in ratios which, as represented by him in atomic formulas, seemed to be indefinite. He also insisted on the importance in silicates of small portions of water, which, though generally neglected in the formulas, ought not to be regarded as accidental. This later paper,† however, while reflecting the perplexed state of chemical mineralogy, fails to propose any solution of the difficulties. The reader will note the broad distinction between the simple formulas, with an indefinite divisibility of molecules, adopted by Laurent, and the complex formulas, necessarily including many atoms of base, employed by the writer, further supplemented by the conception of crystalline admixtures of homœomorphous species.

§ 28. It was not until 1860 that the doctrines of high equivalents, and of the existence of polycarbonates and polysilicates, maintained by the writer in 1852 and 1853, found an advocate; when Ad. Wurtz again put forth the notion of polysilicates, explaining their genesis from the union of several molecules of silicic hydrate and the successive elimination of water. He cited in this connection the example of the metastannates of Frémy, which contain five quadrivalent molecules of tin. Wurtz did not, however, attempt in any way to discuss the difficulties presented by the composition of the native polysilicates (for

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* Comptes Rendus des Trav. de Chimie, July, 1847, from Comptes Rendus de l'Acad. xxiii., 1050, and xxiv., 94. For an analysis of Laurent's memoir by the writer, see Amer. Jour. Science, 1848, v., 405.

† Sur les Silicates; Comptes Rendus des Trav. de Chimie, 1849, pp. 256–288.

certain of which he proposed structural formulas), or to fix their molecular weights, and he seems to have overlooked the previous contributions to the subject by the present writer.*

§ 29. In 1859, in a paper on "Euphotide and Saussurite," † the writer, having made an extended chemical and mineralogical study of the typical saussurite, as found in the euphotide of Monte Rosa, in Switzerland, showed that it was not a feldspar, as generally supposed, but a finely granular or compact silicate having the hardness of quartz, a specific gravity of 3.365–3.385, and the composition of a lime-soda epidote, or a zoisite, to which latter species it was referred. In this connection he called attention to the observation of Rammelsberg, that zoisite is apparently identical in centesimal composition with meionite, the most basic of the scapolites, which has a hardness of 6.0, a specific gravity of 2.6–2.7, and is readily decomposed by strong acids. It was further noticed that, while boiling concentrated sulphuric acid did not attack pulverized saussurite, "it was, however, partially decomposed by this acid after having been strongly ignited." Attention was then called to changes produced in the denser silicates by heat, and it was noted that epidote, according to Rammelsberg, has its density reduced from 3.40 to 3.20 by ignition, while saussurite, according to the original observation of Saussure himself, is converted by fusion into a soft glass having a density of 2.8. The specific gravity of garnet was found by Magnus to be reduced one fifth by fusion, and that of idocrase from 3.34 to 2.94.‡ The silicates thus modified by heat are, like

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* Ad. Wurtz, Rep. de Chimie, 1860, ii., 464; also Jour. Chem. Soc. of London, 1862, p. 387; and Leçons de Philosophie Chimique, 1864, p. 180. See farther, on polysilicates, Naquet, Principes de Chimie, 1867, i., 175.

† Contributions to the History of Euphotide and Saussurite, Amer. Jour. Science, 1859, xxvii., 336–349.

‡ The observations of Greville Williams on beryl show that this mineral, having a density of 2.65–2.69, when fused before the oxyhydrogen blowpipe, gives a clear glass, which may be scratched by quartz, and has a density of 2.40–2.42. The fusion of quartz gives in like manner a glass

meionite and nephelite, decomposable by acids, and all these facts were adduced as evidences that the action of heat is to reduce such complex silicates to simpler and less dense forms.

§ 30. In conclusion it was said that "the two silicates zoisite and meionite offer a remarkable example of that isomerism in mineral species upon whose importance I have long insisted. The relation of the specific gravity to the empirical equivalent weights of minerals must enter as an essential element into a classification which shall unite the chemical and natural-historical systems. Similar isomeric relations exist between cyanite and sillimanite (fibrolite), rutile and anatase, and, as I have elsewhere endeavored to show, among the carbon-spars. It becomes necessary in the study of mineral species to determine their relative equivalent weights, to which specific gravity must be the chief guide."

§ 31. The relations of the members of the scapolite group * as a series parallel to the feldspars, already pointed out by the author in 1855, were not lost sight of, nor their connection with saussurite, but were the subject of a communication to the French Academy of Sciences, in 1863, which was translated by the author and published at the time, in the American Journal of Science, as already

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to which a density of 2.22 has been assigned. Williams, in repeating the experiment with rock-crystal, of density 2.65, obtained before the oxyhydrogen blowpipe fused globules, which in five experiments gave a specific gravity of 2.17–2.21. He noted, moreover, that alumina thus fused, as in the experiments of Gaudin, becomes crystalline on cooling, and has a density of only 3.45; that of corundum being about 4.00. The crystals of alumina got by the method of Frémy and Feil, which consists in decomposing an aluminate of lead by fusion in contact with silica, have, however, all the characteristics of corundum, and a density of 3.9–4.1 (Greville Williams, Proc. Roy. Soc. London, 1873, p. 409, and also Fouqué and Michel Lévy, Synthèse des Mineraux, etc., p. 222).

* The scapolites have very lately been taken up and discussed from the author's point of view by Tschermak, Monatshefte der Chemie, December, 1883, as will be noticed farther on. The slight change in the empirical formula of meionite suggested by Tschermak does not affect the present argument.

noticed in § 10.* In this paper, after recalling the general argument so often set forth as to the principles of a new system of mineralogical classification, it was said, "Meionite, with the oxygen-ratios 3 : 2 : 1, is the most basic term known of the series of the wernerites (scapolites). The proportion of silica in these minerals augments until we reach in dipyre the ratios 6 : 2 : 1, with a density which does not exceed 2.66. We might then expect to find a silicate which should be to dipyre what zoisite or saussurite is to meionite, and Mr. Damour has recently had the good fortune to meet with such a mineral in a specimen of jade from China, of which he has given us the description and the analysis. (Comptes Rendus, May 4, 1863.) This substance closely resembles in its physical and chemical characters the saussurite or jade from Monte Rosa, of which it has the density, 3.34. It is a silicate of alumina, lime, and soda, and gives the same empirical formula as dipyre. We may expect to find between saussurite and this new species, to which Damour gives the name of jadeite, other jades, having formulas which will correspond with the wernerites intermediate between meionite and dipyre. . . . By its hardness, its specific gravity, and its indifference to acids, jadeite is completely separated from the wernerite group, and takes its place alongside of zoisite or saussurite, with the garnets, idocrase, and epidotes."

§ 32. To this last succeeded the paper of 1867, on "The Objects and Methods of Mineralogy," already noticed (§§ 12–14), in which was given a review of the subject as discussed by me in various publications from 1853 up to that date. Before proceeding to show the systematic application of the principles already set forth, it is now proposed to consider farther the question of the relation between the atomic weights and densities, so often insisted upon in the above publications. The study

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* Compte Rendu de l'Acad., June 29, 1863, and Amer. Jour. Science, 1863, xxxvi., 426–428; also the author's Chem. and Geol. Essays, p. 446.

of the so-called equivalent or atomic volumes of solid and liquid species, got by dividing the assumed equivalent weight of these by their specific gravities,—water being taken as unity,—has occupied the attention of many chemists since the early investigation of the subject by Le Royer and Dumas. The application of this method to hydrocarbonaceous bodies, or to hydrated or double salts of admitted high equivalent, is comparatively simple, but it becomes more difficult when we have to deal with such compounds as mineral silicates, for which, as in the case of feldspars, micas, epidotes, and tourmalines, the ingenuity of mineralogical chemists has devised chemical formulas often exceedingly complex and difficultly commensurable. For all such cases I have shown that the atomic formulas already described furnish a simple solution.

§ 33. In the atomic notation adopted by me since 1853, the ordinary chemical symbols of the elements are employed to represent one part by weight of hydrogen, or eight parts by weight of oxygen, and the proportions of other elements which unite with these respectively. In other words, the coefficients of the symbols of the elements in the ordinary notation are multiplied by the atomicities of the respective elements, for the atomic notation. The symbols in the latter are distinguished from those representing molecular weights by the use of small letters, and, to prevent the confusion which might otherwise arise from the absence of capital letters in the formulas, a coefficient is in all cases employed after the symbol of the element; while in constructing condensed formulas the values of "m" may be represented by fractions. Thus, the general formula of pyroxene in the atomic notation being $n(\mathrm{si}_2\mathrm{m}_1\mathrm{o}_3)$, if the value of n be 30, and $\mathrm{m} = (\mathrm{ca}^3_6\mathrm{mg}^2_6\mathrm{fe}^1_6)$, the proper atomic formula of pyroxene will be $\mathrm{si}_{60}(\mathrm{ca}_{15}\mathrm{mg}_{10}\mathrm{fe}_5)\mathrm{o}_{90}$.

§ 34. But, as we have elsewhere shown (§ 21), the variable relations between silica, alumina, and protoxyds, in closely related species; the intervention of boron and titanium, on the one hand, and of sulphur, fluorine, and chlorine, on the other, permit a farther generalization, by which silicates are affiliated to quartz, on the one hand, and to corundum and spinels, on the other. We thus arrive at a general atomic formula $n(A+E)$, in which A represents an atom of silicon, boron, or titanium, or of hydrogen or any metal, and E, an atom of oxygen or sulphur, or of fluorine, chlorine, or oxysulphion. Dividing now the molecular weight of the compound by n, we get the value of $A+E$, which is the mean weight of the individual or atomic unit of the species, whether this be oxyd, silicate, oxyfluorid, oxychlorid, or oxysulphid. It is this weight, designated as P, which for each such species must be the term of comparison in fixing the atomic condensation of the species. The mean unit-weight thus deduced, divided by the specific gravity of the species, water being unity, gives the volume, V, of the atomic unit. In silicates, the value of P is deduced by dividing that of the empirical atomic formula by the whole number of oxygen atoms, to which, in the case of oxyfluorids, oxychlorids, or oxysulphids, the number of atoms of fluorine, chlorine, or sulphur is to be added. In this way only is it possible to obtain direct comparisons of volume between different mineral species, as was indicated in 1852, and will be fully shown in the third part of this paper.*

§ 35. The principles hitherto maintained by the author as the basis of a natural system in mineralogy, may be resumed as follows: —

1. The conception of high equivalent or molecular

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* Dana, in his inquiry into the subject of atomic volumes in 1850 (Amer. Jour. Science, ix., 221), proposed to divide the volumes deduced from the empirical chemical formulas by the number of atoms of elements in these formulas. Thus $(O=8)$, SiO_3, Al_2O_3, and CaO, were, in the notation adopted by him, supposed to contain respectively four, five, and two elemental atoms, whereas in atomic notation they evidently correspond to three, three and one oxyd-units. Hence, as I long since showed, the results obtained by such a discussion of atomic volumes were fallacious. (Amer. Jour. Science, 1853, xvi., 214.)

weights like those of the carbon series in so-called organic chemistry, extended to all mineral compounds; as was especially maintained for the carbon-spars, the spinels, and the various natural silicates, and illustrated by the hypothesis of polysilicates and polycarbonates, with many atoms of base.

2. The conception that the laws of progressive or homologous series, previously recognized only in hydrocarbonaceous bodies, must be extended to mineral species, and are of universal application.

3. The conception that the variations observed in the chemical composition of such mineral species are due, not only to their highly polybasic character, but also, in certain cases, to indefinite admixtures of homœomorphous species, as previously indicated by Delesse, Scheerer, and Von Waltershausen, extended and generalized by myself, and subsequently adopted by Tschermak.

4. The attempt to fix the molecular weights of such compounds as the polysilicates and polycarbonates from their densities as compared with those of species the minimum molecular weights of which are otherwise determined; and the assumption that for homœomorphous solids, and probably for all solids, the molecular volumes are identical.

5. The adoption of atomic formulas to represent the composition of mineral species, and the showing that comparisons of the volumes or spatial relations of complex species, like the silicates, should be based on the numbers which are deduced from these atomic formulas, and which represent the relative volumes of the unit-weight in the species compared. P being the unit-weight got by dividing the empirical molecular weight by the number of oxyd-atoms in the formula (including any chlorid, fluorid, or sulphid atoms which may be present), and D the specific gravity, the volume of the unit, designated as V, is represented by the quotient obtained by dividing P by D.

6. The showing that, in related and homologous species, the hardness and chemical indifference are inversely as the

value of V; or, in other words, that they increase with the condensation, the relative amount of which in the species compared is shown by the diminution of V.

III. — A CLASSIFICATION OF SILICATES.

§ 36. In order to show the application of the principles already set forth in the second part of this paper to the classification of mineral species, I have chosen the Natural Silicates, for the reason that, while they present the most complex and the largest group of native species, their physical and their chemical history alike have been more thoroughly studied than those of any other group. To this it may be added that the writer has, for many years, employed a classification based on these principles for the arrangement of his own private collection of the native silicates. These may be regarded as constituting one great natural order, and, without again adverting to the importance of considering in a natural system alike the chemical and the physical history of species, it may be said that a fundamental distinction in silicates is that presented by their chemical constitution, as including either protoxyd or sesquioxyd-bases, or both united; for which reason the order Silicate is divided into three sub-orders: Protosilicate, Protopersilicate, and Persilicate.

The names of protoxyd and protosalt for ferrous compounds, and of peroxyd and persalt, instead of sesquioxyd and sesquisalt, for ferric compounds, are familiar to chemists; and when, in naming the sub-orders of silicates, it became necessary to select a term to designate alike ferric compounds, aluminic compounds, and those in which ferric and aluminic sesquioxyds partially replace each other, I ventured to substitute for sesquisilicate and protosesquisilicate the shorter and more euphonious names of persilicate and protopersilicate. With these sesquioxyd bases, which also include chromic and manganic oxyds, is ranged zirconia, since, notwithstanding the quadrivalence of zirconium, the relations of its oxyd in silicates are such as to place it at the side of alumina. Here also bismuthic oxyd probably belongs. Boric, titanic, niobic, and tantalic oxyds, all of which are found in silicates, are ranged, as already stated, with silica, which they are regarded as replacing.

§ 37. Inasmuch as zirconia and chromic and manganic oxyds are but exceptionally present in silicates, and ferric oxyd, though more commonly found than they, is much less frequent therein than the alumina which it sometimes replaces, it may be said that it is essentially the relations of alumina to the protoxyds and to silica which we are now called to consider. Native silicates may be divided into those with and those without alumina, the latter division constituting the first sub-order — *Protosilicate.* Again, the aluminiferous silicates either contain combined protoxyds, constituting the second sub-order — *Protopersilicate;* or are without protoxyds, making the third sub-order — *Persilicate.* The presence or absence of combined water, — it being an element widely diffused in nature, — is of subordinate importance in the study of the silicates. Upon the general distribution of silica and alumina in the crust of the earth, and the relations of these to each other, to protoxyd-bases, and to igneous and aqueous solvents, is based the whole genetic history not only of the three sub-orders of silicates, but of quartz, and the non-silicated oxyds.

The affinities which determine the nearly contemporaneous formation of protosilicates and of protopersilicates are displayed in many different and unlike conditions, which merit especial consideration. This distinction is well seen in the basic crystalline rocks, wherein pyroxene and chrysolite, often with magnetite, are found side by side with feldspars. Whether this separation, which may be supposed to have taken place in a plutonic magma, was effected with or without the intervention of water, is immaterial to our present inquiry, since we know that the chemical affinities involved lead to similar results alike in the presence and the absence of water, and through a wide range of temperature. Thus, a slow cooling from igneous fusion, as shown in the experiments of Fouqué and Michel Lévy, enables us to separate from the same basic magma, successively, chrysolite, magnetite, pyroxene, and feldspar. That similar affinities come into play in presence of water at elevated temperatures is shown by the minerals in concretionary granitoid veins, where wollastonite, amphibole, and pyroxene are found crystallized with feldspars, scapolite, micas, garnet, and epidote, often with free quartz, on the one hand, and with magnetite, spinel, and corundum, on the other.

§ 38. A similar differentiation of protosilicates and protopersilicates is presented in the secretions from basic rocks. In the veins and geodes found in such rocks are seen, side by side, the protosilicates, pectolite, okenite, datolite, and apophyllite, and the protopersilicates represented by prehnite, epidote, and the various zeolites, and more rarely by orthoclase and albite, by garnet and tourmaline, — both quartz and magnetite being also present. The same distinction is observed in the products now forming in the channels of certain thermal springs, where pectolitic and zeolitic silicates are associated. Nor is the differentiation less marked when, as in the experiments of Daubrée, water at a high temperature acts upon glass. A protosilicate allied to okenite is then formed, together with pyroxene and quartz, the alkaliferous solution retaining silica, with a portion of alumina. From similar superheated solutions, holding other proportions of these same elements, crystals of orthoclase, of albite, of analcite, and other zeolites, with quartz and tridymite, have been obtained.

§ 39. To these considerations on the genesis of the two sub-orders of protosilicates and protopersilicates must be added the history of their decay and transformations. It is known that the sub-aerial decay of protosilicates through the action of atmospheric waters effects their complete decomposition. The lime and magnesia of amphibole, pyroxene, and chrysolite, are thereby dissolved, together with a large proportion of the silica itself; a part of this, however, according to Ebelmen, remains behind, together with the iron, changed from a ferrous condition to that of ferric hydrate. In the sub-aerial decay of such protopersilicates as the feldspars and closely related species, the protoxyd-bases, chiefly alkalies and lime, pass into solution, together with a large part of the silica; and the alumina, united with the remainder of the silica, and with a portion of water, remains as an insoluble compound, which in many cases has the composition of kaolin. This decay of the feldspars plays an important part in terrestrial chemistry. The process is slow and gradual, and the feldspar softens and becomes disintegrated before the loss of protoxyds is complete, so that the clays thus formed still retain, in many cases, a portion of alkali, which may amount to two or three hundredths (*ante*, page 254). The decomposition of the more basic feldspars and feldspathic minerals will be considered farther on, as also the genesis of various micaceous and colloid or clay-like persilicates.

§ 40. From the subsequent transformation of clays more or less completely deprived of alkalies, are apparently derived, in many cases at least, muscovitic micas and tourmaline, together with the crystalline persilicates, kaolinite, pyrophyllite, andalusite, cyanite, fibrolite, and related species. The micas just mentioned are more stable under atmospheric influences than the feldspars, while those which, like phlogopite and biotite, abound in protoxyds, yield readily to decay. The harder and gem-like protopersilicates resist to a greater extent this process, and the more common species of these — garnet, epidote, and tourmaline — are found unchanged in sands, together with persilicates, such as andalusite, topaz, and zircon, and with quartz, corundum, spinel, and menaccanite.

Thus the natural processes of sub-aerial decay destroy the protosilicates, and transform the predominant types of protopersilicates either into more highly aluminous and more stable types of the same sub-order, or into persilicates, in all cases with the separation of the elements of protosilicates, that is to say, of silica and protoxyd-bases. Of these, while iron is separated in an insoluble ferric state, the alkalies and lime, as well as the magnesia of the protosilicates, pass into the condition of carbonates, the silica being liberated in a soluble form.

§ 41. The minerals of granitoid veins, and those secreted in basic rocks, show that a distinct subterranean process of solution of silicated compounds goes on under conditions as yet imperfectly understood, and probably under the influence of thermal alkaline waters. From the matters thus dissolved come not only the protopersilicates deposited in the forms of zeolites, and of feldspars, micas, garnets, and tourmalines, but also the calcic and alkaline protosilicates which take the forms of pectolite, xonaltite, okenite, apophyllite, and wollastonite. Such protosilicate-solutions, coming in contact with atmospheric carbonic dioxyd, would be decomposed with separation of carbonates, but with dissolved magnesian salts would yield by double exchange silicates, such as sepiolite, talc, serpentine, enstatite, chrysolite, and their associated amphiboles and pyroxenes. It will be remembered that these protosilicates may, like the feldspars, be formed alike by aqueous and by igneous processes, and that a broad distinction as to origin must be drawn between those anhydrous silicates, of both sub-orders, which are due to aqueous deposition, and are often associated with calcite and with quartz, and the same species which are found in plutonic rocks, and may be the result of crystallization from a cooling igneous mass. Protopersilicate-solutions, by like reactions with magnesian salts, may, by double exchange, give rise to compounds like iolite, the magnesian micas, and the chlorites, while the source of glauconite is probably to be sought in the reaction between dissolved protosilicates and ferrous solutions, followed by a partial peroxydation of the resulting hydrous ferro-potassic silicate (*ante*, page 197). Thus, as we have endeavored to show, while natural processes, both igneous and aqueous, unite in giving origin to the protosilicates and the protopersilicates, it is the transformation of the latter, by sub-aerial aqueous action, which, by removing the protoxyd-bases, generates the persilicates.

§ 42. While the distinctions between the sub-orders which have been deduced from their genetic history are generally well defined, there are, however, remarkable examples which serve to connect the protosilicates with the protopersilicates. With the typical species of amphibole and pyroxene, which are protosilicates, there have hitherto been included certain compounds which, while apparently identical with these in external characters, contain notable portions of alumina. Taking as a type of the aluminous amphiboles, a lime-magnesia pargasite, we find for the atomic ratio of protoxyds, alumina, and silica, 2 : 1 : 3, which requires alumina 15.9, silica 42.2. This, if the alumina replaces atomically, as has been suggested, a portion of the silica, would give the ordinary amphibole ratio of 2 : 4. It is, however, a true protopersilicate, having the same atomic ratios as melilite; while the aluminous species, glaucophane, from the analysis of Liversidge, gives the ratios 3 : 2 : 8, and gastaldite, a still more aluminous species, 1 : 2 : 6. The example offered by species like these, which from physical characters have been compared with amphibole, shows in a striking manner the importance of chemical consideration in mineralogy. An aluminous augite near to pargasite in its atomic relations has also been examined by Fouqué (*ante*, p. 213).

From gastaldite, in which the atomic ratios of protoxyd and alumina are 1 : 2, to glaucophane with 1 : $\frac{2}{3}$, and pargasite 1 : $\frac{1}{2}$, we have a series in which the ratio becomes, as in humboldtilite, 1 : $\frac{4}{10}$, and so on to the less aluminous amphiboles and pyroxenes, in which it becomes 1 : $\frac{1}{10}$, or even less, establishing a transition through these species to the protosilicates. In like manner, towards the other limit of the protopersilicates, we find this ratio changing from 1 : 6 to 1 : 9 and 1 : 12, in indicolite, rubellite, and the muscovitic micas; thus marking the transition to gem-like persilicates like andalusite and topaz, and to persilicate micas like kaolinite and pyrophyllite.

§ 43. We may conceive the relation of the three suborders to each other to be represented by a design of two bands of equal breadth, but of unlike color, and of diminishing intensity of color, protracted in opposite directions along a common course, for a considerable part of which the two bands overlie or rather blend with each other. The unmingled portions of these two color-bands represent the protosilicates and the persilicates. As a result of such an arrangement, the protopersilicates, towards the protosilicate-end of the continuous series, include comparatively little alumina, as in melilite, pargasite, and phlogopite, while towards the persilicate-end they hold but little protoxyd, as seen in indicolite, rubellite, the muscovites, and pinite.

§ 44. It follows from what has been already set forth that the more or less arbitrary ratios generally assigned by chemists to various silicates, and deduced from empirical formulas which in many cases represent but approximately the results of chemical analysis, are not always to be regarded as exact. Thus, in examining the various formulas hitherto devised for protosilicates, we find that for the whole succession from chondrodite to apophyllite, the atomic proportions between the bases and the silica may be represented by some twelve simple ratios between 4 : 3 and 1 : 7. It is probable, in view of the complex constitution, involving from twenty to thirty atoms of base, which we have assigned to these polysilicates, that, while some of these ratios are exact, others represent but approximations to the truth. The same remark applies with equal force to the persilicates, where a like number of similar ratios is made to include all of the known species. In the present state of our knowledge of their composition, however, the usually accepted atomic ratios of oxyds and silica are retained for the formulas, and for the tabular views of protosilicates and persilicates, given farther on.

§ 45. In the study of both of these sub-orders we note many mineralogical resemblances between species which differ widely in atomic ratios, and similar resemblances become still more apparent when we examine the larger and more complex group of the protopersilicates. Here, for example, in the families of the zeolites, the feldspars, and the scapolites, we find physically similar and homœomorphous species in which, with a constant ratio of protoxyds and alumina, the silica is variable. The same thing may be observed among the micas of this sub-order; as when corundophilite is compared with biotite, or margarite with certain muscovites. These latter also present another type of variations in composition, for in different analyses of muscovite, while the ratio of sesquioxyd and silica remains unchanged, that of the protoxyds, represented by alkalies, is variable. Both of these modes appear in the tourmaline group, where species physically similar present, at the same time, variation in the ratio of protoxyd-bases to alumina, and in that of alumina to silica. These divergences in chemical composition, without sensible changes in external characters, afford strong arguments in favor of the necessity of the aid of chemistry in a true mineralogical classification.

§ 46. To distinguish in general formulas between protoxyd-metals, on the one hand, and aluminium and its replacing elements, on the other, several devices have been proposed by chemists, of which the most simple is perhaps the employment of Roman and Italic letters respectively. Accordingly, in these pages "*m*" is used for an atom of aluminium, ferricum, manganicum, chromicum, bismuth, or zirconium, while "m" represents an atom of any other metal, and (the presence of oxygen being understood) the atomic ratios of the protosilicates are given under the head of m : si; those of the persilicates, *m* : si; and those of the protopersilicates, m : *m* : si.

§ 47. Having shown the wide chemical differences existing between the three great divisions of the order Silicate, we proceed to consider those differences, alike chemical and physical, which are found between species often having identical or similar centesimal composition. Physical characters, irrespective of chemical composition, constitute, in the language of Mohs, the "characteristic" of mineral species, and served as the basis of his system of classification. We propose to show that, by a re-examination of these characters in the light of modern chemistry, it is possible to devise a new mineralogical method, which shall retain all that was good in the Natural History System, and at the same time bring it in accordance with the facts of chemistry, thus giving a veritable Natural System to Mineralogy.

§ 48. The great divisions marked by external characters were made by Mohs and his school the basis of a system of classification, as is exemplified in his orders of MICA, SPAR, and GEM, already noticed in §§ 5–6. We have there seen the heterogeneous nature of the order SPAR, wherein — besides the genera, *Schiller-Spar; Disthene-Spar*, including cyanite; *Triphene-Spar*, comprising spodumene and prehnite; *Petaline-Spar*, for petalite; *Azure-Spar*, for lapis-lazuli and lazulite; *Augite-Spar*, including pyroxene, amphibole, wollastonite, and epidote; *Feld-Spar*, embracing adularia, albite, anorthite, labradolite, and scapolite — there was a genus, *Kouphone-Spar*, in which were grouped not only leucite and sodalite, but the characteristic zeolites, mesotype, laumontite, harmotome, analcite, chabazite, stilbite, and heulandite. With these was also placed apophyllite, while datolite was assigned to another genus, *Dystome-Spar*. When, in 1844, Shepard divided the order SPAR, by the separation from it of a new order, ZEOLITE, he transferred to this the whole of the species of the latter two genera. The order SPAR of

Mohs, and the united orders of SPAR and ZEOLITE of Shepard, thus included alike protosilicates, protopersilicates, and persilicates of very various degrees of hardness and chemical unlikeness; since not only datolite, apophyllite, and pyroxene, but mesolite and stilbite, leucite and albite, spodumene and epidote, and even cyanite, found a place therein. A still more heterogeneous assemblage was seen in Dana's order, CHALCINEA, which comprised not only the order SPAR of Mohs, but also the protopersilicate micas of his order MICA.

§ 49. We propose, while keeping in view the great chemical sub-orders already defined in our system, to group mineral species with more regard to these external characters than has hitherto been done. The obvious distinctions of structure, hardness, and density, which separate protopersilicates, like garnet, staurolite, and tourmaline, from the micas, on the one hand, and from the feldspars, scapolite, and zeolites, on the other, though but imperfectly appreciated, underlay the division by Mohs into Gem, Mica, and Spar, and the necessity of a sub-division of the sparry or spathoid type was soon felt by Shepard. The need of this is most apparent in the great sub-order of the protopersilicates, where it will be seen that, alike on chemical and physical grounds, the natural line of division coincides with that between hydrous and anhydrous species, — the latter including the feldspars, leucite, sodalite, and scapolites, and the former, or hydrospathoid, the zeolites. A similar distinction of hydrous and anhydrous spathoids is equally marked in the protosilicates. Upon the foregoing distinctions, and upon the still farther one which, in each sub-order, separates all these crystalline species from amorphous colloid compounds, we may proceed to divide the various sub-orders into Tribes.

§ 50. Beginning with the PROTOSILICATES, we recognize first among them a type of crystalline hydrous species, of inferior hardness and comparatively low density, which are decomposed by strong acids with the formation of a jelly, or, to use Graham's phrase, pectise with acids. These hydrospathoids, which are represented by pectolite, apophyllite, datolite, calamine, etc., may be conveniently designated as the tribe of the *Pectolitoids*. A second type, not very dissimilar to the first, but somewhat harder, and anhydrous, though still pectising with acids, is represented by willemite, tephroite, helvite, wollastonite, etc. These anhydrous spar-like species we designate as the tribe of the *Protospathoids*. In the third place, we note a group of species not unlike the second in general aspect, and, like them, generally anhydrous; which are, however, harder, and considerably denser, as appears from the reduced value of V. This group is represented by chondrodite, chrysolite, phenacite, amphibole, pyroxene, danburite, titanite, etc. Many of these species present a hardness and transparency which caused them to be included by Mohs and his school in the order GEM, and this gem-like or adamantoid character suggests for them the tribal name of *Protadamantoids*. As regards their relation to acids, it may be noted that while the spathoid wollastonite is readily decomposed thereby, the corresponding adamantoid bisilicates, amphibole and pyroxene, are unattacked. The highly basic chrysolite pectises with acids, but the more condensed phenacite and bertrandite, with the same atomic formula, resist their action. The case of titanite, a titanosilicate, is peculiar, for the reason that the titanic oxyd, of which it contains so large a proportion, is soluble in chlorhydric acid. This decomposition of titanite was long ago studied by the writer, who showed that the titanic oxyd thus dissolved presents chemical reactions very different from that got from menaccanite by the same solvent, or from titanite itself by the action of hot sulphuric acid, and then described it as a peculiar modification of titanic acid.*

§ 51. We recognize in the fourth place among the protosilicates a group characterized by a hardness less than

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* Amer. Jour. Science, 1852, xiv., 346.

that of the three preceding tribes, and by a very marked basal cleavage, yielding more or less flexible laminæ, as is well seen in talc, and in the foliated serpentines. This type, but sparingly shown in the first sub-order, is largely developed in the micas and the chlorites of the second, and from its foliated structure is naturally designated as "phylloid," for which reason the fourth tribe of the protosilicates may be called *Protophylloids*. There still remains in this order a considerable group of soft hydrous silicates, chiefly magnesian, represented by much that is called serpentine, by deweylite, cerolite, chrysocolla, etc. To these the tribal designation of *Ophitoids*, suggested by the Greek name for serpentine, is given. They are, for the most part, readily decomposed by acids without pectisation, and are amorphous colloid substances. The crystalline silicates which approach these protocolloids in physical and chemical characters, — in part phylloids, and in part, perhaps, spathoids, — will be considered in the further discussion of the ophitoids.

§ 52. Passing now to the second sub-order, that of the PROTOPERSILICATES, we recognize, as in the protosilicates, five tribes, which repeat the general characters of those just noticed. The first is that of the great family of the zeolites, with prehnite and some related species, which together constitute a hydrospathoid tribe, conveniently designated as *Zeolitoids*. The resemblances, as regards hardness, density, aspect, and mode of occurrence, between this tribe of hydrous silicates and the pectolitoids are such that, notwithstanding their wide difference in chemical composition, the calcareous pectolitoids have generally been confounded with the zeolites.

The spathoids of the second sub-order, constituting the tribe of the *Protoperspathoids*, include a large number of species represented by melilite, gehlenite, ilvaite, the whole family of the feldspars, sodalite, nephelite, leucite, iolite, and petalite, of which the more basic species are, like the protospathoids, decomposed by acids. The *Proto-*

peradamantoids form a large and important tribe of hard and gem-like species, including pargasite, glaucophane, gastaldite, idocrase, garnet, beryl, euclase, ardennite, axinite, epidote, spodumene, sapphirine, staurolite, and the tourmalines; besides allanite, the titanic species, keilhauite and schorlomite, and the remarkable ferric species, ægirite, acmite, and arfvedsonite. These, though differing in this regard among themselves, have all of them a more condensed molecule than the densest of the spathoids, and it is to be noted that their resistance to acids is correspondingly greater. The highly basic adamantoids of this sub-order, such as garnet, epidote, and zoisite, are not attacked, while the basic spathoids (as scapolites and feldspars) are readily decomposed, by acids. The phylloid type in this sub-order is represented by the great group of the micas and chlorites, constituting the tribe of *Protoperphylloids* and including a large number of species, both hydrous and anhydrous, which are more condensed than the spathoids, though less so than the adamantoids.

In the fifth place, we find the uncrystalline colloidal species of this sub-order represented by the tribe of the *Pinitoids*, named for the typical species, pinite, and corresponding to the ophitoids, with which they have many analogies. This tribe includes several species which are essentially hydrous silicates of alumina, with more or less alkali. With the true pinitoids are probably confounded other substances which are compact forms of the corresponding phylloids. The hydrous silicates palagonite and pitchstone, and the anhydrous tachylite and obsidian, though not definite mineral species, are placed in this tribe, as being colloidal protopersilicates.

§ 53. The hydrospathoid and spathoid tribes are scarcely represented among the less protobasic silicates of the second sub-order, and, with the exception of westanite, which seems to be a *Perzeolitoid*, and the bismuthic silicates, eulytite, agricolite, and bismutoferrite, apparently

Perspathoids, are as yet unrecognized in the sub-order of the PERSILICATES. The *Peradamantoids*, however, constitute an important tribe, including andalusite, topaz, dumortierite, fibrolite, xenolite, cyanite, and the zircons. The *Perphylloid* tribe is represented by a few micaceous species, such as pholerite, talcosite, kaolinite, and pyrophyllite; while the uncrystalline or colloid type in this sub-order, which we have designated the *Argilloid* tribe, includes the various clays or amorphous hydrous silicates of alumina, from schrötterite through allophane and halloysite to cimolite and smectite, together with wolchonskoite and chloropal.

§ 54. In the preceding scheme it will be seen that the first place has been given to the great chemical distinctions which are embodied in the three sub-orders of silicates. It might be thought that the well marked physical types which we have seen recurring in the different sub-orders should be made the ground of a first subdivision of the order Silicate, rather than the chemical distinctions here adopted. These resemblances, dependent upon similar molecular aggregations, and upon physical structure, are, however, less fundamental than those based upon elemental constitution. These, as we have sought to show, are genetic, and should, therefore, have assigned to them a greater significance than the analogies based on similarity of aggregation and structure, which, although of much importance in classification, are essentially mimetic. The foundations alike of the order and the sub-orders are wholly chemical, and the division of each of the sub-orders into tribes is primarily and essentially chemical and genetic. On the other hand, the remarkable resemblances between the corresponding tribes in the different sub-orders, which are chemically distinct, is imitative or mimetic, and should, therefore, be assigned a subordinate rank in classification.

§ 55. In arranging still farther the different families, genera, and species in each tribe, the question arises, what kind of chemical variation should take precedence. Considering the general persistence of type in series of protopersilicates like those of the zeolites and the feldspars, in each of which the ratio of protoxyds to alumina is constant, that of the silica being variable, I have, in a tabular view of the sub-order, arranged species so related on the same horizontal lines; while species belonging to the same tribe, but having different relations between the protoxyds and the alumina, are arranged in successive horizontal lines; those with the larger proportion of protoxyds being above, and those with the smaller proportion below, so as to represent the passage towards protosilicates, in the one direction, and to persilicates, in the other. It should here be remarked that in many cases, as in tourmalines and in micas, the species thus vertically arranged present physical resemblances not less close than those between species on the same horizontal line, within the tribe, as may be seen in the synoptical table of the protopersilicates, mentioned below. As regards the relative condensation, the successive species or genera of a tribe on a given line may be placed with regard to the value of V, — the denser, or those with the lesser atomic volume, following those which are less dense.

§ 56. For the better understanding of the formulas given in the accompanying tables of the various tribes of silicates, it may be well to recall the values of the chemical symbols here employed, which are atomic, — the small letters representing atoms of the elements. Hence, while for univalent elements, or monads, like sodium, chlorine, and fluorine, the symbols represent the received molecular weights, these weights for dyads, like glucinum, calcium, ferrosum, oxygen, and sulphur, are divided by two; for triads, like boron, aluminium, chromicum, ferricum, manganicum, and bismuth, by three; for the tetrads, silicon, titanium, zirconium, and thorium, by four; and for a pentad, like niobium, by five. Thus the numerical values of the symbols here used, hydrogen being unity, are as follows: —

ATOMIC SYMBOLS AND WEIGHTS.

aq	9.00	cs	133.00	cu	31.65	fi	18.66
o	8.00	gl	4.50	ni	29.00	mni	18.50
s	16.00	mg	12.00	zn	32.50	bi	69.33
fl	19.00	ca	20.00	ce	47.00	si	7.00
cl	35.50	sr	43.75	yt	44.50	ti	12.50
li	7.00	ba	68.50	b	3.66	zr	22.50
na	23.00	fe	28.00	al	9.00	th	58.00
k	39.00	mn	27.50	cri	17.33	nb	18.80

§ 57. The sub-orders and tribes of the order Silicate, as already set forth, are here presented, and are followed by a list of the principal species in each tribe. The several minerals of the various tribes, in their sequence, will then be briefly noticed, and tables of them will be given, showing the atomic formulas of the species, and the values of P and V as calculated therefrom. For the crystalline tribes, the form, when known, will be designated in these tables under X, initial letters being used, as follows: I, Isometric; T, Tetragonal; O, Orthorhombic; C, Clinorhombic; A, Anorthic or Triclinic; H, Hexagonal, and R, Rhombohedral.

This will be followed, in a fourth part of the essay, by a brief discussion of the non-silicated oxyds or Oxydates, and the non-oxydized metallic ores or Metallates, together constituting two additional orders, the places of which are then assigned in a general scheme of classification that includes all native mineral species. Following this, is a discussion of the question of molecular weights, and its bearing on a new departure in chemistry. Finally, the principal minerals of each sub-order, arranged under their respective tribes, in the sequence already explained, will be presented in synoptical tables, giving at a single view the new classification of the silicates.*

Order Silicate.

Sub-Order I. Protosilicate.
- Tribe 1. Hydroprotospathoid (Pectolitoid).
- Tribe 2. Protospathoid.
- Tribe 3. Protadamantoid.
- Tribe 4. Protophylloid.
- Tribe 5. Protocolloid (Ophitoid).

Sub-Order II. Protopersilicate.
- Tribe 6. Hydroprotoperspathoid (Zeolitoid).
- Tribe 7. Protoperspathoid.
- Tribe 8. Protoperadamantoid.
- Tribe 9. Protoperphylloid.
- Tribe 10. Protopercolloid (Pinitoid).

Sub-Order III. Persilicate.
- Tribe 11. Hydroperspathoid (Perzeolitoid).
- Tribe 12. Perspathoid.
- Tribe 13. Peradamantoid.
- Tribe 14. Perphylloid.
- Tribe 15. Percolloid (Argilloid).

Tribe 1. Pectolitoid. Calamine, Thorite, Cerite, Gyrolite, Friedelite, Pyrosmalite, Xonaltite, Plombierite, Dioptase, Pectolite, Datolite, Apophyllite, Okenite; together with Villarsite, Matricite, Picrosmine, Picrolite, and Chrysotile. (Table I.)

Tribe 2. Protospathoid. Danalite, Willemite, Batrachite, Tephroite, Knebelite, Gadolinite, Helvite, Leucophanite, Wollastonite, Tscheffkinite. (Table II.)

Tribe 3. Protadamantoid. Chondrodite, Monticellite, Chrysolite, Phenacite, Bertrandite, Amphibole, Rhodonite, Pyroxene, Enstatite, Guarinite, Titanite, Danburite. (Table III.)

Tribe 4. Protophylloid. Thermophyllite, Marmolite, Talc. (Table IV.)

Tribe 5. Ophitoid. Serpentine, Retinalite, Deweylite, Genthite, Aphrodite, Cerolite, Chrysocolla, Spadaite, Rensselaerite, Sepiolite, Glauconite. (Table V.)

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* As regards the designation of the tribes, the use of a term which ends in a syllable expressing likeness, to include not only bodies resembling a given type, but the type itself, is justified by the meaning given to such words as haloid, albuminoid, and colloid, and also by the use in botany of the name of *Aroideæ* for an order which comprises not only *Araceæ*, but the typical genus *Arum*.

Tribe 6. Zeolitoid. Xanthorthite, Hamelite, Catapleiite, the various Zeolites; with Cancrinite and Ittnerite, Edingtonite, Sloanite, Forestite. (Table VI.)

Tribe 7. Protoperspathoid. Melilite, Eudialyte, Wöhlerite, Humboldtilite, Ilvaite, Gehlenite, Sarcolite, Milarite, Barylite, Meionite, with Marialite and intermediate Scapolites, Sodalite, Nosite, Hauÿne, Lapis-lazuli, Leucite, Hyalophane, Orthoclase, Microcline, Nephelite, Paranthite, Eucryptite, Anorthite, Albite and intermediate Feldspars, Iolite, Petalite. (Table VII.)

Tribe 8. Protoperadamantoid. Pargasite, Keilhauite, Idocrase, Glaucophane, Schorlomite, Garnet, Ægirite, Allanite, Beryl, Euclase, Prehnite, Arfvedsonite, Ardennite, Axinite, Epidote, Zoisite, Jadeite, Gastaldite, Acmite, Spodumene, Sapphirine, Staurolite; and the Tourmalines, including Coronite, Schorlite, Aphrizite, Indicolite, Rubellite. (Table VIII.)

Tribe 9. Protoperphylloid. Astrophyllite, Phlogopite, Pyrosclerite, Penninite, Ripidolite, Prochlorite, Cronstedite, Leuchtenbergite, Venerite, Corundophilite, Biotite, Voigtite, Cryophyllite, Seybertite, Thuringite, Jefferisite, Annite, Willcoxite, Chloritoid, Lepidomelane, Zinnwaldite, Oellacherite, Lepidolite, Margarite, Euphyllite, Cookeite, Damourite, Paragonite, Muscovite. (Table IX.)

Tribe 10. Pinitoid. Jollyte, Fahlunite, Esmarkite, Bravaisite, Sordavalite, Hygrophilite, Pinite, Cossaite; with Palagonite, Tachylite, Pitchstone, and Obsidian. (Table X.)

Tribe 11. Perzeolitoid. No species known except perhaps Westanite.

Tribe 12. Perspathoid. No species known to represent this tribe except Eulytite and other related bismuthic silicates.

Tribe 13. Peradamantoid. Dumortierite, Topaz, Andalusite, Fibrolite, Cyanite, Bucholzite, Xenolite, Wörthite, Lyncurite, Malacone, Zircon, Auerbachite, Anthosiderite. (Table XI.)

Tribe 14. Perphylloid. Pholerite, Talcosite, Kaolinite, Pyrophyllite. (Table XII.)

Tribe 15. Argilloid. Schrötterite, Collyrite, Allophane, Samoite, Halloysite, Kaolin, Keramite, Hisingerite, Wolchonskoite, Montmorillonite, Chloropal, Cimolite, Smectite. (Table XIII.)

Tribe 1. *Pectolitoid.*

§ 58. We notice first in this tribe the hydrated silicates of lime, often with alkali, most of which are frequently found among the secretions of basic rocks, and which include pectolite, xonaltite, gyrolite, plombierite, datolite, okenite, and apophyllite. The name selected for the tribe recalls at the same time the most common of these species, and also the property which belongs to most of them of pectising or being decomposed by strong acids, such as chlorhydric, with the separation of gelatinous silica.* It has also the advantage of distinguishing them from the zeolitoids, the corresponding type in the next sub-order, with which they are generally associated, and sometimes confounded. Differing considerably in the proportion of combined water, the pectolitoids have a hardness below that of quartz, and, with but few exceptions, a comparatively large atomic volume. In the case of apophyllite a little fluorine is present, and in datolite a large amount of boric oxyd, which in our atomic formula

TABLE I.—PECTOLITOIDS.

SPECIES.	FORMULA.	P	D	V	X
Calamine . . .	$(zn_1si_1)o_2 + \frac{1}{2}aq$	24.00	3.50	6.87	O.
Thorite	$(th_1si_1)o_2 + \frac{2}{3}aq$	32.62	5.30	6.15	I.
Cerite	$(ce_1si_1)o_2 + \frac{1}{2}aq$	29.80	4.90	6.08	?
Gyrolite	$(ca_2si_3)o_5 + 1aq$	18.33	....	....	?
Friedelite . . .	$(mn_2si_3)o_5 + 2aq$	19.14	3.07	6.23	R.
Pyrosmalite . .	$(fe_2si_3)o_5 + 1aq$	21.58	3.17	6.80	H.
Chrysotile . . .	$(mg_3si_4)o_7 + 2aq$	15.33	2.22	6.98	?
Xonaltite . . .	$(ca_1si_2)o_3 + \frac{1}{4}aq$	18.53	2.71	6.83	?
Plombierite . .	$(ca_1si_2)o_3 + 2aq$	15.20	....	....	?
Dioptase	$(cu_1si_2)o_3 + 1aq$	19.67	3.34	5.88	R.
Pectolite	$(ca_5si_{12})o_{17} + 1aq$	18.27	2.78	6.57	C.
Datolite	$(ca_2si_4b_3)o_9 + 1aq$	16.00	2.99	5.35	C.
Apophyllite . . .	$(ca_1si_4)o_5 + 2aq$	15.14	2.35	6.44	T.
Okenite	$(ca_1si_4)o_5 + 2aq$	15.14	2.35	6.44	O.

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* The name pectolite is said to be from the Latin *pecten*, in allusion to the comb-like structure of some varieties of the mineral, but it at the same time suggests the Greek *πηκτός* (curdled or congealed), from which have been derived the chemical terms *pectose* and *pectin*, and the verb *to pectise*, employed by Graham to denote the gelatinizing property of certain substances.

is represented as replacing a portion of silica. They are all native species, some of which have also been artificially formed, and at least one of them, apophyllite, is found of recent origin in the channels of the thermal waters of Plombières, in France, where another species, plombierite, has also been met with. An unnamed pectolitoid was got by Daubrée as a product of the action of superheated water on glass. Belonging to this same tribe are: the zinc-silicate, calamine; the rare species, thorite and cerite; the manganesian silicate, friedelite; pyrosmalite, a ferro-manganesian species containing chlorine; and the copper-silicate, dioptase. The composition of tritomite is not certain, but approaches that of cerite. Here, also, mosandrite probably belongs.

§ 59. We place here also chrysotile, which constitutes the common amianthus, and has hitherto been regarded as a variety of serpentine, with which it agrees in centesimal composition. It is, however, distinguished therefrom by a lower specific gravity, and by its fibrous character, which, like that of amianthoid amphibole, indicates a prismatic crystallization. As will be shown farther on, at least two other species, one phylloid, and another ophitoid, have been confounded under the name of serpentine. While the density of these last is 2.60, or higher, that of chrysotile, according to three determinations, is 2.142, 2.220, and 2.238, the first and the last of these being by E. S. Smith, and according to his analyses, corresponding to specimens containing respectively 2.23 and 3.36 of ferrous oxyd.* If this oxyd be to the magnesia as 1 : 30, it would give for P a value of 15.51, which, with a density of 2.22, would make V=6.98.

Fibrous silicates having the same centesimal composition as the last are, however, met with, having a much higher specific gravity. A well defined mineral, described many years since by the writer, from Bolton (Quebec), under the name of picrolite, is separable into long, rigid, elastic

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* Amer. Jour. Science, 1885, xxix., 32.

fibres, and has, with a specific gravity of 2.607, the composition, silica 43.70, magnesia 40.68, ferrous oxyd 3.51, with traces of oxyds of nickel and chromium, and 12.45 of water, = 100.34.*

§ 60. While the above species of unlike density agree in having the serpentine ratio, 3 : 4 : 2, there are several other hydrous silicates of magnesia which present other ratios, and should, like these, be included among hydrospathoids. Such are the orthorhombic sparry villarsite, with D = 2.98, which has been described as a hydrous chrysolite, and is represented by the atomic formula $(mg_1si_1)o_2 + \frac{1}{4}aq$; and the fibrous crystalline matricite, with D = 2.53, more hydrous in composition, with the formula $(mg_1si_1)o_2 + 1aq$, nearly. The sparry orthorhombic picrosmine, with D = 2.66, which is sometimes fibrous and asbestiform, is a hydrous bisilicate, represented by $(mg_1si_2)o_3 + \frac{1}{2}aq$, and Terreil has very recently described as chrysotile, from an unnamed locality in Canada, with D = 2.56, an asbestiform silicate, which is at once more basic, more hydrous, and heavier than ordinary chrysotile, and approaches matricite in composition. His analysis gives silica 37.10, magnesia 39.94, ferrous oxyd 5.73, alumina, traces, water 16.85 = 99.62. This corresponds very closely to $(mg_{6.5}fe_{0.5}si_8)o_{15} + 6aq$.† These various prismatic hydrous silicates of magnesia, including chrysotile and picrolite, constitute an important group of what may be designated as magnesian pectolitoids, which have for the most part an atomic volume approaching to dioptase and to datolite, and demand farther study, but, with the exception of chrysotile, have not been placed in our table.

§ 61. In the accompanying table (No. I.) of the principal pectolitoids, are given their atomic formulas as deduced from chemical analysis, the unit-weight, P, calculated from these, the density, D (water = 1.00), and the atomic volume, V, which = P ÷ D. In calculating the

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* Geology of Canada, 1863, p. 472.

† Compte Rendu de l'Acad. des Sciences, January 26, 1885.

value of P for these silicates, we have to consider that two or more protoxyd-bases are often present, and that the proportions of these must be estimated as nearly as possible. As the specific gravity of species is in many cases inexactly determined, we have, where more than one value of D is given by mineralogists, selected that which seemed most probably correct, and, where determinations of density are wanting, have left a blank in the table. Of the species in this table, datolite is a borosilicate, pyrosmalite a chlorosilicate, and apophyllite a fluorosilicate.

§ 62. It has been thought well, for reasons which will be apparent when we compare the pectolitoids with other tribes, to represent their contained water by the symbol aq, preceded by the sign +. It will be noted that in the atomic formulas here employed, the symbols of the metals, with those of silicon, boron, and titanium, are placed within parentheses, and those of oxygen, sulphur, fluorine, and chlorine, together with water, without. From this it will be clear that the atomic weight deduced from these formulas must, in order to arrive at P (the weight of the atomic unit), be divided by the number of these units; that is to say, by the sum of the coefficients of the elements outside of the parenthesis. The present table is far from complete; the determinations of density are in many cases uncertain, those assigned to the same species by different observers often presenting wide variations. Again, the value of P in cerite is calculated as if it were simply a silicate of cerium, while it contains unknown proportions of lanthanum, didymium, and samarium. In calculating the value of P for pyrosmalite, it is regarded as a ferrous silicate in which $o_{\frac{1}{8}}$ is replaced by $cl_{\frac{1}{8}}$, equal to 3.46 of chlorine. The general agreement in the value of V is noticeable, save in two cases,—that of dioptase, for which another recorded determination of $D = 3.28$ gives $V = 6.00$, and that of datolite, whose volume shows a condensation approaching to that of the adamantoid protosilicates.

Tribe 2. Protospathoid.

§ 63. In the second tribe, which we have called Protospathoids, shown in table No. II., are the sparry silicates of zinc and manganese, willemite and tephroite, and the ferro-manganesian species, knebelite,—all having the ratio of unisilicates. To these are joined the double silicate of lime and magnesia, batrachite, with gadolinite, a silicate chiefly of yttria, giving apparently the same atomic ratios, and helvite, a silicate of glucina and manganese, remarkable for containing a large amount of sulphur; in which respect it resembles the more basic silicate of glucina, iron and zinc, danalite, belonging to the same tribe. With these are also placed leucophanite, which is interesting as being a fluoriferous silicate of glucina, lime, and

TABLE II.—PROTOSPATHOIDS.*

SPECIES.	FORMULA.	P	D	V	X
Danalite. - - -	$(m_7si_6)o_{13}$ - ($m = gl, fe, zn$) - *a*	22.15	3.43	6.76	I.
Willemite. - -	$(zn_1si_1)o_2$ - - - - - - - -	27.75	4.18	6.63	H.
Batrachite. - -	$(m_1si_1)o_2$ - ($m = ca_{0\cdot5}mg_{0\cdot5}$) - -	10.50	3.03	6.43	O.
Tephroite. - - -	$(mn_1si_1)o_2$ - - - - - - -	25.25	4.12	6.13	O.
Knebelite. - - -	$(m_1si_1)o_2$ - ($m = fe_{0\cdot5}mn_{0\cdot5}$) - -	25.37	4.12	6.15	?
Gadolinite. - -	$(m_1si_1)o_2$ - ($m = gl, yt, fe$) - *b*	25.66	4.20	6.10	O.
Helvite. - - -	$(m_1si_1)o_2$ - ($m = gl, mn$) - - -	20.16	3.30	6.11	I.
Leucophanite. -	$(m_3si_4)o_7$ - ($m = gl, ca, na$) - *c*	18.05	2.97	6.07	O.
Wollastonite. - -	$(ca_1si_2)o_3$ - - - - - - - -	19.33	2.92	6.62	C.
Tscheffkinite. -	$(m_1si_2)o_3$ - ($m = ce, ca, fe$) - *d*	27.00	4.26	6.34	?

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* The formulas employed in calculating the values of P and V for the following species are

a. Danalite — $(gl_{3.0}fe_{2.0}mn_{0.5}zn_{1.5}si_{6.0})o_{12.0}s_{1.0}$.
b. Gadolinite — $(gl_{2.00}yt_{2.00}fe_{0.75}ce_{0.25}si_{4.00})o_{9.00}$.
c. Leucophanite — $(ca_{5.0}gl_{5.0}na_{2.0}si_{16.0})o_{28.0}$.
d. Tscheffkinite — [Damour] $(ce_{0.65}fe_{0.20}ca_{0.15}si_{1.30}ti_{0.70})o_{3.00}$.

soda, having the same atomic ratio for its bases as serpentine and chrysotile. Among bisilicates we find, in this tribe, wollastonite, a simple lime-silicate, and tscheffkinite, a titanosilicate of lime with cerous and ferrous oxyds. All of the silicates of this tribe are decomposed by acids with pectisation.

Tribe 3. *Protadamantoids.*

§ 64. We next proceed to note the adamantoid protosilicates or Protadamantoids, closely connected with the Protospathoids, but distinguished from them by a more condensed molecule and a greater resistance to acids. First in order comes the fluoriferous magnesian silicate, chondrodite, next the double silicate of lime and magnesia, monticellite (which, from its recorded specific gravity, would seem to be a denser silicate, isomeric with the spathoid batrachite), and the chrysolites, belonging to a more condensed type than either. The genus chrysolite includes not only the ordinary more or less ferrous species, but forsterite, on the one hand, and hortonolite and fayalite, on the other. To this succeed the two glucinic species, phenacite and bertrandite, the former of which is the most highly condensed protadamantoid known, while the latter is remarkable for containing a portion of water. Next in order comes the manganesian species, rhodonite, together with the amphiboles and pyroxenes, two important genera, or rather families, which (with the apparent exception of certain amphiboles having the atomic ratio of bases to silica of 4 : 9) are bisilicates. While rhodonite and pyroxene are clinorhombic in crystallization, the magnesian species enstatite, with hypersthene and diaclasite, is orthorhombic. Anthophyllite appears to be an orthorhombic species having the composition of amphibole, and kupfferite, a magnesian amphibole. Their very varied composition, and the great number of bases which enter into the composition of some of the amphiboles and the pyroxenes, are illustrations of the polybasic character of the silicates. With the pyroxenes, some mineralogists have grouped spodumene, ægirite, arfvedsonite, and acmite, the association being based on similarity of crystalline form, and supported by a misconception of their chemical relations. All of these species find their position in the

TABLE III. — PROTADAMANTOIDS.

SPECIES.	FORMULA.	P	D	V	X.
Chondrodite.	$(mg_4si_3)o_7$	18.64	3.20	5.82	O.
Monticellite.	$(m_1si_1)o_2$ - $(m = mg_{0\cdot 5}ca_{0\cdot 5})$	19.50	3.25	6.00	O.
Forsterite.	$(mg_1si_1)o_2$	17.50	3.30	5.30	O.
Chrysolite (1).	$(m_1si_1)o_2$ - $(m = mg_{0\cdot 9}fe_{0\cdot 1}$	18.30	3.40	5.38	O.
Chrysolite (2).	$(m_1si_1)o_2$ - $(m = mg_{0\cdot 8}fe_{0\cdot 2}$	19.10	3.50	5.45	O.
Bertrandite.	$(gl_1si_1)o_2 + \frac{1}{4}aq$	13.22	2.59	5.10	O.
Phenacite.	$(gl_1si_1)o_2$	15.75	3.00	4.58	R.
Amphibole (1).	$(m_1si_2)o_3$ - $(m = mg_{0\cdot 75}, ca_{0\cdot 25})$	17.33	2.97	5.88	C.
Amphibole (2).	$(m_1si_2)o_3$ - $(m = mg_{0\cdot 8}ca_{0\cdot 3}fe_{0\cdot 1})$	18.00	3.06	5.88	C.
Rhodonite.	$(mn_1si_2)o_3$	21.83	3.60	6.06	C.
Pyroxene (1).	$(m_1si_2)o_3$ - $(m = ca_{0\cdot 5}mg_{0\cdot 5})$	18.00	3.27	5.50	C.
Pyroxene (2).	$(m_1si_2)o_3$ - $(m = ca_{0\cdot 5}mg_{0\cdot 5})$	18.00	3.28	5.48	C.
Pyroxene (3).	$(m_1si_2)o_3$ - $(m = ca_{\frac{1}{3}}mg_{\frac{2}{3}})$	17.55	3.22	5.45	C.
Pyroxene (4).	$(m_1si_2)o_3$ - $(m = ca_{\frac{4}{8}}mg_{\frac{3}{8}}fe_{\frac{1}{8}})$	18.66	3.41	5.47	C.
Enstatite (1).	$(m_1si_2)o_3$ - $(m = mg_{0\cdot 9}fe_{0\cdot 1})$	17.20	3.10	5.54	O.
Enstatite (2).	$(m_1si_2)o_3$ - $(m = mg_{0\cdot 8}fe_{0\cdot 2})$	17.73	3.25	5.45	O.
Titanite.	$(ca_1si_2ti_2)o_5$	19.80	3.50	5.65	C.
Guarinite.	$(ca_1si_2ti_2)o_5$	19.80	3.50	5.65	T.
Danburite.	$(ca_1si_4b_3)o_8$	15.37	3.00	5.12	O.

next sub-order, and the place of the last three is near to garnet and to epidote. We have already shown, in § 42, how, on similar grounds, the aluminous species pargasite, glaucophane, and gastaldite have been erroneously placed with amphibole.

§ 65. The relations of amphibole and pyroxene to each other and to wollastonite, as shown in the unlike degrees of condensation made evident by the different values of V, were pointed out by the present writer, in 1853, as examples of isomerism in polysilicates, when the three were represented as belonging to as many homologous types (§ 18). These relations, so far as amphibole and pyroxene are concerned, were mentioned some years later by Dana, in 1868, when he noticed that the pyroxenes have a specific gravity about one tenth greater than that of the corresponding amphiboles.* The chemical difference between these species and the corresponding spathoids is seen in the resistance of both amphibole and pyroxene to acids, which decompose wollastonite. Rhodonite, a manganesian species with the crystalline form of pyroxene, appears, from its volume, to be more closely related to amphibole, and is partly decomposed by acids. Different and unlike varieties of pyroxene agree closely with each other, with enstatite, and with chrysolite, in the value of V, as will be made evident by the accompanying table, No. III. In this, the four pyroxenes compared were examined and analyzed by the writer.

To this tribe of Protadamantoids we add titanite and guarinite, two titanosilicates of unlike crystalline form, but of identical composition and specific gravity. The solubility of titanite in acids has already been noticed, in § 57. Here, also, is the place of danburite, a borosilicate, remarkable for having a value of V near to that of the pectolitoid borosilicate, datolite. The amphiboles, rhodonite, chondrodite, and monticellite, are the adamantoids which approach nearest to the spathoids, from the denser species of which, tephroite, helvite, and leucophanite, they are not far removed in volume.

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* System of Mineralogy, 5th ed., p. 240.

Tribe 4. *Protophylloids.*

§ 66. The phylloid type in the protosilicates is represented by a small number of magnesian minerals, of which the best known is talc, apparently including two species with different atomic formulas, but indistinguishable save by chemical analysis. To these must be added one or more of the species generally classed under the head of serpentine. Among them is thermophyllite, having a recorded density of 2.56–2.61, while marmolite, with a similar composition, should, if its density be really 2.41, constitute another Protophylloid species, as indicated in Table IV. From the structure of these minerals, Dana has suggested that serpentine may be micaceous in crystallization, like talc and chlorite.* This is so far true that a silicate having the centesimal composition of serpentine assumes a phylloid type, as seen in thermophyllite and in marmolite; but it also takes on a prismatic fibrous type in chrysotile and in picrolite, silicates of unlike density, already mentioned in § 65, and is, moreover, found as an amorphous colloid species included in the next tribe, that of the Ophitoids, of which it may be regarded as the type.

TABLE IV. — PROTOPHYLLOIDS.

SPECIES.	FORMULA.	P	D	V	X.
Thermophyllite.	$(mg_3si_4)o_7 + 2aq$	15·33	2·61	5·87	?
Marmolite.	$(mg_3si_4)o_7 + 2aq$	15·33	2·41	6·35	?
Talc.	$(mg_4si_{10})o_{14} + 1aq$	15·93	2·70	5·90	O.
Talc.	$(mg_3si_9)o_{12} + \frac{3}{4}aq$	15·82	2·60	6·07	O.

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* System of Mineralogy, 5th ed., p. 465.

Tribe 5. Ophitoids.

§ 67. In considering this tribe, we begin by noting certain differences in composition and in specific gravity among the magnesian silicates, which (besides thermophyllite, marmolite, picrolite, and chrysotile) have hitherto been grouped under the name of serpentine. A density of from 2.60 to 2.70 is generally assigned to this silicate, but bowenite, according to the analysis of J. Lawrence Smith and Brush, is a nearly pure serpentine, with a density of 2.69 to 2.78, and a hardness of 5.5 to 6.0. Retinalite, a clearly marked ophitoid or amorphous species, which includes much of the serpentine of the Laurentian limestones, is a very pure magnesian silicate, distinguished from ordinary serpentine by its lower density, and its larger proportion of water, which, from several analyses, the writer found to be over fifteen hundredths. The specific gravity of retinalite is 2.36 to 2.38, or nearly that assigned to the phylloid species marmolite. The name of

TABLE V. — OPHITOIDS.

SPECIES.	FORMULA.	P	D	V
Serpentine. - -	$(mg_3si_4)o_7 + 2aq$	15·33	2·65	5·78
Retinalite. - -	$(mg_3si_4)o_7 + 2\frac{1}{2}aq$	15·00	2·40	6·25
Deweylite. - -	$(mg_2si_3)o_5 + 3aq$	14·00	2·25	6·22
Genthite. - - -	$(ni_2si_3)o_5 + 3aq$	18·25	2·40	7·60
Aphrodite. - -	$(mg_1si_2)o_3 + \frac{3}{4}aq$	15·13	2·21	6·84
Cerolite. - - -	$(mg_1si_2)o_3 + 1\frac{1}{2}aq$	14·11	2·30	6·13
Chrysocolla. - -	$(cu_1si_2)o_3 + 2aq$	17·53	2·24	7·82
Spadaite. - - -	$mg_5si_{12})o_{17} + 4aq$	15.04	—— ?	....
Rensselaerite. -	$(mg_4si_{10})o_{14} + 1aq$	15·93	2·70	5·90
Sepiolite. - - -	$(mg_1si_3)o_4 + 1aq$	14·80	—— ?	....
Glauconite. - -	- - - - - -	....	....	....

serpentine may, perhaps, be retained for the amorphous silicate with density 2.6 to 2.7, which must be distinguished from retinalite, as well as from chrysotile, from picrolite, from thermophyllite, and from marmolite. This last requires farther study, as does, likewise, bowenite, which merits particular notice from its superior density and hardness, and requires optical examination.

§ 68. Following serpentine and retinalite in Table V. are deweylite and genthite, — the latter a niccoliferous ophitoid, as chrysocolla is a cupric one. With the latter are placed the bisilicates aphrodite and cerolite, which last appears to have the volume of retinalite and of deweylite. After these we have placed spadaite, as also rensselaerite or pyrallolite (which is, perhaps, a compact phylloid rather than an ophitoid), and sepiolite. Alongside of this, a position has been conjecturally assigned to glauconite as not improbably a ferrous potassic ophitoid, of which a large part of the iron has subsequently passed into the ferric condition. (See, for a discussion of its composition, pages 196–198.)

§ 69. The significance of this tribe of amorphous hydrous silicates in mineralogy will be more apparent when we come to study the corresponding tribes among the other two sub-orders of silicates, and among the non-silicated oxyds. In each of these we find a group of compounds which, although, in parallel tribes, occasionally assuming crystalline form, require for their crystallization conditions not always present. The particular silicate of magnesia which constitutes serpentine, although sometimes crystallizing in hydrous forms, as in thermophyllite and chrysotile, appears incapable of forming an anhydrous species like the more and the less basic crystalline silicates of the same base, such as chrysolite and enstatite. Hence we often find the hydrous colloid, serpentine, still associated with the one or the other of these, into a mixture of which it is resolved when its dehydration and fusion are effected by heat.

Tribe 6. *Zeolitoids.*

§ 70. The sixth tribe, being the first in the sub-order of the Protopersilicates, has been designated Zeolitoid for the reason that it includes, and is chiefly represented by, that large family of silicates familiarly known as zeolites, which have been aptly described as hydrated feldspars. These are double silicates of a protoxyd-base and alumina, the atomic ratio between the two being 1 : 3, and the protoxyds essentially lime and alkalies, occasionally with baryta and strontia, — magnesia being for the most part absent, or found only in traces. The proportion of silica varies from that of thomsonite, which gives the ratios 1 : 3 : 4, to stilbite and related species, with 1 : 3 : 12. The water is also subject to great variations, and is held with different degrees of force — some species, such as laumontite and chabazite, parting with a portion in dry air at ordinary or slightly elevated temperatures, while others are much more stable. The intumescence before the blowpipe-flame, which is characteristic of many species of this family, and which suggested the name of "zeolite," would seem to indicate that a partial melting of these takes place before the complete expulsion of water, or, in other words, that the silicate fuses in its water of crystallization. The zeolites are attacked by acids, generally with pectisation, and are but little condensed, having high values for V. We have given, in the accompanying table (No. VI.), some of the more important species of this large family. Pollucite, from the analysis of Rammelsberg, is a zeolite, in which two-thirds of the protoxyd-base is oxyd of cæsium.

§ 71. In the same tribe of Zeolitoids we place several other hydrous silicates, which are distinguished from the zeolites by presenting different ratios between the protoxyd and sesquioxyd bases. The species here called hamelite was described by the writer many years since as a crystalline hydrous silicate of ferrous oxyd, magnesia,

TABLE VI.—ZEOLITOIDS.

SPECIES.	FORMULA.	P	D	V	X
Xanthorthite.	$(m_1al_1si_2)o_4 + 2aq$ - $(m = ce, fe)$	....	2.90	...	C.
Hamelite.	$(m_1al_2si_3)o_6 + 1aq$ - $(m = mg, fe, na)$	....	...	...	?
Catapleiite.	$(m_1zr_2si_6)o_9 + 2aq$	18.09	2.80	6.46	H.
Cancrinite.	$(na_6al_{18}si_{27})o_{51} + 3c_1ca_1o_3 + 4\frac{1}{2}aq$	....	2.42	...	H.
Thomsonite.	$(m_1al_3si_4)o_8 + 2\frac{1}{2}aq$ - $(m = ca_{\frac{1}{4}}na_{\frac{3}{4}})$	13.58	2.38	6.54	O.
Gismondite.	$(ca_1al_3si_{4\cdot50})o_{8\cdot50} + 4\frac{1}{2}aq$	14.38	2.26	6.36	O.
Natrolite.	$(na_1al_3si_6)o_{10} + 2aq$	15.83	2.25	7.03	O.
Scolecite.	$(ca_1al_3si_6)o_{10} + 3aq$	15.08	2.40	6.28	C.
Mesolite.	$(m_1al_3si_6)o_{10} + 3aq$ - $(m = ca_{\frac{2}{3}}na_{\frac{1}{3}})$	15.15	2.40	6.31	C.
Levynite.	$(ca_1al_3si_6)o_{10} + 4aq$	14.64	2.16	6.77	R.
Pollucite.	$(m_1al_3si_8)o_{12} + 1aq$ - $(m = cs_{\frac{2}{3}}na_{\frac{1}{3}})$	21.46	2.90	7.40	I.
Analcite.	$(na_1al_3si_8)o_{12} + 2aq$	15.71	2.29	6.86	I.
Eudnophite.	$(na_1al_3si_8)o_{12} + 2aq$	1[illegible].71	2.27	6.92	O.
Laumontite.	$(ca_1al_3si_8)o_{12} + 4aq$	14.68	2.30	6.38	C.
Herschelite.	$(m_1al_3si_8)o_{12} + 5aq$ - $(m = na_{\frac{3}{4}}k_{\frac{1}{4}})$	14.76	2.06	7.16	O.
Phillipsite.	$(m_1al_3si_8)o_{12} + 5aq$ - $(m = ca_{\frac{2}{3}}na_{\frac{1}{3}})$	14.41	2.20	6.55	O.
Chabazite.	$(ca_1al_3si_8)o_{12} + 6aq$	14.05	2.19	6.41	R.
Gmelinite.	$(m_1al_3si_8)o_{12} + 6aq$ - $(m = ca_{\frac{1}{2}}na_{\frac{1}{2}})$	14.11	2.17	6.50	R.
Faujasite.	$(m_1al_3si_9)o_{13} + 9aq$ - $(m = na_{\frac{1}{2}}ca_{\frac{1}{2}})$	13.45	1.92	7.00	I.
Hypostilbite	$(ca_1al_3si_9)o_{13} + 6aq$	14.10	2.20	6.40	?
Harmotome.	$(m_1al_3si_{10})o_{14} + 5aq$ - $(m = ba_{\frac{9}{10}}na_{\frac{1}{10}})$	16.73	2.45	6.82	O.
Epistilbite.	$(ca_1al_3si_{12})o_{16} + 5aq$	14.47	2.25	6.43	O.
Brewsterite.	$(m_1al_3si_{12})o_{16} + 5aq$ - $(m = sr_{\frac{2}{3}}na_{\frac{1}{3}})$	15.27	2.45	6.23	C.
Stilbite.	$(ca_1al_3si_{12})o_{16} + 6aq$	14.23	2.20	6.46	O.
Heulandite.	$(ca_1al_3si_{12})o_{16} + 5aq$	14.47	2.20	6.58	C.
Edingtonite.	$(ba_1al_4si_7)o_{12} + 4aq$	17.84	2.71	6.58	T.
Sloanite.	$(ca_1al_5si_7)o_{13} + 3aq$	15.31	2.44	6.27	O.
Forestite.	$(ca_1al_6si_{12})o_{19} + 6aq$	14.56	2.40	6.06	O.

and soda, which is found filling the pores of a paleozoic crinoid,* while catapleiite is a zirconic zeolitoid, in which zirconia takes the place of alumina. Here also we have

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* Amer. Jour. Science, 1871, i., 379; see also *ante*, p. 194, for details.

placed xanthorthite, a hydrous species which, by its composition and its low density, is widely separated from the anhydrous dense adamantoid orthite, or allanite, to be noticed farther on. While the species just noticed are more protobasic than the zeolites, there are not wanting examples of zeolitoid species less protobasic than these. Such is the curious barytic silicate, edingtonite, to which analysis assigns for protoxyds and alumina the ratio, 1:4; sloanite, zeolitic in habit, with a ratio of 1 : 5, and forestite, a species closely resembling stilbite, to which is given the ratio, 1 : 6. The hydrous carbosilicate, cancrinite, and the sulphatosilicate, ittnerite, which properly belong to the zeolitoids, will be noticed under the following tribe, in §§ 83, 84.

Tribe 7. *Protoperspathoids.*

§ 72. We have next to consider the Protoperspathoids, which include, besides the feldspars and the scapolites, a number of other species of double silicates, chiefly aluminous. The species of this tribe are distinguished from the preceding by their higher density, superior hardness, and greater resistance to acids; since, while the whole of the zeolites and zeolitoids are decomposed thereby, generally with pectisation, only the more basic of the protoperspathoids are thus attacked.

The feldspars, like the zeolites, have the atomic ratio between the protoxyds and alumina represented by 1 : 3, the silica in both being subject to the same variations. As in the zeolites, the protoxyd-bases are alkalies and lime, rarely with baryta, while magnesia and ferrous oxyd are but exceptionally present. Unlike the zeolites, they are anhydrous, or contain occasionally one or two hundredths of water.

§ 73. The feldspar family includes, first, the feldspars proper, represented by the anorthite-albite genus; secondly, orthoclase, microcline, and hyalophane, near which may be placed nephelite and paranthite; and, thirdly,

TABLE VII. — PROTOPERSPATHOIDS.

SPECIES.	FORMULA.	P	D	V	X
Melilite.	$(ca_2m_1si_3)o_8$ - $(m = al\frac{1}{2}fi\frac{1}{2})$	20.46	3.10	6.60	T.
Eudialyte.	$(m_4zr_2si_{12})o_{16}$ - $(m = na_{1\cdot5}ca_{1\cdot5}fe_{1\cdot0})$	20.30	3.00	6.76	R.
Wöhlerite.		....	3.41	...	C.
Humboldtilite.	$(ca_3al_2si_5)o_{10}$	19.30	2.90	6.65	T.
Ilvaite.	$(m_3fi_2si_5)o_{10}$ - $(m = fe\frac{2}{3}ca\frac{1}{3})$	[illegible]	3.71	6.15	O.
Gehlenite.	$(ca_{1\cdot0}m_{1\cdot0}si_{1\cdot3})o_{3\cdot3}$ - (m = al[illegible])	[illegible]	3.06	6.48	T.
Sarcolite	$(ca_1al_1si_2)o_4$	18.75	2.93	6.40	T.
Milarite.	$(m_1al_1si_8)o_{10}$ - $(m = ca_{0\cdot8}k_{0\cdot2})$	13.88	2.59	6.51	O.
Barylite.	$(ba_2al_3si_7)o_{12}$	25.75	4.03	6.38	?
Meionite.	$(ca_4al_9si_{12})o_{25}$	17.80	2.74	6.49	T.
Wernerite.	$(m_4al_9si_{18})o_{29}$	17.41	2.70	6.44	T.
Ekebergite.	$(m_4al_9si_{18})o_{31}$	17.42	2.74	6.32	T.
Mizzonite.	$(m_4al_9si_{21})o_{34}$	17.20	2.62	6.56	T.
Dipyre.	$(m_4al_9si_{24})o_{37}$	16.89	2.64	6.39	T.
Marialite.	$(m_4al_9si_{36})o_{49}$	16.43	2.57	6.39	T.
Sodalite.	$(na_1al_9si_{12})o_{24}cl_1$	19.88	2.30	8.28	I.
Nosite.	$(na_1al_3si_4)o_8 + \frac{1}{3}na_1s_1o_4$	20.28	2.40	8.25	I.
Hauÿne.	$(na_1al_3si_4)o_8 + \frac{2}{3}ca_1s_1o_4$	21.60	2.50	8.64	I.
Lapis lazuli.		....	2.45	...	I
Leucite.	$(k_1al_3si_8)o_{12}$	18.16	2.56	7.09	I.
Hyalophane.	$m_1al_3si_8)o_{12}$ - $(m = ba\frac{1}{2}k\frac{1}{2})$	19.39	2.80	6.92	C.
Orthoclase.	$(k_1al_3si_{12})o_{16}$	17.37	2.54	6.83	C.
Microcline.	$(k_1al_3si_{12})o_{16}$	17.37	2.54	6.83	A.
Nephelite.	$(na_1al_3si_{4\cdot5})o_{8\cdot5}$	17.58	2.66	6.60	H.
Paranthite.	$(ca_1al_3si_4)o_8$	17.37	2.75	6.31	T.
Eucryptite.	$(li_1al_3si_4)o_8$	15.75	2.67	5.93	H.
Anorthite.	$(ca_1al_3si_4)o_8$	17.37	2.75	6.32	A.
Barsowite.	$(ca_1al_3si_5)o_9$	17.11	2.73	6.27	?
Labradorite.	$(m_1al_3si_6)o_{10}$ - $(m = ca\frac{3}{4}na\frac{1}{4})$	16.97	2.70	6.28	A.
Andesite.	$(m_1al_3si_8)o_{12}$ - $(m = ca\frac{1}{2}na\frac{1}{2})$	16.70	2.68	6.23	A.
Oligoclase.	$(m_1al_3si_9)o_{13}$ - $(m = na\frac{3}{4}ca\frac{1}{4})$	16.63	2.65	6.27	A.
Albite.	$(na_1al_3si_{12})o_{16}$	16.37	2.62	6.24	A.
Iolite.	$(m_1al_3si_5)o_9$ - $(m = mg\frac{2}{3}fe\frac{1}{3})$	16.81	2.67	6.29	H.
Petalite.	$(li_1al_4si_{20})o_{25}$	15.32	2.42	6.33	C.

leucite. These distinctions, as may be seen from the table No. VII. correspond to different values of V. Iolite, a ferro-magnesian feldspathide, though peculiar in composition, and differing in crystallization from the feldspars, agrees in volume with anorthite and albite. Eucryptite, which has the formula of a lithia-anorthite, seems to differ from these in possessing a more condensed molecule. The possibility of a more silicious feldspar than albite, corresponding to the supposed krablite of Forchhammer, with its ratios of 1 : 3 : 24, should not be overlooked. The specific gravities of orthoclase and microcline show for these species a considerably greater atomic volume than for albite and its related species, a fact which was noted in 1854 by the writer as a reason for referring orthoclase to a less condensed molecule than these (§ 30). Nephelite also shows a volume near that of orthoclase, as does the baryta-potash feldspar, hyalophane, which has the same general atomic formula as andesite; while leucite, with the same atomic formula, has a still larger volume.

§ 74. The history of that feldspar genus which includes the species anorthite and albite has been noticed at length on pages 294–296, where was discussed the view that the feldspars intermediate in composition between these may be mixtures of two homœomorphous species. The notion was there expressed that while such mixtures are, as was long since suggested, not uncommon in nature, many if not all of these intermediate feldspars are really definite species. The careful studies of the late George W. Hawes have thrown much light on this subject, by showing that in similar and apparently identical rocks the feldspathic element may be represented by two associated feldspars of the same genus, — in one case, apparently, anorthite and albite; in another, labradorite and andesite. The diabase which along the Atlantic border of North America is found irrupted among mesozoic strata, from Nova Scotia to North Carolina, is singularly uniform in chemical composition and in density, and by many observers has been found to be essentially an admixture of pyroxene, magnetite, and a triclinic feldspar, which has been represented as labradorite, and with which the composition of the rock, as a whole, accords.* Hawes, however, observed that this diabase, as found at West Rock, New Haven, Connecticut, includes anorthite, of which the larger feldspathic grains are composed, and showed by calculation that the rock might contain, in 100.00 parts, anorthite 15.52, albite 22.16, orthoclase 2.32, the remainder being pyroxene with a little menaccanite and magnetite; apatite and some combined water being present.

A farther attempt to determine the composition of the feldspathic element in a similar diabase was then made with that from the Palisades of the Hudson at Jersey City. The feldspar from this, separated from the other ingredients by the aid of a solution of potassio-mercuric iodid of specific gravity 2.90, was, by a similar solution, of 2.69, clearly divided into two portions, a lighter and a heavier, which gave by analysis, respectively, the composition very nearly of andesite and of labradorite, — the atomic ratios for the first portion being 1 : 3 : 8 and for the second 1 : 3 : 6½, without including 0.59 of water in the first and 1.06 in the second. Hawes reasons with regard to these facts, that slight variations in the conditions of cooling in a fused mass might determine either the separation of the feldspathic element as the two species, anorthite and albite, or the formation of one or more intermediate species. He adds, with rare insight, "An exquisite balance of composition and circumstance would be necessary to crystallize such a rock with a single feldspar," and conceives that we have evidence that massive rocks are rarely simple as regards their feldspathic element,† as was previously shown by Fouqué for the recent

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* See J. D. Dana, Amer. Jour. Science, vi., 194.

† Proc. U. S. National Museum for 1881, pp. 129–134.

lavas of Santorin (*ante*, page 213). Meanwhile it will remain to be decided for each individual case, whether a feldspathic material intermediate in composition between albite and anorthite is an integer, or an admixture of two integers, which may themselves be either the extremes of the series or integral intermediate species.

Mention should here be made of petalite, a species in many respects closely related to the feldspars, but presenting the ratios 1 : 4 : 20. As regards the proportion between protoxyds and alumina, it is important as the one spathoid which corresponds with the rare and less protobasic zeolitoids; while if krablite be rejected, petalite is the most silicious species known. Its atomic volume is identical with that of anorthite, albite, and iolite.

§ 75. The scapolites apparently constitute a single genus of silicates which, approaching in composition, hardness, and density the feldspars, were, from an early time, compared with them, so that when, in 1854, the writer attempted to generalize the notion of Von Waltershausen as to crystalline intermixtures in the intermediate feldspars, he extended, as already shown (§ 31), a similar view to the scapolites. The ratio between the protoxyds and alumina in the scapolites has, until recently, generally been regarded as 1 : 2, and the writer, in 1863, in farther discussing the relations of the scapolites, described them as a group of which the extreme terms were meionite, with the ratios 1 : 2 : 4, and dipyre, with 1 : 2 : 6; including intermediate species which might be regarded as crystalline admixtures of the two isomorphous silicates.

Very recently, however, Tschermak has reviewed the scapolites,* and has reached the conclusion that the atomic ratio of the protoxyds to alumina therein is not 1 : 2, as hitherto supposed, but 4 : 9, or 1 : $2\frac{1}{4}$. In other words, if we would compare them with the feldspars by multiplying their atomic formulas so as to get in each the same amount of silica, while anorthite becomes $(\mathrm{ca_3al_9si_{12}})\mathrm{o_{24}}$,

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* Monatshefte für Chemie, December, 1883.

meionite is not $(ca_4al_8si_{12})o_{24}$, but, according to Tschermak, $(ca_4si_9si_{12})o_{25}$; that is to say, the ratio of al : si in the two species remaining unchanged, there is an addition of an atom of ca_1o_1. But dipyre, which was made the other term of the series, is no longer the most silicic scapolite. This, in accordance with the former notation, would be 1 : 2 : 9, or, multiplying and correcting to bring the formula into accordance with Tschermak's conclusion, 4 : 9 : 36. Reverting to the simplest atomic formulas, the two scapolites which form the extremes of our series differ from anorthite, and from albite, in containing each one third of an atom additional of protoxyd, being $(ca_1al_3si_4)o_{12} + \frac{1}{3}m_1o_1$ and $(m_1al_3si_{12})o_{16} + \frac{1}{3}m_1o_1$. Multiplying by three, to compare with the formula given above for meionite, we have, for this last and most silicic scapolite, $(m_4al_9si_{36})o_{49}$, which represents the marialite of Pianura, described by Vom Rath.

§ 76. The scapolites, however, contain more or less chlorine, as observed by F. Adams, and by others. Found in small quantities in meionite, it equals in some examples 2.48 per cent, though apparently absent in marialite. The theoretical chloriferous scapolite is, however, according to Tschermak, a marialite in which, with the above formula, one atom of oxygen is replaced by chlorine (4.20 per cent), or, in other words, is albite $(m_1al_3si_{12})o_{16} + \frac{1}{3}na_1cl_1$, the additional basic element being here chlorid instead of oxyd. In the scapolites, as in the feldspars, in ascending the series, there appears a progressive increase in alkalies, which gradually replace the lime, until in mizzonite and marialite we find considerable soda, and some potash. A general decrease in density is at the same time apparent, but more accurate determinations of this factor are needed for the scapolites. We have, in the preceding table, page 337, revised the atomic formulas so as to correspond with the ratio of 4 : 9 for protoxyds and alumina.

The intermediate scapolites of the meionite-marialite series are imagined by Tschermak to be, not as proposed by Von Waltershausen and myself, crystalline intermixtures, but binary combinations, in different proportions, of the two silicates, meionite and marialite. He notes, (1) compounds holding one equivalent of marialite to two of meionite, which are almost or completely soluble in acids; (2) compounds with one of meionite to two of marialite, — incompletely soluble; and (3) compounds with less than the latter proportion of marialite, — insoluble in acids. This variation in solubility will, in the chemist's eyes, be, as already shown (§ 32), a reason for rejecting the notion that they are admixtures, while he will at the same time repudiate the attempt to perpetuate in their formulas the dualistic notions of a former day. These intermediate scapolites, like the feldspars, labradorite, and oligoclase, and the various zeolites between thomsonite and stilbite, must be regarded as distinct species.

§ 77. In close relation to the scapolites comes a remarkable group comprising sodalite, nosite, and hauÿne. Sodalite has the atomic formula of a chlorinated soda-meionite, being $(na_4al_9si_{12})o_{24}cl_1$. Nosite is a similar species, in which the chlorine is replaced by oxysulphion, while hauÿne is another species, in which the proportion of protoxyd-base is greater than in these, giving the ratio 5 : 9 : 12. The relations of these various species to anorthite and to each other, may, if anorthite be written $(ca_3al_9si_{12})o_{24}$, be represented as follows: meionite, $(ca_3al_9si_{19})o_{24} + ca_1o_1$; sodalite, $(na_3al_9si_{12})o_{24} + na_1cl_1$; nosite, $(na_3al_9si_{12})o_{24} + na_1s_1o_4$; hauÿne, $(na_3al_9si_{12})o_{24} + 2(ca_1s_1o_4)$. Both of these sulphatic species contain also small amounts of chlorine. Ittnerite is a hydrous species related to these, but containing a smaller proportion of sulphates than either, and, like the associated scolopsite, requires farther study. Lapis-lazuli, a sulphatic and sulphuretted species, the composition of which is not accurately determined, is apparently related to the sodalite group. Notwithstanding the resemblance in composition between these silicates and the scapolites, they differ very widely from the latter in degree of condensation; for, while the scapolites approach the feldspars in volume, the species of the sodalite group give a higher value for V than leucite, or indeed than any other known natural silicates.

§ 78. The relations between anorthite, meionite, and the silicates, sodalite, nosite, and hauÿne, which we include under the general name of the sodalite group, help us to understand the nature of cancrinite, and its relation to nephelite. This latter species, which has an atomic volume near that of orthoclase, is a little more silicious than anorthite, and its atomic formula, $(na_{1\cdot0}al_{3\cdot0}si_{4\cdot5})o_{8\cdot5}$, may be multiplied by six, making it $(na_6al_{18}si_{27})o_{51}$, to show more simply its relation to cancrinite. This mineral, which was formerly imagined to be an admixture of carbonate of lime with a hydrated nephelite, appears from recent studies to be an integral carbosilicate, comparable with the sulphatosilicates and the chlorosilicates of the sodalite and scapolite groups. The cancrinite of Miask, with a specific gravity of 2.45, as analyzed by Rauff, is represented by $(na_6al_{18}si_{27})o_{51} + 3(c_1ca_1o_4) + 4\frac{1}{2}aq$ $(c=6)$, while the cancrinite of Ditro, according to Koch, contains a portion of potash, and offers slight variations from the above formula in the amounts of lime and silica. This hydrous carbosilicate, like the hydrous sulphatosilicate ittnerite, will find a place among zeolitoids rather than among spathoids, and is inscribed in table No. VI., page 335.

§ 79. Coming next to more highly protobasic spathoids, we have the remarkable barytic species, barylite, presenting the anomaly of a highly basic silicate which, while having the ratios 2 : 3 : 7, and the volume of the feldspars and scapolites, is said to resist the action of acids. Milarite, sarcolite, and gehlenite present an interesting group in which, the ratio of protoxyd to alumina being 1 : 1, there is a great variation in the proportion of silica, from 1 : 1 : 8, in milarite, to 1 : 1 : 2, in sarcolite, and 1 : 1 :

$1\frac{1}{3}$ in gehlenite. In the native gehlenite a small portion of alumina appears to be replaced by ferric oxyd, but the artificial gehlenite from furnace-slags, analyzed by Percy, is without iron, and is an oxysulphid, containing 1.50 per cènt of sulphur. Melilite, a spathoid silicate, is also found as a furnace-product, and, according to Percy, contains a variable amount of sulphur, equal in one case to 1.62 per cent, while the native melilite is destitute of sulphur. Under this name are, perhaps, confounded two distinct species. The artificial melilite, which approaches the so-called humboldtilite in composition, has an atomic formula near to $(ca_3al_2si_5)o_{10}$, and a volume almost identical with gehlenite, while the native melilite is more nearly $(ca_2al_1si_3)o_6$. Similar atomic ratios to the last, as regards the bases, are presented by eudialyte, a zirconic spathoid, the composition of which is nearly represented by $(m_4zr_2si_{12})o_{18}$, and which contains much lime and soda, with a little chlorine. The atomic formula of wöhlerite, another zirconic spathoid, containing some niobic acid replacing silica, also with lime and soda, is not well established. In these two species we have examples of the complete replacement of alumina by zirconia. In melilite as analyzed by Damour, and also in gehlenite, a partial replacement of alumina by ferric oxyd is shown, and a complete substitution of this kind appears in ilvaite, a spathoid species having a density of 3.71. The higher specific gravity of 4.00, observed for some examples of ilvaite, may show a related species, or more probably, as suggested by Dana, may be due to an admixture of göthite or other iron-oxyd. Of the species included in this tribe, wöhlerite, is a niobosilicate, eudialyte, the scapolites, and sodalite are silicates more or less chlorinated, nosite and hauÿne are sulphatosilicates, while lapis lazuli is also sulphuretted.

Tribe 8. *Protoperadamantoids.*

§ 80. We come next to the Protoperadamantoids, a very important tribe. Beginning with the most highly

TABLE VIII.—PROTOPERADAMANTOIDS.

SPECIES.	FORMULA.	P	D	V	X
Pargasite.	$(m_2al_1si_3)o_6$ - $(m = ca_{0\cdot5}mg_{1\cdot5})$	17.60	3.05	5.79	C.
Keilhauite.	$(m_2\mathit{m}_1si_4ti_3)o_{10}$	...	3.72	...	C.
Schorlomite.	$(ca_4fi_3si_6ti_4)o_{17}$	21.41	3.80	5.63	?
Idocrase.	$(ca_3al_2si_5)o_{10}$	19.30	3.40	5.67	T.
Garnet.	$(ca_1al_1si_2)o_4$	18.75	3.50	5.37	I.
Allanite.	$(m_1al_1si_2)o_4$ - $(m = ce_{\frac{1}{3}}ca_{\frac{1}{3}}fe_{\frac{1}{3}})$	21.67	4.00	5.42	C.
Ægirite.	$(m_3fi_3si_{12})o_{18}$ - $(m_3 = na_1ca_1fe_1)$	19.72	3.58	5.50	C.
Beryl.	$(be_3al_3si_{12})o_{18}$	14.92	2.70	5.52	H.
Euclase.	$(be_2al_3si_4)o_9 + 1aq$	14.50	3.10	4.67	C.
Arfvedsonite.	$(m_2fi_3si_{10})o_{15}$ - $(m_2 = na_1ca_1)$	19.26	8.59	5.33	C.
Ardennite.	$(mn_2al_3si_4)o_9 + 1aq$	...	3.62	...	O.
Axinite.	$(ca_1\mathit{m}_2si_{3\cdot5}bo_{0\cdot5})o_7$ - $(\mathit{m}_2 = al_{\frac{4}{3}}fi_{\frac{2}{3}})$	18.11	3.27	5.53	A.
Epidote.	$(ca_1\mathit{m}_2si_3)o_6 + \frac{1}{3}aq$ - $(\mathit{m}_2 = al_{\frac{4}{3}}fi_{\frac{2}{3}})$	18.38	3.40	5.40	C.
Zoisite.	$(ca_1al_2si_3)o_6$	17.83	3.35	5.32	O.
Jadeite.	$(na_1al_2si_6)o_9$	16.88	3.32	5.08	?
Gastaldite.	$(m_1al_2si_6)o_9$	17.08	3.04	5.61	C.
Glaucophane.	$(m_3al_2si_8)o_{13}$	17.57	3.12	5.63	C.
Prehnite.	$(ca_2al_3si_6)o_{11} + 1aq$	16.66	2.95	5.64	O.
Acmite.	$(m_2fi_4si_{12})o_{18}$ - $(m_2 = na_{1\cdot5}fe_{0\cdot5})$	19.50	3.53	5.52	C.
Spodumene.	$(li\text{-}al_4si_{10})o_{15}$	15.53	3.18	4.88	C.
Sapphirine.	$(mg_1al_4si_1)o_6$	17.16	3.48	4.90	O.
Staurolite.	$(fe_1al_4si_{2\cdot5})o_{7\cdot5} + \frac{1}{3}aq$	18.45	3.75	4.92	O.
Coronite.	$(m_1al_3si_5)o_9$	16.36	3.05	5.36	R.
Schorlite.	$(m_1al_4si_6)o_{11}$	16.68	3.10	5.38	R.
Aphrizite.	$(m_1al_6si_8)o_{15}$	17.24	3 20	5.38	R.
Indicolite.	$(m_1al_9si_{12})o_{22}$	16.42	3.08	5.33	R.
Rubellite.	$(m_1al_{12}si_{15})o_{28}$	16.06	3.00	5.35	R.

protobasic species, we find in the first line, pargasite, which we have already noticed as an aluminous amphibole, connecting the protopersilicates with the preceding sub-order. With this we place keilhauite, a titaniferous silicate, which, like titanite, is attacked by chlorhydric acid, a character not common to many adamantoids, except the more highly basic species of the first sub-order, and already noticed (§ 57). In keilhauite, one-third of the alumina is replaced by ferric oxyd, and in the titaniferous schorlomite, which is also attacked by the acid, and has a ratio very near to keilhauite, the whole of the sesquioxyd base is ferric, while a partial replacement of the same kind is observed in some varieties of idocrase. Next in order comes garnet, including many species, in some of which ferric or chromic oxyd replaces, more or less completely, alumina; while the protoxyd-base is either wholly lime, or in part magnesia or manganous or ferrous oxyd. The single example of garnet given in table VIII. is that of a pure lime-alumina species examined by the writer.

We have placed allanite near to garnet, for the reason that, according to Rammelsberg, the best determinations give approximately the garnet-ratio, 1 : 1 : 2, rather than that of epidote, 1 : 2 : 3, notwithstanding that the species is homœomorphous with epidote, and is often spoken of as a cerium-epidote, to the atomic ratios of which some analyses apparently conform. A farther study of the group of minerals commonly included under the name of allanite or orthite is required. The great differences in density; the facts that some resist the action of acids, while others are attacked thereby; that some are anhydrous, while others are more or less highly hydrated, — all lead to the conclusion that several species are here included. We have already separated therefrom the so-called xanthorthite, as a cerium-zeolitoid, and it is probable that besides one or two hydrous species, and a true adamantoid, there will be found at least one intermediate spathoid species. The alumina in the allanites is often in part replaced by ferric oxyd. A pure alumina-allanite, with the garnet-ratio, in which the protoxyd-bases are equally divided between cerous and ferrous oxyds and lime, gives the value for V as here calculated. Of the species in the table, keilhauite and schorlomite are titano-silicates, ardennite, a vanadosilicate or arsenosilicate, and axinite, a borosilicate, while both boric oxyd and fluorine enter into the composition of the tourmalines.

§ 81. The glucinic species, beryl, is generally regarded as having the atomic ratio 1 : 1 : 4, and has a volume near to garnet. The late analyses of Penfield* have, however, shown that beryl contains a small and variable amount of alkalies, replacing glucina, besides a portion of water varying from 1.50 to 2.50 per cent. He finds that the composition of the mineral is best expressed by the more complex formula $(gl_5al_6si_{22})o_{33}+4aq$, a change which, however, affects very slightly the values calculated in the table, that of V being thereby changed to 5.48.

Euclase, though closely related to beryl in composition, and, like it, hydrated, shows a much greater condensation. Ardennite, which presents the atomic ratio of euclase, and is also hydrated, is essentially a manganese-alumina silicate, with some magnesia and lime, besides a small portion of vanadate, more or less completely replaced, in some instances, by arsenate. These latter elements are probably comparable, in their relations, to the sulphates in nosite and hauÿne. Abstracting them, we find for the silicate essentially the formula given in the table, which can, however, only be regarded as approximate. Prehnite, although classed by Shepard in the order ZEOLITE, belongs to the present tribe. It has the ratios 2 : 3 : 6, which are those of euclase and ardennite, and like these, and epidote, is hydrated, while its volume is near to those of beryl and idocrase.

The species axinite is noticeable for containing some boric oxyd. The formula which we have deduced in the table, in which one eighth of the silica is thus replaced, and one third of the sesquioxyd is ferric, is, also, but an approximation. The composition of this, like that of beryl, of ardennite, and a great number of polysilicates,

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* Amer. Jour. Science, 1884, xxviii., 25.

cannot be accurately represented by such simple formulas, which, however, suffice to show, with sufficient exactness, the atomic volume and the place of the species in the system.

§ 82. We come next to epidote, the composition of which presents many variations, due in part to a greater or less replacement of alumina by ferric oxyd, and, in the so-called piedmontite, by manganese sesquioxyd. The presence of a small amount of water, equal to about 2.0 per cent, seems, as in beryl, euclase, and ardennite, to be essential to the composition of the species. The atomic formula for a pure lime-alumina epidote, as imagined by Rammelsberg, is $(ca_1al_2si_3)o_6$; but such an epidote is unknown in nature, and we have, for the purpose of determining the volume of the species, selected a variety in which one third of the sesquioxyd is ferric. The formula, moreover, takes no note of the small amount of water present in the species.

Zoisite is essentially a lime-alumina silicate, seldom containing over five or six hundredths of ferric oxyd, and often traces only. It is not improbable that the true ratio of the protoxyd and sesquioxyd bases in these two species, as in meionite, with which they have been paralleled, may be represented by 4 : 9, rather than by 1 : 2. We note next the more silicious jadeite, whose formula, as already pointed out (§ 31), is related to that of zoisite as that of dipyre is to meionite. While zoisite is essentially a calcic species, seldom containing over three or four hundredths of soda, jadeite is sodic, and it appears, like the compact zoisite or saussurite, to be anhydrous. The atomic volume of jadeite, as shown in the table, appears to be less than those of garnet, epidote, and zoisite, showing a more condensed molecule. Gastaldite has the atomic formula of jadeite $(m_1al_2si_6)o_9$, but, with a density 3.044, gives a volume of 5.61.

§ 83. We have next to notice three remarkable adamantoids, closely related to those just mentioned, and also to the spathoid, ilvaite. In garnet, axinite, epidote, and keilhauite, the sesquioxyd may be in large part ferric, and in schorlomite and ilvaite it is entirely so, the protoxyd-bases in these being chiefly lime, magnesia, and ferrous oxyd. We have in ægirite, arfvedsonite, and acmite, three well defined protopersilicates in which the sesquioxyd is entirely ferric and the protoxyd in large part sodic. These three species, which have hitherto been little understood, will be seen from the table to be related, respectively, ægirite to garnet, acmite to epidote, and arfvedsonite to euclase, and to have a common value for V very near to that of garnet and epidote.

The presence in each of these ferric species of large amounts of soda, equal to ten or twelve hundredths, is the more remarkable since the aluminous silicates with which we have compared them contain little or no alkali. This association recalls the highly alkaliferous character of another iron-silicate, glauconite. While these three homœomorphous species, all ferric bisilicates with soda, having very different ratios between protoxyds and sesquioxyds, are, from their condensed molecules and their indifference to acids, assigned a place among adamantoids, the related species, ilvaite, with a larger volume, has been placed among the spathoids. It is possible, from the analysis of Rammelsberg, that babingtonite may be a ferric species belonging to the one or other of these tribes, but without farther analyses it would be premature to fix its place.

§ 84. We come next to spodumene, a lithia-alumina species with the atomic ratio 1 : 4 : 10, remarkable for its great condensation and its volume of 4.88. It is instructive to compare it with the still more silicious lithia-alumina silicate, petalite, which, with its lower density, has a volume of 6.33, and takes its place among the spathoids. The relations between these two silicates are analogous to those between zoisite or jadeite and a scapolite like marialite. While these two lithia-bearing species, with the ratio of protoxyd to alumina of 1 : 4, are among the most silicious known, sapphirine, which has the same ratio, is the most basic, and, with its atomic formula of $(mg_1al_4si_1)o_6$, serves to connect the silicates with the spinellids, while, by its great condensation, it takes a place by the side of spodumene.

Staurolite is essentially an aluminous double silicate, with the ratios of 1 : 4 : 2½, the protoxyds being ferrous oxyd with a little magnesia and, rarely, a portion of oxyd of zinc. In one variety it would seem that manganese-sesquioxyd replaces a portion of alumina, and a small portion of water appears to be an essential element. Omitting the water, we get a volume of 5.01.

§ 85. We come now to the tourmalines, a family of silicates which, perhaps, might be called a sub-tribe, since the five distinct species, representing as many genera, differ from each other not only as the related silicates, albite, labradorite, and anorthite, or as zoisite and jadeite, but also, at the same time, as anorthite differs from meionite, or as lime-garnet from idocrase or epidote. In other words, not only the relations of the protoxyds to the sesquioxyds, but the relations of both of these to the silica, are subject to notable variations in species of tourmaline which so closely resemble each other that it is difficult, if not impossible, to distinguish them by physical characters alone. The studies of Rammelsberg, which first clearly showed the varying composition of the tourmalines, enabled him to divide them into five species, each of which is the type of a genus, distinguished by the ratios of protoxyd to sesquioxyd. We follow him in regarding the boric oxyd, which is not constant in amount, as replacing silica, and recognize the fact that the tourmalines are oxyfluorids containing a small and variable amount of fluorine.

For the brown magnesia-tourmaline, the most highly protobasic species, with the atomic ratios of 1 : 3 : 5, a trivial name was needed, and we have ventured to suggest that of "coronite," from Crown Point, in New York, a well known locality of this species; while to the black magnesia-iron tourmaline, with the ratios 1 : 4 : 6, we have given the name of "schorlite," from the ancient trivial designation of schorl, under which the tourmalines were formerly included with many other species. The names of "aphrizite" for the black ferrous tourmaline, 1 : 6 : 8; of "indicolite" for the blue and green tourmalines, 1 : 9 : 12, holding both ferrous and manganous oxyds; and of "rubellite" for the red and colorless tourmalines, 1 : 12 : 15, containing manganese but no iron, are familiar to mineralogists. It is worthy of notice that we pass, in this family, from compounds having the ratio of protoxyds to sesquioxyds found in the feldspars (coronite having the general atomic formula of barsowite and iolite) to the ratios of the muscovitic micas, and that with the diminution in the proportions of protoxyd-bases the relative amount of alkalies is augmented; while indicolite and rubellite become, like beryl, lithia-bearing. The atomic ratio of the sesquioxyds (in which alumina is sometimes partially replaced by ferric and, apparently, by manganic oxyd) to the silica, with its included and varying amount of boric oxyd, is, moreover, not constant, but differs in the different species of tourmaline. There are thus many chemical variables to be taken into account in the study of a group of minerals which, from their similarity in external characters, were, previous to the careful researches of chemists, united in one species, the supposed varieties of which were distinguished only by differences in color.

§ 86. We have given in the preceding paragraph, and also in table No. VIII., the ratios deduced by Rammelsberg for the five species named and defined, to which it should be added that he found for a red tourmaline from Rozena, with a density of 2.998, the ratios 1 : 15 : 21. This, the least protobasic silicate of the order, should constitute a new species. The mean densities of these species, as deduced by him from a large number of examples, show but small variations, and, with the exception of the highly ferriferous aphrizite, which is 3.20, range from 3.10 to 3.04.[*] These figures are adopted in the table, save that for rubellite the density has been placed at 3.00. The equivalent volumes, as calculated by Rammelsberg from his own arbitrary formulas for these five species, respectively, gave him the discordant and apparently incommensurable numbers, 144.6, 167.3, 241.0, 117.0, and 148.0, which fail to show any relations between the species compared.

These, however, from their close resemblance in external characters, on the one hand, and their chemical differences, on the other; from their varying relations between protoxyds, sesquioxyds, and silica; from the partial replacement of silica by boric oxyd, and of alumina by ferric and manganic oxyds, are peculiarly fitted to test the correctness of the new method of study; and this the careful determinations of Rammelsberg enable us to apply to the tourmalines with guaranties for accuracy not often to be met with. The results of such a study of these five species, as set down in the table above, may here be stated at greater length. In calculating the mean weight (P) of the oxyd-unit for each species of tourmaline, care has been taken to get the nearest approximation to the results of Rammelsberg's analyses of that species. The manganic oxyd in indicolite and rubellite is included with ferric oxyd, and the various protobases always present are grouped under the heads of ferrous oxyd, magnesia, soda, and lithia. The formulas thus arrived at, with their fractional coefficients, and the value of the oxyd-unit, got by dividing the calculated equivalents by the number of units in each formula, are subjoined. But these formulas do not take into account the fact that all of these tourmalines contain from 1.5 to 2.5 of fluorine, replacing a por-

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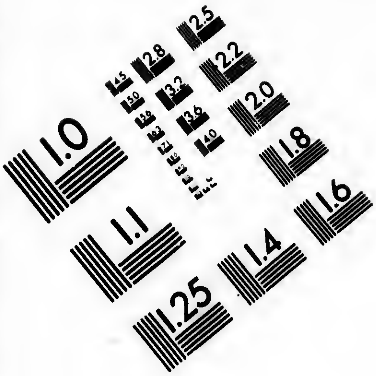
[*] For the original memoir of Rammelsberg, see Pogg. Ann., 1850, lxxx., 449; and for a summary of his results, Amer. Jour. Science, xi., 257; also a farther discussion thereof by the present writer, *ibid.*, xvi., 211. For later studies of the tourmalines by Rammelsberg, see Annal. Phys. Chem., 1870, cxxxix., 379 and 547.

tion of oxygen, the mean of this, as calculated for coronite, being about one sixtieth in atomic ratio This proportion would give for coronite 1.93, and for rubellite 1.90 of fluorine, an addition of 0.17 and 0.18 to the value of P, as calculated for the above formulas without fluorine. These values are placed within parentheses, while the corrected values for this mean proportion of fluorine are given in the adjoined table, under P, and are those employed for calculating the atomic volume of the tourmalines. The values of V show for these five species a remarkable agreement, which testifies at once to the correctness of the principles upon which our system is based, and to the accuracy of the determinations of Rammelsberg.

TOURMALINES.	m : *m* : si	FORMULA.	P	D	V
Coronite. - -	1 : 3 : 5	$(si_{3\cdot75}b_{1\cdot25}al_{2\cdot80}fl_{0\cdot20}mg_{0\cdot80}na_{0\cdot20})o_{8\cdot00}$ - - - - (16·19)	16·36	3·05	5·36
Schorlite. - -	1 : 4 : 6	$(si_{4\cdot80}b_{1\cdot20}al_{3\cdot50}fl_{0\cdot50}mg_{0\cdot75}na_{0\cdot25})o_{11\cdot00}$ - - - - (16·50)	16·68	3·10	5·38
Aphrizite. - -	1 : 6 : 8	$(si_{6\cdot25}b_{1\cdot75}al_{5\cdot20}fl_{0\cdot80}fe_{0\cdot60}mg_{0\cdot20}na_{0\cdot20})o_{15\cdot00}$ - - (17·06)	17·24	3·20	5·38
Indicolite. - -	1 : 9 : 12	$(si_{9\cdot50}b_{2\cdot50}al_{8\cdot00}fl_{1\cdot00}li_{0\cdot50}na_{0\cdot50})o_{22\cdot00}$ - - - - - (16·24)	16·42	3·08	5·33
Rubellite. - -	1 : 12 : 15	$(si_{12\cdot00}b_{3\cdot00}al_{11\cdot70}fl_{0\cdot30}li_{0\cdot50}na_{0\cdot50})o_{28\cdot00}$ - - - - (15·88)	16·06	3·00	5·35

Tribe 9. *Protoperphylloids.*

§ 87. The tribe of the Protoperphylloids presents illustrations of all the principles which we have endeavored to set forth in the accounts of preceding tribes. It shows great variations in the relations of protoxyds to sesquioxyds, from highly protobasic species like phlogopite and the chlorites, with the ratio 2 : 1, to muscovites, in which it is 1 : 12. Ferric and chromic oxyds, in some species, replace, more or less completely, alumina, and the



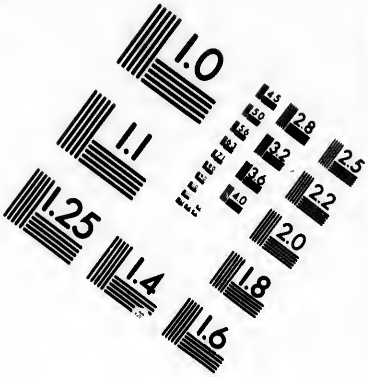


IMAGE EVALUATION
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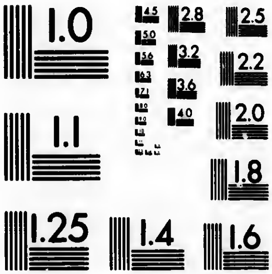

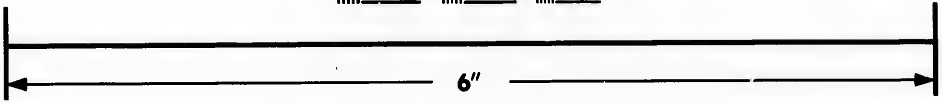

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TABLE IX. — PROTOPERPHYLLOIDS.

SPECIES.	FORMULA.	P	D	V	X
Astrophyllite.	$(\mathrm{m}_5 m_2 \mathrm{si}_{10})\mathrm{o}_{17}$	...	3.32	...	O.
Phlogopite.	$(\mathrm{m}_4\mathrm{al}_2\mathrm{si}_6)\mathrm{o}_{12}$ - $(\mathrm{m}_4 = \mathrm{mg}_{3\cdot5}\mathrm{k}_{0\cdot5})$	18.12	2.85	6.35	O.
Pyrosclerite.	$(\mathrm{mg}_4\mathrm{al}_2\mathrm{si}_6)\mathrm{o}_{12} + 3\mathrm{aq}$	15.40	2.74	5.62	O.
Penninite.	$(\mathrm{mg}_{4\cdot0}\mathrm{al}_{2\cdot0}\mathrm{si}_{4\cdot5})\mathrm{o}_{10\cdot5} + 3\mathrm{aq}$	15.40	2.67	5.76	R.
Ripidolite.	$(\mathrm{mg}_5\mathrm{al}_3\mathrm{si}_6)\mathrm{o}_{14} + 4\mathrm{aq}$	15.38	2.70	5.70	C.
Prochlorite.	$(\mathrm{m}_4\mathrm{al}_3\mathrm{si}_{4\cdot66})\mathrm{o}_{11\cdot66} + 3\mathrm{aq}$ - $(\mathrm{m}_4 = \mathrm{mg}_2\mathrm{fe}_2)$	17.72	2.96	5.98	H.
Leuchtenbergite.	$(\mathrm{mg}_{4\cdot5}\mathrm{al}_{3\cdot0}\mathrm{si}_{5\cdot0})\mathrm{o}_{12\cdot5} + 3\tfrac{1}{2}\mathrm{aq}$	15.46	2.65	5.83	H.
Venerite.	$(\mathrm{m}_4 m_3 \mathrm{si}_6)\mathrm{o}_{13} + 4\mathrm{aq}$	16.84	...	...	?
Corundophilite.	$(\mathrm{m}_4\mathrm{al}_4\mathrm{si}_4)\mathrm{o}_{12} + 3\tfrac{1}{3}\mathrm{aq}$ - $(\mathrm{m}_4 = \mathrm{mg}_3\mathrm{fe}_1)$	15.20	2.90	5.21	C.
Biotite.	$(\mathrm{m}_4 m_4 \mathrm{si}_6)\mathrm{o}_{16}$ - $(\mathrm{m}_4 = \mathrm{mg}_{3\cdot5}\mathrm{k}_{0\cdot5})$	18.18	3.00	6.06	H.
Voigtite.	$(\mathrm{m}_4 m_4 \mathrm{si}_6)\mathrm{o}_{16} + 4\mathrm{aq}$ - $(\mathrm{m}_4 = \mathrm{mg}_3\mathrm{fe}_1)$	16.48	2.91	5.66	?
Cryophyllite.	$(\mathrm{m}_3\mathrm{al}_4\mathrm{si}_{14})\mathrm{o}_{21}$ - $(\mathrm{m}_3 = \mathrm{fe}_1\mathrm{k}_1\mathrm{li}_1)$	17.90	2.91	6.15	O.
Seybertite.	$(\mathrm{m}_6\mathrm{al}_9\mathrm{si}_5)\mathrm{o}_{20} + \tfrac{1}{2}\mathrm{aq}$ - $(\mathrm{m}_6 = \mathrm{mg}_4\mathrm{ca}_2)$	17.97	3.15	5.70	O.
Thuringite.	$(\mathrm{fe}_6 m_9 \mathrm{si}_9)\mathrm{o}_{24} + 6\mathrm{aq}$ - $(m_9 = \mathrm{al}_6\mathrm{fi}_3)$	19.56	3.19	6.13	?
Jefferisite.	$(\mathrm{mg}_6 m_9 \mathrm{si}_{15})\mathrm{o}_{30} + 7\tfrac{1}{2}\mathrm{aq}$ - $(m = \mathrm{al}_6\mathrm{fi}_3)$	14.92	2.30	6.50	O.
Annite.	$(\mathrm{m}_6 m_{12} \mathrm{si}_{18})\mathrm{o}_{56}$ - $(\mathrm{m}_6 = \mathrm{fe}_4\mathrm{k}_2)$	20.84	3.17	6.57	?
Willcoxite.	$(\mathrm{m}_6\mathrm{al}_{12}\mathrm{si}_{10})\mathrm{o}_{28} + 2\mathrm{aq}$ - $(\mathrm{m}_6 = \mathrm{mg}_5\mathrm{na}_1)$	16.76	...	...	?
Chloritoid.	$(\mathrm{fe}_1\mathrm{al}_3\mathrm{si}_2)\mathrm{o}_6 + 1\mathrm{aq}$	18.00	3.55	5.07	C.
Lepidomelane.	$(\mathrm{m}_1 m_3 \mathrm{si}_4)\mathrm{o}_8$	...	3.00	...	H.
Zinnwaldite.	$(\mathrm{m}_1\mathrm{al}_3\mathrm{si}_6)\mathrm{o}_{10}$ - $(\mathrm{m} = \mathrm{k}_{0\cdot5}\mathrm{li}_{0\cdot5})$	17.20	3.00	5.73	O.
Oellacherite.	$(\mathrm{m}_1\mathrm{al}_3\mathrm{si}_6)\mathrm{o}_{10} + 1\mathrm{aq}$ - $(\mathrm{m} = \mathrm{k}\tfrac{1}{4}\mathrm{ba}\tfrac{1}{4}\mathrm{mg}\tfrac{1}{2})$	17.33	2.99	5.70	?
Lepidolite.	$(\mathrm{m}_{1\cdot0}\mathrm{al}_{4\cdot5}\mathrm{si}_{6\cdot0})\mathrm{o}_{13\cdot5}$ - $(\mathrm{m} = \mathrm{k}_{0\cdot5}\mathrm{li}_{0\cdot5})$	16.85	3.00	5.61	O.
Margarite.	$(\mathrm{ca}_1\mathrm{al}_6\mathrm{si}_4)\mathrm{o}_{11} + 1\mathrm{aq}$	16.58	2.99	5.54	O.
Euphyllite.	$(\mathrm{m}_1\mathrm{al}_8\mathrm{si}_9)\mathrm{o}_{18}$ - $(\mathrm{m} = \mathrm{k}_{0\cdot33}\mathrm{na}_{0\cdot66})$	17.07	3.00	5.69	?
Cookeite.	$(\mathrm{m}_1\mathrm{al}_{10}\mathrm{si}_9)\mathrm{o}_{20} + 5\tfrac{1}{2}\mathrm{aq}$ - $(\mathrm{m} = \mathrm{li}_{0\cdot75}\mathrm{k}_{0\cdot25})$	14.80	2.70	5.48	?
Muscovite.	$(\mathrm{k}_1\mathrm{al}_6\mathrm{si}_9)\mathrm{o}_{16}$	17.75	3.12	5.68	O.
Muscovite.	$(\mathrm{k}_1\mathrm{al}_6\mathrm{si}_9)\mathrm{o}_{16} + 2\mathrm{aq}$	16.77	2.85	5.88	O.
Muscovite.	$(\mathrm{k}_1\mathrm{al}_9\mathrm{si}_{12})\mathrm{o}_{22}$	17.27	...	...	O.
Damourite.	$(\mathrm{k}_1\mathrm{al}_9\mathrm{si}_{12})\mathrm{o}_{22} + 2\mathrm{aq}$	16.58	2.79	5.94	O.
Muscovite.	$(\mathrm{k}_{0\cdot5}\mathrm{al}_{6\cdot0}\mathrm{si}_{9\cdot0})\mathrm{o}_{15\cdot5}$	16.80	...	...	O.
Muscovite.	$(\mathrm{k}_{0\cdot5}\mathrm{al}_{6\cdot0}\mathrm{si}_{9\cdot0})\mathrm{o}_{15\cdot5} + 2\mathrm{aq}$	15.91	2.75	5.78	O.

protobases vary from species in which alkalies only are present to others in which alkalies are wanting, their places being partially or wholly supplied by ferrous oxyd, cupric oxyd, magnesia, lime, and even baryta. The ratio of silica to the bases varies widely in species having the same proportions of protoxyd and sesquioxyd bases; and, moreover, species having otherwise the same chemical composition, and similar external characters, differ in the presence or the absence of water. Finally, the degree of condensation, as shown by the value of V, varies considerably among phylloids, all of which are, nevertheless, so well marked in their physical characteristics that the micaceous or phylloid type is one of the first recognized by the student.

§ 88. We have spoken of mica and chlorites, but the distinction is an arbitrary one, and the transition from hydrous magnesian micas, like some phlogopites, to chlorites, is not so great as that from these same micas to those of the muscovitic type, often themselves hydrated. The difficulties of adequately discussing this great tribe are increased by the fact that different formulas are assigned to minerals having the same specific name. Phlogopite, biotite, and muscovite, each include chemically unlike compounds, which should form distinct species. The muscovites present among themselves compounds differing like the tourmalines in their atomic ratios, and the micas included under the name of phlogopite show variations in the ratio of protoxyds to sesquioxyds from 2 : 1 to 3 : 2; while there are biotites from 1 : 1 to 1 : 1½ and 1 : 2. More highly protobasic than any phlogopite is, however, astrophyllite, a titaniferous mica in which the sesquioxyd is represented in part by alumina and in part by ferric and zirconic oxyds, according to Pisani, while in the specimens from Colorado, analyzed by Koenig, alumina is present in traces only. With biotites having the atomic formula, 1 : 1 : 2, we may note the more basic corundophilite, 1 : 1 : 1, near to which in the ratio of protoxyds and sesquioxyds, come the highly silicious fluoric lithia-mica, cryophyllite, 3 : 4 : 14, and the basic seybertite and willcoxite. The ratio of protoxyds and sesquioxyds in the latter, 1 : 2, is that of some biotites, and of the ferric species, annite, near to which is the still more ferriferous lepidomelane, apparently 1 : 3 : 4. A like ratio appears in the dense basic chloritoid, 1 : 3 : 2, and the more silicic zinnwaldite, 1 : 3 : 6, followed by the barytic species, oellacherite, 1 : 4 : 6. In biotite and voigtite one fourth, in annite, thuringite, and jefferisite one third of the sesquioxyd is ferric.

After lepidolite, probably 1 : 4½ : 8, and, like zinnwaldite, a highly fluoriferous mica, remarkable for containing lithia with caesium and rubidium, we come to the muscovites proper, with which the last two species are connected by the fact that their protoxyd-bases are alkalies only. The variations noted in the ratio of these to the sesquioxyds (in which ferric oxyd replaces a small portion of alumina) are from 1 : 6 to 1 : 9 and 1 : 12, and the ratio of the sum of these to the silica in different analyses is from 1 : 1¼ to 1 : 1½. From various muscovites have been deduced the atomic ratios, 1 : 6 : 9, 1 : 9 : 12, and 1 : 12 : 18, with others intermediate, and a careful study would probably show, as in the case of the tourmalines, the existence of a series of muscovites. Near the muscovite with the ratio first named must be placed the less silicious and somewhat calcareous species, margarite, 1 : 6 : 4, and farther on, euphyllite, 1 : 8 : 9, and cookeite, 1 : 10 : 9. Of the phylloids, phlogopite and cryophyllite contain more or less fluorine. In calculating the value of P for both biotite and voigtite, $m_4 = \mathrm{al}_3\mathrm{fi}_1$.

§ 89. It will be noted that in this list we have included both hydrous and anhydrous species, between which it is impossible to draw a line of demarcation. Phlogopites and biotites are reputed anhydrous, but, as is well known, contain in many cases from two to four hundredths of water, while corundophilite, willcoxite, seybertite, chloritoid, oellacherite, margarite, euphyllite, and cookeite are all more or less hydrous; the amount of water rising to six hundredths in euphyllite, and to twice that amount in cookeite. Among muscovites, in like manner, water is found in all proportions, up to such hydrous species as damourite and paragonite, which last may be described as a hydrous soda-muscovite. The presence or absence of water in phylloids cannot form the ground of a distinction in classification among phylloids any more than in adamantoids, where we find bertrandite, beryl, euclase, ardennite, prehnite, epidote, and malacone, in all of which water enters as an essential element.

§ 90. The various minerals which constitute the chloritic group are hydrous magnesian micas, nearly related to the phlogopites and the biotites. While pyrosclerite is simply a hydrous phlogopite, with the atomic ratios, apart from the water, of 4 : 2 : 6, penninite is a less silicious species, represented by 4 : 2 : 4½. After these come the closely related ripidolite, leuchtenbergite, venerite, and prochlorite. Cronstedite, with the atomic ratios 3 : 3 : 4, is a wholly ferric chlorite. Venerite is remarkable as an example of a well defined and crystalline chloritic species very near to prochlorite in composition, but containing a large proportion of copper.* Corundophilite

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* This species, which was described by the writer in 1876, is found in the Jones (or Johannes) mine, in Carnarvon, Bucks County, Pennsylvania, long known as a large deposit of magnetite associated with chalcopyrite, malachite, chrysocolla, and a substance which had hitherto been called clay-carbonate copper ore, of which several thousand tons, yielding from six to seven per cent of copper, had up to that time been mined and utilized in smelting. These ores are found in the Taconian crystalline schists of the region, the so-called Primal slates of Rogers, and the mineral in question is distributed in greater or less abundance through several feet of the strata, alternating with layers of a coarse granular material poor in copper, the whole marked with ferruginous bands which coincide with the bedding, and are intersected with veins of quartz; layers of half an inch or more in thickness were found to contain ten or twelve per cent of copper.

"These pure portions have a pea-green or apple-green color when moist, becoming greenish-white on drying, when the mass falls into a powder, which is seen under the microscope to consist of minute, transparent, shining scales, mixed, however, with some grains of quartz and a small follows, with 4 : 4 : 4, and the more silicious species, voigtite, 4 : 4 : 8, a hydrous biotite. From this we pass to

portion of magnetite. A qualitative examination of this material showed that it contains no carbonates, and is not of the nature of a clay, but consists of a hydrous silicate of magnesia, copper-oxyd, alumina, and iron-oxyd, constituting a kind of copper-chlorite. It is but feebly attacked by dilute acids, while strong acids, and notably sulphuric acid diluted with two or three parts of water, and aided by a gentle heat, readily and completely decompose it, with separation of flocculent silica, which, by solution in dilute soda-lye, is readily separated from the accompanying quartz and magnetite. A single somewhat rough analysis made in this way gave me, for 100 parts: insoluble sand, 14.10; silica, 24.60; alumina, 13.00; magnesia, 15.15; ferric oxyd, 7.11; cupric oxyd, 15.30; water, 11.50. =100.70. The qualitative examination of a considerable portion of another and less pure specimen, gave an appreciable quantity of zinc, and a distinct trace of nickel. A portion of the specimen of this copper-silicate of which the analysis is given above, was freed by careful washing alike from the coarser grains and from the lighter portion, which remained long suspended in water. The material thus purified was somewhat richer in copper than before, and has been carefully analyzed by my friend, Mr. George W. Hawes, of New Haven, who found: insoluble sand, 6.22; silica, 28.93; alumina, 13.81; ferric oxyd, 5.04; ferrous oxyd, 0.27; magnesia, 17.47; cupric oxyd, 16.55; water, 12.08=100.37. This, deducting the insoluble matter, gives, for 100 parts: silica, 30.73; alumina, 14.67; ferric oxyd, 5.35; ferrous oxyd, 0.29; magnesia, 18.55; cupric oxyd, 17.58; water, 12.83=100.00. This, as remarked by Mr. Hawes, gives, on calculation, an oxygen-ratio between protoxyds, sesquioxyds, silica, and water, of 4 : 3 : 6 : 4, very nearly, which puts this mineral, if it be a homogeneous substance (as its microscopic characters would indicate), among the chlorites, some of which it resembles very closely in its atomic ratios. Before the blowpipe, on charcoal, it swells, then fuses quietly into a black globule, giving the usual reactions for copper. The iron is almost wholly in the state of sesquioxyd, as shown by two determinations of the amount of protoxyd of iron, which gave, respectively, 0.27 and 0.29 per cent. This copper-chlorite appears, alike from its physical and chemical characters, to constitute a distinct mineral species, for which I propose the name of **Venerite**, in allusion to the mythological and alchemistic name of copper." ("A New Ore of Copper and its Metallurgy.") Trans. Amer. Inst. Mining Engineers, iv., 325.

The atomic formula for venerite given in the table above represents it as a chlorite in which a part of the sesquioxyd is ferric and a part of the protoxyd is cupric. This formula $(mg_{2.75}cu_{1.25}al_{2.50}fi_{0.50}si_{6.00})o_{13.00}+4aq$, requires: silica, 31.4; alumina, 14.8; ferric oxyd, 4.6; magnesia, 19.2; cupric oxyd, 17.4; water, 12.6=100.00, which agrees very closely with the numbers deduced by Hawes from his analysis, and varies but little from my own analysis, given above, of a less pure specimen, when calculated for 100.00 parts. A microscopic examination of this curious chlorite will jefferisite, 4 : 6 : 10, a highly hydrated species having the same ratio of protoxyds and sesquioxyds as thuringite, and as the more basic and nearly anhydrous seybertite, 4 : 6 : 3⅓. Following these, among hydrous species, are willcoxite, chloritoid, oellacherite, margarite, cookeite, and damourite. We have, in fact, throughout the whole protoperphylloid tribe, from phlogopite to muscovite, an anhydrous and a hydrous series, and the chloritic group is made up of the more highly protobasic members of the latter. In these comparisons we have generally deduced the atomic ratios from the formulas given in Dana's "System of Mineralogy," which represent approximately the results of chemical analysis. The late elaborate chemical studies of Rammelsberg, when properly interpreted, will throw much light on the constitution of the micas.* For greater simplicity, the water-ratios, which are given in Table X., have been omitted in discussing the preceding formulas.

§ 91. Related to the chlorites, but differing in structure, is the epichlorite of Rammelsberg, described as fibrous or columnar, and having the atomic ratios, 4 : 3 : 9 : 4, which corresponds to a more silicious prochlorite. In this connection may be mentioned a hitherto undescribed mineral which is found in veins in the anthracite and its accompanying carbonaceous shales at Portsmouth, Rhode Island. This substance is sometimes seen penetrating quartz, but in its pure state appears as a grayish-green mass, consisting of fine, transverse, flexible fibres, resembling chrysotile or amianthus, with which it has been confounded. A portion from a vein about an eighth of an inch wide gave me by analysis: silica, 27.80; alumina, 21.80; ferrous oxyd, 26.10; magnesia, 8.96; lime, 2.01;

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suffice to show its distinctness, and the judgment of Hawes thereon is confirmed by that of Descloizeaux, according to his private communication to the writer.

* I have to acknowledge my indebtedness in very many cases to the First Appendix to Dana's Mineralogy by Brush in 1872, and to the Second and Third Appendices by E. S. Dana in 1875 and 1882.

potash, 2.69; soda, 4.24; volatile, 9.30 = 102.90. A subsequent microscopic examination of the material analyzed showed the presence therein of interspersed films of pyrites, thereby vitiating to some extent the results of the analysis, which deserves to be repeated on a portion of the mineral purified by the aid of bromine-water. Making allowance for some pyrites, the atomic ratios of this fibrous species are 4 : 4 : 6 : 3, being near to prochlorite, and to voigtite, which like it contains a little lime and soda. In this unnamed amianthoid mineral from Portsmouth, possessing nearly the composition of a chlorite or a hydrous biotite, and in the epichlorite of Rammelsberg, we have apparently examples of a hydrospathoid form of these alumino-magnesian protopersilicates.

With these should be noted the pilolite of Heddle, who has described under that name the substances hitherto known as mountain cork and mountain leather, which have a fibrous texture, are more or less flexible and tough, and occur in veins or fissures alike in crystalline limestone, in sandstones and shales, and also, as observed by the writer, as a deposit upon quartz crystals in granitic veins. From several analyses by Heddle, pilolite is shown to be a highly hydrated silicate of alumina and magnesia with ferrous oxyd, and is nearly represented by $(mg_{2.5}fe_{0.5}al_2si_{15})o_{20}+12aq$, a formula requiring: silica 51.7; alumina, 7.8; magnesia, 11.5; ferrous oxyd, 6.2; water, 24.8 = 100.00. More than one third of the combined water is expelled at a temperature of 100° Centigrade.*

Tribe 10. *Pinitoids.*

§ 92. Corresponding with the ophitoids of the protosilicates, we find in the present sub-order a tribe of hydrous silicates which, since the species known as pinite may be taken as the type, we have called Pinitoids. These bodies approach in composition and in density the

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* Mineralogical Magazine, 1879, ii., 206, cited in the Third Appendix to Dana's Mineralogy, p. 94.

hydrous muscovitic micas, with compact varieties of which they may be confounded. The true pinitoids, however, appear to be amorphous colloidal silicates like serpentine; while pinite itself with its varieties, which have been described under the various names of gieseckite, agalmatolite, dysyntribite, and parophite, though generally amorphous, seems in some cases, like the serpentinic silicate, to be crystalline. We have elsewhere noted the occurrence of this material in rock-masses (*ante*, page 163), but it also appears as a result of the alteration of crystals of other species. Pinite is essentially a silicate of potash and alumina, having the atomic ratios of 1 : 8 : 12 : 3, and thus approaching closely in composition to a hydrous muscovite. Cossaite, which has the ratios of 1 : 9 : 12 : 2, is, if not a pinitoid, a compact paragonite or hydrous soda-muscovite, and gümbellite, which resembles it, with the ratios, 1 : 12 : 21 : 5, is probably rather a compact phylloid than a pinitoid. A careful study of the optical characters of these species will serve to fix their place in the system of classification. Jollyte, the most protobasic of the species which we have included in this tribe, has the atomic ratios, 1 : 2 : 3 : 2, the protoxyd-bases being ferrous oxyd and magnesia. The minerals known as fahlunite, esmarkite, aspasiolite, and hydrous iolite (*ante*, page 142), are

TABLE X. — PINITOIDS.

SPECIES.	FORMULA.	P	D	V
Jollyte. - - -	$(m_1al_2si_3)o_6 + 2aq$ - $(m = fe_{0·6}mg_{0·4})$	15.75	2.61	6.03
Fahlunite. - -	$(m_1al_3si_5)o_9 + 1aq$ - $(m = fe_{\frac{1}{3}}mg_{\frac{2}{3}})$ -	16.03	2.70	5.93
Esmarkite. -	$(m_1al_3si_5)o_9 + 2aq$ - - - - - -	15.39	...	...
Bravaisite. -	$(k_1al_3si_9)o_{18} + 4aq$ - - - - - -	15.82	...	...
Hygrophilite.	$(k_1al_5si_9)o_{15} + 3aq$ - - - - - -	16.33	...	...
Pinite. - - -	$(k_1al_9si_{12})o_{21} + 3aq$ - - - - - -	16.25	2.80	5.08
Cossaite. - -	$(na_1al_9si_{12})o_{22} + 2aq$ - - - - - -	15.91	2.89	5.50

amorphous silicates with varying amounts of water, and the atomic ratios, 1 : 3 : 5, — the protoxyd-bases, as in jollyte, being chiefly ferrous oxyd and magnesia, with a little potash. Bravaisite, with the ratios, 1 : 3 : 9 : 4, and hygrophilite, 1 : 5 : 9 : 3, are similar species, the protoxyd-base of which, as in pinite, is chiefly potash. Near to this is sordavalite, a similar hydrous species, of which the protoxyd is magnesia and the peroxyd is in part ferric. With these pinitoids we have placed obsidian, pitchstone, tachylite, and palagonite, to which latter the atomic ratios, 1 : 2 : 4, excluding water, have been assigned. That its composition is not clearly fixed, or rather that more than one silicate may have been included under this title, does not detract from the interest which attaches to this curious, unstable, hydrous colloid, so long since the object of studies by Bunsen, the importance of which I have elsewhere pointed out (*ante*, page 129), and which are noted below, in § 109.

§ 93. The species of the sub-order of protopersilicates which approach the persilicates in composition, resist chemical agencies more than those species which contain larger amounts of protoxyd-bases. To this greater stability is due the fact that such species are often produced by the partial transformation, through aqueous influences, of silicates like the protoperspathoids. Such silicates, formed originally by igneous or by aqueous action, may thus continue to lose protoxyd-bases, often with silica, until a condition of comparative fixity is reached by the production of bodies having the chemical composition of pinite, of the muscovitic micas, and even of pyrophyllite or of kaolin. Inasmuch as such compounds are in many cases the result of secondary processes like that just described, chemists have been disposed to assign a similar origin to them wherever found, not considering that where the proper chemical conditions unite, these compounds may be directly formed. That nephelite, for example, may, as is supposed, under favoring circumstances, be transformed into pinite, is due to the chemical stability under these circumstances of this latter compound, and the frequent occurrences of pinite and the similar silicates, under such conditions, are illustrations of "the survival of the fittest" in the inorganic world. But these very relations which conduce to the production of such stable compounds by epigenesis, that is to say, as a result of transformation through aqueous action, are evidently such as would lead, under favoring conditions, to the direct generation of the same or chemically similar compounds. Thus, for example, while the pseudocrystalline form of pinite, in the case just mentioned, shows its epigenic origin, the occurrence in granitic veinstones, in intimate association with orthoclase, tourmaline, and quartz, of muscovite, a silicate very similar in centesimal composition to pinite, is unquestionably an example of direct production from solution. As regards the large beds of stratiform rocks, evidently of aqueous origin, made up chiefly or entirely of a silicate having the composition and the physical characters of pinite,. such as occur at various geological horizons, and as I have described,* it seems not less difficult to assign to them an epigenic origin. In other words, the beds of pinite, or beds of mica-schist, like the muscovitic micas of granitic veins, have not been produced by the transformation *in situ* of more highly alkaliferous silicates, but are either the results of the subsequent molecular re-arrangement or diagenesis of sediments derived from partially decomposed silicates, perhaps not without admixtures of aqueous deposits of chemical origin,—or else, as in the case of such minerals in veinstones, are entirely from the latter source.

§ 94. Crystalline forms, as displayed in what are called pseudomorphs, may and often do give evidence of transformations, through aqueous agency, in silicates, as in other orders of minerals. Such changes have been especially effected in fissures and open cavities, which have been

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* *Ante*, page 163, and Geology of Canada, 1863, pp. 482-486.

channels for waters of changing composition and temperature, during the long process which has filled these openings with mineral masses. In this way, crystals deposited at one stage are attacked at another, and are either more or less completely dissolved or transformed into insoluble products which are now found surrounding nuclei of the unchanged mineral, or in some cases penetrating its substance. Examples of such actions are familiar to all who have studied attentively the history of granitic and related veinstones. Care should, however, always be taken in the study of pseudomorphs to keep in mind another and a different phenomenon, namely, that resulting from the power of a substance in the process of crystallization to cause other bodies to assume its own geometric form. Examples of these are seen in the cases of calcite, dolomite, and gypsum crystallizing in the midst of silicious sand, by which are generated such aggregates as the so-called crystallized sandstone of Fontainebleau, which, while having a crystalline shape belonging to calcite, includes from 50 to 63 per cent of quartz grains. A not less remarkable case is seen in staurolite, which, according to Lechartier, retains its crystalline form and general aspect even when by the inclusion of foreign matters, chiefly quartz, the proportion of silica is raised from the normal content of 28.0 to 50.0, and even 54.0 per cent, corresponding to more than one part of quartz with two parts of staurolite, the mixture still retaining the crystalline form of the latter species. Thus a compound in crystallizing may give its geometric form to a large portion of some extraneous matter, which it compels, as it were, to assume its own crystalline shape.

Tribe 13. *Peradamantoid.*

§ 95. It may be noticed that in the second sub-order the less protobasic silicates do not assume zeolitoid or spathoid forms. With the exception of sloanite and forestite (both of which demand further study), we find no species in these tribes having a ratio of protoxyds to sesquioxyds greater than 1 : 4; those presenting the higher ratios, up to 1 : 12, being adamantoids, phylloids, and pinitoids, through each of which this sub-order is connected with that of the persilicates. As might be expected, we find similar conditions continued in the latter sub-order, in which the species known are, with rare

TABLE XI. — PERADAMANTOIDS.

SPECIES.	FORMULA.	P	D	V	X
Dumortierite.	$(al_2si_1)o_3$	16·33	3·36	4·86	C.
Andalusite.	$(al_3si_2)o_5$	16·20	3·35	4·83	O.
Fibrolite.	$(al_3si_2)o_5$	16·20	3·35	4·83	C.
Topaz.	$(al_3si_2)o_4fl_1$	18·40	3·65	5·04	O.
Cyanite.	$(al_3si_2)o_5$	16·20	3·66	4·42	A.
Bucholzite.	$(al_3si_3)o_6$	16·00	3·24	4·90	C.
Xenolite.	$(al_3si_3)o_6$	16·00	3·58	4·46	C.
Wörthite.	$(al_6si_5)o_{11} + 1aq$	15·50	....	....	C.
Lyncurite.	$(zr_1si_1)o_2$	22·75	4·05	5·61	T.
Malacone.	$(zr_1si_1)o_2 + \frac{1}{4}aq$	21·22	4·00	5·30	T.
Zircon.	$(zr_1si_1)o_2$	22·75	4·70	4·84	T.
Auerbachite.	$(zr_2si_3)o_5$	21·20	4·06	5·22	T.
Anthosiderite.	$(fi_1si_3)o_4 + \frac{1}{3}aq$	17·21	3·00	5·73	?

exceptions, included in the corresponding tribes. These are designated, as we have seen, peradamantoid, perphylloid, and argilloid, which latter represents the pinitoid and ophitoid tribes of the preceding sub-orders. Westanite, described by Blomstrand, would seem, however, from the details given respecting it, to be a perzeolitoid, having the atomic ratios for alumina and silica of the peradamantoid wörthite. [If bismuthic oxyd be ranged with aluminic, zirconic, and ferric oxyds, the rare anhydrous sparry silicate of bismuth, known as bismuth-blende or eulytite, and the related agricolite and bismutoferrite, will, from their chemical and physical characters, take a place in the tribe of perspathoids.]

§ 96. The adamantoid persilicates constitute a characteristic and remarkable group. Of the aluminic species, we find dumortierite, andalusite, fibrolite, bucholzite, and wörthite, with differing atomic ratios, and in one case hydrous, all presenting the same value for V; besides the remarkable oxyfluorid, topaz, and the more highly condensed kyanite and xenolite, the latter two having a smaller atomic volume than any other silicates known. A single ferric species, anthosiderite, appears, and more than one zirconic species.

It is known that minerals having the crystalline form and the centesimal composition of zircon present variations in density from 4.86 to 4.02. The careful studies of A. H. Church, in 1875, confirmed the previous statements of others as to the differences in density among the minerals included under the name of zircon. Thus he found the hyacinth-red crystals from Expailly to have a specific gravity 4.863, which was not changed by ignition. Of a large number of zircons examined by him. not less than twelve varied from 4.60 to 4.70, while an opaque brown zircon from North Carolina had a density of 4.54, which was changed to 4.67 by long ignition, and a transparent brown zircon from Frederickvärn had its density by the same process raised from 4.48 to 4.63. Another zircon, dark green in color, slightly opalescent, and flawless, had a specific gravity of only 4.02, which was not changed by ignition. It was, nevertheless, according to Church, a true zircon, giving by analysis the percentages of that species.* Auerbachite, an isomorphous zirconic species, has, with different atomic ratios, a specific gravity of 4.05, and agrees in volume with malacone, a hydrous zircon, which has a similar density, while other related hydrous

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* Church on Densities of Precious Stones, Geological Magazine for 1875.

zirconic silicates give specific gravities of from 4.00 to 3.60. It would appear that the zirconic, like the aluminic adamantoids, include species varying alike in atomic ratio, in condensation, and in the presence and absence of water. An anhydrous zircon with the ratio 1 : 1, and a density of 4.86, has an atomic volume of 4.68; and one of 4.70, a volume of 4.84; while a zircon with the lower density of 4.02 has a volume of 5.65. This last we may distinguish by the trivial name of "lyncurite," from the *lyncurion* of Theophrastus,* while the denser zircon of Expailly will also, perhaps, require a distinctive name. [Oerstedite appears to be a less silicious zirconic species than those already named, and hydrous, like malacone. Its analysis affords ratios approaching those of the aluminic species, dumortierite; but a small amount of protoxyd-bases serves to make its composition doubtful. If these make an integral part of the species, it will take its place, with catapleiïte, wöhlerite, eudialyte, and astrophyllite among Protopersilicates.]

Tribe 14. *Perphylloid.*

§ 97. As regards the phylloid tribe of the persilicates, an important chapter of their history is connected with pholerite and kaolinite. It was in 1825 that Guillemin described, under the name of pholerite, a hydrous silicate of alumina, micaceous in structure, to which he assigned the atomic ratio for alumina, silica, and water of 3 : 3 : 2. This was the same as that deduced from the analyses of Brongniart and Malaguti for ordinary kaolin, although Forchhammer had proposed for the latter the ratios 3 : 4 : 2. The uncertainty as to the composition of these silicates which prevailed thirty years since is reflected in the fourth edition of Dana's "System of Mineralogy," published in 1854, where the first-named ratio was ascribed to kaolin, with the remark that it occasionally presents the second ratio; while of pholerite it was said "that it does not

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* Moore's Ancient Mineralogy, p. 145.

differ much from kaolin in composition." Hence it was that when, in the same year, the writer found and analyzed a crystalline micaceous kaolin giving for its composition, silica 45.50–46.05, alumina 38.37, lime 0.61, magnesia 0.63, water 13.90 = 99.56, the analyses of pholerite and of kaolin were discussed by him, and the conclusion was reached that the first ratio mentioned might represent the composition of both of these substances when free from foreign matters, and consequently that "the mineral in its pure form is no other than a crystalline kaolin." In 1863, in accordance with this view, kaolin and pholerite were regarded as identical. Of pholerite it was then said that "it may be regarded as that substance [kaolin] in a crystalline condition. From its foliated or micaceous structure it may be considered as a hydrated mica."* It should here be added that the writer had in 1855 an opportunity of comparing the crystalline mineral from Canada with the original pholerite, and of discussing the question of the minerals with Guillemin, in Paris.

TABLE XII. — PERPHYLLOIDS.

SPECIES.	FORMULA.	P	D	V	X
Pholerite . . .	$(al_3si_3)o_6 + 2aq$ . . .	14.25	2.51	5.67	O.
Talcosite . . .	$(al_5si_6)o_{11} + 1aq$ . . .	15.33	2.50	6.13	?
Kaolinite . . .	$(al_3si_4)o_7 + 2aq$ . . .	14.33	2.63	5.44	O.
Pyrophyllite . .	$(al_2si_5)o_7 + \frac{2}{3}aq$ . . .	15.00	2.80	5.35	O.
Pyrophyllite . .	$(al_2si_4)o_6 + \frac{2}{3}aq$ . . .	15.00	2.92	5.13	O.

§ 98. It was not until 1867 that this subject was again taken up, and this time by S. W. Johnson and J. M. Blake,† who showed that, as regards the composition of

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* See Hunt, Report of Geological Survey of Canada, 1853–56, p. 386, and further, Geology of Canada, 1863, p. 495.

† Amer. Jour. Science, xliii., 351.

kaolin, the ratio of 3 : 3 : 2 was inadmissible, and that the ratio 3 : 4 : 2, deduced by Forchhammer, was the true one. They farther called attention to numerous observations showing the occurrence of kaolin in a foliated crystalline form, which, according to them, is never wanting in the mineral, and proposed for crystalline kaolin the name of "kaolinite," without, however, alluding to my own published observations on the subject. This historical sketch will serve to show why the present writer, while recognizing in 1854 and 1863 the crystalline character of kaolin, was led, from the uncertainty then prevailing as to the true composition of these substances, to describe crystallized kaolin under the name of "pholerite," as a hydrous mica. While the title of kaolin to the rank of a hydrous phylloid or persilicate mica, with the ratios 3 : 4 : 2, is clear, the name of pholerite must be reserved for a similar species with the ratios 3 : 3 : 2. Intermediate between pholerite and kaolinite in composition is the talcosite of Ulrich, to which he has ascribed the atomic ratios for alumina, silica, and water, of 5 : 6 : 1. To these succeed the pyrophyllites, the two formulas assigned to which give the same value for P, while the recorded densities indicate for the mineral a high degree of condensation.

Tribe 15. *Argilloid.*

§ 99. In the last place remains to be noticed the percolloid tribe, which, from the fact that it includes various hydrous aluminous silicates known as clays, we have designated Argilloid. While a mineral having the composition assigned to kaolin appears as a phylloid, and while Johnson and Blake, from their microscopic examinations, concluded that such a phylloid species appears in all kaolins, it is not improbable that there may, at the same time, exist a true argilloid or colloidal silicate having the composition assigned to kaolin, and, consequently, less hydrated than halloysite. For this reason kaolin is retained in the accompanying table of argilloids. We have noticed in the other sub-orders the close relations between the ophitoids and pinitoids and their corresponding phylloids. Beginning with the most basic of the clays, we have given in Table XIII. their atomic formulas, with the values of P and V, so far as these can be determined.

§ 100. The genesis of these persilicates, whether phylloid or colloid, here demands consideration. The sub-aerial decay of the aluminous spathoids, orthoclase and albite, is apparently the direct source of ordinary kaolin, for which the ratios of protoxyd, alumina, silica, and water are 0 : 3 : 4 : 2. The derivation of this from feldspars, having for the same elements the ratios 1 : 3 : 12 : 0, is due to the loss of all protoxyds and two thirds of the silica, and the hydration of the residue. The adamantoid and phylloid aluminous protopersilicates are not generally subject to such transformations, although Damour has described a silicate with the composition of kaolin, derived from the decay of beryl. It is important, in this connection, to study farther the sub-aerial decay of other

TABLE XIII. — ARGILLOIDS.

SPECIES.	FORMULA.	P	D	V
Schrötterite.	$(al_4si_1)o_5 + 5aq$	12.80	2.15	5.95
Collyrite.	$(al_3si_1)o_4 + 4\frac{1}{2}aq$	12.53	2.15	5.83
Allophane.	$(al_3si_2)o_5 + 6aq$	12.27	1.89	6.49
Samoite.	$(al_3si_3)o_6 + 5aq$	12.81	1.89	6.66
Halloysite.	$(al_3si_4)o_7 + 3aq$	13.80	2.40	5.75
Kaolin.	$(al_3si_4)o_7 + 2aq$	14.33	...	...
Keramite.	$(al_2si_3)o_5 + 2aq$	13.85	...	...
Wolchonskoite.	$(cr_2si_3)o_5 + 3aq$	15.33	2.30	6.66
Montmorillonite.	$(al_1si_2)o_3 + 2aq$	13.00	2.04	6.37
Chloropal.	$(fi_1si_2)o_3 + 1\frac{1}{2}aq$	15.51	2.10	7.38
Cimolite.	$(al_1si_3)o_4 + 1aq$	14.20	2.30	6.17
Smectite.	$(al_1si_4)o_5 + 4aq$	12.55	2.10	5.97

aluminous spathoids, regarding the results of whose transformations very little is known. The kaolin of Passau in Bavaria, coming from the decay of a scapolite, of which it sometimes retains the external forms, differs alike in its composition and in the process of its generation from the kaolin of orthoclase or albite. The scapolite of Passau is ekebergite, with the atomic ratios 4 : 9 : 18; or, if we compare its formula with that of albite, has for protoxyds, alumina, silica, and water, $1\frac{1}{3}$: 3 : 6 : 0. The resulting aluminous silicate gives, according to the analysis of Von Fuchs, not 0 : 3 : 4 : 2, but 0 : 2 : 3 : 2 (= silica 46.4, alumina 35.0, water 18.6). This distinct and hitherto unnamed clay may be called "keramite," and is remarkable as resulting from the decay of a spathoid near in composition to labradorite, the ratios for which are 1 : 3 : 6 : 0. A similar kaolinization of labradorite would involve the removal with the protoxyds of only one fourth of the silica. The possible results of such a transformation of this and related feldspars, great quantities of which exist in the earlier crystalline rocks, are important alike in relation to the soluble matters removed and the residual aluminous silicates, both of which, in past ages, must have played a considerable part in the chemistry of sea and land.

The apparent kaolinization of leucite is remarkable in its chemical result. It was shown by Rammelsberg that the crystals of white and kaolin-like leucite found at Rocca Monfina, in Italy, consist of a hydrous soda-alumina silicate, having the composition of analcite. This observation the writer has confirmed, a large crystal from the same locality, soft, white, and earthy in texture, having yielded him on analysis ten per cent of soda, besides a little potash.

§ 101. In the study of these persilicates it becomes necessary in each case to determine whether we have to do with really amorphous and argilloid species, or, as in the case of crystalline kaolin and pholerite, with phylloids, which are apparently less hydrated than the argilloids.

The origin of the more and of the less aluminous species, like allophane and schrötterite, on the one hand, and like montmorillonite and cimolite, on the other, remains to be discovered. These seem, for the most part, to be, like halloysite, true colloids, and their separation from aqueous solution is apparent from the occurrence noted by Daubrée of an amorphous halloysite-like matter deposited by the thermal water of Plombières, in France, which is probably identical with the saponite of Nickles, a highly hydrated silicate, more silicious than halloysite, from the same thermal spring.

These aluminous silicates, like other colloids, such as opal and bauxite, are probably capable of assuming a soluble modification, and have all been deposited from solutions. That such a dissolution and deposition take place on a large scale is apparent from the existence of the so-called indianaite. This name has been given to a material found in the coal-measures in the State of Indiana, where it has been mined and employed to a considerable extent in the manufacture of potter's ware. It occurs in irregular beds, often several feet in thickness, beneath a stratum of sandstone, and is associated with and overlies limonite. It is often translucent in aspect, with a conchoidal fracture, and has all the aspect of a colloid. In composition it is somewhat more basic than halloysite, the atomic ratios of alumina and silica being about 6 : 7, and may, perhaps, be regarded as this species with an admixture of allophane, translucent masses of which, in a pure state, are found imbedded therein. Indianaite contains about 23.0 hundredths of water, which, after a long exposure to a temperature of 100° Centigrade, is reduced to 14.5.* The species wolchonskoite and chloropal, which we have placed in the table near to keramite and montmorillonite, show that chromic and ferric silicates present similar conditions to the silicates of alumina. Hisingerite, according

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* Reports of the Geological Survey of Indiana, 1874, p. 15, and 1878, p. 154.

to some analyses, is a simple hydrous ferric silicate, and we have therefore placed it in the synoptical table of Persilicates at the end of this essay.

§ 102. We have thus far, in the third part of this essay, briefly explained the application of our system of mineral classification to the natural silicates, and have endeavored to show how the three sub-orders into which these may, on chemical and genetic grounds, be separated, are each divided into five tribes by physical differences repeated more or less completely in each sub-order. The spathoid type is naturally separated into two parts, the one highly hydrated, constituting the hydrospathoid tribes, represented in the first and second of these sub-orders by what we have called the pectolitoids and zeolitoids, both readily decomposed by acids, even in the case of the more highly silicious species. The other part, anhydrous, or with a smaller portion of combined water, seldom over one or two hundredths, includes the protospathoid and protoperspathoid tribes, in the latter of which the more silicious species resist the action of acids. The hydrospathoids and spathoids in the first two sub-orders (with a few exceptions, which have been noted) agree in having a larger volume than the species of the succeeding tribes.

The adamantoids in the three sub-orders of silicates are distinguished by their hardness and their molecular condensation, and, save in the case of the more basic protadamantoids, by their resistance to acids. A small proportion of water enters into the composition of many of these species, not only in bertrandite, but in euclase and beryl, and even in epidote and tourmaline, in wörthite and in malacone. It is to be noted, also, that the aluminic protoperadamantoids are not, so far as is known (with the apparent exception of garnet), generated by cooling from igneous fusion; but, on the contrary, by the action of heat, even below their melting points, undergo a chemical change, shown by a diminution of density and by a susceptibility to the action of acids (§ 36). The atomic volume of the adamantoids, while in certain cases not very far removed from that of spathoids, is always less, and in the harder or more gem-like species indicates a great degree of condensation. These characters are especially marked in the peradamantoids, which include the silicates of the lowest known atomic volumes.

The great phylloid or micaceous type is, like the adamantoid type, represented in each sub-order, and approaches it in condensation. The phylloids in the second sub-order, where they are most largely developed, include both anhydrous and hydrated species, and in the less protobasic forms exhibit much of the same chemical indifference to acids, and to atmospheric action, which distinguishes the aluminic adamantoids. The species of all these tribes are crystalline; and the system of crystallization to which they belong has, wherever known, been given in the preceding tables.

§ 103. The colloid forms of matter which appear in each sub-order, and which we have designated respectively ophitoids, pinitoids, and argilloids, are, as is well known, generated both by aqueous and igneous processes, and hence include, as might be expected, both hydrous and anhydrous species. Those formed either directly or indirectly by the igneous method are necessarily very indefinite in composition, being volcanic glasses or the results of their hydration. The tendency to chemical change exhibited by colloids was insisted on by Graham; and, in view of this characteristic (as shown by Bunsen in his studies of palagonite, which is readily transformed by heat, in part, into a crystalline zeolite), the writer has elsewhere spoken of this hydrated protopercolloid as a mineral protoplasm (*ante*, page 188), a designation equally applicable to other colloidal silicates. Of these, serpentine gives rise to various crystalline species, often hydrated, such as chrysotile, marmolite, talc, enstatite, and chrysolite, which are generated in its mass by aqueous action, while by igneous fusion it is changed into a mixture of enstatite and chrysolite.

§ 104. Obsidian and pitchstone with its varieties, and tachylite and palagonite, are examples of protopercolloid silicates more or less hydrated, with the exception of the first, and susceptible, like artificial glasses, of devitrification or conversion into crystalline silicates. This process is well illustrated by the studies of Fouqué and Michel Lévy, who have shown that by maintaining in fusion for many hours vitreous mixtures of proper composition, it is possible to produce at will such crystallized species as chrysolite, pyroxene, magnetite, feldspar, leucite, and melilite, which separate from the colloid mass, as from a solution, at temperatures below the fusing points of these species.* Similar transformations occur in the presence of water, as when common glass by the action of water at high temperatures, under pressure, is changed into crystalline quartz, pyroxene, and a pectolitic silicate, or when at ordinary temperatures gelatinous precipitates become crystalline in an aqueous medium. In like manner, the amorphous persilicates left by the decay of aluminous spathoids, such as feldspars, pass into phylloid species like kaolinite and pyrophyllite, or into adamantoid species like andalusite, fibrolite, and cyanite, while the spontaneous change of certain anhydrous colloids into the crystalline state at ordinary temperatures is seen in the well known examples of vitreous arsenic trioxyd and barley-sugar. The above considerations as to the nature and relations of colloids, upon which the writer has elsewhere insisted (*ante*, page 188), will help to show their importance in a scientific study of mineralogy.

IV. — THE CLASSIFICATION OF OTHER SPECIES.

§ 105. The same mineral types which serve to divide each of the sub-orders of natural silicates into well defined

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* Synthèse des Minéraux et des Roches, Fouqué et Michel Lévy, 1882, pp. 45, 80, and *ante*, p. 209.

tribes re-appear in the non-silicated oxyds, and serve for their classification. Reserving for another occasion the details of classification of this great order of OXYDATES, we may note that, while the Oxadamantoid tribe embraces such species as periclasite, chrysoberyl, the spinels, magnetite, corundum, diaspore, hematite, quartz, rutile, cassiterite, etc., the Oxyspathoids include cuprite, zincite, crednerite, pyrolusite, tridymite, and senarmontite, and the Hydroxyspathoids, gibbsite, göthite, and manganite. Among the Oxyphylloids are brucite, pyrochroite, massicot, minium, melaconite, hydrotalcite, and pyraurite; while the Oxycolloids or Opaloids embrace bauxite, limonite, opal, uran-gummite, and eliasite.

The plan of the present essay does not embrace a discussion of the species of this order; but it will be advantageous, in connection with the history of the silicates, to notice some facts regarding the atomic volume of certain of these oxyds. The adamantoid tribe of the Oxydates includes a large number of species crystallizing alike in the isometric and the rhombohedral systems, which give for V a value approximating to that of the adamantoid silicates, chrysolite, pyroxene, garnet, epidote, beryl, and tourmaline. Ch. Gerhardt, in 1847, published a note on "The Atomic Volume of some Oxyds of the Regular System," which was translated and given in English by the present writer in the same year.* Therein accepting the view held by Laurent (§ 27) of an indefinite or unlimited divisibility of the molecule, Gerhardt proposed to reduce to a common formula, M_2O (m_2o_2 of our present notation), not only protoxyds like periclasite and protoperoxyds like the spinels, magnetite, chromite, and franklinite, but sesquioxyds like martite, hematite, and braunite, and titanates like perowskite and menaccanite, including thus not only isometric and rhombohedral but tetragonal

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* Ann. de Pharmacie, 1847, xii., 381-385, and Amer. Jour. Science, 1847, iv., 405-408; see also *ibid.*, 1852, xiii., 370-372, where the same subject was further discussed by the present writer.

forms. In the fractional formulas then proposed by him were employed the atomic values for aluminium, ferricum, chromicum, and titanium, which have since been adopted by the writer (§ 68). For all of the species above named, reduced to his common formula of M_2O, Gerhardt deduced atomic volumes varying from 10.6 to 11.4, which, divided by two, to correspond with our chemical unit, give for the value of V from 5.30 to 5.70. These variations were ascribed by Gerhardt to errors in the determinations of density, to impurities, and to the difficulty of taking into account small portions of various oxyds present, and he conceived that for all of these species the atomic volume, if correctly determined, would be the same. He, moreover, pointed out that in these oxyds, as in organic compounds, examples of polymerism might be looked for, and cited as examples cuprous and arsenious oxyds, which (like zincite and tridymite) have much greater volumes. Gerhardt, however, left untouched the question of the molecular weights of these more or less condensed oxyds thus compared by him.

§ 106. Near in condensation to the great group of oxyds thus studied by Gerhardt is the rhombohedral species, quartz, which, with D, 2.65, gives V, 5.66, while the tetragonal cassiterite, D, 6.75, gives V, 5.55. Coming next to titanic oxyd, we find for the tetragonal rutile and the orthorhombic brookite alike, with D, 4.20, a value for V of 4.88; while the tetragonal octohedrite, if we take D, 3.82 (which is also near that assigned by several observers to arkansite), gives for V, 5.36. A still more condensed molecule than that of rutile appears in the rhombohedral corundum, which with D, 4.00, gives V, 4.25; while the hydrous adamantoid diaspore, orthorhombic in form, if we take its maximum observed specific gravity, 3.50, gives for V, 4.28. Near to these is the orthorhombic protoperoxyd, chrysoberyl, which, with D, 3.80, gives V, 4.18. Thus rutile and brookite agree in atomic volume with spodumene, sapphirine, staurolite, andalusite, fibrolite, bucholzite, and zircon ($V = 4.80-4.90$), while cassiterite and quartz are near to the spinel group, and to chrysolite, pyroxene, garnet, epidote, beryl, and lyncurite. Corundum, diaspore, and chrysoberyl stand apart from all of these as having a more condensed molecule than even cyanite and xenolite, the most highly condensed silicates known.

§ 107. While small differences in atomic volume may, as Gerhardt insisted, be set down to impurities and errors in determination, a careful survey of many silicates and oxyds leads to the conclusion that among these there are great groups which, essentially agreeing among themselves in molecular condensation, differ in the value of V from other groups by quantities less than those admitted as accidental variations in volume in the large series brought together by Gerhardt; which may thus very well be found to include two or more distinct groups with unlike volumes. At the same time, the comparisons which we have here made among the adamantoid oxyds, not less than those among the various tribes of silicates, serve to strengthen the conviction that the accident of geometric form, however valuable as a means of diagnosis, is of altogether minor importance in investigating the general relations of mineral species.

§ 108. The metals proper, together with the bodies of the sulphur and the arsenic series, and the various binary and ternary compounds of all these, make up the great natural order of METALLATES, which include two suborders. Of these, the first, or *Metallometallates*, distinguished by opacity and metallic lustre, is divided into six tribes, which are: 1. Metalloids, — native metals and metal-like elements; 2. Galenoids, — argentite, galenite, bornite, chalcocite, metacinnabar, onofrite, stibnite, etc.; 3. Pyritoids, — pyrite, linnæite, stannite, chalcopyrite, pyrrhotite, etc.; 4. Smaltoids, — smaltite, niccolite, breithauptite, with other arsenids, antimonids, etc.; 5. Arsenopyritoids, — including arsenopyrite, cobaltite, etc.; 6. Bournonoids, — enargite, bournonite, zinkenite, etc.

The various selenids and tellurids form sub-tribes distinct from the sulphurous or Thiogalenoids. In the second sub-order are included those species more or less resinous or adamantine in lustre, generally red in color or in streak, and often transparent or translucent, whence the distinctive name of *Spathometallates.* In this sub-order we distinguish at least two tribes: 1. Sphaleroids, — corresponding to galenoids, and including cinnabar, realgar, christophite, marmatite, sphalerite, greenockite, and hauerite; 2. Proustoids, — corresponding to bournonoids, and embracing proustite and other red silver ores, tetrahedrite, livingstonite, dufrenoysite, binnite, etc. It is worthy of notice that while sulphid of mercury, in the forms of metacinnabar and cinnabar, appears in both sub-orders of the Metallates, the sulphid of antimony is also represented among the Spathometallates by the well known red and generally uncrystalline kermes. The various forms of sulphur and of phosphorus, together with vitreous selenium, will constitute a third tribe of the second sub-order of Metallates. The Spathometallates, as seen in their typical forms, sphalerite, wurtzite, greenockite, cinnabar, proustite, etc., serve, through the sulphoxydates, kermesite and voltzite, and through sulphosilicates like helvite and danalite, to connect the order of Metallates with spathoid Oxydates and Silicates.

§ 109. In these various tribes the relations of hardness to condensation are not less apparent than in Silicates and Oxydates. Dividing the simplest atomic formula of the complex Metallates by the number of atoms, we get, as the most convenient term for comparison, the mean weight of the elemental unit from which to deduce the volume, V. We thus find for the pyritoids, pyrite and marcasite, values for V of 4.0 and 4.2; for linnæite, 4.4; stannipyrite, 5.3; for pyrrhotite and chalcopyrite, 5.0 and 5.3; and for alabandite, 5.4. The smaltoids, niccolite, and smaltite, give 4.4 and 5.1; the arsenopyritoids, cobaltite and gersdorffite, from 4.3 to 4.6; the thiogalenoids, for chalcocite, 7.0; for stibnite, 7.4; for galenite, 7.9; and for argentite, 8.5. Of the sphaleroids, hauerite gives 5.7; sphalerite, 6.0; and other species, 7.0–7.4. The contrasts between the last two tribes and the preceding three, alike in their hardness and in their condensation, as shown in the different values of V, are apparent; and these are not less marked when the hard and dense arsenopyritoids are compared with the chemically analogous, but softer, bournonoids and proustoids. Of the former of these, enargite gives for V, 6.9, and bournonite, zinkenite, and jamesonite, 7.7–7.8; while of the proustoids, miargyrite, proustite, pyrargyrite, and polybasite give from 8.0 to 9.0, and dufrenoysite and tetrahedrite, from 7.2 to 8.3. By reason of the variations in the recorded specific gravities of most of the species compared, the values here given for V must be regarded as but approximations, to be corrected with the help of more exact determinations.

§ 110. The native compounds of the haloid elements may be included under the order HALOIDATE, with the four sub-orders of *Fluorid*, *Chlorid*, *Bromid*, and *Iodid.* Titanates, niobates, tantalates, tungstates, molybdates, chromates, vanadates, antimonates, arsenates, phosphates, nitrates, sulphates, borates, carbonates, and oxalates constitute as many distinct orders. Of these the soluble chlorids, sulphates, borates, carbonates, etc., belonging to the salinoid type, form tribes under their respective orders, as Chlorosalinoid, Sulphatosalinoid, Borosalinoid, and Carbosalinoid. The native combustible carbons and hydrocarbonaceous bodies are included in a single order, which, from the fire-making property of these, may be aptly designated as the order of PYRICAUSTATES. This is divided into two sub-orders: 1. *Carbates*, including the phylloid, graphite, and the adamantoid, diamond, representing two tribes; and 2. *Carbhydrates*, which may be conveniently grouped in the four tribes, Naphthoid, Asphaltoid, Resinoid, and Anthracoid.

§ 111. It is impossible to arrange in a single line the whole of the orders of natural mineral species in such a manner as to show their affiliations. If, however, we place consecutively in a horizontal line the four orders of Metallate, Oxydate, Haloidate, and Pyricaustate, the second of these will form the summit of a vertical column in which, beneath the Oxydates, may be placed successively all the other orders: Silicate, Titanate, Niobate, Tantalate, Tungstate, Molybdate, Chromate, Vanadate, Antimonate, Arsenate, Phosphate, Nitrate, Sulphate, Borate, Carbonate, and Oxalate,— an arrangement of these orders of oxydized compounds in which general physical characters have been considered. The Metallates are connected with the vertical column by sulphuretted oxyds like kermesite and voltzite, and by sulphosilicates like helvite and danalite; while the sulphuretted carbhydrates show the affiliation of the Metallates with the Pyricaustates. The Haloidates are connected with the same vertical column by the oxychlorids, by chlorosilicates and fluorosilicates like sodalite, pyrosmalite, tourmaline, chondrodite, and topaz, and by the haloid elements in certain arsenates, phosphates, borates, and carbonates. The affiliations between the orders in the vertical column are seen in titanosilicates like titanite and astrophyllite, in niobosilicates like wöhlerite, in sulphatosilicates like hauÿne, in borosilicates like datolite and tourmaline, and in carbosilicates like cancrinite. Of these orders, Metallates, Pyricaustates, and Haloidates will each constitute a class,—all the remaining orders being included in another class.*

* Weisbach, the successor to Breithaupt at Freiberg, published in 1875, in his Synopsis Mineralogica, a modification of the system of Mohs. Class I. of Weisbach, HYDROLYTE, or Salts, includes compounds soluble in water; while Class II., LITHE, or Stones, is divided into three orders: 1. *Kuphoxyde;* 2. *Pyritite* (silicate), including four families: *a.* Sklerite; *b.* Zeolite; *c.* Phyllite; *d.* Amorphite; and 3. *Apyritite* (non-silicate). Class III., METALLITE, or Ores, is divided into four orders: 1. *Halometallite;* 2. *Metalloxyde;* 3. *Metalle;* 4. *Thiometalle*, the last including three families: *a.* Pyrite; *b.* Galenite (Glances); *c.* Cinnabarite (Blendes). Class IV., KAUSTE, or Combustibles, includes five orders: 1. *Ametalle* (Sulphur); 2. *Anthracite* (Coals); 3. *Asphaltite* (Pitches);

These four classes of Metalline, Oxydized, Haloid, and Combustible species, with their orders and sub-orders, may be tabulated as follows: —

CLASSES.	ORDERS AND SUB-ORDERS.
I.	1. METALLATES: *a.* Metallometallates; *b.* Spathometallates.
II.	2. OXYDATES. — 3. SILICATES: *a.* Protosilicates; *b.* Protopersilicates; *c.* Persilicates.—4. TITANATES. — 5. NIOBATES. — 6. TANTALATES. — 7. TUNGSTATES. — 8. MOLYBDATES.— 9. CHROMATES.— 10. VANADATES.— 11. ANTIMONATES. — 12. ARSENATES. — 13. PHOSPHATES. — 14. NITRATES. — 15. SULPHATES. — 16. BORATES. — 17. CARBONATES. — 18. OXALATES.
III.	19. HALOIDATES: *a.* Fluorids; *b.* Chlorids; *c.* Bromids; *d.* Iodids.
IV.	20. PYRICAUSTATES: *a.* Carbates; *b.* Carbhydrates.

§ 112. The conceptions of high molecular weights in mineral chemistry, and of the existence of compounds

4. *Rhetinite* (Resins); 5. *Paraffine* (Waxes). The silicates of heavy metals are placed in Class III., but with these exceptions the Sklerite include the spathoids and adamantoids, the Phyllite the phylloids, and the Amorphite the colloids of our three sub-orders of Silicates, arranged in part crystallographically and in part chemically. The Oxydates are divided between the Kuphoxyde and the Metalloxyde, or those of the lighter and the heavier metals. In Halometallite are found the silicates of yttrium, zirconium, thorium, cerium, zinc, copper, iron, and manganese, together with niobates, tantalates, tungstates, chromates, as well as arsenates, phosphates, sulphates, carbonates, fluorids, and chlorids of the heavy metals; the corresponding compounds of the lighter metals coming under the order Apyritite of Class II. In a second edition of the Synopsis, in 1884, the Halometallite are made an order in a new class, called *Metallolithe*, or Metalstones; while the order *Asphaltite* is divided by separating from it the order *Elaoite* (Petroleums). In the order of *Thiometalle*, the family Pyrite includes alike the pyritoids, smaltoids, and arsenopyritoids; Galenite, the galenoids and bournonoids, and Cinnabarite, the sphaleroids and proustoids.

From the point of view chosen for our essentially chemical system it seems unnatural to place in two distinct classes analogous and closely related oxyds, silicates, carbonates, etc. Again, the different degrees of condensation, as shown in atomic volume, and in the relations of this to hardness and susceptibility to chemical change, which underlie the dislike polycarbonates and polysilicates, made up of a great many chemical units, and including a large number of basic atoms, taught by the writer in 1853 and 1854, and then illustrated by the carbon-spars, pyroxenes, feldspars, and tourmalines, are now only, after a whole generation, beginning to be recognized by chemists. The first step in this argument is believed to have been the conclusion then deduced from the study of equivalent volumes, — that the law of condensation already known in gases and vapors applies also to solids; "so that their equivalent weights, as in the case of vapors, are directly as their densities, and the equivalents of mineral species are as much more elevated than those of the carbon series as their specific gravities are higher." By reference to the context of this, as already cited in § 15, it will be seen that a notion of the importance of geometric form in conditioning density was then entertained by the writer, which led

tinction between spathoids and adamantoids, must not be lost sight of. It may be further remarked that instead of making, as Mohs and Weisbach have done, solubility in water and sapidity the ground of a class-distinction, we subordinate it to the order, constituting such soluble species tribes of their respective orders.

[The same may be said of the colloid or amorphous character which we have made the basis of tribes alike in the three sub-orders of Silicates, and in the Oxydates, and which is equally well marked in some other orders. Breithaupt, who early insisted upon the importance of this character, established upon it, in his class LAPIDES, an order, *Porodini*, and embraced therein most of the silicates of our three porodinous or colloidal tribes, together with some Oxydates, as well as the colloidal Sulphates, Phosphates, and Arseniates. He subsequently recognized the wider significance of this character by making in the order *Sclerites* a genus, Amorphites, which he declared to be porodinous, including opal, pitchstone, tachylite, and obsidian. Still farther, in his class MINERAE, under the order *Aerea*, he proposed several porodinous genera, comprising various colloidal oxyds, such as limonite, asbolite, psilomelane, and urangummite. (Handbuch der Mineralogie, 1836, 1841, 1847.) Weisbach, following Breithaupt, has made of the colloidal silicates an order, *Amorphite*. The conception underlying the five orders of *Zeolithi*, *Grammites*, *Sclerites*, *Micae*, and *Porodini*, in which Breithaupt included, with many other species, most of the silicates, though but imperfectly carried out in his scheme, corresponds to that of the five tribes which we have defined alike in each sub-order of Silicates and in the order of Oxydates.]

him, in his paper published a few months later in 1853, on the Constitution and Equivalent Volume of Mineral Species (§ 17-18), to suppose the existence of differences between the volumes of isometric, rhombohedral, and various prismatic species. This notion was, however, soon afterwards discarded, as may be seen from the citations from his paper of 1867, already given in § 12-14.

§ 113. In further illustration of the supposed relations of density and equivalent, the following additional passage is quoted from the paper last cited: —

"There probably exists between the true equivalent weights of non-gaseous species and their densities, a relation as simple as that between the equivalent weights of gaseous species and their specific gravities. The gas or vapor of a volatile body constitutes a species distinct from that same body in its liquid or solid state, the chemical formula of the latter being some multiple of the first; and the liquid and solid species themselves often constitute two distinct species, of different equivalent weights. In the case of analogous volatile compounds, as the hydrocarbons and their derivatives, the equivalent weights of the liquid or solid species approximate to a constant quantity, so that the densities of those species, in the case of homologous or related alcohols, acids, ethers, and glycerids, are subject to no great variation. These non-gaseous species are generated by the chemical union or identification of a number of volumes or equivalents of the gaseous species, which number varies inversely as the density of these species. It follows from this that the equivalent weights of the liquid and solid alcohols and fats must be so high as to be a common measure [multiple] of the vapor-equivalents of all the bodies belonging to these series. The empirical formula $C_{114}H_{110}O_{12}$, which is the lowest one representing the tri-stearic glycerid (ordinary stearine), is probably far from representing the true equivalent weight of this fat in its liquid or solid state; and if it should hereafter be found that its density corresponds to six times the above formula, it would follow that liquid acetic acid, whose density differs but slightly from that of fused stearine, must have a formula and an equivalent weight about one hundred times that which we deduce from the density of acetic acid vapor, $C_4H_4O_4$."

§ 114. In the papers of 1853 the equivalent or molecular weights assigned by me to mineral species were confessedly arbitrary. Taking as a term of comparison the formulas of such well known species as the alums, the orthophosphates of soda, ferrocyanid of potassium, lactose, the compound of glucose and sodium-chlorid (the empirical equivalents of which were doubled to compare with that of piperine), minimum molecular weights were adopted for the various polycarbonates and polysilicates which it was sought to compare in volume with the species just named. Thus it was, that in the notation of the time the formulas and molecular weights of the rhombohedral carbon-spars, smithsonite and calcite, were represented respectively by $C_{40}Zn_{40}O_{120} = 2500$, and $C_{30}Ca_{30}O_{90} = 1500$; and those of the polysilicates, spodumene and diopside, by $si_{60}(al_{24}Li_4Na_2)O_{90} = 1400$, and $si_{52}(Ca_{13}Mg_{13})O_{78} = 1404$. The question of the relations of these provisional formulas and provisional weights to the still higher (and as yet unknown) values which belong to these species was left untouched. These silicates and carbon-spars are, so far as known, incapable of any chemical combinations or decompositions but such as affect their more or less complete resolution, and at the same time afford no guide to the molecular constitution of the species.

§ 115. We have already noticed the partial adoption of the notion of polysilicates, in 1860, by Ad. Wurtz, who did not in any way consider the great problem of their molecular weights, or their specific gravities. Meanwhile, however, the arguments adduced by me in 1853 in favor of high molecular weights have been strengthened by discoveries which serve to show the wide application of the analogies then drawn from the chemistry of the carbon series. First among them may be noticed the various artificial crystallized cobalt compounds, such as the potassio-cobaltous nitrate, to which was assigned a formula with 2Co, 6K, and 12N, and a unit-weight of 958. More remarkable still are the ammonio-cobalt bases, studied by Frémy and other chemists, but made more completely known by the elaborate researches of Wolcott Gibbs and F. A. Genth, in 1857. Among these may be noted the chlorid of purpureo-cobalt of the latter chemists, tetragonal in form, with a specific gravity of 1.802, which includes in its formula, with 2Co, not less than 6Cl and 10N, and has a unit-weight of 501; the chlorid of luteo-cobalt of Frémy, clinorhombic in form, with specific gravity 1.701, which, with the same proportions of cobalt and chlorine, contains not less than 12N, and has a unit-weight of 535; and, finally, the orthometaphosphate of luteo-cobalt of Braun, for which is deduced a formula including 6Co and 36N, with 10P, giving a unit-weight of 2540.* These numbers, like those deduced for alums, ferrocyanids, sugars, and alkaloids, represent the weight of the chemical units of which the species are supposed to be in all cases polymerides, the molecular weights of which are as yet unknown.

§ 116. Still farther light has, however, been thrown on the subject of polybasic salts of great complexity by the studies of the compounds of tungsten and molybdenum. It was in 1861 that Marignac made known the existence of two types of silicotungstates, in which one molecule of SiO_2 is united, respectively, with ten and twelve molecules of WO_3. Subsequent studies by Scheibler made us acquainted with series of phosphotungstates in which six molecules and twenty molecules of WO_3 are united with one of P_2O_5; while Henri Sainte-Claire Deville and Debray made known analogous phosphomolybdates. Wolcott

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* See Gibbs and Genth, Smithsonian Contributions, ix., 1857, and Amer. Jour. Science, xxiii.-xxiv.; also farther Gmelin-Kraut, Handbuch, iii., *sub voce* "Kobalt."

Gibbs has resumed the study of these various compounds, designated by him "Complex Inorganic Acids," and has greatly extended our knowledge of them. He now recognizes a series of metatungstates, the lowest of which, considered as an acid, is $4WO_3 . H_2O$, and the highest $16WO_3 . 7H_2O$; while he finds not less than ten phosphotungstates, constituting a homologous series, "the homologizing term" being $2WO_3$, the extremes $6WO_3 . P_2O_5 . 6H_2O$, and $24WO_3 . P_2O_5 . 6H_2O$, and the salts apparently 12-basic. Similar series are got for molybdenum, and arsenic, vanadic, and antimonic oxyds may replace the phosphoric oxyd in these compounds. Hypophosphorous and phosphorous and metaphosphoric acids may also take the place of phosphoric acid in these complex salts, and portions of the oxygen in molybdic and tungstic oxyds may be replaced by fluorine, while hydrocarbon radicals like ethyl, methyl, and phenyl, appear also to be capable of entering into the the compounds.

§ 117. The silicotungstates of Marignac have also been the subject of farther generalization by Gibbs, and it is found that the molecule of silica therein may be replaced by the oxyds of platinum, selenium, tellurium, etc. The oxyds of tin, titanium, zirconium, niobium, and tantalum also appear to form similar combinations with the tungstates and molybdates. All of these series of salts are soluble in water, and crystallizable, generally assuming clinorhombic or triclinic forms. Nor are these complex salts confined to the compounds of tungsten and molybdenum; Gibbs has found several new series made up from vanadic with phosphoric or arsenic acid, one of which he represents by $20V_2O_5 . P_2O_5 . 6H_2O + 53H_2O$, and he concludes that "these complex inorganic acids form a new department of inorganic chemistry, and not a series of isolated compounds."

§ 118. With regard to all such complex species, Gibbs justly remarks, "We have no positive knowledge of the composition of these salts, their molecular weights being, as in the case of most inorganic compounds, entirely unknown." He adds that the progress of science "tends constantly to show that the structure of inorganic molecules is more complex than we formerly supposed," * and illustrates the great complexity in these compounds by a phosphotungstate including vanadium and barium, represented by the formula $60WO_3.\,3P_2O_5.\,2V_2O_5.\,VO_2.\,18BaO+144H_2O$, and having in his opinion "the highest molecular weight yet observed, 20,058." He describes another similar compound, $60WO_3.\,3P_2O_5.V_2O_5.VO_2.\,18BaO+150H_2O$, of which he says, "It is almost certainly a double or triple salt, but it still shows how five different oxyds may exist in a single well defined and beautifully crystallized compound." Besides these soluble and hydrous species, all produced in the moist way, is the curious gold-colored insoluble anhydrous crystalline body discovered by Wöhler, which is formed at a red heat, and is generally described as a tungstate of tungstous oxyd and soda. This, Gibbs suggests, may possibly be represented by $16WO_3.\,4WO_2.\,7NaO$, which corresponds to a unit-weight of 5002.

§ 119. The researches of Gibbs upon these complex inorganic acids, resuming, extending, and generalizing those of other laborers in the same field, are of much

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* Wolcott Gibbs on Complex Inorganic Acids; Amer. Jour. Science, 1877, xiv., 61; also, in abstract, Proc. Brit. Assoc. Adv. Science, Montreal, 1884, p. 667, and more fully in Amer. Jour. Chemistry, 1879–1883, i., 1, 217; ii., 217, 281; iii., 317, 402; iv., 377; v., 361, 391. [See farther *ibid.*, vii., 392–417, wherein are noticed the pyrophosphates of Wallroth, such as $Ca_{10}.\,Na_{16}.\,(P_2O_7)_9$, etc. It would appear, says Gibbs, that complex molecules similar to these "enter directly into combination with twenty-two molecules of tungstic oxyd" to form the still more complex pyrophosphotungstates. He also notes the molybdates described by Struve, in 1854, in which aluminic, chromic, ferric, and manganic oxyds are united with molybdic oxyd, and give such salts as $Al_2O_3.\,12MO_2.\,6K_2O+20Aq$; and $Mn_2O_3.\,12MO_3.\,5H_2.O+21Aq$; and, farther, the salts of Parmentier, $Al_2O_3.\,10MO_3.\,2K_2O+15Aq$, etc., as additional examples of salts having necessarily high molecular weights.]

significance to the chemist in his study of natural mineral species, both by establishing the doctrine of a great complexity of molecule in similar bodies, and by showing the influence of very small portions of some one constituent in a compound. Thus the addition to twelve molecules, or 2784 parts of tungstic oxyd, of one molecule, or sixty parts of silica, determines the formation of an octobasic silicotungstate, which differs notably in its chemical relations from the corresponding decabasic metatungstate, equally with twelve molecules of tungstic oxyd. In like manner, the addition to twenty-four molecules of tungstic oxyd of one of phosphoric oxyd gives rise to a new and distinct complex acid; while small proportions of very various oxyds produce other new and well defined compounds. By an analogy not too remote, we are helped to understand the part played in many natural silicates by small portions of fluorine, of chlorine, of sulphur, of sulphates and carbonates, and even of phosphates, arsenates, and vanadates, which have hitherto been in many cases regarded as accidental impurities.

§ 120. The readers of the second part of this essay will recall that in putting forth, in 1853, the views ever since maintained with regard to the condensation of the molecule, and the very complex structure of so-called inorganic compounds, it was affirmed that these views would not only "lead to a correct mineralogical system," but would "be found to enlarge and simplify the plan of chemical science." This latter result, it was then farther shown, was to be attained by establishing, for mineral or inorganic species, complex formulas and high molecular weights, and by applying "to these bodies the laws of substitution, homology, and polymerism, which have long been recognized in the chemical study of the hydrocarbon series." A generation has passed since then, and chemists are now, by the methods then first indicated, advancing in this direction towards what Roscoe calls "the establishment of a systematic inorganic chemistry which needs not fear comparison with the order which reigns in the organic branch of our science." He adds, "It is well to be reminded that complexity of constitution is not the sole prerogative of the carbon compounds, and that before this systematization of inorganic chemistry can be effected we shall have to come to terms with many compounds concerning whose composition we are at present wholly in ignorance," and by way of illustration refers to the complex inorganic acids of Gibbs.*

§ 121. Recognizing from the beginning of this inquiry, in 1853, that the molecular weights of mineral species, while far exceeding those of hydrocarbonaceous or so-called organic liquids and solids, are equally unknown, we have sought, nevertheless, to show the comparative condensation in different mineral species, and at the same time the existence of homologous series among them, by the use of atomic formulas. In these the results of chemical analysis are reduced to their simplest term, and are presented independent of all hypotheses as to the structure or the molecular weight of the species. These formulas suggest to the chemist something more than the elemental atoms represented by the symbols employed. While he admits in the simplest mineral silicate or oxyd the existence of oxygen, silicon, and one or more metals, all being chemical elements physically dissimilar to each other, and to the species before him, the tendency of the mind is to conceive this as made up of identical or of similar units or individuals. The justification of this mental process appears in the fact that it is in the comparison of such individuals or chemical units that we find the chief data for the intelligent study of the chemical species. Such a conception of units underlies the doctrine of polymerism, and that of homologous or progressive series, and enables us to compare silicates, oxyds, and carbon-spars in a manner the correctness of which is

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* Sir H. E. Roscoe, Address to the Chemical Section of the British Assoc. Adv. Science, Montreal, Aug., 1884, Report, p. 663.

verified by the close relations revealed between atomic weight and specific gravity. While we may take for the chemical unit either its simplest expression, or some multiple thereof, we have, for convenience in the study of silicates and oxyds, preferred the former, which for both of these may be represented as a compound of a monatomic elemental atom, or its equivalent, with an atom of oxygen, sulphur, fluorine, or chlorine. For compounds of metals with sulphur, arsenic, antimony, etc., the elemental atom itself may be assumed as the unit. For carbonates, however, it has not seemed expedient to divide the weight of the tetrad carbon beyond that portion which in the normal carbonate is found with a univalent metal; while in complex sulphates like alum, in orthophosphates, etc., convenience suggests the less simple individuals which we have employed in these pages.

§ 122. Having adopted for all mineral silicates and oxyds the simplest conceivable chemical unit, as above indicated, the second step in our inquiry was to determine for each species, from its atomic formula, the mean weight of the unit, the atom of hydrogen being taken as one, and that of oxygen as eight; this mean weight has been designated P. The next point to be considered is the relation of this chemical unit to space, a relation which is the nexus between the chemical and the physical, and is determined by dividing the mean unit-weight by the specific gravity of the species (water being unity), represented by D. The quantity thus obtained we have designated as the unit-volume, or atomic volume, and have represented by V. The relations alike of this unit-weight and unit-volume to those of the molecule to which it belongs are unknown. But this molecule has, by our hypothesis, a constant volume, for which an expression is yet wanting, and can, so far as now known, only be attained by assuming as unity the number which corresponds to the highest discovered value of V. The true unit of molecular volume will probably still be some multiple of this quantity, and will, at the same time, be the common multiple of all the atomic volumes deduced from various chemical units.

§ 123. In approaching the consideration of this molecular volume, it may be noted that while in salts of the same type the specific gravity sometimes rises with the molecular weight of the base, as when zinc replaces magnesium, or lead replaces strontium, in carbon-spars, the specific gravity of double or triple salts is essentially the same as that of the corresponding salts with a single base, as may be seen by comparing the densities of simple and double hydrous sulphates, orthophosphates, and tartrates; so that the value of P, deduced from the more complex salts, considered as chemical units, will be essentially the same as that of the apparently simple salts of the type. Taking, then, of the ammonia-cobalt salts (§ 115), not the simple chlorids, but Braun's complex phosphate of luteo-cobalt, with a unit-weight of 2540 (of which the specific gravity is undetermined), we have, if we assume for it a density of 1.701 (which is that of the chlorid of the same base), a unit-volume of not less than 1493.

§ 124. The complex tungstates give still higher volumes. The golden anhydrous tungstico-tungstate of sodium has a specific gravity of 6.617, while for two allied tungstic compounds, the one potassic and the other sodic, are given the numbers 7.60 and 7.28, showing that these are similar in condensation to the anhydrous calcic and ferrous tungstates, scheelite and wolfram. For the soluble and hydrated polytungstates, Scheibler found the specific gravity of $4WO_3.Na_2O+10Aq$ to be 3.987, while that of the corresponding barium salt, with 9Aq, is 4.298, and that of $14WO_3.6Na_2O+32Aq$ is 3.846.* The density of the complex hydrous phospho-vanadio-tungstate of barium described by Gibbs (§ 114), with a unit-weight of 20,058, is unknown, but, if we assume for it the number

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* See Constants of Nature, by F. W. Clarke, Part i., 83.

found by Scheibler for the hydrous barytic metatungstate, we have a unit-volume of not less than 4666, or more than three times the volume of the cobalt salt. What greater unit-volume than this can be determined, remains for the chemist to discover, but it should be considered that such elevated unit-weights as that last mentioned are not readily attained, save with a few elements of high atomic weight, such as tungsten, vanadium, and barium. Moreover, with elements of lower atomic weight, the difficulty of fixing definite formulas for their compounds is notably increased, so that the remarkable results obtained by Gibbs may, for a long time to come, mark the limits of the chemist's skill in this direction of research.

§ 125. If, then, as we have argued, the molecules of mineral species are so complex, and their minimum molecular weight is so large that their volume may be represented by a sum not less than about 4666, or more probably some multiple thereof, it follows that a silicate like pyroxene, for the simplest atomic unit of which we have found a volume of about 5.5, must include in its molecule not less than 848 such atomic units, and wollastonite, with a corresponding volume of 6.6, about 700. But as our simplest atomic formula for these species embraces three of these units $(m_1si_2)o_3$, it will be evident that with the molecular volume of 4666, here assumed, the constitution of pyroxene may be represented very nearly by $282(m_1si\ )o_3$, and that of wollastonite by $236(m_1si_2)o_3$. In like manner, the atomic volume of the feldspars, anorthite and albite, approximately represented by 6.3, is contained in our assumed molecular volume 742 times. The simplest atomic formula for anorthite being $(ca_1al_3si_4)o_8$, and for albite $(na_1al_3si_{12})o_{16}$, the constitution of anorthite may be represented by $92(ca_1al_3si_4)o_8$, and that of albite by $46(na_1al_3si_{12})o_{16}$; while for orthoclase and microcline, with a unit-volume of 6.8, we deduce a formula of $42(k_1al_3si_{12})o_{16}$.

It will be evident that attempts like these at molecular formulas are of value only so far as they serve for illustration, since the unit-volumes assigned to the various species are but approximations, and the molecular volume, 4666, which has been assumed, is based on a supposed specific gravity, and can only be conjectured to be not far from the truth. A series of careful studies of the specific gravities of various salts of the complex inorganic acids may furnish us with more trustworthy data for similar calculations. Meanwhile, it is to be repeated that the formulas here given for pyroxene, wollastonite, and the feldspars, are of value only as they serve to illustrate our conception of the complex constitution of these silicates. For the purposes of comparison, and for the elucidation of polymerism and homologies, the unit-volumes which we have calculated for the preceding tables of species of the different tribes of silicates, serve every purpose, and show in a simple manner the relative condensation of the molecule in the various species. Attempts to devise structural formulas for these very complex silicates appear, in the present state of our knowledge of their constitution, to be premature, and, at the same time, unnecessary.

§ 126. We have seen in our studies of the volume of mineral species two cases; the first being that in which, in analogous compounds, the density varies with the unit-weight, so that the species compared have identical unit-volumes; and the second, that in which species, otherwise analogous, have such densities as give very unlike unit-volumes, — a fact showing the existence of progressive or homologous series of polymerides, as illustrated in the case of many silicates and carbon-spars. Examples of these differences are seen in the chlorids of potassium and sodium, the latter of which itself presents remarkable differences in density. Thus, while the numerous determinations for potassium-chlorid do not vary very much from a specific gravity of 1.99, the careful observations of different experimenters with sodium-chlorid show variations from 2.011 by Playfair and Joule to 2.15–2.16 by

Stolba, 2.195–2.204 by Deville, and 2.24–2.26 by Mohs and Filhol.* With these various determinations of density before us, says Henry Wurtz, "we are forced to infer the existence of four modifications of sodium-chlorid," while he adds, "common salt is far from being alone among saline combinations in its passage into divers modifications or allotropes. On the contrary, the circumstance is almost universal among salts, throughout the whole range of chemistry." It would seem, in fact, that such variations in specific gravity in a homogeneous solid (like those in the specific gravity of a vapor or gas at constant pressure and temperature) can have but one meaning; which is that these sodium-chlorids of different densities are so many distinct species, related to each other as fibrolite to cyanite, as lyncurite to zircon, and as tridymite to quartz.

§ 127. All such allotropic variations in compound species, which are marked not only by differences of density, but in many cases, if not in all, by differences in hardness and in chemical relations, are by Henry Wurtz conceived to be "dependent on a variability through a certain (sometimes not very narrow) range of diameters, of one element, always the basylic or electropositive of a group, — in salts, therefore, always the metallic base." According to him, the volumes of elemental molecules, that of oxygen excepted, "are expressed by quantities having, at the temperature of ice-fusion, the relations of even cubes of a series of whole numbers, of which series the number pertaining to the molecule of ice at this temperature is 27." This, he adds, is "a standard volume in nature, to which the volumes of all liquid and solid bodies may be compared when at the same temperature." The cube roots of these numbers are by Wurtz designated as "molecular diameters," and the variations in specific gravity in the different forms of sodium-chlorid are explained by supposing the diameters of one or more of the sodium molecules in a complex group including 4NaCl to vary from 23 to 24

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* Constants of Nature, by F. W. Clarke, Part i., 30.

and 25, the diameter of the chlorine molecules remaining invariable.* This method enables him, by admitting more or less complex groups, in which the similar elemental molecules have varying diameters, to approximate closely to the densities of liquid and solid species.

§ 128. To such a scheme it must be objected that it involves the notion of existing elements or groups of elements, dissimilar to each other as well as to the species under examination. The conception that the chemical elements enter as such into combination, and there retain their volumes, is, it is believed, inadmissible in chemical philosophy. The view which I have constantly maintained, and have set forth in the present essay, is that differences in density, such as we have just considered, are not dependent on variations in the hypothetical units adopted for convenience in calculation, but belong to the species as an integer, and correspond to a greater or less condensation of its mass, — that is to say, to the identification in a constant volume of a greater or less number of chemical units. The very terms of atom and molecule, which we apply to these imaginary units and to the mass, are concessions to a popular terminology borrowed from physics, and are not only inadequate but to a certain extent misleading when applied to chemical operations. I venture in this connection to reprint the words employed in 1874 † in the discussion of this same question: —

"The phenomena of chemistry lie on a plane above those of physics, and, to my apprehension, the processes with which the latter science makes us acquainted can afford, at best, only imperfect analogies when applied to the explanation of chemical phenomena, to the elucidation of which they are wholly inadequate. In chemical change, the uniting bodies come to occupy the same space

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* Geometrical Chemistry, by Henry Wurtz, page 72, 1876; reprinted from the American Chemist, March, 1876.

† A Century's Progress in Theoretical Chemistry: being an address at the grave of Priestley, July 31, 1874, reprinted from the American Chemist for August and September, 1874. See, also, *ante*, pp. 13–15.

at the same time, and the impenetrability of matter is seen to be no longer a fact; the volume of the combining masses is confounded, and all the physical and physiological characters which are our guides in the region of physics fail us, gravity alone excepted; the diamond dissolves in oxygen gas, and the identities of chlorine and of sodium are lost in that of sea-salt. To say that chemical union is, in its essence, identification, as Hegel has defined it, appears to me the simplest statement conceivable. The type of the chemical process is found in solution, from which it is possible, under changed physical conditions, to regenerate the original species. Can our science affirm more than this, and are we not going beyond the limits of a sound philosophy when we endeavor by hypothesis of hard particles, with void spaces, of atoms and molecules, with bonds and links, to explain chemical affinities; and when we give a concrete form to our mechanical conceptions of the great laws of definite and multiple proportions to which the chemical process is subordinated? Let us not confound the image with the thing itself, until, in the language of Brodie, in the discussion of this very question, 'we mistake the suggestions of fancy for the reality of nature, and we cease to distinguish between conjecture and fact.'"

§ 129. We here terminate, for the present, the discussion of the principles which, as we have claimed, serve "to enlarge and simplify the plan of chemical science," and, as a necessary result thereof, to form the basis of a Natural System in Mineralogy. We have endeavored to set forth in some detail the application of these principles to the Silicates, and more briefly to the non-silicated oxyds, which we have included in the order of Oxydates, as well as to the order of Metallates. We have, moreover, given (§§ 110, 111) an outline of a system of classification which embraces all natural mineral species. It is here the place to repeat the language employed in 1867, and already cited, in § 13, that all chemical species really belong to the mineral kingdom, and that, "in this extended sense, mineralogy takes in not only the few metals, oxyds, sulphids, silicates, and other salts which are found in nature, but also all those which are the products of the chemist's skill. It embraces, not only the few native resins and hydrocarbons, but all the bodies of the carbon series made known by the researches of modern chemistry." A Manual of Mineralogy, based on the principles here set forth, such as we hope to prepare, would, however, be limited to the consideration of natural species.

§ 130. In conclusion, we give three synoptical tables, in which are resumed, under their respective tribes, the principal species of the three sub-orders into which we have divided the order of SILICATES. In these tables the dominant atomic ratios are given in the left-hand columns, while more rarely recurring ratios, as in danalite, schorlomite, sloanite, etc., are placed in parentheses after the names of the species, which are in their appropriate positions in their respective columns. In the case of Tribe 4, the exigencies of construction have caused its displacement in the table, and hence the atomic ratios of its included species are there also appended. The calculated values of V are given with the respective tribes. These tables are necessarily much abridged, and should be studied in connection with the systematic grouping of sub-orders, tribes, and species, to be found under § 55 of the present essay.

For the colloid tribes the reader is referred to pages 374–375, where the very variable composition of the vitreous products of igneous fusion is insisted upon. As regards the limits of species in such cases, the question which arises is similar to that presented by the various intermediate feldspars and scapolites, already discussed, and by the intermediate carbon-spars, and is one intimately connected with the high molecular weights which must be assigned to mineral species.

SUB-ORDER I.—PROTOSILICATE.

m : si.	1. Pectolitoid. V=7·0—5·3	2. Protospathoid. V=6·7—6·0	3. Protadamantoid. V = 6·0—4·6	5. Ophitoid. V = 7·3—5·5
1 : ¾	- - - - - - - - - -	Danalite (7 : 6). - - - - - - -	Chondrodite.	
1 : 1	Calamine. Thorite. Cerite. -	Willemite. Knebelite. Batrachite. Tephroite. Gadolinite. Helvite.	Monticellite. Chrysolite. Phenacite. Bertrandite.	
1 : 1¼	Chrysotile. - - - - - -	Leucophanite. - - - - - - - -	- - - - - - - - - - - - -	Serpentine. Retinalite.
1 : 1½	Gyrolite. Friedelite. Pyrosmalite. - - - - -	- - - - - - - - - - - - - -	- - - - - - - - - - - - -	Deweylite. Genthite.
1 : 2	Xonaltite. Plombierite. Dioptase - - - - - - -	Wollastonite. Tscheffkinite. - - -	Amphibole. Rhodonite. Pyroxene. Enstatite. -	Aphrodite. Cerolite. Chrysocolla.
1 : 2¼	Pectolite. - - - - - - - -	- - - - - - - - - - - - - -	Amphibole. - - - - - - -	Spadaite.
1 : 2½	- - - - - - - - - - - - -	- - - - - - - - - - - - - -	- - - - - - - - - - - - -	Rensselaerite.
1 : 3	- - - - - - - - - - - - -	- - - - - - - - - - - - - -	- - - - - - - - - - - - -	Sepiolite. Glauconite.
1 : 3½	Datolite.			
1 : 4	Apophyllite. Okenite. - -	- - - - - - - - - - - - - -	Guarinite. Titanite.	4. Protophylloid.
1 : 7	- - - - - - - - - - - - -	- - - - - - - - - - - - - -	Danburite.	Thermophyllite (3 : 4). Talc (2 : 5). Talc (2 : 6).

SUB-ORDER II.—PROTOPERSILICATE.

m : *m* : si.	6. ZEOLITOID. V=7·2—6·3	7. PROTOPERSPATHOID. V = 8·6 — 6·1	8. PROTOPERADAMANTOID. V = 5·8 — 4·7		9. PROTOPERPHYLLOID. V = 6·2 — 5·1	
1 : ½ : n	- - - - -	Melilite. Eudialyte. -	Pargasite. Keilhauite. - - - - - -		MICAS. Phlogopite. -	CHLORITES. A large group of hydrous magnesian species.
1 : ¾ : n	- - - -	Wöhlerite. Ilvaite. -	Idocrase. Schorlomite (4 : 3). - - -		Phlogopite. -	
1 : 1 : n	Xanthorthite.	Gehlenite. Sarcolite. Milarite. - - - -	Garnet. Ægirite, Allanite. Beryl. -		Biotite. - -	
1 : 1½ : n	- - - - -	Barylite. - - - - -	Euclase. Ardennite. Prehnite. -		Seybertite.	10. PINITOID.
1 : 2 : n	Hamelite. Catapleiite.	Scapolites. Sodalites.	Axinite. Epidote. Zoisite. Jadeite. Gastaldite. Acmite. - - - - -		Willcoxite. -	Jollyte.
1 : 3 : n	ZEOLITES. - -	FELDSPATHIDES. - - -	- - - - - - - - - -	TOURMALINES. Coronite.	Zinnwaldite.	Fahlunite. Bravaisite.
1 : 4 : n	Edingtonite. Sloanite.	Petalite. - - - - -	Spodumene. Sapphirine. Staurolite. - - - -	Schorlite.	Lepidolite. -	Hygrophilite (1 : 5).
1 : 6 : n	Forestite. -	- - - - - - - - -	- - - - - - - - - -	- - - -	Margarite. Muscovite.	Sordavalite.
1 : 8 : n	- - - - -	- - - - - - - - -	- - - - - - - - - -	Aphrizite.	Euphyllite.	Pinite.
1 : 9 : n	- - - - -	- - - - - - - - -	- - - - - - - - - -	Indicolite.	Damourite. Muscovite.	Cossaite.
1 : 12 : n	- - - - -	- - - - - - - - -	- - - - - - - - - -	Rubellite.	Muscovite.	(Palagonite. Tachylite. Pitchstone. Obsidian.)
					(With other species).	

SUB-ORDER III. — PERSILICATE.

m : si.	11. PERZEOLITOID. V = ——	12. PERSPATHOID. V = 7·7—7·2	13. PERADAMANTOID. V = 5·7—4·4	14. PERPHYLLOID. V = 6·1—5·1	15. ARGILLOID. V = 6·5—5·4
1 : ¼	- - - - - - -	- - - - - - -	- - - - - - - - - - -	- - - - - - - -	Schrötterite.
1 : ⅓	- - - - - - -	- - - - - - -	Dumortierite. - - - - - -	- - - - - - - -	Collyrite.
1 : ⅔	- - - - - - -	- - - - - - -	Topaz. Andalusite. Fibrolite. Cyanite. Wörthite (6 : 5). -	- - - - - - - -	Allophane.
1 : 1	Westanite. - - -	Bismutoferrite. Eulytite.	Bucholzite. Xenolite. Lyncurite. Zircon. Malacone.	Pholerite. Talcosite (5 : 6).	Samoite.
1 : 1⅓	- - - - - - -	- - - - - - -	- - - - - - - - - - -	Kaolinite. - - - -	Kaolin. Halloysite.
1 : 1½	- - - - - - -	- - - - - - -	Auerbachite. - - - - - - -		Hisingerite.
1 : 2	- - - - - - -	- - - - - - -	- - - - - - - - - - -	Pyrophyllite. - - -	Keramite. Wolchonskoite.
1 : 2½	- - - - - - -	- - - - - - -	- - - - - - - - - - -	Pyrophyllite. - - -	Montmorillonite. Chloropal.
1 : 3	- - - - - - -	- - - - - - -	Anthosiderite. - - - - - -	- - - - - - - -	Cimolite.
1 : 4	- - - - - - -	- - - - - - -	- - - - - - - - - - -	- - - - - - - -	Smectite.

IX.

THE HISTORY OF PRE-CAMBRIAN ROCKS.

The following summary is in good part a condensation from the account given in my volume on "*Azoic Rocks*," to which, for details previous to 1878, the reader is referred. It is intended to serve as an introduction to the two succeeding essays in which certain parts of the history of these rocks are discussed. The chief portion of the text was published in the American Journal of Science for May, 1880. There are, however, many later additions, principally from a paper read before the British Association for the Advancement of Science, at Montreal, in August, 1884, and published in the Geological Magazine of London for November of that year.

I. — PRE-CAMBRIAN ROCKS IN NORTH AMERICA.

§ 1. It is proposed to give in these pages a brief analysis of the principal facts already published elsewhere respecting the systematic sub-division and classification of the pre-Cambrian rocks. These, according to the writer, present in North America, and elsewhere, an invariable succession of crystalline stratiform masses, divided by him into several great groups, the constituents of which become progressively less massive and less crystalline until we reach the sediments of paleozoic time, of which the Cambrian is regarded as the basal member. Since all of these pre-Cambrian rocks, with the exception, perhaps, of the lowest or fundamental gneiss, present evidences, direct or indirect, of the existence of organic life at the time of their deposition, it seems proper to include them under the general title of Eozoic, proposed by Sir J. W. Dawson. That of Archæan, employed by some geologists to designate these pre-Cambrian rocks, appears too indefinite in its signification, and, moreover, is not in accordance with the nomenclature generally adopted for the great divisions succeeding. These Eozoic rocks include both the Primitive and the Transition divisions of Werner.

§ 2. As regards the early history of our knowledge of American crystalline rocks, we find that the lithological characters of the Primary gneissic formation of northern New York were known to Maclure in 1817, and were clearly defined, in 1832, by Eaton, who, under the name of the Macomb Mountains, described what have since been called the Adirondacks, and, moreover, distinguished their rocks from the Primary of New England. Emmons, in 1842, added much to our lithological knowledge of the crystalline rocks of northern New York, but regarded the gneisses, with their associated limestones, serpentines, and iron-ores, as all of plutonic origin. Nuttall, who had previously studied the similar rocks in the Highlands of southern New York and New Jersey, had, however, maintained, as early as 1822, that these have resulted from an alteration of the adjacent paleozoic graywackes and limestones, into which he supposed them to graduate. This view was at the time opposed by Vanuxem and Keating, but was again set forth, in 1843, by Mather, who, while admitting the existence of an older or Primary series of crystalline rocks, conceived a great part of these rocks in southern New York to be altered paleozoic, and distinguished them as Metamorphic rocks. To this latter class he referred all the crystalline stratified rocks of New England, and ended by doubting whether a great part of what he had described as Primary was not to be included in his Metamorphic class. The subsequent labors of Kitchell and of Cooke have, however, clearly established the views of Vanuxem and Keating as to the Primary or pre-Cambrian age alike of the gneisses and the crystalline limestones of the Highlands.

§ 3. The similar gneissic series in Canada, which was known to Bigsby and to Eaton as an extension of that of northern New York, was noticed by Murray in 1843, and by Logan in 1847, as pre-paleozoic, though apparently of sedimentary origin, and hence, according to them, entitled to be called Metamorphic rather than Primary. It was described by Logan, in 1847, as consisting of a lower group of hornblendic gneisses, without limestones, and an upper group of similar gneisses, distinguished by interstratified crystalline limestones.

These rocks were found by Logan and by Murray to be overlaid, both on the north shore of Lake Superior and in the valley of the upper Ottawa, by a series consisting of chloritic and epidotic schists, with bedded greenstones, and with conglomerates holding pebbles derived from the ancient gneiss below. The same overlying series had, as early as 1824, been described by Bigsby on Lake Superior, and by him distinguished from the Primary and classed with Transition rocks.

§ 4. Labradoritic and hypersthenic rocks, like those previously described by Emmons in the Primary region of northern New York, were, in 1853 and 1854, discovered and carefully studied in the Laurentide hills to the north of Montreal, when they were described as being gneissoid in structure, and as interstratified with true gneisses and with crystalline limestones. In 1854, the writer, in concert with Logan, proposed for the ancient crystalline rocks of the Laurentides, including the lower and upper gneissic groups already mentioned, and the succeeding labradoritic rocks (but excluding the chloritic and greenstone series), the name of Laurentian. In the same year he wrote that, "in position and lithological characters, the Laurentian series appears to correspond with the old gneiss formation of Lapland, Finland, and Scandinavia." * Subsequently, in an essay published in 1855, these gneisses of Scandinavia, together with the oldest gneisses of Scotland, were, on lithological and on stratigraphical grounds, referred to the Laurentian series, and, at the same time, the name of Huronian was proposed for the chloritic and greenstone series, which had been shown to overlie unconformably the Laurentian series in Canada.

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* Amer. Jour. Science, 1854, xix., 195.

§ 5. Previous to this, in 1851, Foster and Whitney had described the Laurentian and Huronian rocks of Lake Superior as constituting one Azoic system of Metamorphic rocks, with granites, porphyries, and iron-ores of igneous origin: and, in 1857, Whitney attacked the two-fold division adopted by the Canadian geological survey, maintaining that the stratified crystalline rocks of the region belong to a single series, with a granitic nucleus. The observations of Kimball, in 1865, and the later studies of Credner, of Brooks and Pumpelly, and of Irving, have, however, all confirmed the early views of the Canadian survey as to the relations of the Laurentian and Huronian in this region.

§ 6. The Primary age of the Highlands of southern New York, and their extension into Pennsylvania in what is called the South Mountain, was now unquestioned, but the crystalline rocks to the east of this range, while regarded by Eaton and by Emmons as also forming a part of the Primary, were by Mather, as we have already seen, supposed to be altered paleozoic strata. These rocks in New England (with the exception of the quartzites and limestones of the Taconic range) were by him assigned to a horizon above the Trenton limestone of the New York system, and portions of them were conjectured by other geologists (who adopted and extended the views of Mather) to be of Devonian age.

§ 7. The characteristic crystalline schists of western New England and southeastern New York, passing beneath the Mesozoic strata of New Jersey, re-appear in southeastern Pennsylvania, where they were studied and finally described by H. D. Rogers, in 1858. According to him, these crystalline schists, while resting unconformably upon an ancient (Hypozoic) gneissic system, were themselves more ancient than the Scolithus-sandstone, which he regarded as the equivalent of the Potsdam. While he supposed these newer crystalline schists, called by him Azoic, to be connected stratigraphically with the base of the Paleozoic series, he nevertheless assigned them to a position below the base of the New York system; thus recognizing in Pennsylvania, beneath this horizon, two unconformable groups of crystalline rocks. The existence among these newer crystalline schists of Pennsylvania, of a series distinct from the Huronian, and representing the White Mountain or Montalban rocks (the Philadelphia and Manhattan gneissic group), had not then been recognized. A farther discussion in some detail of these rocks in Pennsylvania, will be found farther on, Essay XI., §§ 37–42.

§ 8. The views of H. D. Rogers with regard to the crystalline schists of the Atlantic belt were thus, in effect, if not in terms, a return to those held by Eaton and by Emmons, but were in direct opposition to that maintained by Mather, which had been adopted at that time by Logan and by the present writer. The belt of chloritic and epidotic schists with greenstones, serpentines, and steatites, the extension of a part of the Azoic of Rogers, which, through western New England, is traced into Canada (where it has been known as the Green Mountain range), was, previous to 1862, called by the geological survey of Canada, "Altered Hudson River group." It was subsequently referred to the Upper Taconic of Emmons, to which Logan, at that date, gave the name of the Quebec group, assigning it, as had long before (in 1846) been done by Emmons, to a Cambrian horizon between the Potsdam and the Trenton of the New York system. Henceforth the crystalline schists in question were by Logan designated the "Altered Quebec group."

§ 9. In 1862 and 1863 appeared, independently, two important papers bearing on the question of the age of these crystalline rocks. The first of these was by Thomas Macfarlane, who, after a personal examination of the three regions, compared the Huronian of Lake Huron and the Green Mountain range of Canada with portions of the Urschiefer or Primitive schists which, in Norway, intervene between the ancient gneisses and the oldest Paleozoic (Lower Cambrian) strata. The second paper was by Bigsby (who had been, as we have seen, the earliest student of the Huronian in the Northwest), pointing out that these rocks could not in any sense be called Cambrian, but were the equivalents of the Norwegian Urschiefer. The conclusions of Macfarlane were noticed, in connection with the views of Keilhau on these rocks of Norway, in "The Geology of Canada," in 1863, with farther comparisons between the New England crystalline schists and the Huronian, but official reasons then, and for some years after, prevented the writer from expressing any dissent from the views of the director of the geological survey of Canada.

§ 10. Meanwhile, the existence of an equivalent series of crystalline schists was being made known in southern New Brunswick, where they were described by G. F. Matthews, in 1863, under the name of the Coldbrook group, which included a lower and an upper division. In a joint report of Matthews and Bailey to the geological survey of Canada, in 1865, these rocks were declared to be overlaid unconformably by the slates in which Hartt had made known a Lower Cambrian (Menevian) fauna, and were compared with the Huronian of Canada. The lower division of the Coldbrook group was then described as including a large amount of pink feldspathic quartzite and of bluish and reddish porphyritic slates. In the same report was described, under the name of the Bloomsbury group, a series lithologically similar to the Coldbrook, but apparently resting on the Menevian, and overlaid by fossiliferous Upper Devonian beds, into which it was supposed to graduate. The Bloomsbury group was therefore regarded as altered Upper Devonian, and its similarity to the pre-Cambrian Coldbrook was explained by supposing both groups to consist in large part of volcanic rocks.

§ 11. In 1869 and 1870, however, the writer, in company with the gentlemen just named, devoted many weeks to a careful study of these rocks in southern New Brunswick, when it was made apparent that the Bloomsbury group was but a repetition of the Coldbrook, on the opposite side of a closely folded synclinal holding Menevian sediments. These two areas of pre-Cambrian rocks were accordingly described by Messrs. Matthews and Bailey in their report, in 1871, as Huronian, in which were also included the similar crystalline rocks belonging to two other areas, which had been previously described by the same observers under the names of the Kingston and Coastal groups, and by them regarded as respectively altered Silurian and Devonian.

§ 12. After studying the Huronian rocks in southern New Brunswick, and their continuation along the eastern coast of New England, especially in Massachusetts (where, also, they are overlaid by Menevian sediments), the writer, in 1870, announced his conclusion that the crystalline schists of these regions are all of them pre-Cambrian, and lithologically and stratigraphically equivalent to those of the Green Mountain range of western New England and eastern Canada. These he further declared, in 1871, to be a prolongation of the newer crystalline or Azoic schists of Rogers in Pennsylvania, and the equivalents of the Huronian of the Northwest. The pre-Cambrian age of these crystalline schists in eastern Canada has now been clearly proved by the presence of their fragments in the fossiliferous Cambrian strata in many localities along the northwestern border of the Green Mountain belt, and farther by the recent stratigraphical studies of the geological survey of Canada.

§ 13. In close association with these Huronian strata in eastern Massachusetts is found a great development of petrosilex rocks, generally either jaspery or porphyritic in character, and sometimes fissile, which by Edward Hitchcock were regarded as igneous. These were now found to be identical with the rocks designated, by Matthews and Bailey, feldspathic quartzites and silicious and porphyritic slates, which form the chief part of the Lower Coldbrook or inferior division of the Huronian series in New Brunswick. The petrosilexes of Massachusetts were, after careful examinations by the writer, described by him, in 1870 and 1871, as indigenous stratified rocks forming a part of the Huronian series. He subsequently, in 1871, studied the similar rocks in southeastern Missouri, and, in 1872, on the north shore of Lake Superior, but was unable to find them in the Green Mountain belt, or in its southward continuation, until, in 1875, he detected them occupying a considerable area in the South Mountain range, in southern Pennsylvania. The stratified petrosilex rocks of all these regions were described in a communication to the American Association for the Advancement of Science, in 1876, as apparently corresponding to the *hälleflinta* rocks of Sweden, and, having in view their stratigraphical position, both in that country and in New Brunswick, they were then "provisionally referred" to "a position near the base of the Huronian series." Their absence in the Huronian belt in western New England, and in the province of Quebec, as well as at several observed points of contact between the Laurentian and the well defined Huronian in the Northwest, led to the suspicion that these rocks might belong to an intermediate group (since named Arvonian). They may be briefly described as a series of stratified rocks, composed essentially of petrosilex, often passing into a quartziferous porphyry. There are found with it strata of vitreous quartzite, and thin layers of soft micaceous schists, besides great beds of hematite, and, more rarely, layers of crystalline limestone.

§ 14. C. H. Hitchcock has pointed out that the characteristic Huronian rocks do not form the higher parts of the Green Mountain range in Vermont, which he conceives to belong to an older gneissic series. He, however, in his final report on the geology of New Hampshire, in 1877, adopts the name of Huronian for the crystalline rocks of the Altered Quebec group of Logan, which make up the chief part of the Green Mountain range in Quebec, are largely developed along it in Vermont, and appear in a parallel range farther east, which extends southward into New Hampshire. In his tabular view of the geognostic groups in this State, Hitchcock assigns to these rocks a thickness of over 12,000 feet, with the name of Upper Huronian; while he designates as Lower Huronian the petrosilex series of eastern Massachusetts, already noticed, where these rocks are of great, though undetermined, thickness. The similar petrosilex or hälleflinta rocks in Wisconsin, where they have lately been described by Irving as Huronian, have, according to this observer, a thickness, in a single section, of 3200 feet. They here sometimes become schistose, are interbedded with unctuous schists, and rest in apparent conformity upon a great mass of vitreous quartzite. The writer has since examined these rocks as seen on the Baraboo River, and elsewhere, in Wisconsin, and has satisfied himself of their identity with the similar rocks previously studied by him on the Atlantic coast, in Pennsylvania, in Missouri, and on Lake Superior. Besides the details respecting these petrosilex rocks to be found in the writer's volume on "Azoic Rocks," pp. 189–195, and, again, pp. 231–232, the reader is referred to Essay XI. in this present volume, §§ 37–42, for a farther account of their occurrence in Pennsylvania. The general high inclination both of this series and of the typical Huronian, renders the determination of their thickness difficult. The maximum thickness of the Huronian (excluding the petrosilex or Arvonian series) to the south of Lake Superior, may, according to Brooks, exceed 12,000 feet, while the estimates of Credner and Murray, respectively, for this region, and for the north shore of Lake Huron, are 20,000 and 18,000 feet.

§ 15. The original Huronian series is seen in many places to rest, often unconformably, upon the ancient gneiss, without the interposition of the petrosilex group, leading to the conclusion that the latter is an unconformable intermediate series, a conclusion confirmed, in 1879, by the observations of Bailey in New Brunswick, where he found between the lower or petrosilex group and the typical Huronian a marked physical break. This is indicated by a stratigraphical discordance and by the presence, in the lower part of the latter division, of coarse conglomerates made up from the ruins of the underlying or petrosilex division. The Huronian includes elsewhere, in many places, pebbles and fragments of the older gneisses, a character common to this and the still younger crystalline series, which led some earlier geologists in America to class all of these with Transition rocks.

The Huronian contains a considerable proportion of epidote, hornblende, and pyroxene, and is marked by varieties of diabasic rocks, often called gabbros, which are truly stratified, but are not to be confounded with the norites of the Norian series, to which the name of gabbro is also frequently given. The Huronian series, moreover, includes imperfect gneisses, quartzites, dolomite, serpentine, and steatite, besides large amounts of chloritic, micaceous, and argillaceous schists. It appears to be identical with the *pietri verdi* or greenstone group of the Alps, which is there found in many parts between the ancient gneisses below and a younger series of gneisses and mica-schists, the history of all which is given at length in Essay X., part iv., in discussing the geology of the Alps and the Apennines.

§ 16. As regards this younger gneissic or Montalban series in North America, it need here only be said that it contains fine-grained white gneisses, sometimes porphyritic, but distinct from the granitoid gneisses of the Laurentian, and passing into granulites, on the one hand, and into very quartzose coarse-grained mica-schists, on the other. It also includes hornblendic gneisses and black hornblende-schists, together with serpentine, chrysolite-rocks, dichroite-gneiss, and crystalline limestones. The mica-schists of the series often contain garnets, staurolite, andalusite, fibrolite, and cyanite, while in the granitic veins which traverse the series are found tourmaline, beryl, and cassiterite. The total thickness of the Montalban is apparently much greater than that assigned to the Huronian, upon which it sometimes rests unconformably, or, in the absence of the Huronian, as is often the case, directly upon the Laurentian.

§ 17. As we are here following not the stratigraphical succession but the historic development of our knowledge of the American pre-Cambrian rocks, we return to a consideration of the more ancient gneisses. We distinguish at the base of the Eozoic system a massive and essentially granitoid gneiss, with little or no mica. To this fundamental rock, sometimes called the Ottawa gneiss, and of unknown thickness, succeeds what has been named in Canada the Grenville gneissic series, made up in great part of a gneiss somewhat similar to that last mentioned, with intercalations of hornblendic gneiss, of quartzite, of pyroxenite, of serpentine, of magnetite, and of crystalline limestones, the latter often magnesian, occasionally graphitic, and sometimes attaining thicknesses of a thousand feet or more. The Grenville series, the strata of which are generally highly inclined, has an aggregate volume of not less than 15,000 or 20,000 feet, and appears to rest unconformably upon the fundamental or Ottawa gneiss. This gneissic series, with its intercalated limestones, some of which contain *Eozoön Canadense*, was the typical Laurentian of Logan and Hunt, named by them in 1854, with which they included, at that time, however, not only the underlying fundamental gneiss, but an upper granitoid and gneissoid series, composed in large part of plagioclase feldspars, chiefly labradorite.

§ 18. These three divisions of the Eozoic system were thus confounded under the common name of Laurentian until, in 1862, the last was separated, under the provisional name of Upper Laurentian, the two other divisions united being called Lower Laurentian. The synonym of Labradorian was subsequently, for a time, employed by Logan to designate the upper division, until 1870, when the present writer proposed for it the name of Norian, retaining that of Laurentian for the two lower divisions. It will probably be found desirable to separate the typical Laurentian or Grenville series, as studied and mapped by Logan, Hunt, and Dawson, from the less known fundamental or Ottawa gneiss, and to make of this latter a distinct group. The name of Middle Laurentian, sometimes given to the typical Laurentian, loses its significance with the disappearance of that of Upper Laurentian, now replaced by Norian.

The Norian series is made up in great part of granitoid or gneissoid rocks, composed essentially of plagioclase feldspars, without quartz, but with a little pyroxene or hypersthene, often with titanic iron-ore, and apparently identical with the norites of Norway. With these rocks are, however, found alternations of gneiss and of quartzite, and also crystalline limestones, scarcely different from those of the Laurentian. We therein find also a granitoid rock made up of pink orthoclase, quartz, and bluish labradorite. This Norian series is found in many places covering considerable areas, and apparently resting in discordant stratification upon the typical Laurentian. Its thickness has been estimated at over 10,000 feet.

§ 19. Passing now above the younger or Montalban gneisses and mica-schists, we come to a series composed essentially of quartzites, limestones, and micaceous and argillaceous schists. The quartzites, occasionally conglomerate, are sometimes vitreous, sometimes granular, and often micaceous, graduating into mica-schists very distinct from those of the Montalban. The mica is often damourite or sericite, and gives rise to unctuous glossy schists, passing into argillites, which sometimes contain a feldspathic admixture. The limestones of this series, often magnesian, are crystalline, and include statuary marbles and cipolins. We find in the schists, which are intercalated alike among the quartzites and the limestones of this series, masses of serpentine and of ophicalcite, and occasionally of chloritic and hornblendic minerals, as well as siderite, magnetite, and hematite, the iron-oxyds being often mingled with the quartzites. These last are sometimes flexible and elastic, and the whole series much resembles the Itacolumitic group of Brazil. It has a thickness in different parts of North America of from 4000 to 10,000 feet, and is seen lying unconformably alike upon the Laurentian, the Huronian, and the Montalban. There are found in the quartzites of this series the impressions of *Scolithus*, and in the limestones other undetermined forms. This is the Lower Taconic series of the late Dr. Emmons, which we distinguish by the name of Taconian. Some recent writers have by mistake confounded it with the Upper Taconic of the same author, a distinct group, which Emmons declared to be the equivalent of the Primordial (Cambrian) of Barrande, and which is the original or unaltered Quebec group of Logan.

§ 20. The Taconian series is widely spread over eastern North America, to the eastward of the great paleozoic basin, from the Gulf of St. Lawrence to Alabama. It is also found in an area to the north of Lake Ontario, in Hastings County, where it was described by the Canadian geological survey under the provisional name of the Hastings series, and is represented around Lake Superior by what has been called the Animikie series. This, though early recognized as Taconian in northern Michigan, and early separated by Logan from the Huronian on the north shore of the lake, has since been confounded with it. Much that in the northern peninsula of Michigan, as elsewhere, has been called Huronian, is Taconian.

The latter, the writer has elsewhere compared with a great series of similar schists and quartzites, including serpentine, anhydrite, dolomite, and marbles, greatly developed in northern Italy, where it overlies the younger gneisses and mica-schists, and has been by various observers successively referred to the mesozoic, the paleozoic, and the eozoic periods. A full account of the Taconian series, its stratigraphical relations, and its distribution in North America and elsewhere, will be found farther on, in Essay XI.

§ 21. The Taconian on the north shore of Lake Superior was by Logan made the lower division of his Upper Copper-bearing series, which, as a whole, was by him, after 1862, described as a modification of what he then called the Quebec group. The upper division of this Copper-bearing series, remarkable for its native copper, had been previously, for a time, confounded by Logan with the Huronian itself, while by others it was referred to the Potsdam period, or even conjectured to be of mesozoic age. The geological distinctness of this great series of more than 20,000 feet of strata was, however, finally asserted by the present writer in 1873, when he called it the Keweenaw group, a name subsequently changed by him to Keweenian. It has since been shown by various observers that the fossiliferous sandstones which rest in horizontal layers upon the inclined strata of the Keweenian, belong to the Cambrian, and hold the fauna of the Potsdam. The conglomerates of the Keweenian cupriferous series contain portions alike of Laurentian, Arvonian, Huronian, and Montalban rocks, and overlie the schists which we have referred to the Taconian. The sandstones and argillites of the Keweenian, which are interstratified with great masses of melaphyre, are uncrystalline. It remains to be determined whether the intermediate Keweenian series has greater affinities with the Taconian than with the Cambrian, from both of which it is distinct.

We have thus sought to include, provisionally, the whole vast system of Primitive and Transition crystalline rocks, from the fundamental granitoid gneiss upward, under the names of Laurentian, Norian, Arvonian, Huronian, Montalban, and Taconian. Certain considerations regarding the distribution and the stratigraphical relations of these have already been set forth, on page 184, to which the reader is referred.

II.—PRE-CAMBRIAN ROCKS IN EUROPE.

§ 22. In an address before the American Association for the Advancement of Science, in 1871, in which the writer maintained the Huronian age of a portion of the crystalline schists of New England and Quebec, he expressed the opinion, based in part upon his examinations at Holyhead in 1867, and in part upon the study of collections in London, that certain crystalline schists in North Wales would be found to belong to the Huronian series. The rocks in question were by Sedgwick, in 1838, separated from the base of the Cambrian, as belonging to an older series, but were subsequently, by De la Beche, Murchison, and Ramsay, described and mapped as altered Cambrian strata with associated intrusive syenites and feldspar-porphyries.

§ 23. In South Wales, at St. David's in Pembrokeshire, is another area of crystalline rocks, which the geological survey of Great Britain had mapped as intrusive syenite, granite, and felstone (petrosilex-porphyry), having Cambrian strata converted into crystalline schists on one side, and unaltered fossiliferous Cambrian beds on the other. So long ago as 1864, Messrs. Hicks and Salter were led to regard these granitoid and porphyritic rocks as pre-Cambrian, and in 1866 concluded that they were not eruptive but stratified crystalline or metamorphic rocks. After farther study, Hicks, in connection with Harkness, published, in 1867, additional proofs of the bedded character of these ancient crystalline rocks, and in 1877 the first-named observer announced the conclusion that they belong to two distinct and unconformable series. Of these, the older consisted of the granitoid and porphyritic felstone rocks, and the younger of greenish crystalline schists, the so-called Altered Cambrian of the official geologists; both of these being overlaid by the undoubted Lower Cambrian (Harlech and Menevian) of the region, which holds their ruins in its conglomerates. To the lower of these pre-Cambrian groups, Hicks gave the name of Dimetian, and to the upper that of Pebidian. The last, with a measured thickness of 8000 feet, he supposed to be the equivalent of the Huronian, and compared the Dimetian with the Upper Laurentian of Logan.

The Dimetian, including the granitoid and gneissic rocks of both North and South Wales, so far as seen by the writer in the limited outcrops, resembles the Laurentian of North America. It was by a misconception that Hicks provisionally referred the Dimetian to the Upper Laurentian, — a name at one time used by the geological survey of Canada to designate the Norian series. Hicks, at the same time, designated as Lower Laurentian the gneiss of the Hebrides (Lewisian of Murchison), which he believed to be distinct from and older than the Dimetian. These two may correspond to the Ottawa and Grenville divisions of the proper Laurentian in Canada.

§ 24. The similar crystalline rocks of North Wales, already noticed, were now studied by Prof. T. McKenna Hughes, of Cambridge, who described them in 1878. These include in Carnarvonshire and Anglesey the greenish crystalline schists which the writer, in 1871, referred to the Huronian (pre-Cambrian of Sedgwick, and Altered Cambrian of the geological survey), certain granitoid rocks formerly described as intrusive syenite, and also a reddish feldspar-porphyry which forms two great ridges in Carnarvonshire. This latter was by Professor Sedgwick regarded as intrusive, and is, moreover, mapped as such by the geological survey, though described in Ramsay's memoir on the geology of North Wales as probably the result of an extreme metamorphism of the lower beds of the Cambrian. The pre-Cambrian age of all these rocks was clearly shown by Hughes, who, however, considered that the whole might belong to one great stratified series; while Hicks, from an examination of the same region, regarded them as identical with the Dimetian and Pebidian of South Wales.

§ 25. Dr. Hicks continued his studies in both of these regions in 1878, — being at times accompanied by Dr. Torell of Sweden, Professor Hughes and Mr. Tawney of Cambridge, and the writer, — and was led to conclude that, besides the chloritic schists and the greenstones of the Pebidian series, and the older granitoid and gneissic rocks, there exists, both in North and South Wales, another independent and intermediate series, to which belongs the stratified petrosilex or quartziferous porphyry already noticed. This is sometimes wanting at the base of the Pebidian, and at other times forms masses some thousands of feet in thickness. At one locality, near St. David's, a great body of breccia or conglomerate, consisting of fragments of the petrosilex united by a crystalline dioritic cement, forms the base of the Pebidian. For this intermediate series, which constitutes the quartziferous porphyry-ridges of Carnarvonshire, Hicks and his friends then proposed the name of Arvonian, from Arvonia, the Roman name of the region.

§ 26. This important conclusion was announced by Dr. Hicks at the meeting of the British Association for the Advancement of Science, at Dublin, in August, 1878. The writer, previous to attending this meeting, had the good fortune to examine these various pre-Cambrian rocks in parts of Carnarvonshire and Anglesey with Messrs. Hicks, Torell, and Tawney. He subsequently, in company with Hicks, visited the region in South Wales where these older rocks had been studied, and was enabled to satisfy himself of the correctness both of the observations and conclusions of Hicks, and of the complete parallelism in stratigraphy and in mineral composition between these pre-Cambrian rocks on the two sides of the Atlantic. It may here be mentioned that Torell, who, during his visit to America in 1876, had an opportunity of studying, with the writer, the petrosilexes of New England and Pennsylvania, — which he regarded as identical with the hälleflinta of Sweden, — at once recognized them in the Arvonian series of North Wales. Of the many areas of these various pre-Cambrian rocks which the writer was enabled to examine in company with Hicks, may be mentioned the granitoid mass of Twt Hill in the town of Carnarvon, and the succeeding Arvonian to Port Dinorwic, followed, across the Menai Strait, by the Pebidian on the island of Anglesey, near the Menai bridge. Farther on, the Pebidian was again met with, near the railway station of Ty Croes, in the southwest part of the island, succeeded by a large body of Arvonian petrosilex, and a ridge of granitoid gneiss, fragments of which make up a breccia at the base of the Arvonian series. The Pebidian is again well displayed at Holyhead.

§ 27. In South Wales, the similar rocks were examined by him at St. David's, where three small bands or veins of an impure, coarsely crystalline limestone are included in the Dimetian granitoid rock, which is here often exceedingly quartzose. It may be remarked that the Dimetian, as originally defined at this, its first recognized locality, included a great mass of Arvonian petrosilex, the two forming a ridge which extends for some miles in a northeast direction, flanked by Pebidian rocks, which are sometimes in contact with the one and sometimes with the other series. At Clegyr Bridge was seen the base of the Pebidian, already mentioned as consisting of a conglomerate of Arvonian fragments. Another belt of the same crystalline rocks was also visited, a few miles to the eastward of the last, and not far from Haverfordwest, forming, according to Hicks, a ridge several miles in length and about a mile wide. Where seen at Roch Castle, it was found to consist of Arvonian petrosilex, with some granitoid rock near by. The ridge is flanked on the northwest side by Pebidian and Cambrian, and on the southeast by Silurian strata, let down by a fault.

§ 28. On the shore of Llyn Padarn, near the foot of Snowdon, in North Wales, the porphyritic petrosilex of the Arvonian is again well displayed, while in contact with it, and at the base of the Llanberis (Lower Cambrian) slates, is a conglomerate made up almost wholly of the petrosilex. This locality was supposed by Ramsay and others to show that the petrosilex is the result of a metamorphosis of the lower portion of the Cambrian, the conglomerates being regarded as beds of passage. The writer, after a careful examination of the locality, agrees with Messrs. Hicks, Hughes, and Bonney that there is no ground for such an opinion, but that the conglomerate marks the base of the Cambrian, which here reposes on Arvonian rocks, and is chiefly made up of their ruins. In like manner, according to Hughes, the Cambrian in other parts of this region includes beds made of the *débris* of adjacent granitoid rocks.

§ 29. These petrosilex conglomerates of Llyn Padarn are indistinguishable from those found at Marblehead and other localities near Boston, Massachusetts, which have been in like manner interpreted as evidences of the secondary origin of the adjacent petrosilex beds, into which they have been supposed to graduate. The writer has, however, always held, in opposition to this view, that these conglomerates are really newer rocks, made up of the ruins of the ancient petrosilex. He has found similar petrosilex conglomerates at various points on the Atlantic coast of New Brunswick, of Lower Cambrian, Silurian, and Lower Carboniferous ages, all of which have, in their turn, been by others regarded as formed by the alteration of strata of these geological periods. The evidence now furnished in South Wales of still older (Huronian) beds of petrosilex conglomerate should be noted by students of North American geology. From observations near Boston, made by one of my former students, I have for some time suspected the existence of petrosilex conglomerates of pre-Cambrian age.

§ 30. To the eastward of the localities already mentioned in Wales, are some other small areas of crystalline rocks, including those of the Malverns, and the Wrekin and other hills in Shropshire, all of which appear as islands among Cambrian strata; also those of Charnwood Forest, in Leicestershire, which rise in like manner among Triassic rocks. The Wrekin, regarded by Murchison as a post-Cambrian intrusion, has been shown by Callaway to be unconformably overlaid by Lower Cambrian strata, and consists in part of bedded greenstones, and in part of banded reddish petrosilex-porphyries, closely resembling the Arvonian of North Wales and the corresponding rocks of North America. The geology of Charnwood has within the past two years been carefully studied by Messrs. Hill and Bonney. The ancient rocks of this region are in part crystalline schists (embracing, in the opinion of Hicks and of the writer, — who have seen collections of them, — representatives both of the Pebidian and the Arvonian of Wales) and in part eruptive masses, including the granitic rocks of Mount Sorrel.

§ 31. The crystalline schists of Charnwood offer, as was pointed out by Messrs. Hill and Bonney, many resemblances with parts of the Ardennian series of Dumont in France and Belgium. These, which have been in turn regarded as altered Devonian, Silurian, and Lower Cambrian, were, as shown by Gosselet, islands of crystalline rock in the Devonian sea, and in one part include argillites with impressions of *Oldhamia* and an undetermined graptolite. These rocks have lately been described in detail in the admirable memoir of De la Vallée Poussin and Renard. The writer had the good fortune, in 1878, to visit this region, and, in company with Gosselet and Renard, to examine the section along the valley of the Meuse. The crystalline rocks here displayed greatly resemble those of the American Huronian, in which may be found most of the types described by the authors of the memoir just mentioned.*

§ 32. Hicks, in a paper on the Classification of the British Pre-Cambrian Rocks, which is published in the Geological Magazine for October, 1879, concludes that the Pebidian is "a group of enormous thickness, which is largely distributed over Great Britain, where it has a prevailing strike of N.N.E. and S.S.W., or from this to N.E. and S.W." In addition to the localities which we have

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* The following is a partial list of recent publications regarding these rocks, as discussed in §§ 23–32, to the close of 1879. For their later history, see farther on, Essay XI., §§ 189–193.

In the Quar. Jour. Geol. Soc. of London are the following papers on these rocks in Wales: Hicks, May, 1877, p. 230; Hicks & Davies, February, 1878, p. 147, and May, 1878, p. 153; Hughes & Bonney, February, 1878, p. 137; Hicks & Davies, May, 1879, p. 285; Hicks & Bonney, *ibid.*, p. 295; Bonney, *ibid.*, p. 309; Bonney & Houghton, *ibid.*, p. 821; Hughes, November, 1879, p. 682; Maw, August, 1878, p. 764. Also Hicks, Rocks of Ross-shire, November, 1878, p. 811; Tawney, Older Rocks of St. David's: Proc. Bristol Naturalists' Society, vol. ii., part 2, p. 110.

On these rocks in Shropshire, Quar. Jour. Geol. Soc., Allport, August, 1877, p. 449; Callaway, November, 1877, p. 653, and August, 1878, p. 754; Callaway & Bonney, November, 1879, p. 643. On these rocks in Charnwood Forest, in the same journal, Hill & Bonney, November, 1877, p. 753, and May, 1878, p. 199. See farther, Hunt, Chemical and Geological Essays, pp. 34, 269, 270, 272, 278, 283; also his Azoic Rocks (Second Geol. Survey of Penn., 1878), pp. 187, 188.

For the rocks of the Ardennes, see Mémoire sur les Roches dites Plutoniques, etc. (4to, pp. 264), by De la Vallée Poussin and Renard, from Mémoires de l'Acad. Royale de la Belgique for 1876; Mémoire sur la Comp. Minéralogique du Coticule, by Renard, from the same for 1877; and The Mineralogical and Microscopical Characters of the Belgian Whetstones, by Renard, Monthly Microscopical Journal for 1877, vol. xvii., p. 269. Also Gosselet and Malaise, Terrain Silurien des Ardennes, Bull. Acad. Roy. de la Belgique (2), No. 7, 1868; Dewalque, Terrain Cambrien des Ardennes, Ann. Soc. Géol. de la Belgique, tom. I., p. 63; and farther, Hunt, Chem. and Geol. Essays, p. 270.

already mentioned in Great Britain, he notes its occurrence in Shropshire and in Charnwood Forest, and also in the northwest of Scotland, where, as elsewhere, it enters largely into the Lower Cambrian conglomerates. The group is concisely described by him as consisting, "for the most part, of chloritic, talcose, feldspathic, and micaceous schistose rocks, alternating with slaty and massive greenstones, dolomitic limestones, serpentines, lava-flows, porcellanites, breccias, and conglomerates. It is also traversed frequently by dikes of granite, dolerite, etc."

§ 33. There is not, so far as yet known, in any of the British localities especially mentioned, any representative either of the Taconian or the Montalban series. The presence of rocks having the characters of the Huronian was, however, indicated as having been observed by me in various parts of Perthshire and Argyleshire, and also on Lough Foyle, in Ireland, where I have observed the Montalban well displayed in the Dublin and Wicklow Hills, and pointed out the probable presence of both Huronian and Montalban in specimens of rocks from Donegal. To the latter series I also referred, from similar evidence, in 1871, certain crystalline schists from the Scottish Highlands, where the typical Pebidian of Hicks, previously designated by me as Huronian, is also largely displayed.

Hicks has since found there a series of crystalline strata which succeed the Pebidian, and which he has called Upper Pebidian. These, as they are the predominant rocks in the Grampian Hills, he proposed to name the Grampian series. They consist in great part of tender gneisses or granulites, with mica-schists, and, as I have elsewhere pointed out, have all the characters of the Montalban or younger gneiss series, as seen alike in North America and in the Alps. The conclusion from all the observation of Hicks and Callaway up to 1882, as then stated by me, was that "the crystalline strata of the Scottish Highlands, regarded by the geological survey of Great

Britain as altered paleozoic strata, include representatives of various pre-Cambrian groups, including Montalban (Grampian), Huronian (Pebidian), and Arvonian, to which group Hicks refers the petrosilex series found in Glencoe." *

§ 34. For an account of more recent investigations in these crystalline rocks of the Scottish Highlands, the reader is referred to Essay XI., §§ 190–193. In this essay, which discusses the Taconian, and its relations alike to newer and to older series, will be found much on the various divisions of Eozoic rocks. Therein is noticed the recent attempt of Dana to resuscitate the long abandoned views of Nuttall and Mather as to the paleozoic age of a great area of crystalline rocks, principally Laurentian, in Westchester County, New York. The veinstones of these ancient crystalline rocks, and especially of the Laurentian series, have been described at length, *ante*, pages 223–238. An account of the pre-Cambrian rocks of the Alps and the Apennines will be found farther on, in part iv. of Essay X.

§ 35. In closing this historical sketch, mention should be made of the statements put forth, in 1879, by A. R. C. Selwyn, director of the geological survey of Canada, in his report of progress for 1877–78 (p. 14 A), in which he sought to set aside the whole of the preceding classification of Eozoic rocks. He then proposed to unite in one group, under the name of Huronian, not only the rocks around Lakes Superior and Huron, to which this name was originally given, and the crystalline belt in the province of Quebec (which I had already, in 1871, called Huronian), but the whole of the Upper Copper-bearing series of Lake Superior, thus embracing both the Taconian, or lower division of the latter, and the Keweenian. Not content with this, he would farther include in the Huronian the "Templeton, Buckingham, Grenville, and Rawdon crystalline limestone series," which is the

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* Progress of Geology, Smithsonian Report for 1882.

Grenville gneissic series of Logan and myself, and also the "Upper Laurentian or Norian." He moreover added to these the Hastings limestone series, which he supposed might be an equivalent of the Grenville series. The Montalban and the Arvonian were overlooked in his scheme, but with these exceptions the Huronian, as imagined by Selwyn, was made to include every known group of strata, whether crystalline or uncrystalline, from the base of the fossiliferous Cambrian to what he designated as "those clearly lower unconformable granitoid or syenitic gneisses" which contain no bands of calcareous or other extraneous rock; and which may be supposed to correspond to that basal division described above as the Ottawa gneiss. The whole of the vast succeeding series of 16,000 feet of granitoid gneisses, with quartzites, crystalline limestones, etc., which had been studied during thirty years by Logan, Murray, and myself, and constituted, with the Norian, the Laurentian system as originally defined and named in 1854, was thus to be confounded, under one name, with the widely different series to which the designation of Huronian had been given in 1855, and with the entire Upper Copper-bearing series of Logan, embracing alike the Taconian and the Keweenian. It may be presumed that longer study and larger opportunities of observation will lead Mr. Selwyn to conclusions more in harmony with those of his predecessors.

APPENDIX.

The whetstone or coticule of the Ardennes, named on page 422, consists, according to the chemical and microscopical studies of Rénard, of rounded grains or minute crystals of manganese-alumina garnet (spessartine), with others of green tourmaline and probably of chrysoberyl, included in a damourite-like mica, sometimes with pyrophyllite in fissures, and with intersecting veins of quartz. Layers of this aggregate from one to ten centimetres thick, pale yellow in color, conchoidal in fracture, and with density 3.22, are interstratified with, and graduate into, a fine-grained schist or phyllade, itself with transverse cleavage, made up chiefly of similar micas, but containing besides the garnets, etc., plates of hematite, and carbonaceous grains. The evidence of contemporaneous formation of these various species is clear, and illustrates well the crenitic process.

X.

THE GEOLOGICAL HISTORY OF SERPENTINES, WITH STUDIES OF PRE-CAMBRIAN ROCKS.

This essay was presented to the Royal Society of Canada, May 23, 1883, and printed under its present title in the first volume of the Transactions of the Society.

I. — HISTORICAL INTRODUCTION.

§ 1. Few questions in geology are involved in greater obscurity or more contradiction than the history of serpentine. As a preliminary to a discussion of certain observations by myself and others thereon, it seems, therefore, desirable to recall some passages in this history, which may serve to show the differences of opinion now existing, and, it is hoped, prepare the way for their reconciliation. These differences may be considered under two heads, namely: the geognosy of serpentine, or its relation to the other rocks of the earth's crust; and the geogeny, or the origin and mode of formation of serpentine, the mineralogical relations of which are discussed on page 333.

Setting aside for the moment the question of the occurrence of serpentine as an accidental mineral disseminated in calcareous rocks, and considering only its occurrence in rock-masses, either pure or mingled with other silicates, the first question which presents itself is whether such massive serpentines are contemporaneous with the enclosing rocks, or whether they have been subsequently intruded among these,—in other words, whether serpentines are indigenous or exotic rocks.

§ 2. We find at the beginning of our century that the most competent observers were agreed in regarding serpentines as stratified contemporaneous deposits in the so-called primary rocks. Patrin described those of Mont

Rose and of the Rothhorn as interstratified with calcareous and micaceous schists, while Saussure found those of Mont Cervin to present similar conditions, and described certain serpentines, found near Genoa, as alternating with bands of calcareous, quartzose, and micaceous schists or argillites. Humboldt, in like manner, noticed the stratified character of the serpentines near Bareith, and Jameson found those of Rothsay, in Scotland, to be interstratified with micaceous and talcose schists, and with crystalline limestone, in repeated alternations, of which he gives a diagram, mentioning, however, as an opinion held by some, that the masses both of serpentine and of limestone "form great veins rather than vertical sheets." He elsewhere describes serpentine as a primitive stratified rock, contemporaneous, and alternating with crystalline schists.*

§ 3. A little later we find, in 1826, Macculloch, in his "Geological Classification of Rocks," separating the primitive rocks into two groups, stratified and unstratified, the latter consisting of granite and serpentine. He assigned as a reason for placing serpentine in the latter class that it does not appear to be decidedly stratified, but, at the same time, remarks that, unlike other unstratified rocks, as granite or trap, he had not found serpentines to present ramifying veins. Subsequent studies in the Shetland Isles led him to make what he calls "an important correction" in its history, in the Appendix to the volume just named, where he announces his conclusion that the serpentines are stratified rocks, like gneiss or mica-schists, adding a revised tabular view, in which they are included with these in the stratified division of the primitive rocks, granite alone being retained in the unstratified division.†

§ 4. Boase, in his "Primary Geology," in 1834, describes the serpentines of Cornwall as associated with tal-

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* See, for the text of the above references, the quotations in Pinkerton's Petralogy, 1821, i., 334-343 ; ii., 608-612.

† Macculloch, loc. cit., pp. 78, 243, 652-655.

cose and chloritic and actinolite-schists, and what had been "called hornblende-slate," to which the serpentine seemed in some instances subordinated. He farther compares these associations and modes of occurrences with those described by Macculloch.* De la Beche, in like manner, in his "Geology of Cornwall and Devon," notes the seeming passage of the serpentine into the hornblende-slate in many places, but also its apparent "intrusion amid the latter with force"; a seeming contradiction, which he recognizes, but endeavors to explain.†

§ 5. Unlike Macculloch and Boase, De la Beche regarded serpentine as an eruptive rock of posterior origin to the associated schists, agreeing in this with Brongniart, who had placed serpentine among plutonic rocks. A similar view was held by Elie de Beaumont ‡ and by Savi, and, without entering into farther details, we may notice that they have been followed by Sismondi, Lory, and others, who maintain the plutonic origin of the Alpine serpentines, while, on the other hand, Scipion Gras, Gastaldi, Favre, and Stapff regard them as of aqueous and sedimentary origin. The views of the present school of Italian geologists, as well as Dieulefait and Lotti, will be noticed in part vi. of this essay.

§ 6. In the United States, we find Edward Hitchcock, in 1841, reviewing the opinions of Macculloch, Brongniart, De la Beche, and others, and deciding that the serpentines of Massachusetts are to be regarded as stratified rocks.§ Emmons, in 1842, after noticing the conclusions of Hitchcock as to serpentine, regarded it, nevertheless, as an unstratified rock, but distinguished it from trappean rocks,

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* Boase, loc. cit., p. 46.

† De la Beche, loc. cit., pp. 35, 99.

‡ After discussing the question with Élie de Beaumont, in 1855, I asked his eminent colleague, De Senarmont, as to the eruptive origin of serpentines. He replied that his own extended studies of the serpentines of Europe had led him to reject as wholly untenable the theory of their plutonic character.

§ Geology of Massachusetts, II., 616.

inasmuch as, according to him, it is never found in injected veins or dikes.* Later, however, in 1855, he separated it from so-called pyroplastic rocks, like "basalt, trap, and greenstone," and included it in both divisions of his pyrocrystalline class: that is to say, (1) as laminated serpentine, with gneiss, micaceous, talcose, and hornblendic slates and limestone; and (2) as massive serpentine, with granite, syenite, etc.†

§ 7. J. D. Whitney, in 1851, included hornblende and serpentine rocks, together with the magnetic and specular oxyds of iron, under the title of "Igneous," and the subtitle of "Trappean and Volcanic Rocks."‡ Henry D. Rogers, in 1858, described the steatite belt on the Schuylkill River, in Pennsylvania, as formed from the mica-schists of the region through impregnation from "the dike of serpentine which everywhere adjoins it," thus implying the posterior origin and eruptive character of the latter. Elsewhere he describes the crystalline rocks of the same region as including "true injected serpentines." He, however, looked on veins of quartz and epidote, and even of carbonate of lime, as also of eruptive origin.§ Lieber, at the same time, in his report on the geology of South Carolina, regarded not only the serpentines of that region, but the associated steatite and actinolite rocks, as eruptive masses.

§ 8. In opposition to these plutonic views, the geological survey of Canada, from an early date (1848), insisted upon the stratified character of the serpentines found in the northern extension of the Green Mountain range in eastern Canada. They were shown to be accompanied by hornblendic, steatitic, dioritic, and other schistose rocks, as well as by dolomites and magnesites. The writer, in dis-

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* Geology of New York, Northern District, pp. 67–70.

† American Geology, I., 43.

‡ Geology of Lake Superior, II., 2.

§ Geology of Pennsylvania, vol. I., *passim*. See also the author, in Azoic Rocks, pp. 15–19.

cussing the relations of these in 1863, announced "the conclusion that the whole series of rocks . . . from diorites, diallages, and serpentines, to talcs, chlorites, and epidosites, have been formed under similar conditions," and were aqueous deposits.*

§ 9. Here it will be seen that we approach the second question mentioned in § 1, namely, that of the origin and mode of formation of serpentines, which, in the view of those who maintain its indigenous character, is, of course, closely connected with the problem of the origin of its associated crystalline rocks. The notions of the earlier geologists with regard to this latter problem were, in most cases, very vague, some of them holding the view, still taught in our own day by Hébert, that these rocks, including gneisses, micaceous, chloritic, and hornblendic schists, were all formed by some unexplained process during the cooling of the globe, without the intervention of water.† With few exceptions, however, they admitted, with Werner, the aqueous origin of these, whether holding, with De la Beche and with Daubrée, that they were deposited successively from the highly heated waters of a primeval sea,‡ or the more commonly received view, that the sediments were laid down under conditions of temperature not unlike those of the present time, and were afterwards the subject of internal change (*diagenesis*), or of indefinite replacement and substitution (*metasomatosis*).

§ 10. The latter doctrine, which, in the hands of some of its disciples, has found an extension limited only by their imaginations, was at once applied to explain the origin of serpentine. Silicated rocks destitute of magnesia, and carbonated rocks destitute of silica could alike, it was maintained, be converted into serpentine, which was

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* Geology of Canada, p. 612. See also the author's Contributions to the History of Ophiolites, 1858, Amer. Jour. Sci., xxv., 217-226, and xxvi., 234-240.

† Bull. Soc. Géol. de France, 1882, xi., 30, and *ante*, p. 85.

‡ Chemical and Geological Essays, p. 301, and *ante*, pp. 104-106.

held to be the last term in the metasomatic changes of a vast number of mineral species. Hence, it was no longer necessary to suppose the direct deposition of a magnesian sediment, or an eruption of an igneous magnesian rock, to explain the presence of contemporaneous or of injected serpentines. The legitimate outcome of this hypothesis is found in the teaching of Delesse, in 1858 (when he yet held the eruptive nature of serpentine, which he classed with other "trappean rocks"),—namely, that "granitic and trappean rocks" may, in certain cases, be changed into a magnesian silicate, which may be serpentine, talc, chlorite, or saponite.[*]

§ 11. I have elsewhere shown how Delesse, three years later, abandoned alike the metasomatic hypothesis and the notion of the eruptive origin of the serpentines, in favor of that view which I had put forth in 1859 and 1860, that the serpentines were "undoubtedly indigenous rocks, resulting from the alteration of silico-magnesian sediments." At the same time, as a concession to those who maintained the occurrence of eruptive serpentines, it was said that "the final result of heat, aided by water, on silicated rocks would be their softening, and in certain cases their extravasation as plutonic rocks," which were to be regarded as "in all cases altered and displaced sediments."[†] Later, in re-stating this point in 1880, it was said, "The eruptive rocks, or, at least, a large portion of them, are softened and displaced portions of ancient neptunian rocks, of which they retain many of the mineralogical and lithological characters."[‡] The proviso contained in the last sentence is explained by the view since maintained at length, in Essays V. and VI. in this volume, that the rocks of the basaltic and doleritic types are portions of an original igneous mass, which antedated the appearance of liquid water at the surface of the globe.

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[*] Ann. des Mines (5), xii., 509, and xiii., 393, 415.

[†] Chem. and Geol. Essays, pp. 316–318.

[‡] Amer. Jour. Science, xix., 270, and *ante*, p. 126.

§ 12. After careful studies, alike in the field and in the laboratory, I was led, in 1860, to maintain that the origin of serpentine and related magnesian rocks was to be found in deposits of hydrous silicates, like the magnesian marls of the Paris basin; and in 1861 we not only find Delesse teaching this doctrine of the origin of these rocks from the alteration, or so-called metamorphism, of such magnesian precipitates, but declaring, in the spirit of my teaching, as above, that "the plutonic rocks are formed from the metamorphic rocks and represent the maximum of intensity, or the extreme term of general metamorphism."* The history of the abandonment by Delesse of his former view of the plutonic for that of the neptunian origin of serpentines, and his acceptance at the same time of the hypothesis of an aqueous origin of plutonic rooks, is significant as a recognition of the new ideas for which I had contended, and which constitute a new departure in theoretical geogeny. See, farther, on this point, a note to § 116, by Dieulefait.†

§ 13. In farther explanation of this source of magnesian silicates, it was shown by the writer, in a series of experiments the results of which were published in 1865, that whenever the comparatively soluble silicates of alkalies or of lime (which are set free by the decay of crystalline silicates, and are found in many natural waters) are brought in contact with solutions, like sea-

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* Delesse, Études sur le Metamorphisme, 1861, p. 87.

† The testimony of Scipion Gras, in 1854, in his learned memoir, "Sur le Terrain Anthraxifère des Alpes" (Ann. des Mines [5], v., 473-602), against the igneous hypothesis, should here be recorded. Of the serpentines, euphotides, variolites, and so-called spilites, of the Alps, having said that they are either eruptive or rocks altered in place, he adds: "We have long since adopted this latter hypothesis, which alone appears to us to be in accordance with observation. It is not uncommon to see these so-called plutonic rocks of the Alps offer a distinct stratification, the appearances of which are exactly like those of adjacent sediments. This is especially true for the spilites and the serpentines, the epigenic origin of which is evident." (Loc. cit., p. 601.) This epigenic hypothesis involved a metamorphosis of sediments by heat and moisture, apparently not unlike that mentioned farther on, in § 111.

water, holding magnesian sulphate or chlorid, double decomposition takes place, with the separation of a very insoluble gelatinous silicate of magnesia; and farther, that precipitated silicate of lime is decomposed by digestion with such magnesian solutions, its lime becoming partially or wholly replaced by magnesia.

This process, it was pointed out, is the reverse of that which happens when carbonates of alkalies or of magnesia come in contact with sea-water, in which case the comparative insolubility of carbonate of lime causes the decomposition of the soluble calcium-salts present. "In the one case, the lime is separated as carbonate, the magnesia remaining in solution; while in the other, by the action of silicate of soda (or of lime), the magnesia is removed, and the lime remains. Hence carbonate of lime and silicates of magnesia are found abundantly in nature, while carbonate of magnesia and silicates of lime are produced only under local and exceptional conditions. It is evident that the production from the waters of the early seas of beds of sepiolite, talc, serpentine, and other rocks, in which a magnesian silicate abounds, must, in closed basins, have given rise to waters in which chlorid of calcium would predominate."* The generation of magnesian silicates in aqueous sediments was thus shown to be the result of a natural process as simple as that giving rise to carbonate of lime.

§ 14. There are many questions connected with this theory of the source of serpentine and related rocks, such as the probable variations in the composition of the original silicates; their admixture with other silicates and carbonates; the changes wrought in these by subsequent chemical reactions, resulting in the genesis of talc, serpentine, enstatite, and olivine, and, in certain cases, the subsequent changes of these anhydrous species; the presence, in these magnesian minerals, of ferrous silicate, which is so abundant in many serpentines, and its relations to

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* Amer. Jour. Sci. (2), xl., 49; also, Chem. and Geol. Essays, p. 123.

the problem of the origin of glauconite, itself sometimes a more or less magnesian silicate; finally, the notable fact of the presence in most of these magnesian rocks of small portions of the rarer metals, such as nickel and chromium, which is to be considered in connection with the similar metallic impregnation of certain mineral waters that may well have intervened in the production of these magnesian silicates. All of these are important points, which must be reserved for future discussion. [Some of these have since been considered, in connection with the question of glauconite, on pages 196–198.]

§ 15. One great object in geology is to discover by what natural processes the different chemical elements have been segregated and combined during successive ages in the forms in which we now find them in the earth's crust; in other words, how from a once homogeneous mass have been separated quartz, corundum, bauxite, carbonates of calcium and magnesium, as well as carbonates, oxyds, and sulphids of manganese, iron, zinc, copper, and other metals. Not less important is the problem of the genesis of the corresponding protoxyd-silicates, and especially of those of calcium, magnesium, and iron, which form, often with little or no admixture, considerable masses in the earth's crust. Of these, it is unnecessary to say, the magnesian rocks under consideration constitute an important part, and all analogies lead to the conclusion that their constituent elements have been brought together by aqueous processes, such as we have already indicated.

II. — SERPENTINES IN NORTH AMERICA.

§ 16. It is evident that if we once come to regard serpentine as a rock formed from aqueous sediments of chemical origin, there is no reason, *a priori*, why it may not be found, like limestone, dolomite, or gypsum, intercalated in stratified deposits at different geological horizons, and with different lithological associations. Several such horizons of serpentine have been observed in North America, which will be noticed in ascending order.

Included in the ancient gneissic series to which the name of Laurentian has been given, serpentine is frequently met with, associated alike with crystalline limestone and with dolomite. In these, the serpentine is often disseminated in grains or small irregular masses, giving rise to varieties of so-called ophicalcite. These imbedded masses of serpentine are sometimes concretionary in aspect, and may have a nucleus of white granular pyroxene. They often recall, in their arrangement, imbedded chert or flint, and, like it, sometimes attain large dimensions. These serpentines occasionally include the calcareous skeletons of *Eozoön Canadense*, the silicate replacing the soft parts of the organism, as described by Dawson and Carpenter. Occasionally, the serpentines of this horizon form beds of considerable size, either pure or mingled only with small portions of calcite or dolomite. Of these, many instances are seen with the limestones of the Laurentian in Canada, and a remarkable example occurs at New Rochelle, on Long Island Sound, near New York city, where massive bedded serpentine, highly inclined, and interstratified with crystalline limestone, often itself mingled with serpentine, occupies a breadth of about 400 feet across the strike, the whole being conformably interstratified with massive gneisses and black hornblendic rocks with red garnet.* The general characters of the serpentines found with the Laurentian limestones have been elsewhere described by the present writer.† Their lower specific gravity, and generally paler colors, together with a larger proportion of combined

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* For an account of this locality, see Mather, Geol First District of New York (1842), p. 462; also J. D. Dana, Amer. Jour. Sci. (3), xx., 30–32.

† For descriptions and analyses, by the author, of Laurentian serpentines, see Geol. Canada, 1863, pp. 471, 591; also Contributions to the History of Ophiolites (1858), Amer. Jour. Sci. (2), xxvi., pp. 234–236, 239. Much of this so-called serpentine belongs to the species retinalite, *ante*, p. 332.

water, serve, in some cases at least, to distinguish the serpentines of this horizon from those to be mentioned as occurring in the Huronian series. To this may be added a smaller amount of combined iron-oxyd, and, in most cases, the absence of compounds of nickel and chrome, which are almost invariably present in the latter. This distinction is probably not absolute, since chromite is said to occur in the serpentine of New Rochelle, and a chromiferous garnet has been found in the Laurentian rocks in Canada.

§ 17. The serpentines next to be noticed occur in very different lithological associations from the last, and in a group of rocks which has been described under the name of Huronian. These may be defined as in large part greenish hornblendic schistose rocks, passing, on the one hand, into massive greenstones, diorites, or euphotides, and, on the other hand, into steatitic, chloritic, and hydromicaceous, or so-called talcose or nacreous schists, some varieties of which resemble ordinary argillites, with quartzose layers, often with epidote, and with associated beds of ferriferous dolomite and magnesite. In this lithological group (already referred to, in § 8), which is now known to mark a definite geological horizon, the serpentines are found interbedded, sometimes mingled with carbonate of lime or of magnesia, but seldom or never presenting varieties like the granular ophicalcite of the Laurentian. To this horizon belong the serpentines of eastern Canada, found in the continuation of the Green Mountain range, as well as those of Newport, Rhode Island, and apparently those of Cornwall, Anglesey, and Ayrshire, in Great Britain. The serpentines of this series are darker colored than the last, and generally contain small portions of chrome and nickel in combination, the former in part as chromite.*

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* For an account of these serpentines, see Geology of Canada, 1863, pp. 472, 608–612; also Contributions to the History of Ophiolites (1858), Amer. Jour. Sci. (2), xxv., 217–226.

§ 18. Serpentines are also met with in eastern North America in somewhat different associations from the two foregoing groups, and apparently belonging to a third geological horizon. The determination of the precise stratigraphical relations of the serpentines in question presents, however, certain difficulties, arising from considerations which will be made apparent in the sequel. Serpentine, though not exempt from sub-aerial decay, resists this process better than hornblendic, feldspathic, and calcareous rocks. Hence it happens that in regions where these are decomposed and disintegrated to considerable depths, associated masses of serpentine may be found rising out of the soil, without any evidences of the precise nature of the rocks which once enclosed them. Illustrations of this condition of things are found in the vicinity of Westchester and of Media, in Chester County, Pennsylvania. The underlying rocks in this region are known to be chiefly gneisses, with hornblendic and mica-schists, and include what are believed to belong to two distinct series, both of which are well displayed in the section seen on the Schuylkill River, below Norristown. Here the older Laurentian gneiss, such as it appears in the South Mountain and the Welsh Mountain, comes up in Buck Ridge, while the newer gneiss and mica-schist series is seen succeeding it to the southward, at Manayunk and Chestnut Hill, at which latter locality it also appears on the north side of the narrow Laurentian belt. In this section, as it is exposed on the Schuylkill, a belt of serpentine, with steatitic and chloritic rocks, appears between the two series, but elsewhere it is wanting along the outcrop of the older gneiss. In the localities farther west in Chester County, already mentioned, at Westchester and Media, where the rocks adjacent to the serpentine are disintegrated, and have disappeared from decay, it cannot be determined whether these serpentine masses belong to the older or the newer series — which latter appears to be similar to that including the serpentine and chrysolite rocks of Mitchell County, North Carolina. (§ 123.)

§ 19. The serpentine of Brinton's quarry, near Westchester, Pennsylvania, is distinctly bedded, granular, and often finely laminated, with disseminated scales of a micaceous mineral, giving it a gneissoid structure and aspect. A black schistose hornblendic rock, with red garnet, is said to have been found in an excavation adjoining the serpentine, and fragments gathered in the vicinity showed thin interlaminations of black hornblende with greenish serpentine. The dip of the strata, of which several hundred feet are here exposed, is to the northwest, at a high angle, approaching the vertical. They are traversed, nearly at right angles, by a vertical granitic vein, which has been traced for many hundred feet in a northwest course. This vein, which is generally from three to six feet in breadth, is white in color, and in parts may be described as a fine-grained binary granite, the feldspar of which is superficially kaolinized. In other parts, it becomes very coarse-grained, presenting large cleavage-forms of orthoclase. A banded or zoned structure, parallel to the well defined walls, is observed in some parts, and in one case a lenticular mass of white vitreous quartz occupies the centre. This veinstone, which carries black tourmaline, and is said to have afforded beryl, has all the characters of the ordinary endogenous granitic veins found in the gneissic rocks of the Appalachians, which veins I have elsewhere described in detail.*

§ 20. The rocks in the vicinity of the serpentine near Westchester are, as already said, deeply decayed, but wherever seen in cuttings are found to be mica-schist and micaceous gneiss. Such rocks, with a northwest dip, appear to underlie, at no great distance, the mass of serpentine exposed at Strond's Mill. Similar rocks are also found on the railroad between Westchester and Media,

* Amer. Jour. Science (3), i., 182–187, and Chem. and Geol. Essays, pp. 192–200, also *ante*, p. 223.

where they are exposed in a cutting near the latter station, about a mile from which is found a great outcrop of distinctly stratified serpentine, resembling that of Brinton's quarry, and with a steep northwest dip. It includes an interstratified mass, about twenty feet thick, of a fine-grained reddish gneissoid rock, approaching leptynite or granulite in character, divided into distinct beds, generally from four to eight inches in thickness, between which are sometimes found layers of a few inches of a soft serpentine, and, in one case, of a broadly foliated green chloritic mineral. Considerable differences in texture and aspect were observed between the serpentine beds below and those above this quartzo-feldspathic mass, which is indigenous, and not to be confounded with the endogenous transversal mass described at Brinton's quarry. In the study of these rocks near Westchester, I was much aided by Dr. Persifor Frazer, who kindly accompanied me, and, from his previous labors in the geological survey of the district, was familiar with its details.

§ 21. Serpentine rocks also occur on Manhattan Island, in the city of New York, where they are still exposed between Fifty-seventh and Sixtieth Streets, west of Tenth Avenue, and are directly interstratified in gneissic and micaceous rocks, which may either belong to the older gneiss series of the Highlands, or to a newer group. Associated with the massive serpentine of this locality are found small quantities of a granular ophicalcite, and near it is a mass of anthopyllite rock. This locality was long since described by Dr. Gale, when the rocks were more fully exposed than at present.*

§ 22. Serpentine masses are also found in the vicinity of the last, on Staten Island, and at Hoboken, in both of which localities the encasing gneisses, seen in New York city, are wanting, and the serpentine appears along the eastern margin of the triassic belt of the region. The

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* Mather, Geology of the Southern District of New York, p. 461.

serpentine of Staten Island is of much interest, as it presents many features which would seem at first sight to lend support to the view of its igneous origin. The serpentine rocks here occupy an area of a little over thirteen square miles in the northern half of the island, and form a ridge, presenting a succession of rounded hills, from a mile and a half to two miles or more in width, extending in a northeast and southwest course, with an average height of 200 feet, but rising in one part to 420 feet above the sea. Along the western base of this ridge lie the red sandstones of the trias, but the contact of these with the serpentine is concealed beneath the soil. A long ridge of diabase rock, similar to that which penetrates the trias on the west bank of the Hudson, runs through the sandstones for a length of nearly six miles, nearly parallel to the serpentine belt, and at a distance of from half a mile to a mile. Along the southern and eastern borders of the serpentine are spread horizontal cretaceous clays, partially overlaid by drift, while on the north side of the island, where the serpentine hills rise abruptly at a little distance from the shore, are the only known outcrops of other rocks; one, a ledge of anthophyllite rock like that accompanying the serpentine in New York city, and another, a few hundred feet distant from the latter, and from the serpentine, consisting of a coarse pegmatite, having all the aspect of an ordinary concretionary granitic vein, and containing besides crystals of orthoclase, sometimes twelve inches in length, small portions of a white triclinic feldspar, and rare crystals of red garnet. A second, smaller outcrop of a similar kind is found near by. These granitic and anthophyllite rocks appear from beneath the water and the sands of the beach.

§ 23. Such an occurrence of serpentine, rising from out of the nearly horizontal and low-lying mesozoic strata of the island, was well calculated to sustain the notion of the eruptive nature of this rock which was put forth by

Mather in his description of this locality. He, in his report, above cited, included the serpentine in his "Trappean Division," in the same category with the adjacent eruptive mesozoic diabase, regarding the serpentine "as due to the action of the same general causes, modified in a manner unknown to us."*

The history of this area of serpentine becomes intelligible when studied in the light of the facts already mentioned above. It was apparently, in triassic time, a range of hills left by the disintegration of the adjacent gneiss, the lower-lying surfaces of which are concealed beneath the newer sediments of the region. Since that time, as I have elsewhere pointed out,† the serpentine itself has undergone a process of sub-aerial change, as is evident by the layer of decayed matter, with included masses of limonite, which, in those portions that have escaped erosion, still covers the serpentine to the depth of ten or twelve feet (*ante*, p. 268). For many of the above details of this region, I have availed myself of a description of its geology, with map and sections, published in 1880, by Dr. N. L. Britton,‡ of the School of Mines, Columbia College, New York, with whom I had, in 1883, the advantage of visiting this interesting locality, and to whom I desire to make my grateful acknowledgments for valuable information respecting it.

§ 24. The serpentine rock which is seen at Castle Hill, Hoboken, on the west bank of the Hudson, opposite New York city, is believed by Dr. Britton to be a continuation of that of Staten Island, and, like it, lies on the eastern border of the trias; while the serpentine outcrop on the west side of New York city has a strike which would carry it to the east of Staten Island, and probably corresponds to a repetition of the same belt. Gneissic rocks are

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* Loc. cit., p. 283. [For a farther notice of this serpentine, see *post*, Essay XI., § 178.]

† Amer. Jour. Science (3), xxvi., 206.

‡ The Geology of Richmond County (Staten Island), N. Y., Ann. New York Academy of Sciences, Vol. II., No. 6.

met with in a boring near the serpentine at Hoboken, and are found in the small islands between Manhattan and Staten Islands, so that there can be no reasonable doubt that the serpentines of Staten Island and of Hoboken belong, like that of New York city, to the gneissic series of the region. The determination of the precise relations of these gneissic rocks to those accompanying the serpentines of eastern Pennsylvania, already described, remains for farther inquiry. See Essay XI., § 187.

§ 25. We have next to notice the occurrence, in Pennsylvania, of serpentine in the Lower Taconic rocks of Emmons, the Primal slates of Rogers, which he supposed to belong to the horizon of the Potsdam of the New York series. In accordance with this view, we find that in a report by Genth on the mineralogy of Pennsylvania, in 1875, the occurrence of serpentine is mentioned, though without any details, in the "Potsdam sandstone" near Bethlehem, at the iron mines of Cornwall, and also in the township of Warwick, Chester County.* This statement is, however, misleading, inasmuch as the serpentine is not found in the sandstone which has been conjectured to be the equivalent of the New York Potsdam, but in certain schists and limestones, which have been referred to that geological horizon, — namely, the so-called Primal slates. The history of these is given at length in Essay XI.

§ 26. I have had an opportunity of observing the occurrence of serpentine at Cornwall, where it forms small, irregular masses disseminated in a bed of crystalline limestone, itself subordinate to the great mass of crystalline schists which include the magnetite largely mined at this locality. Serpentine, generally with limestone, is found at many other localities associated with iron-ores at the same geological horizon, as at Fritz's Island and elsewhere near Reading, at Boyerstown, and at the Jones iron mine, near to Warwick, where it is found in small, lenticular masses imbedded directly in the crystalline

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* Second Geological Survey of Penn., Report B, p. 115.

schists, which, as at Cornwall, include the cupriferous magnetites of the region. These schists include hydrous micaceous minerals, among which are chlorite, and the greenish foliated silicate of copper, magnesium, and aluminium, to which I have given the name of venerite (*ante*, p. 357). The manner in which lenticular masses of pure serpentine, sometimes only a few ounces in weight, are found imbedded in these schists, not less than the mode of their occurrence in the limestones at this horizon, is such as to suggest very forcibly the notion that they have been formed under conditions not unlike those which have given rise to chert or to iron-stone nodules. No large masses of serpentine have, so far as known, been found at this horizon, yet they may be expected.

§ 27. We have next to notice the existence of a bed of serpentine at Syracuse, New York, which was, in 1839, examined and described by Professor Vanuxem, then engaged in the geological survey of the State. The locality, "on the Fort-Street road, to the east of Syracuse," or, according to Dr. Lewis Beck, "on the hill, a short distance east of the mansion of Major Burnet, at Syracuse," has long since been concealed by the growth of the city, and we have, so far as I am aware, no other description than those given by Vanuxem, in the years 1839 and 1842,* of which, on account of the interest and significance of this curious occurrence of serpentine, I make the following summary: The rocks of the region, as is well known, belong to the Onondaga salt group of the New York series, and occupy a position near the summit of the Silurian, being overlaid by the Lower Helderberg, and resting upon the Niagara division. The strata are, as elsewhere throughout this region, undisturbed and nearly horizontal, the inclination at Syracuse, as measured by Vanuxem,

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* Vanuxem, Third Annual Report on the Geology of the Third District of New York, pp. 260 and 283; also Final Report on the Geology of the Third District, pp. 108 and 110, and Beck's Mineralogy of New York, p. 275.

being less than thirty feet to the mile, in a southwest direction. The thickness of the Onondaga salt group is subject to great variations, and at this point, not far from its eastern limit, it is thinner than farther west. It is described by our author as here consisting, in its lower portion, of a mass of red shales, varying from 100 to 500 feet in thickness, passing upward into a body of greenish shales including more or less gypsum, and followed by a third division, in which are found masses of gypsum of economic value.

§ 28. These occur on two horizons, one at the base and the other at the summit of the division, in the form of lenticular masses included in soft shales or marls, which are often marked by hopper-shaped cavities, doubtless formed through the removal, by solution, of imbedded crystals of sea-salt. Interposed in these marls is found a peculiar porous dolomite, generally drab or buff in color. The cavities in this are very irregular in form, and in most cases communicate with one another. They are sometimes spherical, and contain crystalline crusts, besides some pulverulent carbonate of lime. They also vary greatly in size, in some portions attaining a diameter of half an inch, and giving the rock a vesicular aspect. Our author remarks, "The cavities of these porous rocks have no analogy whatever with those derived from organic remains." As seen in one locality, "the cells show that parts of the rock are disposed to separate into very thin layers which project into the cells, an effect wholly at variance with aeriform cavities, but evidently the result of the simultaneous forming of the rock and of soluble minerals, whose removal caused the cells in question"; a condition of things which Vanuxem considers analogous to that shown by the hopper-shaped cavities in the associated marls.

§ 29. The distribution of this porous dolomite in the third division of the Onondaga group near Syracuse is somewhat irregular. Besides a well defined stratum extending over a large part of the gypsum-bearing region, and from three to four feet in thickness, Vanuxem noticed other "masses, limited in extent, without fixed positions, appearing to have been deposited at irregular intervals in the marls"; while in some places, as at the serpentine locality about to be described, there is a lower mass, with smaller pores than that above, sometimes attaining a thickness of twenty feet. The interval between the upper and lower gypsum-horizons, from various sections noticed by Vanuxem, would appear to be from forty to fifty feet. The marls found in this interval contain more or less disseminated gypsum, and in some cases small grains or crystalline masses of sulphur, and more rarely crystalline plates of specular iron in druses in the dolomite, as observed and shown me by Dr. Goessmann. The marls are described as yellowish or brownish in color, and generally soft and shaly, with harder masses included. Above this gypsiferous division, is a fourth, consisting of a compact magnesian limestone, marked by the presence of numerous small needle-shaped cavities, which forms the summit of the Onondaga group.

§ 30. It is, as already stated, between the two masses of porous dolomite near Syracuse that the bed of the serpentine was observed. Its thickness is not stated, but it was said to extend northward "for many rods." According to the original notes of Vanuxem, there was seen, in ascending the hill, after passing twenty feet of the lower porous dolomite, and an interval concealed by soil, "first, a marly shale, then mixtures with more carbonate of lime, some compact, some crystalline, some confusedly aggregated, presenting cavities lined with crystals of that mineral, and containing also sulphate of strontian in the mass and in the cavities. With these, and above these, are other aggregates like serpentine, marble, etc., with purplish shale or slate, which are followed by a green and blackish trap-like rock, as to appearance, but too soft for that rock." After this,—that is, above it,—is a mass which resembles the material overlying the lower beds of gypsum, and this last is covered by the upper porous dolomite.

§ 31. In a supplement to the report of 1839, above quoted, it is added, "The green and trap-like rocks observed near the top of the hill to the east of Syracuse, have been examined so far as time would admit. They are all serpentines, more or less impure, and of various shades of bottle-green, black, gray, etc. They all produce sulphate of magnesia with oil of vitriol. . . . Some have a peculiar appearance, like bronze, owing to small gold-like particles, with a lamellar structure, resembling bronzite or metalloidal diallage; also other particles, highly translucent, like precious serpentine, with frequently small nuclei, resembling devitrifications or porcellanites, colored white, yellow, blood-red, variegated, etc. The grain of this is like common serpentine. In other kinds, the mass seems to be made of small globuliform concretions, varying in size, being centres of aggregation. Some are of dark vitreous serpentine, others of the compact kind, the enveloping part of a light color." Vanuxem's farther notes, in his final report, add some important details to the above. He says: "The great mass of entirely altered rock is a well characterized serpentine, especially when examined by the microscope." He mentions, moreover, the occurrence of mica, both white or light-colored and black, besides accretions which he compares to granite, and others in which a hornblende takes the place of mica, forming aggregates resembling syenite. He also describes granular carbonate of lime, like marble in texture, which "existed as accretions or nodules enveloped in the serpentine."

§ 32. I endeavored many years since to obtain specimens of these rocks, and, through the kindness of Prof. James Hall, secured a single mass of the serpentine, which contained small plates of a copper-colored bastite or bronzite. Neither mica, hornblende, nor any other crystalline silicate, was, however, present in the mass, which was a well defined serpentine, with some admixture of carbonates. It agrees closely with the description given by Vanuxem, being an aggregate of grains and rounded masses of serpentine, with others of a fine-grained carbonate of lime, imbedded in a greenish-gray calcareous base. The colors of the serpentine vary from blackish-green to greenish-white; it is often translucent, and takes a high polish. An average portion of this rock gave to acetic acid, 34.43 parts of carbonate of lime, and 2.73 of carbonate of magnesia, with 0.34 of iron-oxyd and alumina, leaving a residue of 62.50 of insoluble silicate. This was a nearly pure serpentine, as shown by its analysis. It was completely decomposed by sulphuric acid, and gave silica, 40.67; magnesia, 32.61; ferrous oxyd, 8.12; alumina, 5.13; water, 12.77=99.30. No traces of either chrome or nickel could be detected. One of the small imbedded calcareous masses or concretions found in this serpentine was finely granular, greenish in color, and was nearly pure carbonate of lime.*

§ 33. The associated shales and limestones of this gypsum division are, however, generally, if not always, highly magnesian. Beck found twenty per cent of magnesia in the limestone overlying the lower range of gypsum-beds, and the precisely similar rocks associated with the gypsum at the same horizon in Ontario are dolomitic, the porous or vesicular beds being nearly pure dolomite, and other specimens of the limestones and shales consisting of dolomite with an argillaceous mixture, the latter sometimes predominating.†

§ 34. From a study of the facts before us, it is apparent that we have here evidences of the formation by aqueous deposition of a bed of concretionary silicate of magnesia, taking the form of serpentine, with a little associated bas-

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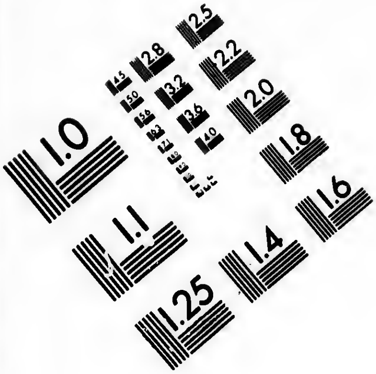
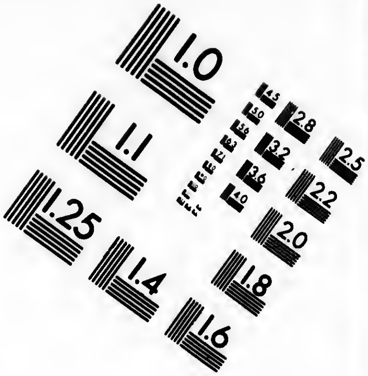
* For details of this serpentine and its analysis, see Amer. Jour. Science (2), xxvi., 263, and Geology of Canada, 1863, p. 635.

† Geology of Canada, 1863, pp. 347, 625.





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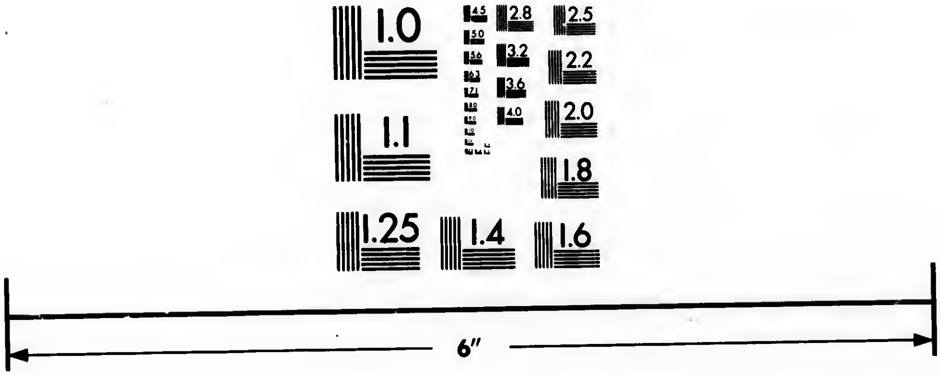

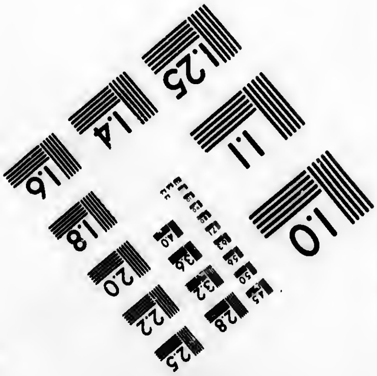

tite or bronzite, and probably some other crystalline silicates. The intimate association of silicate of magnesia with carbonate of lime is significant when it is considered that the magnesia which abounds in the accompanying strata is in the form of dolomite, and serves to illustrate the views set forth in § 13, as to the relation between the carbonates and silicates of these two bases. It seems probable that we have in this deposit the results of some spring bringing to the surface, in this locality, waters holding in solution calcareous or alkaline silicates, which have given rise to a silicate of magnesia, in accordance with the reactions already explained. It is to be hoped that farther researches at this geological horizon may disclose other localities of magnesian silicates similar to that of Syracuse.

§ 35. We may recall in this connection some facts about the occurrence of magnesian silicates in other geological periods more recent than that of Syracuse. Deposits of sepiolite, a hydrous silicate approaching to steatite in composition, are well known in the tertiary strata of the Paris basin, in Spain, and elsewhere along the Mediterranean. I have long since described some of these deposits, and have discussed at length their chemical and geological relations.* Mention should here be made of the talc found with the anhydrous sulphate of lime (karstenite) in the schists at the Mont Cenis tunnel, to be mentioned farther on (§ 62), and also of the association of gypsum and serpentine in the crystalline schists of Fahlun, in Sweden.† Freiesleben, and, after him, Frapolli, has described the occurrence of a magnesian silicate which occurs frequently in the mesozoic gypsums of Thuringia, in nodular imbedded masses resembling flints in their aspect and mode of occurrence, but composed essentially of a soft magnesian silicate, near to talc in composition, and colored brown with bituminous matter.‡

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* Amer. Jour. Science [2], xxix., 284; and xxx., 286.

† See the author's Chem. and Geol. Essays, p. 336.

‡ Bull. Soc. Géol. de France, 1847 [2], iv., 837.

III. — SERPENTINES IN EUROPE.

§ 36. Having thus passed in review some of the principal facts known with regard to the occurrence of serpentines in North America, we proceed to the consideration of the same rocks in different parts of Europe, where, as shown in the opening sections of this essay, they have long been objects of study, and have been alternately regarded as indigenous and as exotic in character.

The hypothesis of the igneous and eruptive origin of serpentine is well illustrated in the paper by Professor Bonney on the serpentines of Cornwall, England, in the "Quarterly Geological Journal," for November, 1877, supplemented by his later observations on the geology of that region, communicated to the Geological Society of London in November, 1882, and published in abstract in the "Geological Magazine," for December, 1882; in which connection should also be consulted his paper on Ligurian and Tuscan serpentines, in the same magazine, for August, 1879.

§ 37. Bonney at first accepted the then generally received opinion that the crystalline schists in which the serpentines of Cornwall are included, are altered paleozoic strata, but in his latest studies of the region he announces the conclusion that they are not paleozoic, but eozoic (archæan), and consist of a great series, divided into three groups. The lower one, of greenish micaceous and hornblendic schists, he compares with those of Holyhead, Anglesey, and the adjacent shores of the Menai Strait, in Wales. The rocks of these localities, belonging to the Pebidian series of Hicks, have been examined by the present writer, and by him compared with the Huronian of North America.*

§ 38. Above these greenish schists in Cornwall, according to Bonney, is a black hornblendic group, and a still higher granulitic group with granitic bands; the charac-

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* Amer. Jour. Science, 1880, vol. xix., pp. 276, 281; and *ante*, pp. 416–419.

ters of these two recalling portions of the Montalban or upper gneissic series of North America and of the Alps. It is in the lowest of these three divisions, consisting chiefly of micaceous and hornblendic schists, that the Cornish serpentines appear, accompanied by so-called gabbros or greenstones. Bonney finds, with Boase and with De la Beche, examples of apparent interstratification and passage between these rocks and the schists, but concludes, nevertheless, that there is evidence that the serpentine was introduced after the crystallization of these, and that its eruption was followed by that of gabbros of two dates, and subsequently by that of granitic and dark-colored trappean rocks. He throws doubt upon the ancient hypothesis of the conversion of hornblendic and pyroxenic rocks into serpentine, and supposes this mineral species to have resulted from the hydration of an olivine-rock, such as lherzolite, which consists essentially of olivine with enstatite; grains of both of which species may be detected by the microscope in thin sections of some of the Cornish serpentines. According to John Arthur Phillips, some of the so-called greenstones of Cornwall are eruptive, while others are undoubtedly indigenous, and graduate into the crystalline schists of the region. Respecting these, the writer said, in 1878, "These bedded greenstones, with their associated crystalline schists, appear to have strong resemblances to the rocks of the Huronian series, to which farther study will probably show them to belong." *

§ 39. Bonney has also extended his observations to the serpentines and associated rocks in Italy, which we have included under the general title of ophiolites. This name, and the kindred one of ophites (Greek, ὀφίτης), alluding to their greenish color, resembling that of the skins of some serpents, has been extended so as to include both true serpentine and the frequently associated rocks which present some analogies with it in color. In fact, we

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* Harpers' Annual Record for 1878, p. 308.

pass from pure serpentine, and admixtures of this with carbonates, to serpentinic rocks including more or less of diallage, bronzite, or bastite, and thence to aggregates in which an admixture of these with a feldspathic element marks a transition to the great group of rocks essentially made up of an anorthic feldspar with a pyroxenic element (hornblende, pyroxene, enstatite, etc.), including the so-called "greenstones,"—diorites, diabases, and euphotides, —which are the frequent associates of serpentines. All of these rocks were embraced by Savi under the convenient name of the ophiolitic group.

§ 40. The name of gabbro (from an Italian locality of these rocks, near Leghorn) was adopted and extended by Tozzetti, in the last century, in a similar sense. His numerous species of gabbro embraced alike serpentine and the various diallagic, hornblendic, and feldspathic rocks already noticed, of which the red gabbro, or *gabbro rosso*, seems but a locally discolored and partially decayed form. The name of gabbro has come, with many lithologists, to mean a diabase; but it is employed in such a very indefinite manner that it would be well if it were dropped altogether from use.* It is often made to include the *granitone* of the Tuscan stone-workers, the so-called euphotide, in which, as we are told, the feldspathic element is replaced by saussurite. Although this latter term is often given to a compact variety of triclinic feldspar, the true saussurite is, as I have elsewhere shown, a compact zoisite, distinguished from feldspar by its much greater density and hardness. The two minerals are, however, intimately associated in the euphotides alike of the Alps and the Apennines, as seen in specimens which I have examined both from Monte Rosa † and from Monteferrato, where I found saussurite in 1881.

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* See, in this connection, Cocchi, Bull. Soc. Géol. de France (1856), xiii., 261; also his valuable memoir on the Igneous and Sedimentary Rocks of Tuscany, *ibid.*, 1861, pp. 227-300. Cocchi was a pupil of Savi.

† Contributions to the History of Euphotide and Saussurite, Amer. Jour. Science, 1858, xxv., 437.

§ 41. The results of Bonney's studies are given in a paper on Ligurian and Tuscan serpentines in the "Geological Magazine," for August, 1879. He therein records his observations in different localities in these regions, which, for reasons to be made apparent farther on, we arrange in three geographical groups. First, ophiolites on the sea-coast west of Genoa, where Bonney describes the serpentines as occurring with dark-colored schists and gabbros, instancing among the mineral species found with them pyroxene, amphibole, glaucophane, chlorite, and saussurite. He states that the serpentines of this region are so like those of Cornwall that he feels justified in claiming for them a similar origin. In a second group, he notices the serpentines of a region immediately eastward of the first, between Genoa and Spezzia, which he describes as very similar to these. Bonney rejects for all of these serpentines, as for those of Cornwall, the notion that they have been formed by metasomatosis from diorite, diabase, or hornblendic rocks, a hypothesis which he conceives to have been founded on hasty and imperfect generalizations, and regards them as generated by the hydration of intruded olivine rocks. In the third geographical group of the ophiolites described by Bonney, he places those of Monteferrato in Prato, near Florence. In each of these districts he notices the close resemblances between the ophiolitic rocks and those met with in the similar areas in Great Britain, and supposes an intrusion of serpentine, or rather of olivine rock, among crystalline schists, followed by a later intrusion of gabbro. He has no hesitation in assigning to the serpentines of these three districts similar conditions and origin to those in Cornwall, North Wales, and Scotland, remarking that, notwithstanding the fact that the Italian serpentines are, in part, at least, assigned to the cenozoic period, "they are practically identical" with the serpentines and gabbros of more ancient times.

§ 42. Bonney further calls attention to the breccias of serpentine with a calcite cement, found at various points with these Italian serpentines, and concludes that the serpentines have been brecciated *in situ*, so that it is possible to trace, in a short distance, the passage from unbroken or slightly fissured blocks to completely crushed and recemented fragments, and even to mixtures of finely broken serpentine cemented by carbonate of lime, in which he notes, here and there, filmy patches of a serpentinous material, as if it had been redissolved and again deposited. He believes that the crushing took place after the rock became a serpentine. The correctness of these views of Bonney, as to the breccias, I can confirm from my own observations in the same regions, and also from my studies of similar breccias, accompanying the ophiolites of eastern Canada. Gastaldi, in this connection, has made an important observation of a breccia in the valley of Trebbia, resting upon a diallagic serpentine, and consisting of cemented fragments of silicious and argillaceous slate with limestone (alberese), the paste being traversed in various directions by veins of chrysotile.*

§ 43. Bonney's observations thus bring us face to face with the views of those Italian geologists who regard certain of these serpentines as of tertiary age, and speak of them as having had an eruptive origin, although, as we shall see, their views of the genesis of these rocks differ as widely as possible from those of Professor Bonney. In anticipation of the International Geological Congress at Bologna, in September, 1881, the Italian geologists had, under the direction of the Royal Geological Commission (R. Comitato Geologico), made extraordinary preparations for the study and the full discussion of the problems offered by the serpentines of Italy. A map, prepared for the occasion, was published, showing the localities of the ophiolitic masses for the whole kingdom on a scale of 1-1,111,111th; besides separate maps of particular regions on a scale of 1-10,000th, as that of Mazzuoli and Issel for

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* Studii geologici sulle Alpi occidentali, parte II., p. 51.

the Riviera di Levante in Liguria, and that of Capacci for Monteferrato in Prato, in Tuscany; with especial memoirs on these districts, also published by the R. Comitato Geologico, in 1881. Ophiolitic rocks are met with in greater or smaller outcrops in many localities from the Alps, throughout the Apennines, and as far as Calabria. To these, the studies of Taramelli, Lovísato, De Giorgi, and De Stefani, among others, in addition to those previously named, have contributed a great body of information. A collèction of ophiolitic rocks from various localities was also made, and submitted to chemical and microscopical study by Cossa of Turin, aided by Mattirolo, the results of which occupy about 200 pages, illustrated with many plates, in the fine quarto volume recently published on Italian lithology.*

§ 44. During the International Geological Congress, a special meeting was held for the discussion of the question of serpentines, on Sept. 30, 1881, in which took part Taramelli, Capacci, Zacagna, Sella, Szabo, Daubrée, De Chancourtois, and the writer, who presided on that occasion. A detailed report of the proceedings at this meeting is published in the first fasciculus of the Bulletin of the new Geological Society of Italy, pages 14–31, followed by an address on the general subject of serpentines by the present writer, pages 32–38, by notes on the same subject by De Chancourtois, pages 39–44, and finally by the extended studies of Taramelli on the Italian serpentines, pages 80–128. It is impossible to speak too highly of the zeal, the industry, and the scientific spirit exhibited by the Italian geologists in these researches undertaken for the solution of the question of the ophiolites, which may well be held up as an example to be followed by other nations in similar circumstances.

§ 45. Mention should also be made of the brief memoir, of thirteen pages, in the French language, by Pellati,

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* Ricerche Chimiche e Microscopiche sui Roccie e Minerali d'Italia, Torino, 1881.

prepared for the Geological Congress, entitled "Études sur les Formations Ophiolitiques de l'Italie," in which are set forth, with great conciseness, the principal facts with regard to the geography and the geology of these ophiolitic masses, and the theoretical views entertained with regard to them by various Italian geologists. According to De Stefani, whose discussion is confined to the ophiolites of the Apennines, these rocks belong to three distinct horizons: — 1. upper eocene; 2. upper trias; 3. paleozoic; none of them pertaining to a more ancient period. These ophiolitic rocks form zones and regular beds in the midst of the sedimentary rocks, and in no case plutonic dikes. The different varieties of serpentine, and of the non-sedimentary rocks which accompany it, are themselves found in regular alternating bands.* The conception of this observer as to the mode of eruption of these rocks appears to be essentially the same as that of Issel, Mattirolo, and Capacci, to be explained farther on (§§ 91–93 and 100).

§ 46. The more recent studies of the R. Comitato Geologico, as announced in 1881, lead them to reject the views of De Stefani as to the age of the ophiolites, and to refer the whole of these rocks in Italy to two geological periods. They distinguish ancient serpentines, probably pre-paleozoic, and younger serpentines, referred to the tertiary. The older serpentines appear in large masses to the west of Genoa, between the valleys of the Polcevera and the Teiro, and from thence are traced to Monviso, from which point the ophiolitic group passes north-northeast to Monte Rosa, and thence, by the canton of Ticino, to the Valtelline. To the same ancient series are also referred the serpentines of the north of Corsica, those of Elba in part, and those of northern Calabria. These ancient serpentines, according to Pellati, follow the contour of the great zone of old gneissic and granitic rocks, which passes along the Alps, through Corsica and the Tuscan archipelago, and re-appears in Calabria. The

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* Boll. Soc. Geologica Italiana, i., pp. 20–33.

older geologists, Collegno, Pareto, and Sismondi, regarded the serpentines of the areas thus defined (in common with the others yet to be mentioned), as having been erupted, like granites, porphyries, and basalts, at various geological ages. Gastaldi, however, as early as 1871, assigned the Alpine serpentines to a distinct pre-paleozoic horizon, which, from the association of the serpentines with various rocks known as greenstones, or *pietre verdi*, he designated as the pietre-verdi zone, and compared with the Huronian of North America, of which he supposed it to occupy the horizon.

§ 47. The conclusions of Gastaldi as to the Alpine serpentines have, according to Pellati, been confirmed by Baretti, and by Taramelli, the latter of whom clearly shows that the view held by many, that the rocks of the pietre verdi are carboniferous or triassic, is inadmissible, and that they belong, as maintained by Gastaldi, to pre-paleozoic or eozoic time. All of the ophiolitic masses west of the meridian of Genoa, as well as those of northern Calabria, are by Pellati included in this class.

To the east of this meridian, according to Pellati, we find the newer or tertiary serpentines, including, first, those of eastern Liguria, which have their greatest development along a line running north-northwest from Spezzia, and second, those of the Bolognese Apennines, consisting of a great number of small masses scattered between Florence and Reggio, in Emilia. A third group includes the masses of serpentine found between Grosseto and San Miniato, in addition to which tertiary serpentines are indicated in Elba and in the upper part of the valley of the Tiber. Farther south, others are met with at Lagonegro in the Basilicate, from which point to Neopoli a remarkable development of serpentines is found along the upper part of the valley of the Sinni. The areas of serpentines thus indicated by Pellati are, according to him, generally found in the midst of the limestones, argillites, and sandstones of the eocene, except in the case of those between Grosseto and San Miniato, the outcrops of which are often seen rising out of pliocene clays and sands.

IV. — GEOLOGY OF THE ALPS AND THE APENNINES.

§ 48. Before proceeding farther in the discussion of the Italian serpentines, it will be well to get a view of the present state of our knowledge of Alpine geology, and especially of the conclusions and generalizations of Gastaldi. These, so far as the Alpine serpentines are concerned, are, as we have seen, accepted by the Comitato Geologico, and, this conceded, it is difficult to escape his wider generalization which brings the whole of the so-called tertiary serpentines of Italy into the same eozoic horizon with those of the Alps.

If we go backward to the early history of Alpine geology we shall therein find the origin of the well known hypothesis that the crystalline stratified rocks are but portions of paleozoic or more recent sediments which, in certain parts of their distribution, have undergone a process of alteration or so-called metamorphism. The infraposition of the uncrystalline to the crystalline rocks in Mont Blanc, first noticed by De Saussure, was thus explained by Bertrand, who suggested that these crystalline schists were altered rocks of a more recent date than the uncrystalline mesozoic strata of Chamonix. This notion was adopted without critical study by Keferstein, Murchison, Lyell, Studer, Sismondi, and Élie de Beaumont, among others, till it was generally believed that the crystalline rocks of the Alps are wholly or in great part of mesozoic and cenozoic age. It is hardly necessary to say that this hypothesis in the Alps, as elsewhere, was based upon false stratigraphy. I have elsewhere discussed it in its relations to Alpine geology, in a review of the great work of Alphonse Favre,* whose life-long studies in the Alps of Savoy have shown for all that region the fallacy

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* Amer. Jour. Science, 1872, vol. iii., pp. 9–10, and Chem. and Geol. Essays, pp. 337–339.

of the metamorphic hypothesis. The farther studies of Gerlach, of Fr. Von Hauer, of Baretti, and especially of Gastaldi, have now fully established the great antiquity of the crystalline rocks in question, and have enabled us to compare them with the pre-Cambrian rocks of other regions. It is not here, however, the time nor the place to discuss this question, except so far as is necessary to the understanding of the geological relations of the Italian serpentines.

§ 49. The work of Gastaldi, interrupted by his death in 1878, was unfortunately left incomplete. We have, however, valuable records of it in a memoir in two parts, published in 1871 and 1874, entitled, "Studii geologici sulle Alpi occidentali"; in a letter to De Mortillet in 1872; in one to Zezi in 1876, and finally in one to Sella in 1877, with a postscript in 1878.* These various papers are illustrated with numerous maps, plans, and diagrams. In attempting to gather from these sources a brief statement of Gastaldi's conclusions as to the geology of the Alps and the Italian peninsula, I feel that I am both rendering a veritable service to science and paying a tribute to the memory of my honored friend and correspondent of many years.

§ 50. The "Studii," etc., contain, besides Gastaldi's own descriptions and sections, many important historical details and extracts from the literature of the subject. In the second part will also be found reproduced two engraved sections, the one by Gerlach, from Monte Rosa, by Varallo and the Lago di Orta to Arona on Lago Maggiore,

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* Studii geologici sulle Alpi occidentali; memorie del Regio Comitato Geologico, vols i. and ii.; Deux mots sur la géologie des Alpes cottiennes; lettre à M. de Mortillet, Comptes Rendus de l'Acad. des Sciences de Turin, vol. vii., 28 avril, 1872; Lettere del Prof. B. Gastaldi all' ingegnere P. Zezi, Boll. del R. Com. Geologico, 1876; Sul rilevamente geologici fatti nelle Alpi Piemontesi durante la campagna del 1877, lettere del Prof. Gastaldi al Presidente Quintino Sella; Reale Accademia dei Lincei, memorie della classe di scienze fisiche, ecc. anno CCLXXV. (1877-78). See, also, the writer, in Azoic Rocks, p. 245, and Chem. and Geol. Essays, pp. 336, 347.

and the other by Carlo Neri, from the same point, in a course more to the southeastward, by Valsesia, to Monte Fenera, and beyond.* A comparison of these sections with those described by Gastaldi, will be found of much value for the elucidation of the questions before us. Starting from the granitic gneiss of Monte Rosa (the central gneiss of Von Hauer, and the ancient gneiss of Gerlach and Gastaldi) we find in Neri's section a breadth of not less than seven kilometres included in the zone of the pietre verdi, and described as a stratified series of "serpentines, talc-schists, etc.," followed by seven kilometres additional, designated as diorites; the two being classed together as a "protozoic terrane." To this succeeds a breadth of not less than fourteen kilometres occupied by what is described as a more recent crystalline terrane, conjecturally referred to the paleozoic period, and consisting of calcareous schists and quartzites, with mica-schists, and a great mass of intruded granite. Succeeding this is a great breadth described as porphyry or porphyritic conglomerate, followed by limestones and dolomites, all of which are referred to the trias, and appear in Monte Fenera, succeeded by fossiliferous liassic and tertiary strata.

The section by Gerlach, from Monte Rosa to Arona, shows above the ancient central gneiss a great breadth described simply as diorite, having at its base a thin belt of micaceous schists, and above it, between Varallo and the lake of Orta, a wide extent of recent gneiss and granite, followed, to the east of the lake, by gneissic mica-schists, succeeded by porphyry, until we reach the dolomitic limestone at Arona.

§ 51. Coming now to Gastaldi's own sections, we have one from Turin passing westward to the French frontier, and crossing a broad mass of the central gneiss; to the

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* The section by Gerlach is probably from his Karte der Penninischen Alpen; Nouv. Mém. de la Soc. Helvét. de Sci. Nat., 1869. That by Neri is from the Boll. del Club Alpino, vol. viii., No. 22, Torino, 1874.

west of which, in a distance of forty kilometres, we have, first, three and a half kilometres of euphotide and serpentine, followed by about the same breadth of mica-schists, calcareous schists, and diorites, and finally by a great extent of calcareous schists, with numerous intercalations of serpentine and, towards the summit, gypsum and dolomite. The less complete section, to the eastward of the central gneiss, shows also the serpentinic and dioritic rocks overlaid by mica-schists, and the same story is repeated in other sections.

Subsequently, in his letter to Zezi, Gastaldi describes and figures a section from Monte Bracco through Monviso and Monte Pelvo, along the upper part of the valley of the Po, and the valley of Varaita, to the frontier. His conclusions from the study of all these sections may be thus summed up: The crystalline rocks of the Western Alps are classed in two great groups, the lower of which (the central gneiss of Von Hauer) was described by Gastaldi as the ancient gneiss, and by him compared with the Laurentian of North America. It consists chiefly of a highly feldspathic granitic gneiss, sometimes porphyritic or glandular, and includes bands and lenticular masses of quartzite and crystalline limestone, with white steatite, and graphite. Reposing upon the ancient gneiss, is a great and complex group, designated by Gastaldi as the "newer crystalline series," which, from the frequent presence therein of serpentines, diorites, diabases, and related rocks of a greenish color, is also called by him the zone of the greenstones, or the *pietre verdi.*

§ 51. In a generalized diagrammatic section which accompanies Gastaldi's last published statement (his letter to Sella, in 1878), the first division of the newer crystalline series is described as a great mass of serpentine, followed by a second division consisting of euphotide, succeeded, after an interval of crystalline schists, limestones, and gneissic rocks, by a series made up of many alternations of epidotic, dioritic, and variolitic schists, with green steatite. In some localities are found great beds of lherzolite and of amphibolite, with varieties of diorite, and rocks in which a triclinic feldspar prevails, together with schists more or less calcareous, and crystalline limestones. The serpentines and their associated ophiolitic rocks, which constitute the lower members of the newer crystalline series, are described by Gastaldi as resting in some cases in nearly horizontal stratification upon the ancient gneisses, and, elsewhere, as overlying the limestones of this older series, from which their unconformable superposition may be inferred.

§ 52. The group of newer crystalline rocks, as given in Gastaldi's section of 1878, includes also what he designates as recent gneiss and granite, besides various undescribed schists, with crystalline limestones, followed by a second horizon of serpentines, to which succeed gypsum and dolomites. All of these, as is shown in the section from Turin to the frontier, are intercalated with quartzite, in a vast series of schists which are placed above the recent gneiss and granite. Finally, the whole series is overlaid by the uncrystalline sediments of the anthracitic group, of carboniferous age.

§ 53. The lithological characters of the lower part of this vast series of newer crystalline schists are sufficiently well defined in the various sections already noticed. As regards those which immediately succeed the serpentinic, chloritic, and talc-schist zone, — the group of "mica-schists" of Neri, the "recent gneiss and granite" of Gerlach and Gastaldi, we get additional light from various passages in the writings of the latter. They are spoken of in one place as gneissic mica-schists, more or less rich in hornblende, in which, at Traversella, are also included serpentines. Elsewhere, the rocks of the same area are successively called mica-schist, recent gneiss and mica-schists, gneissic mica-schists, and also, a very micaceous gneiss, often passing into mica-schist and sometimes hornblendic. With these, or with the lower portions of the series, are associated granitic and syenitic rocks which, in the opinion of Gastaldi, are not eruptive, but the result of local modifications of the surrounding gneiss. From my own observations, I conclude that, while these recent gneisses in the Alps, as in North America, assume a highly granitic aspect in certain beds, they are not to be confounded with veritable intrusive rocks which penetrate them.

§ 54. Gastaldi has described in detail and figured a section in the Biellese, a region carefully mapped by Quintino Sella and G. Berutti, and studied both by Gerlach and Gastaldi.* Here, in the section as given by the latter, the granite or granitic gneiss is bounded to the northwest by serpentine, diallagic rocks, "and other greenstones," followed by a band of diorite. To this succeeds a great breadth of the newer gneisses, in which is included a large dike of melaphyre, evidently of eruptive and posterior origin, and, farther to the westward, a mass of syenite, which is extensively quarried, and has been studied with great care and described by Cossa in his work already mentioned. I had the good fortune to visit this well known region in 1881, in company with Signor Quintino Sella. The granitic rock of the eastern part of the section appeared to be a part of the ancient gneissic series so largely developed elsewhere near Biella, and consisting of reddish granitoid gneisses, sometimes hornblendic, but scarcely micaceous, often thinly banded, highly contorted, and indistinguishable from much of the gneiss of the Laurentides, or of the South Mountain in Pennsylvania, east of Schuylkill. Interstratified with it, near Biella, are beds of coarsely crystalline impure limestone, holding graphite, mica, and hornblende, and resembling closely some Laurentian limestones. Elsewhere in the Alps, it may be noted, similar gneisses include serpentinic limestones, as for example the pale green ophicalcite found by Favre in the gneiss of Mattenbach, near Lauterbrunnen, which is indistinguishable from that of the Lau-

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* Gastaldi, Studii, etc., part I., pp. 3 and 26.

rentian of Canada, and like it contains *Eozoön Canadense.*[*] It is well known that similar serpentinic aggregates are often found with the limestones in the ancient gneisses of Scandinavia and Finland, as well as in North America.

§ 55. This ancient gneissic series in the Biellese is directly overlaid by the ophiolitic and dioritic belt (pietre verdi), and this is followed to the west by the newer gneisses and mica-schists, which cannot be distinguished from those found in the vicinity of Philadelphia, or in the White Mountains of New Hampshire, which I have called Montalban. The intruded mass of syenite, made up of reddish orthoclase with some albite, hornblende, and a little sphene, presents, in the extensive quarries which I visited, the massive character and the comparative homogeneousness which belong to a plutonic rock. The usually great breadth of ophiolitic rocks met with in this part of the Alps is here, as pointed out to me by Signor Sella, rapidly reduced, to the southward, by the encroachment of the newer gneisses on the westward side, and, where the crystalline rocks sink beneath the alluvial plain, does not exceed a kilometre. These relations suggest a transverse superposition of the newer gneiss series alike upon the ophiolitic group and the older gneiss, of which we shall find evidence elsewhere.

§ 56. It has been seen that the designation of *pietre verdi* was by Neri restricted to the ophiolitic group beneath the newer gneisses, which he referred to a later and distinct geological period. Gastaldi, on the other hand, extended the term so as to include not only the newer gneisses and mica-schists, but the vast mass of crystalline strata between these and the anthracitic series, with their included gypsums and dolomites. The grounds of this extension are these: Serpentines are not confined to the lower ophiolitic zone, but also occur alike among the newer gneisses and the succeeding crystalline schists.

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[*] Favre, Recherches géologiques dans la Savoie, etc., iii., 320, and also Chem. and Geol. Essays, p. 342.

It is, says Gastaldi, "in contact with the gypsums and dolomites that we find the last limit of the serpentinous rocks which, for us, characterize the zone of the pietre verdi." This was in 1872, in his letter to De Mortillet, at which time Gastaldi was disposed to place in a separate group the crystalline schists above the horizon of the upper serpentines. He, however, subsequently included the whole of these schists in the zone of the pietre verdi.

§ 57. As will be made apparent, the schists for a great distance below this horizon are not to be separated from those above. We have in them, in fact, a third great crystalline group, overlying the younger gneisses, but by Gastaldi included with these and the lower ophiolitic group under the common name of the pietre-verdi zone. At other times Gastaldi used the term of pietre verdi in the more restricted sense in which it was employed by Neri. He speaks, in 1874, of "the pietre verdi properly so called," and in this sense he declares it to be comprised between "the ancient porphyroid and fundamental gneiss" and "the recent gneiss, which latter is finer grained and more quartzose than the older." He says farther, "I will not assert that when specimens of this newer gneiss are confusedly mixed with those of the more ancient, it would always be practicable to distinguish them petrographically; but I do not hesitate to affirm that, on the ground, the distinction is not difficult, on account of the frequent alternation of the younger gneiss with the other characteristic rocks of the upper series; while the older gneiss, however wide its extent, is generally unmixed with other rocks." *

§ 58. The newest crystalline group, mentioned as overlying the younger gneiss and mica-schist series, is that of the argillo-talcose schists of Favre, the gray lustrous schists of Lory (*glanzschiefer*), with their included serpentine, gypsum, karstenite, dolomite, micaceous limestone, banded and statuary marbles, and quartzites; a group very

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* Studii, part II., p. 31.

conspicuous in Alpine geology. These rocks are well seen in the section from Turin to the French frontier, and are traversed in the Mont Cenis tunnel. (See also §§ 62–66.)

§ 59. The vast thickness assigned by various observers to this entire series of newer crystalline schists, counting from the ancient gneiss below, is a remarkable fact in their history. We have seen the great breadth ascribed to the successive zones or groups in the sections already noticed. Gastaldi, in 1876, estimated the real thickness of the pietre-verdi zone, including the upper lustrous schists, at 24,000 metres, of which 8000 metres, or one-third, was assigned to the lower ophiolitic group, or proper pietre verdi, apparently without including the younger gneisses and mica-schists, which make up the middle group. To the upper group, as seen in the Mont Cenis tunnel, Sismondi and Élie de Beaumont assigned a vertical thickness of not less than 7000 metres, and Renevier finds for it elsewhere an apparent thickness of 6000 metres.

§ 60. We have hitherto spoken of the Western Alps, and the sections as yet noticed do not extend to the eastward of Lago Maggiore. The map by Von Hauer, of the Lombard and Venetian Alps, published in 1866–68, embraces the region from this meridian eastward, and shows the same order of succession as that laid down by Gerlach in the west.* The various groups, as indicated by Von Hauer, are as follows: 1. The ancient gneiss and granitic rocks, designated by him as the "Central gneiss"; 2. Greenish schistose rocks, described as hornblendic, dioritic, and euphotidic, with serpentines, chloritic and talc-schists; 3. Saccharoidal limestones, more or less micaceous, with talc-schists; 4. Serpentines, euphotide, diorite, and talcose and chloritic schists, as before; 5. A fine-

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* Gastaldi, Studii, part I., p. 18, and Fr. Von Hauer, Geologische Übersichtskarte der Osterreichisch-Ungarischen Monarchie, fol. v., West-Alpen, u. fol. vi., Ost-Alpen; Wien, 1866–68.

grained gneiss, designated as "Recent gneiss"; and 6. Mica-schist, with hornblendic and feldspathic varieties. We have evidently here the same great pietre-verdi zone as in the west, comprised between the older gneiss and the younger gneiss with its attendant mica-schists. There appears, however, a considerable development of crystalline limestones in the midst of the pietre verdi.

§ 61. Further light is thrown upon the question of these crystalline rocks of the Alps by the observations of Renevier, Heim, and Lory, especially as embodied in an essay by the latter on the Western Alps, published in 1878, and in a study of the geology of the Simplon, by Renevier, in the same year.* According to Lory, the ancient crystalline rocks, designated by him as the "Primitive schists," as seen in the Simplon, and elsewhere in this region, include three groups, in ascending order: 1. The stage of the Gneiss, properly so called, including varieties from the highly feldspathic and massive granitoid gneisses to others less feldspathic and more distinctly laminated. 2. The stage of the Mica-schists, often garnetiferous, which embraces, however, alternating beds of gneiss, the two rocks passing insensibly the one into the other. These mica-schists, tender, and gray in color, are often more or less impregnated with carbonate of lime, and contain bands of limestone and marble. 3. The stage of the Talc-schists, a term which, as Lory explains, he uses in a very general sense, to include not only steatites, but talcose, chloritic, and hornblendic schists, the latter sometimes without visible feldspar, but often more or less feldspathic, and thus passing into varieties designated by him as talcose, chloritic, or hornblendic gneiss. The so-called protogine of the Alps, according to Lory, is but a granitoid variety of talcose or chloritic gneiss, sub-

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* Essai sur l'orographie des Alpes occidentales, par Charles Lory, p. 76; Paris and Grenoble, 1878. Also, Structure géologique du massif du Simplon, etc., par E. Renevier, Bull. de la soc. vaudoise des sciences naturelles, vol. xv., No. 79.

ordinate to the talc-schist stage, and passing insensibly into the talcose and chloritic schists, with which it alternates. It is not, therefore, as some have supposed, the fundamental rock of the Alps, but belongs to an upper portion of the Primitive schists. The lower gneiss of the Simplon, described by Gerlach as the gneiss of Antigorio, to which this distinction apparently belongs, is further noticed by Renevier, who assigns to it a great thickness, and regards it as the basal rock of the Alps, corresponding to the ancient gneiss of Gastaldi and the central gneiss of Von Hauer. The succeeding mica-schists, often garnetiferous and calcareous, with alternating gneiss and limestone bands, have also a great volume. The hornblendic schists play a less important part in the series. Though these sometimes contain a little mica, or a little chlorite, chloritic schists are rare, and the stage of the talc-schists, indicated by Lory, is not mentioned by Renevier in his description of the Simplon.

§ 62. The term of Primitive schists, as employed by Lory and by Renevier, is not extended to the gray lustrous schists, already noticed as forming the upper part of the great series included by Gastaldi in the pietre verdi. These upper schists are by Lory regarded as altered trias, a view in which Renevier acquiesces. They are, for the most part, soft, glistening, and talcose in aspect, and have been variously described as argillo-micaceous and argillo-talcose schists, being sometimes, according to Lory, true sericite-schists.* They closely resemble the crystalline schists with hydrous micas which abound in the Primal and Auroral divisions of Rogers (Taconian), as seen in eastern Pennsylvania. These schists in the Alps are traversed by veins of calcite and of quartz, and include, besides great beds of quartz-rock (often a detrital sandstone), beds of limestone, sometimes micaceous, of banded and of white granular marbles, of dolomite and of gypsum. This latter, in the subterranean exposures made in

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* Bull. soc. géol. de France, x., 29.

the Mont Cenis tunnel, is represented by anhydrous sulphate of lime (karstenite), and is accompanied by rock-salt and sulphur. Magnesian silicates are also found in this group; nodules of talc are imbedded in the karstenite, chlorite occurs in veins and layers, and beds of serpentine (and of euphotide, according to Gastaldi) are interstratified with these shining argillo-talcose schists.

§ 63. The resemblances in mineral character between these upper argillo-talcose schists with chlorite and with interstratified serpentines, and the lower or true pietre-verdi zone, are obvious. Lory has moreover remarked the likeness between these upper schists with limestones and the mica-schists with limestones in the horizon of the newer gneiss series (included by him in the Primitive schists) as leading to the confounding of the two. This resemblance, he suggests, "may have thrown some obscurity" upon the relations of these various rocks, and the structure of the region. It will not have escaped the notice of our readers that in the description of the section of the Simplon there is no recognition whatever of the great mass of serpentines, euphotides, and other ophiolitic rocks belonging to the pietre verdi, which elsewhere are found at the base of the newer crystalline schists, occupying a horizon between the older and the younger gneisses.

§ 64. It will also be noted that Lory places a horizon of talc-schists, with chloritic rocks, etc., at the summit of the newer gneisses, and the view naturally suggests itself that Lory has himself confounded the lustrous schists of the upper series and their magnesian rocks, with the great lower ophiolitic zone. This latter would appear to be wanting in the section of the Simplon, where it is not noticed by Renevier. Lory thus places above the younger gneisses a talc-schist series to which he refers many of the types of rocks met with in the great ophiolitic and talc-schist zone, which elsewhere underlies these younger gneisses, and in which the protogines are probably included. In this way the apparent discrepancy between

Lory and all the observers hitherto mentioned is explained, as proposed by the present writer in 1881. The relations observed in the Biellese, as already noticed, suggest that the younger gneisses were deposited unconformably, alike upon the older gneisses and the great ophiolitic group, as is the case in many other regions.

§ 65. In like manner, according to Lory, the lustrous schists themselves, with included serpentines (which he regards as contemporaneous eruptions), rest directly upon the ancient gneisses in the Levanna, between Susa and Lanzo. Other evidences of a want of conformity between these various groups of ancient schists in the Alps are not wanting. At the Col de Mont Genèvre, as described by Lory, there appears through the lustrous schists a great "mass of non-stratified rocks, comprising euphotides, serpentines, variolites, and various rocks of passage between these types." These ophiolitic rocks, which correspond to the lower part of the pietre-verdi zone of Gastaldi, are regarded by Lory as eruptive, and have not been recognized in his scheme of the divisions of the primitive schists. Their appearance among the lustrous schists is thus, according to him, an irruption in the midst of the trias, instead of being, as we should rather regard it, a protrusion of a portion of the pietre-verdi zone in the midst of the lustrous schists, which are here unconformably superimposed upon it, as elsewhere upon the ancient gneisses.

§ 66. The history of the upper or argillo-talcose schists of the section under consideration will be found discussed at some length by the present writer in a review of Favre on the geology of the Alps in 1872. It was there shown that these, though very distinct from and unlike the underlying micaceous, hornblendic schists and gneiss, are really crystalline schists, and very unlike the normal trias of the region, to the horizon of which they had been referred by most geologists. The section of them afforded by the Mont Cenis tunnel was then and there discussed, and many reasons were given for rejecting the notion of their triassic age, and for assigning them to the eozoic period. As was shown in a subsequent note to that review, Favre, after publishing his book in 1867, was led to adopt the view advanced by Gastaldi in 1871, that these schists were pre-carboniferous, though probably paleozoic, a conclusion which the latter subsequently exchanged for that of their eozoic age, as maintained by the present writer since 1872.*

§ 67. The section traversed by the St. Gothard tunnel furnishes important details for Alpine geology. This work, beginning at Goschenen, on the north, ends at Airolo on the south side of the mountain, the entire distance being 14,920 metres. The first 2000 metres from the northern portal are in the massive rock of the Finsteraarhorn, called by various observers granite or granitic gneiss, and by Stapff regarded as an older gneiss than that of the remaining part of the section. Between this and the mountain of St. Gothard is included the closely folded synclinal basin of Urseren, while the southern portal, at Airolo, is on the northern side of the similar basin of Ticino; the great intermediate mountain-mass of highly inclined and faulted strata, presenting a fan-shaped arrangement. The basin of Urseren holds, folded in gneiss and mica-schist, a group of strata consisting of argillites, sometimes calcareous and often graphitic, with gray lustrous, unctuous sericite-schists, together with quartzose layers, and others which, from a development of feldspars, pass into an imperfect gneiss. With these are interstratified granular crystalline limestones, white or banded with gray, with dolomite and karstenite. Some of the limestones included in this synclinal have afforded indistinct organic forms, and the series has been referred, like the similar rocks noticed in previous sections, to the mesozoic period. A repetition of these is met with in the

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* Amer. Jour. Science (3), iii., pp. 1-15, also Chem. and Geol. Essays, pp. 333, 336, and 347.

Ticino basin, on the south side of the mountain. Apart from these, the great mass of strata along the line of the tunnel consists of micaceous gneisses and mica-schists with hornblendic bands, the whole having the characters of the younger gneissic series, and very distinct from the older gneiss of the northern portion.* If this latter be the central gneiss, the pietre-verdi zone is here absent.

I have not seen the gneiss of the Finsteraarhorn, but, having examined the gneisses and mica-schists of the St. Gothard and the Ticino, can affirm that they have the lithological characters of the Montalban series of North America and of the younger gneiss and mica-schists of Gastaldi and Von Hauer, in which they were included by the Austro-Hungarian geological survey. (§ 60.) The serpentines of the younger gneiss, as seen in the St. Gothard section, will be described in part vii.

§ 68. With regard to the presence of granites in these regions, Cordier, as cited by Lory, long ago asserted that true granites, occurring in veins or transversal inclusions, are rare in the Western Alps. He, however, excepted some masses, of which the granites of Baveno may be taken as a type, and others, which are rather veins of segregation (endogenous) than of injection.† For the rest, Cordier regarded the granites of the Alps as stratified rocks. Gastaldi, going still farther in his protest against plutonism, admits, in the regions examined by him, none but stratified rocks of aqueous origin, and has included in his sections masses that I regard as igneous and intrusive rocks, but which are by him confounded with true indigenous gneissic rocks under the title of "recent gneiss and granite."

As regards the porphyry mentioned in the sections of Neri as above the recent gneisses, and that placed by Gastaldi above the lustrous schists, it would appear that

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* For full details of this section see Profil géologique du St. Gothard, etc., par Dr. F. M. Stapff; Berne, 1881.

† See the author, in Chem. and Geol. Essays, p. 331.

the latter employed this term in a very vague sense, since he speaks of the feldspathic and quartziferous porphyries of this region as presenting great varieties in structure and in composition, and as passing into other rocks, notably into granites, from which it is often difficult to separate them.* He seems, under the general term of porphyry, to have included both stratified rocks at different horizons, and intruded masses of various kinds.

§ 69. From the various descriptions and sections of the Alpine rocks, which we have here considered, it appears that they may be included in four distinct groups, which are as follows in ascending order: —

I. The central or ancient granitoid gneiss, with occasional quartzites and crystalline limestones, bearing graphite and many crystalline minerals. This group we refer, with Gastaldi, to the Laurentian.

II. The great group of the pietre verdi proper, in which, besides serpentines and ophiolitic rocks, are included bands of limestone, and also apparently certain gneissoid rocks, the protogine or the talcose gneiss of Lory and Taramelli. (§§ 61, 78.) It is worthy of remark that although Gastaldi, like Neri, Gerlach, and Von Hauer, placed the great group of recent gneiss and mica-schists above the true pietre-verdi zone, which he declared to be confined between the older and the newer gneiss, he, in his last published sketch, indicated, besides this, another horizon of "recent gneiss and granite" (not elsewhere noticed by him) intercalated in the pietre-verdi zone, as thus limited, and probably corresponding to these talcose gneisses. This second or pietre-verdi group, we refer with Gastaldi to the Huronian.

III. The younger gneiss and mica-schist series, with hornblendic varieties and intercalated crystalline limestones, and in some cases with serpentines and euphotides. This group, upon the lithological characters of

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* Studii, etc., part II., p. 34.

which we have already insisted (§§ 53, 55, 67), we regard as the representative of the Montalban.

IV. The upper lustrous schists, with gypsums and karstenite and talc, with interstratified serpentines, quartzites, often sandstones, argillites, dolomites, micaceous limestones, and banded and statuary marbles. This group, as we have already indicated, presents many resemblances with the great Lower Taconic or Taconian series of North America. In it are included by Gastaldi, the crystalline limestones of the Apuan Alps, which yield the statuary marbles of Carrara and of Massa.

§ 70. In the Western Alps there is, so far as is known, no evidence of the lower paleozoic rocks, — the sandstones with anthracite, which succeed the crystalline schists, containing in many places a carboniferous flora. The same, according to Gastaldi, is true in the Maritime Alps and the Apennines, where, in many cases, he finds the crystalline schists overlaid by the anthracitic series. Thus, in the valley of Macra, above the serpentines are found calcareous schists with crystalline limestones and quartzites, which are successively overlaid by the carboniferous sandstones, the limestones of the trias, with their characteristic fauna, the lias, the cretaceous and the nummulitic beds. At Torre Mondovi, the serpentines are overlaid by fossiliferous triassic limestones, while in the valley of Bormida they are directly succeeded by the marls, sandstones, and conglomerates of the lower miocene, and in the valleys of Staffora and Polcevera by the alberese and the macigno of the eocene. The supposed pre-carboniferous fauna found by Michelotti in the limestones of Chaberton, has, on farther examination by Prof. Meneghini, been shown to be of triassic age.*

§ 71. Passing now from the mainland of Italy, we come to Corsica and Elba. The serpentines of the former island have long been known to geologists, and have within the last few years been especially studied by Hollande,

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* Gastaldi's letter to Zezi, in 1878, already cited.

Coquand, Dieulefait, and Lotti. Coquand, who described the serpentines of Corsica in 1879, and who, like Hollande, regards them as eruptive, supposes them to be in part very ancient, and in part tertiary, since, according to him, some of them overlie the nummulitic beds.* Pellati, whose essay we have already cited, refers however the whole of the serpentines of this island to a pre-paleozoic period, and Dieulefait, who described these rocks in 1880,† declares that Coquand's reference of the serpentines found near Corte to the tertiary is based on an error of observation. He moreover asserts that the serpentines of Corsica are stratified sedimentary rocks belonging to a single geological horizon, at which they may be traced continuously for a length of more than 200 kilometres from Corso along the northeast coast of the island. The geological succession, according to him, is as follows: — 1, stratified protogine; 2, gneiss; 3, lustrous schists; 4, saccharoidal limestones; 5, schists more or less talcose; 6, schists enclosing serpentines of many varieties; 7, clay-slates; 8, black limestones with carbonaceous matter; 9, beds often detrital; 10, infra-liassic limestones, with *Avicula contorta.*

§ 72. Lotti, who has since studied these rocks,‡ confirms fully the observations of Dieulefait. He describes the crystalline limestones, white or banded, with grayish, greenish, or lead-colored talcose or silky schists (holding a mica, sometimes apparently damourite or sericite), in which are found layers of serpentine. The serpentine itself is generally scaly in texture and glassy, but granular varieties are met with including veins of epidote, others with altered crystals of olivine, and also ophicalcites. The gneisses beneath the serpentine zone pass into quartzose mica-schists, often including almond-shaped masses or segregations of quartz and feldspar, sometimes

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* Coquand. Bull. Soc. Géol. de France (3), vii.

† Dieulefait. Comptes Rendus de l'Acad. des Sciences, xci., p. 1000.

‡ Lotti, Appunti Geologici sulla Corsica; Boll. del Comitato Geologico, anno 1883, Nos. 3–4.

with large plates of mica. It would appear, from the descriptions of Lotti, that these serpentines of Corsica belong to the upper horizon defined by Gastaldi, above the recent gneisses, and in what we have designated as the fourth group of Alpine crystalline rocks. (§ 69.) The underlying protogine is, according to Lotti, a talcose gneiss.

§ 73. The resemblance of these rocks to those associated with similar serpentines on the neighboring island of Elba is declared by Lotti to be very close. There also the serpentinic horizon is underlaid by gneisses and mica-schists, as in Corsica. He concludes with Gastaldi that the great crystalline zone of the Alps is connected through the Maritime and Ligurian Alps with the similar rocks of Corsica and Elba. Resting upon the ophiolitic strata in Elba are found, according to Lotti, paleozoic carbonaceous slates containing *Orthoceras*, *Cardiola*, *Actinocrinus*, and probably also graptolites. Lotti, however, while he asserts the great antiquity of all of the serpentines of Corsica, and part of those of Elba, maintains the existence in the latter island of other serpentines, which, like those of Tuscany, he refers to the eocene period.

A similar question is raised with regard to the granites of the two islands. Thus Pareto, who regarded as ancient, or at any rate pre-triassic, the granites of Corsica, admitted for the granites of Elba, Monte Cristo, and Giglio a post-eocene age, a view which is also sustained by Lotti, while De Stefani, on the other hand, assigns the Elban granites to pre-triassic time. I can scarcely doubt that all of these granites, as well as the ophiolites both of the various islands and the mainland, will be found, as maintained by Gastaldi, of pre-paleozoic age.

§ 74. If we turn to the island of Sardinia we find a series of pre-Cambrian crystalline schists, said to consist, in their upper portions, of argillites, sometimes talcose, sandstones, crystalline limestones, and dolomites. These, which are referred by Bornemann to the Huronian or pietre-verdi zone of the Alps, are overlaid, as was first shown by De la Marmora, by a series of uncrystalline limestones, shales, and sandstones, containing an abundant lower paleozoic fauna.* Of this, the upper Cambrian (Ordovician)† forms were long since described by Meneghini. The subsequent studies of Bornemann, in 1880, showed at the base of the series a zone marked by *Paradoxides*, *Conocephalites*, *Archeocyathus*, etc., which have also been examined by Meneghini, and establish the existence of a Lower Cambrian horizon. The writer had, in 1881, the pleasure of examining at Bologna, in company with James Hall, a collection of these fossils. Above the Ordovician beds in Sardinia is found a great mass of limestone, of undetermined age, remarkable for its beds and included masses of lead, silver, and zinc-ores.

§ 75. We have now shown that these crystalline rocks, which, in parts of the mainland, are directly succeeded by tertiary sediments, are in different areas overlaid by various subdivisions of the mesozoic, and finally by carboniferous, Ordovician, and Cambrian sediments, thus disproving the view of the older geologists, who assigned to these same crystalline rocks a paleozoic or a mesozoic age. It is instructive to mark the steps by which this view has, in the process of investigation, been left behind. In Neri's section the older gneiss and the pietre verdi proper are called azoic or protozoic, but the recent gneiss is conjectured to be paleozoic. Lory, however, included the latter in the primitive series, but claimed the lustrous schists as altered trias, while later, Gastaldi, and with him Favre, placed even these in the paleozoic, until at last we find Gastaldi adopting the conclusion first put forward by the present writer in 1872, that the whole of these crystalline rocks are to be referred to pre-Cambrian time.

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* Bornemann, sur les formations stratifiées anciennes de la Sardaigne. Comptes Rendus du Congrès Géol. Inter. de Bologne, pp. 221–232.

† See *post*, Essay XI., § 17.

§ 76. The story of the crystalline marbles of Carrara, now included in this series, is not less instructive. They were regarded as eruptive by Savi, who taught that dolomites and limestones had been poured out in a fused state, alike in secondary and in tertiary times,* and even indicated what he supposed to be centres of eruption. The marbles of Carrara, with their associated schists, have since been called cretaceous, liassic, rhaetic, infra-carboniferous, and pre-paleozoic.† They were in 1874, in the second part of Gastaldi's *Studii*, included in the rocks of the pietre-verdi zone, the term being then used in its larger sense, as embracing not only the true pietre verdi, but the whole crystalline series above the ancient gneiss.

§ 77. This was also clearly stated by Jervis, in his elaborate work on the mineral resources of Italy,‡ a veritable treasury of information, most carefully and systematically arranged. In his first volume, in a tabular view of the geology of the Alps, he had already adopted the views of Gastaldi, and placed the whole of the crystalline stratified rocks above the ancient gneisses in a "pre-paleozoic group," which he regarded as synonymous with the pietre-verdi zone. In his second volume, in a similar tabular view of the geology of the Apennines and the adjacent islands, he further insists upon the same view, and puts above the ancient gneiss, in what he calls the pre-paleozoic period, the great series of "stratified azoic rocks," including not only the ophiolites, and the recent gneisses and other crystalline schists, but the saccharoidal and compact marbles of the Apuan Alps. (Loc. cit., p. 9.) It is to be remarked, as shown both by Jervis and Gastaldi, that this great younger crystalline series is the metalliferous

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* Boué, Guide du géologue voyageur, II., 168. For the views of others as to the eruptive origin of crystalline limestones, see my Chemical and Geological Essays, p. 218, and *ante*, pp. 90, 94, and 228.

† For a notice of some of the various views which have been put forward with regard to the age of these marbles, see Lebour in the Geological Magazine for 1876, pp. 287 and 383.

‡ I Tesori Sotteranei del' Italia, 3 vols. 8vo, Turin, 1878–1881.

zone of Italy, containing much cupriferous and niccoliferous pyrites, in veins and interstratified beds, together with crystalline iron-ores, lead, zinc, and gold.

§ 78. With the general succession of the Alpine rocks already given, we may compare the observations of Taramelli in the Valtelline, where he describes the ophiolites as lying below a great gneissic and granitic series, from which they are separated by a garnetiferous hornblendic rock and saccharoidal limestones. The lowest division in the series, as observed in the Valtelline, is, according to Taramelli, a quartzose talc-schist, upon which reposes the serpentine in heavy continuous beds, having all the appearance of a stratified rock, followed by potstone, that is to say, steatite or chlorite. To this succeed, in ascending order, hornblendic and epidotic rocks, associated with crystalline limestones, often talciferous; then schistose amphibolite, talcose gneiss, talc-schists, and eclogite, and finally a coarsely crystalline glandular gneiss, itself overlaid by granitic and associated hornblendic rocks. This apparent reversal of the succession as defined by Gastaldi and others, suggests the probability that we may have in the Valtelline an overturn of the strata, such as is well known in many parts of the Alps and elsewhere, placing the more ancient rocks above the younger ones.*

§ 79. It is here the place to notice the mode of occurrence of the serpentines which, in Saxony, are found interstratified in the granulite series of the Mittelgebirge. The granulite-proper may be described as a fine-grained, gray, laminated binary gneiss, consisting essentially of orthoclase and quartz, but often containing garnet, and sometimes cyanite and andalusite. By an admixture of mica, it passes, through ordinary gneiss, into mica-schists, which are abundant in the series. In it are also interstratified dichroite-gneiss, sometimes in great beds, and a greenish hornblendic gneiss, as well as the so-called gabbros of the region (like that of Neurode). These occur

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* Boll. Soc. Geologica Italiana, I., p. 14.

in larger or smaller lenticular interstratified masses, to which the distribution of the diallage in a granular labradorite base gives a well defined gneissoid structure. In this same series, the serpentine is found in interstratified beds, occasionally garnetiferous, and sometimes associated with lherzolite.

§ 80. I have not seen these rocks on the ground, but have examined a large collection of them in Leipzig, with the assistance of my friend, Dr. Hermann Credner, and was struck with their close resemblances to the rocks with which I am familiar in the newer or Montalban series of gneisses and mica-schists throughout the Atlantic belt of North America. The muscovite-gneisses of the Erzgebirge, with their occasional layers of limestone and of hornblende-rock, and their intercalated and overlying mica-schists, I also refer to the same general horizon. It is in these, it will be remembered, that are found the abundant conglomerate beds described by Sauer, the pebbles in which consist chiefly of varieties of granitoid gneiss, resembling closely those of the ancient gneiss of the Alps (Biellese) and the Laurentian gneiss of North America. These are, however, as I have seen, accompanied by pebbles of crystalline limestone.* Mention should also be made, in this connection, of the existence of similar conglomerates in Sweden, at Soljöarne, where pebbles of ancient gneiss and granite are found, at several points, imbedded in fine-grained schistose gneiss, in calcareous mica-schist, and also in a red hälleflinta, the strata of all of which are shown to rest unconformably upon the older granitoid gneiss.†

§ 81. It will be remembered by students in geology that in 1870 the present writer announced his conclusion that there exists in North America, besides the Laurentian gneisses, "a great series of crystalline schists, includ-

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* Zeitschrift f. d. ges. Naturwiss, Band liii.; also, Geol. Mag., January, 1882, and Bull. Soc. Géol. de Fr., x., 26; also, Amer. Jour. Science (3), xxvi., p. 197; and *ante*, p. 255.

† Hummel. Om Sveriges Lagrade Urberg, etc., Stockholm, 1875, p. 30.

ing mica-schists, staurolite, and chiastolite-schists, with quartzose and hornblendic rocks, and some limestones, the whole associated with great masses of fine-grained gneisses, the so-called granites of many parts of New England." * These rocks were especially indicated as occurring in the White Mountains of New Hampshire, but were also said to be found to the northwest of Lake Superior, as well as in Ontario and in Newfoundland, in which last two regions they were believed to rest unconformably upon the Laurentian gneiss. In both of these latter localities, there were provisionally associated with this group some higher limestones, with crystalline schists, and for the whole the name of Terranovan was suggested.

§ 82. In the following year, 1871, in an address before the American Association for the Advancement of Science, these rocks were farther noticed, under the name of the White Mountain series. The higher limestones and schists (which were not found on the geological section then described) were, however, excluded. This great series of younger gneisses and mica-schists was then assigned to a horizon above the Huronian, and as a distinctive name was desirable for a series so conspicuous in American geology, that of Montalban (from the latinized name of the White Mountains) was proposed in the same year.† It was at the same time shown that the view held by most American geologists, that these rocks were altered paleozoic strata, was untenable, and that they were to be regarded as pre-paleozoic. At a later period, the higher limestones and schists, at first associated with these newer gneisses and mica-schists, were referred to the Lower Taconic of Emmons — the Taconian series.‡

When, in 1870 and 1871, I thus attempted to subdivide

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* Amer. Jour. Science (3), 1, 85.

† Proc. Amer. Assoc. Adv. Science, 1871, p. 6; also Chem. and Geol. Essays, pp. 194, 244, 282; Das Ausland, Dec. 25, 1871, p. 1288, and Azoic Rocks, p. 181.

‡ Azoic Rocks, pp. 201–211, 215.

the crystalline schists above the ancient gneiss of North America, and to define, above the Huronian, a younger series of gneisses with mica-shists, I was not aware that Von Hauer had already been led by his studies to similar conclusions for the Eastern Alps, and had discovered above the great *pietre-verdi* zone, a series of gneisses with micaceous schists, as indicated in divisions 5 and 6 of his section (§ 60). Gastaldi, in 1871, and for years after, included these, with all the crystalline schists found above the ancient or central gneiss, in one great group of newer schists, which he assimilated to the Huronian. In reviewing this subject, in 1878,* I pointed out that the uppermost crystalline schists of the Western Alps should be separated from the Huronian, and compared them with the Taconian, while I noted the fact "that gneisses and mica-schists similar to those of the Montalban are found in many parts of the Alps." It was not, however, until after my studies among these rocks in 1881, that I referred the newer gneissic series of that region to the Montalban, for the two-fold reason that it occupies a similar stratigraphical horizon and is lithologically indistinguishable from it.

§ 83. Not less important in this connection is the succession of crystalline rocks in Eastern Bavaria, which may be compared with those of Saxony. We have, in ascending order, according to Gümbel, first, the red or variegated gneiss, called by him Bojian, which is followed immediately by the newer gray or Hercynian gneiss, his second division, and by a third, the Hercynian mica-schist series, occasionally hornblendic. To this succeeds, in the fourth place, the Hercynian primitive clay-slate series, which is immediately overlaid by Lower Cambrian fossiliferous rocks. This primitive clay-slate series contains interstratified beds of limestone, sometimes dolomitic, attaining in places a thickness of 350 feet, and associated with siderite, which gives rise by epigenesis to valuable

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* Azoic Rocks, p. 245.

deposits of limonite along its outcrop. With these limestones are found varieties of hornblende and serpentine, accompanying which is the *Eozoön Bavaricum* of Gümbel.

§ 84. The Hercynian gneiss is described by Gümbel as including much gray quartzose and micaceous gneiss, with frequent beds of dichroite-gneiss, granulite, serpentine, hornblendic schists, and crystalline limestones. With these are associated *Eozoön Canadense*, from which Gümbel supposed this upper gneissic series to represent the Laurentian, a view which was accepted by the present writer, when, in 1866, he translated and edited Gümbel's paper* for the *Canadian Naturalist*, and has since been expressed by him elsewhere; coupled with the suggestion that the Bojian might correspond to the Ottawa gneiss which underlies the Grenville series, the typical Laurentian (Lower Laurentian) of the Canadian survey. We are not, however, as yet prepared to recognize a subdivision in the older gneisses of continental Europe, and meanwhile the analogies between the great Hercynian gneiss and mica-schist series combined, and the younger gneisses and mica-schists of Saxony and of the Alps, lead us to refer what Gümbel has described as the newer gneiss series of Bodenmais and the Danube, to the same horizon as the younger gneisses of Gastaldi and Von Hauer,—the Montalban series, which in eastern Bavaria would seem, as in the Simplon, to rest directly upon the older gneiss, the Huronian being absent. The Hercynian clay-slate series, with its crystalline limestones, may correspond to the fourth group of the Alpine rocks, the argillo-talcose schists, which we have compared with the American Taconian.

V. — THE SERPENTINES OF ITALY.

§ 85. Returning to the Italian Alps, we have now to call attention to a very important conclusion reached by

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* Gümbel, Über der Vorkommen von Eozoon in dem Ostbayerischen Urgebirge, München Akad. Sitzungsb., 1866 (1), pp. 25–70; also Can. Naturalist, iii., 1868, pp. 81–101.

Gastaldi, with regard to the geographical relations of the pietre-verdi zone; using the term in its larger sense, as embracing all the newer crystalline rocks, or those above the ancient gneiss. In 1871, in the first part of his memoir on the Western Alps, he declared it as his opinion that "all the serpentinic masses of the Tuscan and Ligurian Apennines, and the serpentines, ophicalcites, saccharoidal limestones and granites of Calabria, are but a prolongation of this zone." In this were included, as we have already seen, the Apuan Alps, and, farther westward, a large part of the Maritime Alps. In support of these views he pointed out the mineralogical identity of the ophiolites and other crystalline rocks in the Alps and the Apennines. To the same horizon he also referred the so-called ophitic terrane of the Pyrennees.

§ 86. Gastaldi further called attention to the fact that ophiolitic rocks often appear in the form of isolated peaks or hills, for the reason that the accompanying crystalline schists and calcareous rocks, opposing less resistance, have been removed by decay and erosion, adducing many instances in support of this among the Alps. This being the case, he adds, we are not to be surprised when in the Apennines we find isolated masses of ophiolite rising out of the midst of surrounding jurassic, cretaceous, or tertiary strata, which conceal the rocks that accompany the ophiolite. Thus it is, he adds, that "the notion has arisen in the Apennines that the serpentines, diorites, etc., are always eruptive rocks." They are, in his view, to make use of the happy expression of Roland Irving in describing a similar occurrence, "protruding, but not extruded." These views were reiterated by Gastaldi in his letter to Zezi in 1876, when he asserted that the skeleton of the Apennines is a continuation of that of the Alps, and that the crystalline rocks of the Apennines are Alpine rocks. From the summit of Mont Blanc, he declared, they may be followed, more or less concealed by overlying strata of more recent date, to the Danube, to the plains of France, to the Mediterranean, and along the peninsula which separates this sea from the Adriatic;* assertions which he supported in 1878 by many detailed observations, to be noticed farther on.

§ 87. These bold generalizations of Gastaldi have met with but partial acceptance in Italy, as may be seen by the discussions in 1881, and the publications of the R. Comitato Geologico and the Società Geologica Italiana in 1881 and 1882, already referred to in § 43. Pellati, in his summary, declares that the views of Gastaldi as to the antiquity of the Alpine *pietre verdi* are confirmed by the work of Baretti and of Taramelli, the latter of whom clearly shows that the view, entertained by so many, that these rocks are carboniferous or triassic, is inadmissible. Hence, these ancient serpentines are by Pellati designated as prepaleozoic (eozoic). This view he extends to all the ophiolitic masses situated in the Alps, to those of Calabria, and also to those of the Apennines west of the meridian of Genoa, those to the east of this meridian being included in the eocene. (§ 47.)

§ 88. Regarding the so-called eocene serpentine, and its associated rocks, Pellati observes, "as to its composition, it differs but little from the older serpentine, the differences remarked being principally in a structure ordinarily less schistose, and in a greater frequency of subordinate ophiolitic rocks; euphotides, eurites, diorites, variolites, ophicalcites, etc., more or less decomposed. The masses of proper serpentine are ordinarily more scattered, and of smaller dimensions, having almost always gabbros and beds of phthanite and jasper around them." Cossa, it is true, has remarked in the specimens examined by him that the mineral species bastite is more common in the eocene, or Apennine, than in the eozoic, or Alpine, serpentines, but, with this possible exception, the mineralogical and lithological associations of the two are apparently identical. In fact, Pellati admits that it is in some cases

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* See the author, on Azoic Rocks, p. 245.

difficult, if not impossible, to distinguish between them. Within the great basin lying to the east of the meridian of Genoa, and embracing, as we have seen, the so-called tertiary serpentines, we are informed by him that "the paleozoic and mesozoic rocks are generally very thin, and often are entirely absent, in which case the floor of *pietre verdi*, or greenstones, is directly overlaid by the tertiary, and in fact by the very eocene which includes the younger serpentines. This is the case in the vicinity of Genoa, upon the right bank of the Polcevera, where the greenstones come in direct contact with the shales and the limestones of the upper eocene, and here it becomes doubtful whether, along this line of outcrop, portions of tertiary ophiolites are not mixed and confounded with others of the pre-paleozoic period." These supposed tertiary ophiolites "have a very great resemblance to those of the eocene of eastern Liguria, and present, moreover, a large development of the rocks which Issel has designated as amphimorphic (§ 92). Thus, near Pietra Lavezzara, for example, ophicalcites are exploited which are precisely like the green marbles of Levanto. In this same locality, moreover, argillites having the aspect of those of the eocene appear to dip beneath the ophiolites." In support of the belief that these seemingly tertiary ophiolites are really eozoic, however, we are told that their outcrops present lines of continuity, connecting these serpentines with those of which the eozoic origin is undoubted. We have seen (§ 41) that Professor Bonney, in his studies of the serpentines of Italy, fails to remark any distinction between the serpentines thus separated by the Italian geologists, since he describes as similar, both in mineralogical characters and in geognostical relations, the ophiolites lying to the west and those lying to the east of the meridian of Genoa. I shall, farther on, have occasion to refer to my own observations of some of these localities.

§ 89. The older school of Italian geologists, as already noticed, supposed the serpentines to have been erupted, like basalts, at different geological periods, and applied this view, not only to those which are evidently included among eozoic rocks, but also to those which rise among the tertiary deposits. The study of the ophiolitic masses of eastern Liguria and of Tuscany, induced the earlier geologists, like Savi, Pilla, and Pareto, to refer them to various ages between the cretaceous and the pliocene, but more recent observers have been led to include all of these ophiolites in the upper eocene. This view was first advanced for those of the mainland of Tuscany by De Stefani, in 1878, and has since been maintained by Lotti, Taramelli, Issel, Mazzuoli, and Capacci, among others. The horizon in the upper eocene to which these observers refer the serpentines in question, consists of argillaceous and marly shales, alternating with beds of limestone and sandstone, and is below the argillaceous limestones with fucoids and nemertilites, but above the sandstone known as macigno, which is found at the base of the eocene in Liguria.

§ 90. As regards the origin of serpentines, Pellati remarks that the recent studies of Italian geologists have led to hypotheses which differ widely from those formerly received, according to which serpentines were regarded as plutonic or eruptive, having come to the surface after the manner of volcanic lavas, or, at least, like certain massive trachytes, in a pasty state, or one of igneous semifluidity. Gastaldi, he adds, "from his studies of the ancient serpentines of the Alps, regarded them, however, as sedimentary rocks, modified by subsequent hydrothermal actions operating at great depths in the earth." He compared their formation to that of the accompanying gneisses, mica-schists, chlorite-schists, crystalline limestones, diorites, and even the granites, syenites, and porphyries of the Alps, to all of which he ascribed an aqueous origin.

§ 91. This hypothesis has not, however, been favorably received as an explanation of the origin of the so-called tertiary ophiolites of the Tuscan and Ligurian Apennines. Taramelli, from his studies of the serpentines of the valley of the Trebbia, declared that neither the above mentioned view of their igneous eruptive origin, nor that maintained by Gastaldi, could be conciliated with the facts of the stratiform and lenticular arrangement of the masses of serpentine, the want of evidences of alteration in the interstratified layers of limestones and argillites, and the absence of ophiolitic dikes in these same rocks. He was thus led to conclude that the ophiolites had been formed in the midst of the tertiary sediments by contemporaneous submarine eruptions of magnesian and feldspathic magmas, and that the euphotides and other associated ophiolitic rocks had probably resulted from subsequent crystallogenic concentrations, which took place in these erupted magmas. Capacci, from his investigation of the ophiolitic mass of Monteferrato in Prato, advanced a similar view, supplemented by the hypothesis of thermal waters accompanying the eruption of the magnesian magma or succeeding it.

§ 92. Issel and Mazzuoli, from their joint studies in eastern Liguria, have formulated, more at length, an analogous hypothesis to explain alike the origin of the serpentines, and of the rocks there intimately associated with them, such as diorites, aphanites, variolites, and euphotides. To these, they give the general designation of amphimorphic rocks, suggested by the conception that they have had a two-fold origin, and have resulted from mixtures and combinations of slowly deposited argillaceous materials of mechanical origin with elements brought in by abundant thermal springs through a long period, both during and after the eruption of the serpentinous magma. This latter, they suppose, was a phenomenon of short duration, almost instantaneous, while the formation of the euphotides and other amphimorphic rocks was a slow process. Nor is this the only effect ascribed to the hypothetical thermal springs, which our authors suppose to have acted upon pre-existing continuous calcareous and argillaceous strata, penetrating them with waters holding in solution silica and oxyds of iron and manganese, and converting them to jaspers, phthanites, or silicious slates, or to certain ill defined silico-argillaceous or calcareous rocks which Issel has called hypophthanites.

§ 93. The serpentines themselves having nothing in common with the argillites, sandstones, and limestones among which they are found, these observers have imagined that, after the deposition of the eocene sandstone, great eruptions of a hot impalpable mud, consisting principally of silicates of magnesia and iron generated by some unexplained process, were poured out from submarine fissures in the earth's crust, were spread over the bottom of the sea, filling depressions therein, and were subsequently changed into serpentine. Thus, by this hypothesis, "the serpentines are considered as eruptive without being truly igneous, inasmuch as they do not contain in their composition any mineral which has been submitted to igneous fusion, and do not show, at their contact with the sediments adjoining, any metamorphic product due to a very elevated temperature. In order, however, to explain the slight traces of contact-metamorphism which are especially seen in enclosed masses of limestones, they admit that at the moment of its emission the magma may have had a temperature of several hundred degrees. As to the ophicalcites, which are often found at the contact of the serpentine with the sedimentary rocks, and sometimes even at a certain distance from these, their formation is attributed to the cementation of serpentine breccias by calcareous waters discharged in the last phase of the eruptive period."

§ 94. Pellati sets forth, with wise caution, the preceding hypothesis as the one suggested by the observers already named for the Apennine ophiolites, and adds that it might perhaps be also extended to the ophiolites of admitted eozoic age, which, he says, "so far as we know at present, consist essentially of rocks of the same nature and the same composition." He insists, moreover, upon farther researches, even in the case of the supposed eocene serpentines, and upon the importance of discovering the centres of eruption through the pre-existing strata, "or, at least, some positive evidence of such centres."

§ 95. I have thought it desirable to reproduce with some detail this ingenious hypothesis, with Pellati's comments thereon, for the reason that it shows clearly the difficulties which recent observers have found in accepting the older theory of the igneous eruption of ophiolites, and, moreover, brings clearly into view many points which are of importance for the solution of the problem before us of the true relations of these ophiolites to the surrounding strata. In view of the fact that the resemblance between the supposed eocenic and the eozoic ophiolites is so strong that the two cannot be clearly distinguished or separated from one another, — as we have seen alike from the comparisons of Bonney and the admissions of the recent Italian geologists themselves (§ 88), it is not surprising that some observers, like Gastaldi, should have been led to look upon the so-called eocene ophiolites as nothing more than portions of the underlying eozoic or pre-paleozoic series exposed through geological accidents. This explanation becomes more plausible when we reflect that within the great basin over which these ophiolites are met with, the paleozoic and mesozoic rocks have but a slight development, and are often entirely wanting, the tertiary rocks resting directly upon the eozoic pietre verdi.

§ 96. My own observations of the Italian ophiolites have been limited. I have had, however, an opportunity of examining two localities of these so-called eocene serpentines, in eastern Liguria and in Tuscany. It was my good fortune, in October, 1881, to spend a day with Signor Capacci (whose careful memoir on the region, with map and sections, I have already noticed), in going over Monteferrato in Prato, near Florence, a locality for centuries famous for its quarries of serpentine, known as *verde-prato.* About three miles from Prato, a town on the railway between Florence and Pistoia, is the little village of Figline, which lies on the eastern slope of the ophiolitic mass in question, forming a hill which rises boldly from the plain of eocene limestone and shales (alberese and galestro). The mass of ophiolitic rocks occupies an area somewhat oval in form, having, according to the determinations of Capacci, a length of about 2600 metres from north to south, and a maximum breadth of about 1800 metres. In its highest points it attains elevations of 400 and 426 metres above the sea, the level of the surrounding plain being about 70 metres. Figline itself, where the serpentine appears from beneath the eocene strata lying to the east, is at a level of 103 metres, but the similar strata on the western side of the hill, where they apparently dip at high angles beneath the serpentine-mass, rise to heights of 295 and 322 metres above the sea-level.

§ 97. Underlying the alberese, and resting upon the ophiolite along the eastern base of the hill, is seen in many places a fine-grained, laminated, silicious rock, generally reddish, but sometimes greenish or grayish in color, designated as phthanite by the Italian geologists, which abounds in microscopic forms referred by Bonney in part to polycystinae and in part to polyzoa.* This is succeeded, in apparent conformity, by the ordinary type of eocene limestones and shales, which, in some places, however,

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* Upon the organic forms found in these and similar silicious or jaspery beds, see a memoir by Prof. Dante Pantanelli on the jaspers of Tuscany and their fossils (I Diaspri della Toscana, ecc. Mem. R. Accad. dei Lincei, ser. 3, vol. viii., June, 1880; also Geol. Mag. for the same year, pp. 317, 564). These deposits are found alike at various horizons in the upper eocene, and in cretaceous and liassic strata, often in thin layers imbedded in argillaceous sediments. They consist in part of crystalline and in part of amorphous silica, with oxyds of iron and manganese, and contain large numbers of radiolarian forms, of many species, leading the author to conclude with De Stefani that they are deep-sea deposits.

rest directly upon the ophiolite, or with the intervention only of a layer of comminuted serpentine described by Capacci as an ophiolitic sand (*arenaria ofiolitica*). These overlying strata have a general inclination from the serpentine, that is to say to the eastward, of from 20° to 70°, but in some sections, as to the east and northeast of Figline, are represented in Capacci's sections as nearly horizontal, with small undulations exposing in valleys the phthanite, and even the serpentine, beneath the alberese.

§ 98. On the western side of the hill, where, as already said, these eocene strata appear nearly up to the summit, and plunge beneath the ophiolite, their inclination, as seen along the southwest border, is from 54° to 64° to the northeast. Here is observed a significant fact, which is shown in the sections of Capacci, — namely, that the previously noted relations of the serpentine, phthanite, and alberese are reversed. While on the eastern slope these three rocks appear in the ascending order just named, we find on the opposite flank of the hill, in the ascending section, alberese, phthanite, and serpentine; — the serpentine overlying the phthanite, and the latter the alberese. The natural and obvious interpretation of these facts is that we have here simply an inversion of the natural order, resulting from an overturn of the strata on the western side of the hill.

§ 99. The ophiolitic mass itself is not simple, but, as described and figured by Capacci, is essentially composed of two layers of serpentine, with an intercalated lens of euphotide. Besides this rock, which has been the object of repeated studies, the last by Cossa, this lithologist has described associated masses of diabase, while Capacci has observed others of dioritic rocks, including a green variety distinguished as gabbro-verde, sometimes becoming variolitic, as well as the so-called gabbro-rosso, which, as there seen, is an iron-stained, somewhat calcareous dioritic rock, concretionary in structure, and apparently in a decomposing state (§ 40).

§ 100. Capacci's view of the relations of these various rocks to one another, and to the accompanying eocene strata, is in accordance with the hypothesis already set forth (§ 93). He regards the ophiolite of Monteferrato as a great lenticular or almond-shaped mass (*un'amigdala ofiolitica*), "intercalated, in perfect concordance of stratification, among the strata of alberese and galestro of the eocene formation," which have been subsequently tilted, so as to give to the whole series an eastward inclination. In accordance with this conception, he supposes that, at a certain time during the accumulation of the eocene strata, there came, from a rupture in the earth's crust, a sudden effusion of an aqueous magnesian magna, which was spread out beneath the sea, and was subsequently overlaid by a continuation of the eocene beds, as before. The silicious sediment constituting the phthanite which, on the west side, is seen to underlie the ophiolite is, in this view, a portion of previously deposited and altered shale, while the phthanite on the east side is another portion of a similar sediment, subsequently laid down upon the ophiolite.

§ 101. The ophiolitic mass is thus, like all the other serpentines of Tuscany, of eocene age. The various rocks which enter into its constitution appear in the form of "lenticular masses or almond-shaped concentrations," of which the euphotide and the gabbros are examples. The gabbro-rosso is found in masses at the contact of the ophiolite with the phthanite, and results from the alteration of a diabasic rock by the action of thermal waters. These have also changed the galestro into the phthanite, found both above and below the ophiolites, and in perfect conformity with the adjacent eocene strata, "which have all their distinctive characters, and present no traces of alteration or of metamorphism," "the action which produced the phthanites being local, particular, and variable." Recomposed rocks, made up of grains and fragments of serpentine, in a cement generally calcareous, are found on the confines of the serpentine and at its contact with the phthanite. This is especially seen at Poggio, on the southeast side of the hill, where I found a veritable conglomerate of fragments of serpentine imbedded in a paste of silicious slate. These facts, as well remarked by Capacci, show that previous to the deposition of these eocene beds, the serpentine-mass along the shores of a shallow sea was subjected to a process of disintegration; "and that, moreover, the formation of a serpentine corresponds to a kind of pause in the deposition of the eocene strata." The ophicalcites, in like manner, are found at the limits of the serpentine, and are breccias or conglomerates with a calcareous cement.

§ 102. I have thus given, in great measure in language translated from Capacci's memoir, the principal facts observed at Monteferrato, which I have, for the most part, verified. They, however, appear to me inconsistent with the hypothesis propounded by the modern school of Italian geologists, and with the eocene age of the ophiolitic mass in question. The effusion of a great mass of aqueous material from the earth's interior into the eocene sea, its subsequent arrangement and crystallization into mountain-masses of euphotide, diorite, and serpentine, the elevation of these, and their subsequent disintegration to form the ophiolitic sands and conglomerates already described, mark a geological period, and a revolution which ought to have left some traces in the surrounding eocene deposits. These, however, we are to believe, in accordance with the proposed hypothesis, continued after this event to be laid down precisely as before,—the alberese and the galestro previous and subsequent to the ophiolite making with this one conformable series. This process, moreover, we are told, was here confined to an area whose greatest extent was less than three kilometres, and was repeated at a great number of localities in the Italian tertiary basin, in all cases giving rise, not, as in ordinary eruptions, to a single kind of rock, but to a group of different rocks, indistinguishable in character from those which are known to be found in contiguous regions interstratified in crystalline schists of eozoic age.

§ 103. The only explanation which seems to me admissible, and one which is in complete harmony with the facts, is that this area of serpentine, with its associated euphotides, etc., was an eroded and uncovered mass in the midst of the eocene sea; that around its base was deposited the disintegrated material which forms the ophiolitic sands and conglomerates, followed by the silicious sediments which make up the phthanite, and by the limestones and shales of the middle eocene. The subsequent movements of the earth's crust, which caused the folding of these strata together with the intruding mass of eozoic rock upon and around which they were deposited, has resulted in the production of an overturned synclinal on the western side of the hill.

§ 104. As I have elsewhere insisted,* in cases like the present, where newer strata are found in unconformable superposition to older ones, the effect of lateral movements of compression involving the two series, is frequently to cause the newer and more yielding strata, along their border, to dip towards or beneath the older rock. These overlying strata, where they abut against their marginal limit, which was the ancient shore-line, will, in the conditions supposed, assume, according to local circumstances, either an anticlinal or a synclinal form. In the former case, the inclination of the strata towards the older mass, which forms a resisting barrier, follows necessarily, even though the elevation of the arch be slight. In the case of a synclinal fold or inverted arch, we have the strata dipping away from the older rock at a greater or less angle, as seen at the eastern base of Monteferrato, — the strata appearing in their natural order of superposition. When, as is frequently the case, this inclination passes beyond the vertical, giving rise to

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* Geological Magazine (January, 1882), ix., 39.

an overturned synclinal, the same strata will appear to pass in reversed order beneath the overhanging mass of older rock, as along the western border of Monteferrato. It is hardly necessary to recall the fact that sharp or inverted folds, whether synclinal or anticlinal, are often attended with dislocations and vertical displacements. It may seem superfluous to insist upon these obvious principles of geological dynamics, but I have had occasion to notice that they are sometimes overlooked or misunderstood even by teachers of the science to-day.

§ 105. Professor Bonney, who, as we have seen, holds to the igneous origin of ophiolites, finds in the manner in which portions of the stratified silicious rock rest upon the serpentine near Figline what he regards as a "complete proof" of the eruptive nature of the serpentine, placing "the intrusive character of the latter beyond all doubt," while he is also satisfied that the great mass of euphotide (included by him under the name of gabbro) is "intrusive in the serpentine."* Whatever view may be held of the origin of these two rocks and their relations to one another, the occurrence of the layers of recomposed ophiolitic rock (*arenaria ofiolitica* and *conglomerato ofiolitico*) interposed, as already described, between the ophiolitic mass and the beds of phthanite, and even, as I observed in one section along the southeast base of the hill, the presence of fragments of serpentine in the latter, forces us to the conclusion that these sedimentary strata were deposited upon the ophiolite, so that the theory of the eruption of the latter since the deposition of the eocene beds is untenable.

§ 106. The examinations which I have been able to make of the ophiolitic rocks of Eastern Liguria, where I spent a little time near Sestri Levante, under the guidance of Prof. G. Uzielli of Turin, were such as to leave no doubt in my mind that we have here, as maintained by Gastaldi, portions of an ancient stratified series rising out

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* Geol. Magazine, August, 1879, vol. vi., p. 362.

of the overlying eocene. In addition to the varieties of serpentine, and of euphotides, diorites, diabases (the amphimorphic rocks of Issel and Mazzuoli), we find eurites, jaspers, epidotic and steatitic rocks, with occasional limestones, and various types of argillites, including the hypophthanites of these authors. The whole series, including its masses of pyrites, more or less cupriferous and niccoliferous, presents a close resemblance to the group of strata accompanying the serpentine of the Huronian series in Eastern Canada, with which I have long been familiar. These rocks are well seen along the valley of the Acquafredda — near which I found, in an eocene limestone, grains of the underlying serpentine, as also evidences of a considerable dislocation since the deposition of the eocene strata. My observations at this point served to strengthen my conviction that the ophiolite of Monteferrato is also but a small protruding mass of the same series. I was enabled, subsequently, as already noticed (§ 54), to examine with Signor Quintino Sella a portion of the ophiolitic series of admitted eozoic age, as seen in the Biellese, in the province of Novara, and to confirm the judgments of Gastaldi, Cossa, Bonney, and others, as to the apparent identity of these ancient ophiolites with those found in Eastern Liguria.

§ 107. We have already described, in §§ 22, 23, the mass of eozoic serpentine which in Staten Island, New York, rises from out of the horizontal or gently inclined cretaceous and triassic strata that have been deposited around its base. If now we conceive this region to be subjected to such movements as those which, along the eozoic belt a little farther south, have compressed the Primal and Auroral strata against the northwest base of the South Mountain, and given them a southeast dip, we should have a phenomenon not unlike that presented by Monteferrato; that is to say, a lenticular mass of ancient serpentine rising along the outcrop of southeastward dipping mesozoic rocks, and differing only by the accidental circumstance that these, on the two sides, belong to different mesozoic horizons.

VI. — THE GENESIS OF SERPENTINES.

§ 108. As regards the origin of the serpentine-rocks, we have already noticed briefly some of the hypotheses which have been proposed. Although those which suppose them derived by metasomatic changes from aluminous or calcareous rocks, either exotic or indigenous, such as granites, diabases, granulites, or limestones, may be considered as now nearly obsolete, it may not be amiss to recall the fact that they represent two distinct and opposite schools, which agree only in admitting an unlimited alteration or change of substance in previously formed rocks, through aqueous agencies. The first view, which may be described as a general metasomatic hypothesis adapted to plutonism, is that which derives not only serpentine but limestone from ordinary types of feldspathic rocks, such as granites, granulites, gneisses, diabases, and diorites. The integral conversion of all of these into serpentine by the complete elimination of the alumina, alkalies, and lime, and the replacement of these bases by magnesia, have been maintained by many writers of repute belonging to the school in question.*

§ 109. Others still have supposed that the same rocks might be changed into limestone, by a complete removal of the silica, also, and the substitution of carbonate of lime. This extreme view has found its boldest and most consistent advocates in Messrs. King and Rowney, who

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* Bonney, who maintains the origin of serpentines by the hydration of eruptive chrysolite rocks, has, in his paper already cited, given many reasons for rejecting the notion of the formation of serpentines by metasomatosis from the basic feldspathic rocks so often associated therewith. The observed relations of the two are, in his opinion, wholly opposed to this view, and he insists upon the difficulty of conceiving that such a process of change should be limited to certain parts of a great mass, while leaving adjacent portions unaltered. From their distinctness, he is even led to the conclusion that the serpentines and their accompanying euphotides and diorites belong to successive periods of eruption.

not only assert this origin for the limestone-masses found in the gneisses of Sweden and the Hebrides, but imagine that the bedded crystalline limestones, many hundred feet in thickness, which are interstratified in the Laurentian gneissic series of North America, and have been traced in continuous lines of outcrop for hundreds of miles, have resulted from such an entire transformation of corresponding portions of the granitic, gneissic, and pyroxenic rocks of the series.* These very ingenious writers further imagine that serpentine also, — to which they assign, in accordance with the received views of this school, an origin, by metasomatosis (or, as they call it, methylosis), from dolerite, melaphyre, diorite, euphotide, and other supposed plutonic rocks, — is itself subject to a similar change into limestone. The existence of ophicalcites, the presence of masses of serpentine, and of such serpentinic structures as *Eozoön Canadense*, in limestone, are but so many evidences to them of a still uncompleted conversion of serpentine into limestone.

§ 110. Opposed to this view of the genesis of serpentines and limestones by change of substance, from plutonic rocks, is that which may be described as a general metasomatic theory adapted to neptunism, and which, recognizing the aqueous and sedimentary origin of limestone, would derive from it, by alteration, not only serpentine, but the various other silicated rocks mentioned above. Illustrations of this are seen in the supposed conversion of limestone into dolomite, and of this last into serpentine, both of which views have found many advocates. The probable change of limestone into granite and into gneiss, was suggested by Bischof, and Pumpelly subsequently, in 1873, proposed to explain the genesis of the bedded petrosilex-porphyries or hälleflintas of Missouri by the transmutation of a stratified limestone, of which por-

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* See, for a discussion of the views of this school, the author's Chem. and Geol. Essays, pp. 324–325; also, An Old Chapter of the Geological Record, by King and Rowney, 1881, chapters vii. and xii.

tions are found interlaminated with the petrosilex.[*] He, at the same time, suggested a similar origin for the hematitic iron-ore which accompanies these porphyries.

§ 111. With this second hypothesis of the origin of serpentines may be mentioned another, not, however, involving metasomatosis, which has sometimes been discussed, and which was suggested by the present writer in 1857, from the results of certain experiments on the artificial formation of silicates of lime and magnesia by the reaction between carbonates of these bases and free silica in presence of heated solutions of alkaline carbonates. Such a reaction is not without its significance, and, as I have elsewhere shown, has doubtless played a part in the local development of protoxyd-silicates in sediments in the vicinity of igneous rocks and of thermal alkaline waters; but as an explanation of the genesis of great masses of comparatively pure silicates, such as chrysolite, serpentine, and steatite, it is obviously inadequate, and was abandoned by the writer in 1860 for the view maintained below.[†] Even if we could suppose the presence of sedimentary beds containing the requisite elements in proper proportions, it can be shown that the reactions required for the production of silicates were inoperative in the very regions where serpentine and steatite are found, since side by side with beds of these there are met with, in many places, beds of dolomite and of magnesite intimately mixed with quartz, sufficient in amount, if combined, to convert the accompanying carbonates into corresponding silicates.

§ 112. There remain, then, to explain the origin of serpentine, besides the three hypotheses just noticed, three others already mentioned, to which we must again refer. First of these, we have that which supposes the material of serpentine to have come from the earth's interior as an

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[*] Geological Survey of Missouri, Iron ores, etc., pp. 25-27; also the author, on Azoic Rocks, p. 194, and *ante*, p. 103.

[†] Chemical and Geological Essays, pp. 25, 297, 300.

igneous fused mass consisting essentially of chrysolite, which by subsequent hydration has been changed into serpentine. This strictly plutonic hypothesis being, however, by many geologists held to be incompatible with observed facts in the geognosy of serpentine, one which has been called hydroplutonic, and has already been set forth at length in these pages, has found advocates. These, conceding that the geognostical relations of serpentine require us to admit that it was laid down from water, have conjectured that a material so unlike that of ordinary aqueous sediments was ejected from the earth's interior, not in a state of igneous fluidity, but as an aqueous magma or mud, consisting essentially of a hydrous silicate of magnesia, which subsequently consolidated into serpentine, and even into chrysolite and enstatite. This view, as we have seen, is maintained by a school of Italian geologists, and Daubrée, while holding to the origin of serpentine by the hydration of a plutonic chrysolite-rock, supposes this to have passed into a hydrous condition before its ejection.*

§ 113. There are, however, no facts in the history of vulcanism to justify this strange hypothesis of an erupted magnesian mud. The materials known to us as volcanic muds and ashes do not differ essentially, as regards their constituent chemical elements, from other detrital matters, and the origin of this conjecture may perhaps be traced to the unfounded assumption that chrysolite is peculiarly a plutonic mineral, and that rocks in which it and other magnesian silicates predominate are presumably plutonic in their origin. It is at best but a survival of the belief in a subterranean providence, which could send forth at pleasure from its reservoirs alike granite and basalt, chrysolite-rock and limestone, quartz-rock and magnetite. A rational science, however, seeks in the operation of natural causes for the origin of these various and unlike mineral masses, and endeavors to explain their production

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* Géologie Experimentale, p. 542.

in accordance with known chemical and physical laws. Enlightened geologists are now agreed as to the aqueous origin of limestones, of dolomites, of iron-oxyds, and of quartz, by processes which are intelligible to every chemist, and the formation in the humid way of the native silicates of magnesia is equally simple and intelligible.

§ 114. It was, as already set forth in these pages, after a careful study of natural mineral-waters and sediments, and of the chemistry of artificial magnesian silicates, that the present writer, in 1860, ventured to assert the aqueous origin of the masses of native magnesian silicates, and their formation by reactions between the soluble silicates of lime and alkalies from decaying rocks and the magnesian salts of natural waters.* This view, although adopted by Delesse, as we have shown in § 11, and also, soon after, by Gümbel, by Credner, and by Favre,† has not found general recognition. I have, however, to record the recent adhesion to it of Dieulefait, the eminent chemist and geologist of Marseilles, whose arduous and original studies have already placed him in the front rank of students in terrestrial chemistry; and also of Stapff, the learned and acute geologist of the St. Gothard tunnel.

§ 115. The conclusions of Dieulefait, as to the sedimentary character of the serpentines of Corsica, have already been mentioned (§ 71). He rejects the plutonic hypothesis of the origin of serpentines, for the following reasons: The frequent alternation of very thin beds of serpentine with others of schists and of limestone equally thin; the changes in the constitution and composition of the serpentinic layers; these, being in one place pure serpentine, become gradually mingled with carbonate of lime, which at length constitutes a large proportion of the rock, and also forms lenticular masses in the midst of the calcareous serpentines. To all these, which are common to the serpentines of North America, we may add, as noted else-

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* Hunt, Chem. and Geol. Essays, pp. 122, 296, 317.

† Ibid. pp. 304, 305, 347.

where, the frequent occurrence of grains, nodules, layers, or lenticular masses of serpentine in beds of crystalline limestone. Dieulefait notes, moreover, the absence of any signs of igneous action at the contact between the serpentines and the underlying schists. He next adverts to the hydroplutonic hypothesis, and pertinently asks on what grounds we are authorized to suppose the ejection of muds of magnesian silicate from the earth's interior.

§ 116. His own conclusion is that, while these serpentines are sedimentary rocks in the most complete acceptation of the term, the mud or sediment which gave rise to them was not ejected from below, but was formed in estuaries of the sea, by reactions between the silicious matters derived from the decay of pre-existing rocks and the magnesian salts of the sea-water; in which connection he insists upon the frequent metalliferous impregnations of the serpentines, as derived in like manner from the older rocks. This view of Dieulefait's, set forth in 1880,* is, as Lotti remarks, no other than "the hypothesis enunciated by Sterry Hunt," twenty years earlier.† Lotti, for his

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* Comptes Rendus de l'Acad. des Sciences, xci., 1000.

[† This has since been clearly stated by Dieulefait himself, in a recent elaborate memoir on "Les Roches Ophitiques des Pyrennées," the result of a scientific mission confided to him in 1880 by the Minister of Public Instruction in France (Ann. des Sciences Géologiques, 1885, xvi.). Therein, using the word ophite as synonymous with the term ophiolite, employed in these pages to designate not only serpentine, but its associated euphotides, diabases, diorites, etc., he writes: "The whole of the reasoning, and the facts already resumed, lead to the conclusion that the ophitic and serpentinous rocks are of sedimentary origin; they have come into the condition in which we now see them entirely through the influence of chemical reactions in the wet way, and without ever having suffered the action of heat from without. . . . Following this conclusion, I consider it my duty to explicitly formulate the following declaration: In France, an honored veteran in geology, Virlet d'Aoust, first enunciated for the Pyrennees the view that the ophitic rocks are of sedimentary origin. This opinion was soon after accepted by a geologist of great merit, Garrigou, to whom France has not sufficiently rendered justice. But the philosopher who first set forth the question of the sedimentary origin of the ophites in all its bearings, is the illustrious chemist and geologist of Canada, Sterry Hunt. When, in a time which I hope is not far off, the part, while still reserving himself on the question of the supposed tertiary serpentines of Italy, adds, after his own studies of those of Corsica: "In any case, it is impossible, as Dieulefait has said, to regard the phenomena offered by these ancient serpentines as due to eruptions, either of igneous or hydroplutonic magmas. The serpentine has either been deposited as such, as maintained by Sterry Hunt, and by Dieulefait, or is a sedimentary rock subsequently altered."* We shall notice later on the views of Stapff on this subject.

§ 117. The masses of rock known as serpentine are far from homogeneous in composition. Apart from the admixtures of carbonate of lime, dolomite, and magnesian carbonate, which often enter into their composition, they occasionally include, besides the hydrated silicate, serpentine, the anhydrous species, chrysolite and enstatite or bronzite, and more rarely the hydrous species, talc; silicates differing widely in density, in chemical stability, and in the oxygen-ratios between the silica and the fixed bases; that for chrysolite being 1:1, for enstatite 2:1, for talc, approximately, 3:1, and for serpentine 4:3. These differences, in the hypothesis of the aqueous origin of serpentine, may well depend upon variations in the composition of the generating soluble silicates, and upon the balance of affinities between silicic and carbonic acids in the watery menstruum, rather than upon the subsequent transformation of one magnesian silicate to another by addition or elimination of silica or magnesia. The association, in the same mass, of anhydrous chrysolite with serpentine is generally regarded as evidence of the change of chrysolite into serpentine; but, while admitting the con-

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conception of the sedimentary origin of the ophites shall have definitely taken its place in science, the present geologists, and, above all, those of a future generation, will never forget that the promoter and one of the most active workers in this great and fruitful scientific revolution was Sterry Hunt."]

* Lotti, Appunti Geologici sulla Corsica; Boll. R. Comitato Geologico, anno 1883.

version, under certain conditions, of both enstatite and chrysolite into hydrous silicates, the view which supposes the chrysolite or the enstatite to be simply an instance of the crystallization of an anhydrous silicate in the midst of an amorphous hydrous silicate, is more consonant with the hypothesis of the aqueous origin of serpentine-rocks. It is well known that Scheerer, from his studies of the associated chrysolite and serpentine of Snarum, was led to reject the notion of the derivation of this serpentine from a previously formed chrysolite, and to maintain a simultaneous formation of the anhydrous and the hydrous magnesian silicates.*

A somewhat analogous case is presented in the occurrence of grains of anhydrous alumina or corundum found in the earthy and amorphous aluminous hydrate, bauxite, which forms beds in uncrystalline cenozoic rocks.† The notion which has been advanced that the bauxite has come from the hydration of previously formed beds of corundum, is obviously untenable, and we must regard this anhydrous alumina as formed by crystallization in the midst of the uncrystalline mass of hydrated alumina. De Senarmont, in the decomposition of aqueous solutions of chlorid of aluminium, at 250° C., observed a simultaneous production of anhydrous alumina in the form of corundum, and of hydrous alumina as diaspore, both crystallized.‡

§ 118. The late studies of Arno Behr throw further light on the association of hydrous and anhydrous species. He has found that solutions of dextrose, within very narrow limits of temperature and concentration, yield crystals either of hydrated or anhydrous dextrose,

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* Scheerer, Pogg. Annalen, lxviii., 319, and Amer. Jour. Science [2], v., 389, vi., 201, also xvi., 217.

† Deville, An. de Ch. et de Phys. [3], lxi., 309, and Hunt, Origin of Some Magnesian and Aluminous Rocks. Amer. Jour. Sci., 1861 [2], xxxii., 281; also, Chem. and Geol. Essays, p. 326.

‡ Comptes Rendus de l'Acad. des Sciences, 1856, xxxii., 762.

and that under certain conditions we can obtain an admixture of the two, as the result of simultaneous crystallization.* An illustration of the influence of small variations in composition on the result of a chemical process, under conditions otherwise similar, is afforded by the recent experiments of Friedel and Sarrasin on the artificial production of albite in the wet way. When a solution of silicate of soda mixed with silicate of alumina, in the proportions required to form the soda-feldspar, was heated in close vessels to from 400° to 500° C., no albite was formed, but crystals of the hydrated double silicate, analcite; silica, soda, and some alumina remaining in solution. When, however, an excess of the alkaline silicate was employed, the whole of the silicate of alumina was converted into a crystallized anhydrous compound, which was albite.†

§ 119. Much obscurity still surrounds the question of the conversion of chrysolite into serpentine. In the first place, it is to be remembered that the process is one which does not, under ordinary circumstances, take place at or near the surface of the earth, since chrysolite-rocks, whether exotic masses or indigenous crystalline schists, are often met with, presenting no evidence of such change. This is well seen near Montreal, where the hills of chrysolitic dolerite, demonstrably of pre-Silurian age, as well as fragments of the same rock imbedded in Silurian conglomerates, alike contain only unaltered anhydrous chrysolite. This mineral, on exposed surfaces, is subject to a sub-aerial decay, analogous to that suffered by pyroxene and amphibole, by which the magnesia and a large proportion of the silica are removed, leaving a residue of ferric oxyd, as long since observed by Ebelmen. The change of chrysolite into serpentine must then be distinct from

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* For these facts I am indebted to a private communication from Dr. Behr. See also his paper in Jour. Amer. Chem. Soc., in 1882, vol. iv., p. 11.

† Comptes Rendus de l'Acad. des Sciences, July 30, 1883.

that going on under the influence of atmospheric waters near the surface.

§ 120. One hundred parts by volume of chrysolite, with a specific gravity of 3.33, if converted into a serpentine of specific gravity 2.50, without change in its content of silica, must lose one-eighth of its weight of magnesia, and acquire the same amount of water instead, while, at the same time, its volume will be augmented by one-third, or to one hundred and thirty-three parts. I have long since discussed this matter in connection with Scheerer's views as to the relations of these two mineral species, noticed in § 117. A simple hydration of chrysolite would yield, not serpentine, but villarsite. Serpentine, when subjected to dehydration and fusion, yields, as was shown by the experiments of Daubrée, an admixture of enstatite and chrysolite, of which the former should contain one-third and the latter two-thirds of the fixed bases of the serpentine; the oxygen-ratio of these in serpentine being 4 : 3, while that of chrysolite is 2 : 2, and that of enstatite, 2 : 1. Since, however, the natural chrysolite-rock, as is well known, often contains little or no enstatite, it could not have been formed directly from the simple dehydration of a silicate like serpentine.

§ 121. In considering the hypothesis of the derivation of serpentine from chrysolite-rocks, such as the so-called dunite and lherzolite, the question of the geognostical relations of these at once presents itself. The frequent presence of ferriferous chrysolite in igneous rocks, and its artificial production in the furnace, have given rise to a notion that it is generally of igneous origin, which is not justified by a more extended inquiry. It is true that eruptive rocks sometimes contain a large proportion of this mineral, and one of the most remarkable cases of the kind is that presented by the granitoid chrysolitic dolerite long since described by me, which forms the hills of Montarville and Rougemont, masses of paleozoic age in the valley of the Richelieu, near Montreal, which have broken through the Utica shales of the New York system, and converted them, near the contact, to a flinty rock. An account of this dolerite, with analyses, has been given on pages 211, 212.

§ 122. The nearly pure magnesian chrysolite, which has been distinguished by the names of forsterite and boltonite, occurs abundantly disseminated in limestone in eastern Massachusetts (*ante*, page 230), and sometimes forms the greater part of the mass. Its mineralogical relations are similar to the fluoriferous magnesian silicate, chondrodite, with which it is associated at Vesuvius, and which is also found in crystalline limestones in eastern Massachusetts, as well as in those of the Laurentian series elsewhere, and is itself associated with serpentine. The grains of both chondrodite and serpentine are sometimes so arranged as to mark the stratification of the limestone; and in one specimen from an unknown locality, formerly described by me, two contiguous layers in crystalline limestone contain, the one, chondrodite, and the other, serpentine.* The analogies between the limestones holding chondrodite and serpentine, and those containing the pure magnesian chrysolite, forsterite, are very close, and their relations indicate for all of them a common neptunian origin.

§ 123. We pass from the chrysolite-bearing limestones to those rocks, composed chiefly of chrysolite, which have received the names of dunite and lherzolite, and appear to be indigenous interstratified masses. Such was my conclusion after examining them in North Carolina, in strata referred by me to the Montalban series, regarding which I wrote in 1879: "Noticeable among the basic members of the terrane is the granular olivine or chrysolite-rock which, often accompanied by enstatite and by serpentine, appears to be interstratified in the micaceous and hornblendic schists of the Montalban in North Caro-

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* Geology of Canada, p. 465. See also the Geological Report for 1866, p. 205.

lina and in Georgia."* Chrysolite-rocks similar to those of North Carolina, have been observed among the crystalline schists in the province of Quebec, on the south side of the Gulf of St. Lawrence, but have not yet been carefully examined.

§ 124. The typical lherzolite from the Eastern Pyrenees, examined by Zirkel, has since been studied by Bonney, who, in 1877,† described the rock and its locality. It forms several masses of considerable size, near Vicdessos (Ariège), and is in contact with a saccharoidal limestone, in which occur broad tongue-like portions of the lherzolite. This rock consists of chrysolite with admixtures of enstatite, diopside, and picotite (a chromiferous spinel), the constituent minerals showing in their arrangement on weathered surfaces a "linear structure" suggesting "an internal parallelism," which Bonney, who looks upon the rocks as "igneous," regards as due to movements of flow. The rock varies from coarsely to finely granular in texture, and includes in some cases a serpentinic mineral in its joints. The dunite of New Zealand, in specimens before me, presents, in the arrangement of the contained chromite, a well defined gneissic structure.

§ 125. Similar rocks are found in Norway, specimens of which from Tafiord, received by the writer in 1878 from Professor Kjerulf, were micaceous, and showed an evidently gneissoid structure. These rocks, consisting essentially of chrysolite, holding enstatite, diopside, chromite, and a grayish mica, are found interstratified in gneiss, with quartzites and mica-schists, sometimes garnetiferous. From their late studies of this rock in various Norwegian localities, Tornebohm, Reusch, and Brögger agree that it must be classed among the crystalline schists, a judgment in which Rosenbusch concurs. The reasons for this conclusion, as set forth by Brögger, are briefly as follows; First, the invariably laminated structure of the chrysolite-

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* Macfarlane's Geological Hand-Book, page 13.

† Geological Magazine, February, 1877.

rock, which is conformable to that of the enclosing gneiss; and, second, the variations in the composition of the rock itself, as seen in adjacent layers.* With these gneissoid chrysolite-rocks of Norway may be compared the chrysolite known as glinkite, found in nodules in a talcose schist in the Urals, and also the schists lately described from Mount Ida in Greece.† In these, the transition is seen from true talc-schists to talc-schists containing more or less chrysolite, with pyroxene, and finally to massive chrysolite-rock; the whole being associated with other crystalline schists and with limestones. The obvious conclusion from all the above facts is that no argument in favor of the igneous origin of serpentine can be drawn from its supposed derivation from chrysolite-rocks, since these are themselves, for the greater part, of neptunian origin.

In this connection may be noted the well known fact of the aqueous deposition of serpentine in veins, in the forms of marmolite, picrolite, and chrysotile, either alone or with calcite. Such veins, the result of a secondary process, are often found intersecting ophicalcites and serpentine-rocks at various horizons, and are even met with in comparatively recent serpentine breccias, as noticed by Gastaldi (§ 42).

VII. — STRATIGRAPHICAL RELATIONS OF SERPENTINES.

§ 126. The contradictory opinions expressed by different observers as to the geognostical relations of serpentine-rocks in a given area, — one regarding them as indigenous and another as exotic masses, — make it evident that certain appearances are differently interpreted, according to the theoretical point of view of the observer. In greatly crushed and displaced strata, the varying resistance of unlike rocks undoubtedly gives rise to accidents which are regarded by many as evidences of poste-

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* Neues Jahrbuch für Mineralogie, 1880, i., pp. 187, 195, 197.

† Science, August 31, 1883, p. 255.

rior intrusions. The serpentines and related rocks of Carrick, in Ayrshire, Scotland, may be cited as another instance of this conflict of opinion. As described by James Geikie, in 1866,* the serpentine and its associated greenstones are both indigenous bedded rocks, interstratified with greenish crystalline schists, which he, following Murchison, called altered Lower Silurian. Geikie, however, found what he regarded as clear evidence that these strata had been greatly disturbed while in a softened condition. The remarkable resemblance between these crystalline schists of Carrick and those associated with the serpentines of Cornwall, is noticed by Warrington Smyth. Bonney, in 1878,† rejected the conclusions of Geikie, asserting that we have in Carrick, as elsewhere, truly eruptive serpentines, followed by eruptive gabbros of two ages, and, like Geikie, adduced evidence in support of his own views.

§ 127. In a critical notice, in 1878, of Professor Bonney's description of the serpentines of Cornwall and of Ayrshire, the present writer said: "When it is considered that there is abundant evidence that the North American serpentines are indigenous, though often, like deposits of gypsum and of iron-ores, in lenticular masses; and, further, that the movements which the ancient strata have suffered, have produced great crushings and displacements, it is not difficult to understand the deceptive appearance of intrusion which these rocks often exhibit, and which are scarcely more remarkable than the accidents presented by coal-seams in some disturbed and contorted areas." ‡ The alternately thickened and attenuated condition of coal-seams in such districts, and the forcing of the coal into rifts and openings in the enclosing sandstone strata, are familiar to those who have studied the contorted measures of the Appalachian coal-field. The latter phenomenon especially is well displayed in one of

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* Geol. Journal, xx., 527. † *Ibid.*, xxxiv., 789.

‡ Harpers' Annual Record, 1878, p. 293.

the elaborate sections made since 1878 by Mr. Charles A. Ashburner, and published in 1883 by the geological survey of Pennsylvania, in which the so-called Mammoth-vein is shown as it occurs in the Greenwood basin of the Panther-Creek district.* The accidents in this great forty-foot seam of anthracite, there represented on a scale of one inch to four hundred feet, are such as would, in a rock of conjectured igneous origin, be deemed strong evidence of its intrusive character.

§ 128. We have already referred to the conclusions of Stapff, with regard to the indigenous character and sedimentary origin of serpentines. The observations of this eminent engineer and geologist while superintending the work of the tunnel through Mont St. Gothard, from Goschenen to Airolo, in the years 1873–1880, are set forth at length in his recent memoir accompanying a geological section,† which we have noticed in § 67. Lenticular masses of serpentine appear to the east and west of the tunnel, along the line of which they are intersected between 4870 and 5310 metres from the northern terminus. Having described at length the rocks of the section, he adds: "We have in what precedes said nothing of the structure of the serpentine, not only because, from a petrographic point of view, it is to be separated from the other rocks of the St. Gothard, but also because it evidently cuts these last, so that it might be considered as a rock intruded among them." Having stated in detail its relations, he tells us that "the boundaries of the serpentine-mass sometimes follow the stratification of the neighboring rocks, but sometimes go across it." Yet, he hastens to add, "we nowhere find plausible proof of the penetration of the serpentine-mass into the encasing rocks. This serpentine had originally the form of a flattened lenticular

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* Second Geol. Survey of Penn., Vol. I., Southern Coal-Field; Cross-Section Sheet ii., Section 10.

† Profil géologique du St. Gothard dans l'axe du Grand Tunnel, sur une 1:25,000, avec text explicatif, par Dr. F. M. Stapff, 4to, pp. 65, Berne, 1881.

mass, intercalated conformably in the stratification (like the layers of eulysite in the gneiss of Tunaberg, in Sweden), and now appears, as the result of numerous breaks and displacements, outcropping in a series of little lenses, the line joining which intersects at a sharp angle the schistose lamination of the beds. Near to the fissures which, with displacements, cut the mass, the rock adjoining the serpentine is stretched out and pushed back (*étirée et refoulée*), both at the surface and in the interior of the tunnel."

§ 129. This displacement in one case, on the surface, was found equal to 450 metres, and the adjacent strata were bent in the form of an inverted C. The maximum thickness of the serpentine at the outcrop was 100 metres, and the thickness of 440 metres, which it attains in the line of the tunnel, is believed by the author to be due to the accumulation, by the movements described, of successive portions of one and the same lenticular mass: a conclusion which is illustrated by a great number of minute observations. He adds, "The fissures along which this heaping together must have taken place, present striations produced by the sliding of the rock; they are coated with a steatitic matter, and sometimes filled with a friction-breccia. Farther proofs of this crushing are found in the abrupt discontinuity of the schistose and compact portions of the serpentine, and in the indented outline presented by the upper surface of the serpentine-mass; a detail not represented in the profile." The author farther says: "Although we would not consider the serpentine to be an intrusive rock, we must remark that it could not have had precisely the same [mechanical] sedimentary origin as that which we have supposed for the micaceous gneiss which encloses it. We may regard it as originally a deposit of hydrated silicate of magnesia, formed by springs, and enclosed between the sediments which gave rise to the mica-schists." The hydrated magnesian silicate is supposed by our author to have been subsequently converted into anhydrous chrysolite, etc., which by a later hydration has generated serpentine, portions of chrysolite still remaining in the mass. It may be questioned whether the phenomena require this hypothesis of a double change for their explanation. The serpentine contains imbedded, in some portions, not only chrysolite, but hornblende, talc, and garnet. Intercalated with the serpentine, which is often distinctly stratified, are layers of schistose talc, of compact chlorite, of actinolite-rock, of ferriferous dolomite, and of mica-schist. The serpentine itself is chromiferous, and also contains magnetite.

§ 130. Stapff farther adds: "The curious modifications of form which the mass of serpentine has suffered from the effect of faults, etc., correspond to those of the adjacent micaceous gneiss, but in the case of the former they have been better studied, for the reason that it is more easy to define the limits of these forms. If we suppose in the section, in place of the serpentine, a mass of ordinary micaceous gneiss subjected to all the movements of displacement and elevation which we have here displayed, we should perceive nothing more upon the profile than a uniform surface of micaceous gneiss, with some interlacings of beds. It cannot, however, be denied that movements arrested by the hard and tough mass of the serpentine have produced in the neighboring rocks perturbations much more intense than would have resulted from similar movements acting upon a more tender rock." (Loc. cit., pp. 43–44.) It would be difficult to illustrate more clearly than Dr. Stapff has done, the manner in which movements in the earth's crust may affect interstratified masses of unequal hardness and tenacity, giving rise to accidents which simulate to a certain extent those produced by the intrusion of foreign masses, and may thus lead different observers, as we have seen, to opposite conclusions with regard to the geognostical relations of rocks like serpentine and euphotide.

CONCLUSIONS.

The following are the chief points regarding serpentine and ophiolitic rocks which we have sought to set forth in the preceding pages: —

1. To show historically the diversity of opinions as to the geognostical relations of serpentine and related rocks, which have been regarded by some writers as eruptive and of igneous origin, and by others as aqueous and sedimentary.

2. To show how, from the hypothesis of their eruptive origin, came the application of that of metasomatosis, and also to set forth the hypothesis of the aqueous origin of serpentine, explaining how silicates of magnesia may, on chemical grounds, be looked for at any geological horizon.

3. To indicate the various horizons at which serpentines are found in North America; and first, those of the Laurentian, of the Huronian, and of the younger or Montalban gneisses; in which connection we have noticed the serpentines of Chester County, Pennsylvania, and those of New Rochelle, Hoboken, and Manhattan and Staten Islands, all of which are regarded as indigenous stratified rocks; the apparently intrusive character of the serpentine of the latter locality being explained.

4. We have further described the occurrence of serpentine among the Taconian rocks in Pennsylvania, and also among the gypsiferous rocks of the Silurian series at Syracuse, New York.

5. Having noticed some points regarding the nomenclature of serpentine and related rocks, and Bonney's account of the serpentines of Cornwall, and of parts of Italy, we have considered the serpentine-bearing rocks of the Alps, in which we show four great groups, in ascending order, which are the older gneiss, the pietre-verdi or greenstone series, the newer gneisses and mica-schists, and the still younger lustrous schists, corresponding re-

spectively to the Laurentian, Huronian, Montalban, and Taconian of North America; the second and third of these being the Pebidian and the Grampian of Great Britain.* Serpentines, it was shown, occur in the Alps interstratified in the second, third, and fourth of these groups, the youngest of which includes the marbles of Carrara.

6. The view that this youngest group is mesozoic, is discussed, and the relations of all these groups of crystalline schists to the fossiliferous rocks of the mainland, and of those of Elba and Sardinia, are set forth, showing their pre-Cambrian age; while it is maintained that the ophiolites and other crystalline rocks which have there been referred to the tertiary are but exposed portions of these pre-Cambrian rocks.

7. The crystalline rocks of the Simplon and the St. Gothard, and those of Saxony and Bavaria, are considered, and are compared with the younger gneisses of North America.

8. The relations of the so-called tertiary serpentines to the surrounding strata are elucidated by a detailed discussion of the mass of Monteferrato, in Tuscany, which is regarded as of pre-Cambrian or eozoic age.

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* It remains to be seen whether the Arvonian series, which is essentially composed of stratified hälleflinta or petrosilex-rocks, passing into quartziferous porphyries, and is largely developed at the base of the Huronian in parts of North America, and of Great Britain, is not represented in the Alps. Since we have seen the serpentines, lherzolites, euphotides, diabases, and even the marbles of the Alps and other regions, removed from the category of eruptive mesozoic and cenozoic masses, and shown to be regularly interbedded members of pre-Cambrian stratified series, it is, I think, a legitimate subject for inquiry whether the quartziferous porphyries which are so largely developed at Botzen, and elsewhere in the Alps, and have been regarded as eruptive rocks of Permian age, may not prove to belong to a stratified series, the equivalent of the Arvonian, with which, to judge from descriptions, analyses, and specimens, they bear a close resemblance. For an account of these rocks of Botzen by one who regards them as plutonic, see Judd in the Geological Magazine for 1876, vol. xiii., pp. 200–214, and for details with regard to the history of the Arvonian series, see the author in 1880, American Jour. Science [3] (xix., pp. 274, 278, et seq.); also *ante*, page 409.

9. The various theories proposed to explain the genesis of serpentines are considered, and that of their aqueous origin is adopted.

10. The geognostical history of chrysolite is discussed, and the essentially neptunian origin of many chrysolite-rocks is maintained.

11. The contradictory views as to the geognostical relations of serpentine are considered, and an attempt is made to show that the appearances of intrusion, upon which some have insisted, are explained by subsequent movements of the strata in which the serpentines are included.

XI.

THE TACONIC QUESTION IN GEOLOGY.

In the investigation of the age and relations of the crystalline stratified rocks, it became necessary to consider a great series of strata which by Maclure had been called Transition, but by Eaton were, for the greater part, included in his Primitive divisions, though placed by him stratigraphically between the gneisses and related rocks on the one hand, and the paleozoic rocks on the other. That at a later period this intermediate series, through the extension of the doctrine of regional metamorphism, came to be regarded as a local alteration of the lower part of the paleozoic, and that it has been a source of much controversy, are facts well known to all geologists. It had been the task of the writer to attempt with some success the unravelling of the famous Cambrian and Silurian controversy into which the errors of Murchison had introduced confusion, and still it now remained to essay the heavier task of solving the greater problem presented by a vast series of rocks, not less widely spread, which had perplexed the geologists of a generation ; a problem closely connected, moreover, with the Cambrian and Silurian controversy, and involving still wider discordances of opinion, greater contradictions, and more important results for the science of geology. Partial and limited observations, partisan spirit, a neglect of geological literature, and false notions of metamorphism, had each contributed to obscure the question. A personal examination of localities throughout the country, a critical study of the literature of the Taconic controversy, and a candid discussion of all the facts there made known without regard to the preconceived opinions of myself, or of others, were evidently necessary for the solution of the problem. The reader of the following pages must judge to what extent these ends have been attained. This essay was presented to the Royal Society of Canada, the first portion, to the end of § 135, on the 23d of May, 1883, and the remainder on the 21st of May, 1884. These two portions have been published respectively in the first and second volumes of the Transactions of the Society. Additional paragraphs regarding the Green Pond Mountain range of New Jersey, the Taconian and Keweenian of Lake Superior, and the Keweenian and Cambrian of Texas and the great American basin, have been added, giving the results of later studies.

I. — INTRODUCTION.

§ 1. The history of those stratified rocks which in eastern North America have been called the Taconic series, is one of many contradictory opinions, and of much obscurity. Taken in the larger sense in which the name was at one time applied, this history moreover includes, besides those rocks to which the appellation of Taconic or Taconian was subsequently restricted, another important series, sometimes called the Upper Taconic, which, under the names of the Hudson-River group and the Quebec group, has been the subject of prolonged controversy. It may here be noted that one of the latest writers on the subject, whose views will be discussed in the present essay, still maintains for this latter series the name of Taconic.* The questions involved in this history are of fundamental importance, and have hitherto been involved in so much misconception that it seems desirable at the present time to give a concise view both of the facts and of the various theories which have been held with regard to the whole of the rocks in question.

For this purpose we must go back to Amos Eaton, to whom rightly belongs the honor of having laid the foundations of the American school of geology, so worthily continued by his pupils, James Hall, George H. Cook, and the late Ebenezer Emmons. It is now half a century since, in 1832, appeared the second and revised edition of Eaton's "Geological Textbook," from which we may gather his matured views as to the geological succession in northeastern America. From this, and from his previous "Geological and Agricultural Survey of the Erie Canal," published in 1824, I have elsewhere endeavored to frame a connected statement of these views,† which is here briefly resumed.

§ 2. Dividing the stratified rocks of northeastern America into five great groups, — namely: I. Primitive; II. Transition; III. Lower Secondary; IV. Upper Secondary; V. Tertiary, — Eaton supposed that each of these groups "commenced with carboniferous slate, and terminated with calcareous rocks, having a middle formation, the centre of which is quartzose." This three-fold division and alternation in each great series, which Eaton regarded as universal, was, so far as I know, the first recognition of the principle, now so generally understood, of cycles in sedimentation.

§ 3. These three divisions evidently correspond to ar-

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* Marcou, Bull. Soc. Géol. de France, 1880; (3), ix., p. 18.

† Azoic Rocks, etc., pp. 24-29.

gillites, sandstones, and limestones, but in the application of his scheme its author allowed himself considerable liberty of interpretation, and referred to his first or argillaceous division, not only clay-slates, but the great body of crystalline schists. In this way, the first division of the Primitive series was made to embrace both the gneisses of the Adirondacks and the Highlands of the Hudson, and the unlike crystalline rocks of New England; including, besides gneisses, various hornblendic, chloritic, and micaceous schists, in some of which strata the occurrence of graphite was held to justify the title of "carboniferous," applied to these rocks as a whole. Following this first division of the Primitive series (I. 1), Eaton recognized in western New England the second or silicious division (I. 2), and the third or calcareous division (1. 3), represented respectively by the Granular Quartz-rock and the Granular Lime-rock or marble of the Taconic range.

§ 4. Succeeding these, came the rocks of his second or Transition series. Of this, the first or carboniferous division was the Transition Argillite (II. 1) which in many localities directly overlies the Primitive Lime-rock, and consists in part of roofing-slates, with coarser and more silicious layers, and in part of soft unctuous micaceous schists. To this Transition Argillite succeeds, according to Eaton, the First Graywacke or Transition Graywacke, representing the second or silicious division of the Transition series (II. 2), and consisting of the so-called graywacke-slate, with sandstones and conglomerates. The base of the First Graywacke was declared to rest unconformably upon the Transition Argillite.

§ 5. The geographical distribution of the First Graywacke — a very important point in our present inquiry — was carefully indicated by Eaton. "It is seen resting on the Argillite, near Col. Worthington's on the Little Hoosic, near the eastern limit of Rensselaer County. On ascending the western hill or ridge, the graywacke-slate, rubble, and millstone-grit [elsewhere indicated by Eaton as making up the First Graywacke] are found in succession. This ridge extends from Canada, through the State of Vermont and Washington, Rensselaer and Columbia Counties in New York." Elsewhere, we are told by Eaton that the rubble or conglomerate of this First Graywacke "forms the highest ridges between the Massachusetts line and the Hudson." He also supposed that the Shawangunk Mountain of Ulster and Orange Counties, on the west side of the Hudson, now referred by New York geologists to the horizon of the Second Graywacke, "is a continuation of the grit and rubble of the First Graywacke of Rensselaer County." *

§ 6. To the third or calcareous division of the Transition series (II. 3) was referred by Eaton, what he called the Sparry Lime-rock, found at the summit of the First Graywacke, to the east of the Hudson. In the same division also was included a group of strata lying to the west of Lake Champlain, which he designated the Calciferous Sand-rock and the Metalliferous Lime-rock. In this latter region, however, these Transition limestones were found to rest directly upon the lower division of the Primitive series; the whole of the intermediate divisions being absent.

§ 7. The Transition limestones in this western area were, according to Eaton, directly followed by the third or Lower Secondary series, the first division of which (III. 1) was described as an argillite or graywacke-slate, and the second (III. 2) as a sandstone or millstone-grit; the two together making what he called the Second Graywacke; declared by him to be indistinguishable from the First or Transition Graywacke, except by the fact that it overlies the Transition limestones. This Secondary Graywacke is thus clearly indentified with the strata subsequently called the Utica slate, the Pulaski or Loraine shales, and the Gray or Oneida sandstone. Succeeding it, were the Lower Secondary limestones, including the Niag-

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* Geological Textbook, 2d ed., pp. 74, 93, 123.

ara, and the Lower and the Upper Helderberg divisions, of later geologists. The Medina, Clinton, and Onondaga divisions were looked upon by Eaton as constituting subordinate intercalated series. For the understanding of the problems before us, we need not follow our author above the Second Graywacke; though it is important to remark that he first showed that the Lower Secondary limestones underlie alike the bituminous coal and the anthracite of Pennsylvania, both of which he placed in the Upper Secondary series; thus correcting the error of Maclure, who had assigned the anthracite to a lower horizon, and placed it in the Transition series. The subsequent study of the Taconic question will be much facilitated by keeping in view the classification and the definitions of Eaton, the abandonment of which materially retarded the progress of American geology. Some of his once rejected views are now universally accepted, and, in the opinion of the present writer, a similar vindication awaits the entire succession defined by Eaton, so far as his Primitive, Transition, and Lower Secondary series are concerned. The relations of these will be farther shown below, in a table at the end of the next chapter.

II. — THE GEOLOGICAL SURVEY OF NEW YORK.

§ 8. Such was the state of our knowledge of those rocks in 1832. Five years later, the geological survey of New York was begun. The Northern district of the State was then assigned to Ebenezer Emmons, a pupil of Eaton, and to him we owe the present nomenclature of what he called the Champlain division of the New York system of paleozoic rocks; described by him as resting, in that region, directly on the Primary series, and designated as follows, in ascending order: 1. Potsdam sandstone; 2. Calciferous sand-rock (now known to be a dolomite or magnesian limestone); 3. Chazy limestone; 4. Trenton limestone, with its subdivisions, the Birdseye and Black-River limestones; 5. Utica slate; 6. Loraine shale; 7. Gray sandstone; 8. Medina sandstone. The numbers 7 and 8 were, as is well known, subsequently separated from the Champlain division, and joined to what was called the Ontario division of the New York system.

§ 9. This order was evident to the west of Lake Champlain, where the strata are nearly horizontal, and rest in undisturbed succession on the crystalline rocks of the Primary series. To the east of the lake, however, and thence southward along the valley of the Hudson, is found the belt of disturbed strata, dipping generally to the eastward, which had been called by Eaton, the First or Transition Graywacke, the distribution of which has been given in § 5. This belt, described by Emmons as consisting of a great thickness of green, red, and gray sandstones and conglomerates, with green, purple, and black slates, and some associated limestones, was by him now referred to the horizon of the Loraine shale and the succeeding sandstones (Nos. 6, 7, and 8), or, in other words, to the Second Graywacke, lying above the Trenton limestone; which latter, according to Emmons, appears, in some localities, to dip beneath this graywacke. By Eaton, however, the strata of the same belt had been assigned, under the name of the First Graywacke, to a position below the same Trenton limestone.

§ 10. These views were published by Emmons in 1842, at which time, as we see, he dissented from the opinion of Eaton as to the stratigraphical horizon of the First Graywacke of the latter, and adopted that which had been put forth by Mather, to be mentioned below. As regards the quartzite and limestone of the Primitive series, and the Transition Argillite, which, according to Eaton, intervene stratigraphically, as well as geographically, between the crystalline schists of the Primitive and the First Graywacke, Emmons supposed that these three divisions constitute a distinct group or series, which, from its development in the Taconic hills of western Massachusetts, he named the Taconic system. This he regarded as distinct from, and older than, the New York system lying to the westward of it.

§ 11. The survey of the Southern district of New York was assigned to Mather, who, in his final report on the region, in 1843, described the southward extension of the various groups of rocks just mentioned, and maintained, in opposition to both Eaton and Emmons, that the Taconic system of the latter was a modification of the Champlain division; the quartzite being supposed to correspond to the Potsdam, the marble to the Calciferous, Chazy, and Trenton, and the argillite to the Utica and Loraine; for which latter subdivision he adopted, as a synonym, the name of the Hudson slates.

§ 12. As regards the graywacke-belt east of the Hudson River, this consisted in part, according to Mather, of the same slates in a disturbed and altered condition, and in part of higher strata, belonging to the horizon of the Oneida and Medina subdivisions of the New York system. He supposed, with Eaton, that the belt of these rocks, continued from Canada, through Vermont, and along the east side of the Hudson, was prolonged southward, on the west side, in the Shawangunk range; and that the Green-Pond Mountain range, in New Jersey, was also a portion of the same belt, which it lithologically resembled. Thus, in the view of Mather, the whole series of Eaton, from the granular quartzite of the Primitive up to the top of the Second Graywacke, was made up of the rocks of the Champlain division, with some still higher strata. He confounded the First with the Second Graywacke, and supposed both the clay-slates of the former, and the underlying Transition Argillite of Eaton to be nothing more than local modifications of the Utica and Loraine shales. Indeed, as is well known, Mather went so far as to regard the Primitive crystalline schists themselves as a farther modification of the same Champlain series. Emmons, as we have shown, while adhering to the views of Eaton in other respects, adopted, at this time, Mather's conjecture as to the horizon of the eastern graywacke-belt.

§ 13. The name of Hudson slates had already, in his fourth annual report on the Southern district of New York, been given by Mather to the strata which he regarded as equivalent to the Loraine shale; described by Emmons as occurring in Jefferson and Lewis Counties, in the Northern district. These strata were farther studied by Vanuxem in the Central or intermediate district, which included the counties of Oswego, Oneida, Herkimer, and Montgomery, extending southeastward along the valley of the Mohawk. The rocks found in this district were first described by Conrad as dark shales (the Utica slates) succeeded by fossiliferous lead-colored shales alternating with gray sandstones, well displayed at and near Pulaski, in Oswego County. At the summit of these was a sandstone quarried for grindstones, and in Oneida County the series was overlaid by a quartzose conglomerate. These were at first called by Vanuxem (who succeeded Conrad in the charge of the survey of this district) the Pulaski shales and sandstones, and they clearly correspond to the Loraine shale and the Gray sandstone of Emmons. As these shales were also regarded, both by Emmons and by Vanuxem, as identical with the Hudson slates of Mather, Vanuxem included them in what he called the Hudson-River group; a name which, in subsequent geological and paleontological publications, has generally replaced that of Loraine shale, as being synonymous with it.

§ 14. The Hudson-River group, however, according to Vanuxem, embraced two distinct divisions, the upper, a highly fossiliferous member (being the Pulaski shales and sandstone), found west of the Adirondacks, in Jefferson, Lewis, and Pulaski Counties, and disappearing to the southeastward, in Oneida County. The lower member of the Hudson-River group, as defined by Vanuxem, was named the Frankfort division, from Frankfort, in Herkimer County, and was described as consisting of greenish argillites and sandstones; which underlie the Pulaski shales to the northwest, as far as Jefferson County, constitute, in Herkimer and Montgomery Counties, the only representative of the Hudson-River group, and extend eastward, through Schenectady, Albany, and Saratoga Counties, to the Hudson River. This lower division of the group was said to contain none of the organic remains of the Pulaski or upper division, but to include some graptolitic shales. To this lower division, Vanuxem supposed, might belong the thick masses of contorted argillaceous strata, of "controverted age," along the Hudson valley.

He farther remarked that the two divisions of the Hudson-River group "are not co-extensive with each other. The lower one enters from the Southern district, along the Mohawk, and extends north by Rome, through Lewis into Jefferson County. The upper division first appears in Oneida County, and from thence, west and north, is a co-associate of the Frankfort slate or lower division." These two divisions Vanuxem insisted on treating separately, "inclining to the opinion that they ought not to be put together in local geology." * He, moreover, declared that the two divisions, although in juxtaposition in parts of New York, occur separately in Pennsylvania. The Pulaski shales, having in all respects the same characters as in New York, it was said, are found in the Nippenose valley, west of the Susquehanna; while the Frankfort slates and sandstones are seen to the east of the North Mountain, in the Kittatinny or Appalachian valley, and include the roofing-slates of the Delaware.

The Oneida conglomerate, which in Oneida, New York, according to Vanuxem, rests upon the Pulaski shales, is seen in Herkimer County, overlying directly the Frankfort slates and sandstones. The same conditions, according to Horton (Mather's assistant in the Southern district

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* Geology of the Third district of New York, pp. 60-67.

of New York), occur in Orange County, where the sandstone of Shawangunk Mountain is said to rest unconformably upon the edges of the Argillite and Graywacke series.

§ 15. The table on page 529 will show the relations of the various groups of strata already noticed, by a comparison of the divisions established by Eaton with those adopted by the New York geologists, and by others. It should here be repeated that Eaton insisted upon the fact that the Argillite is unconformably overlaid by the First Graywacke. He wrote, "while European geologists have described a change of direction at the meeting of the Lower and Upper Secondary, in which the latter rests unconformably upon the inclined edges of the former, in North America this change takes place at the meeting of the Argillite and the First Graywacke." He was careful to distinguish between the bedding and the slaty cleavage of the Argillite, the plates of which, he tells us, "form a large angle with the general direction of the rock." His diagrams, moreover, show both the non-conformity of stratification between the two, and the independent slaty cleavage of the lower series.*

Eaton did not distinguish the Potsdam sandstone on the west shore of Lake Champlain from what he called the Calciferous Sand-rock, there underlying the Metalliferous Lime-rock, — a term (borrowed from Bakewell) by which he designated the Trenton limestone, with its subdivisions, including what he called the Birdseye or Encrinal marble, and the underlying Chazy. The Calciferous Sand-rock he described and figured as in part marked by geodes (a very distinctive character), and represented it as the equivalent of the somewhat dissimilar Sparry Lime-rock, found, to the eastward, at the summit of the First Graywacke. Of this Sparry Lime-rock, he both designated and figured two varieties, which he called "veiny" and "tessellated." The correctness of these and of other

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* Geological Textbook, pp. 63, 72, 74.

descriptions by Eaton, will be acknowledged by those who examine carefully the rocks which he described.

§ 16. In the Lower Secondary of Eaton, what he named the Corniferous or Cherty Lime-rock, with its beds of chert (called by him "stratified horn-rock"), is the Upper Helderberg of later geologists, and his Geodiferous Lime-rock is as clearly the Niagara; the Lower Helderberg limestone, and the succeeding Oriskany sandstone, now regarded as the basal member of the Devonian, not being then recognized. Besides the regular division of each group into triads of argillaceous, silicious, and calcareous rocks, which he regarded as normal, Eaton admitted the existence of what he called subordinate or interposed strata. To this class of abnormal rocks, he referred, in the Lower Secondary, the Onondaga group, with its marls, salt, and gypsum, and also the hydraulic limestone or Water-lime above it; all of which may be regarded as interpolated between the Niagara and the Helderberg limestones. In the same subordinate class, also, were included by him the red beds of the Medina and the iron-ores of the Clinton.

§ 17. It will be remembered that the Potsdam of Emmons, which (like the Calciferous Sand-rock) is often wanting at the base of the Champlain division, was unknown to Eaton, and hence does not appear in our table, from which what he regarded as subordinate strata are also omitted. The Calciferous Sand-rock of Eaton, and the underlying Potsdam sandstone were, by Emmons, declared to be represented, to the eastward, by the great development of strata included in the Sparry Lime-rock and the First Graywacke, to which, as a whole, he gave the name of Taconic slates, and later that of Upper Taconic. He farther declared, in 1860, that the Primordial zone in Bohemia, which includes Barrande's first fauna, "is in co-ordination with the upper series of the Taconic rocks." *

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* Emmons, Manual of Geology, p. 89.

The name of Ordovician (sometimes contracted to Ordovian) which we have introduced in this table, was proposed by Lapworth, in 1879,* to designate the group of paleozoic rocks found in Wales between the base of the Lower Llandovery and the base of the Lower Arenig. These, corresponding essentially to the Upper Cambrian or Bala group of Sedgwick, — the second fauna of Barrande, — were, as is well known, by a mistake in stratigraphy, joined by Murchison to his Silurian system, under the name of Lower Silurian; and have also since been called Siluro-Cambrian and Cambro-Silurian. By making of this debated ground a separate region between the true Silurian above and the great Cambrian series below (the Middle and Lower Cambrian of Sedgwick), Lapworth has sought to get rid of the confusion in nomenclature, and to restrain the attempts of some to extend the name of Silurian downwards even to the base of the Cambrian itself. This new division is convenient in American geology from the fact that it includes the group of strata between the base of the Silurian (Oneida) sandstone and the base of the Chazy limestone; the latter, together with the Trenton, Utica, and Loraine divisions, being equivalent to the Ordovician. The name was given in allusion to the Ordovices, an ancient British tribe inhabiting North Wales. [Hicks, to whom we owe so much of our knowledge of the paleozoic rocks of Great Britain, has recently proposed to extend the term Cambrian above the limits assigned by Sedgwick, and to regard it as including three divisions, Silurian, Ordovician, and Georgian; the latter name, for the middle and lower divisions of the original Cambrian, being derived from the St. George's Channel, along which its principal groups in Wales are displayed.†]

The question of the relations of the great Keweenian

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* Geological Magazine, vi., p. 13.

† Geol. Magazine, 1885, iii., 359. For a detailed account of the Cambrian and Silurian question, see Chem. and Geol. Essays, pp. 349–386.

TABLE SHOWING THE STRATIGRAPHICAL RELATIONS OF THE TACONIC ROCKS.

Eaton's Nomenclature (1832).				Later Names.	
III. LOWER SECONDARY.	3.	Corniferous Lime-rock		Upper Helderberg	**Devonian.**
		Geodiferous Lime-rock		Niagara	**Silurian.**
	2.	Millstone-grit	**Second Graywacke.**	Oneida — Medina	
	1.	Graywacke-slate		Utica — Loraine	**Ordovician.** (Upper Cambrian.)
II. TRANSITION.	3.	Metalliferous Lime-rock		Chazy — Trenton	
		Sparry Lime-rock, Calciferous Sand-rock		**Upper Taconic.** (Quebec Group.)	**Cambrian.** (Middle and Lower Cambrian.)
	2.	Millstone-grit	**First Graywacke.**		
		Graywacke-slate			
	1.	Argillite		**Lower Taconic.** (Itacolumitic Group.)	**Taconian.**
I. PRIMITIVE.	3.	Granular Lime-rock			
	2.	Granular Quartz-rock			
	1.	Gneiss and other Crystalline Rocks		**Huronian.** **Laurentian.**	**Montalban.** **Norian.** **Arvonian.**

series (unknown to Eaton), already noticed on page 415, which lies at the base of the Cambrian, and above the Taconian, will be discussed at length farther on.

§ 18. We have placed at the base of the column, as representing the gneisses and other crystalline rocks (Eaton's Lower division of the Primitive series), the names of five groups: Laurentian, Norian, Arvonian, Huronian, and Montalban, the distinctness of which, in our opinion, is now established, alike on stratigraphical and lithological grounds, both in North America and in Europe. The following words, published in 1874, before the recognition of the Arvonian, are still applicable: "The distribution of the crystalline rocks of the Norian, Huronian, and Montalban series would seem to show that these are remaining portions of great distinct and unconformable series, once widely spread out over a more ancient floor of granitic gneiss of Laurentian age; but that the four series thus indicated include the whole of the crystalline stratified rocks of New England is by no means affirmed. How many more such formations may have been laid down over this region, and subsequently swept away, leaving no traces, or only isolated fragments, we may never know; but it is probable that a careful study of the geology of New England and the adjacent British provinces may establish the existence of many more than the four series above enumerated." *

III. — GEOLOGICAL STUDIES IN PENNSYLVANIA.

§ 19. The reader's attention is now called to the two districts in Pennsylvania mentioned in § 14; where the present writer has been enabled to confirm the observations of Vanuxem. To the west of the Susquehanna, in Mifflin County, is the Kishacoquillas valley, an eroded anticlinal valley, having a rim of Oneida sandstone (the Levant, or No. IV., of Rogers), which is the summit of the Second Graywacke of Eaton, and is conformably

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* Hunt, Chemical and Geological Essays, p. 281.

overlaid, on both of the monoclinal slopes, by the Medina and Clinton beds. Passing downwards from the massive sandstones of the rim to the centre of the valley, we find alternations of sandstone layers with sandy shales, succeeded, in descending order, by the Utica slate and the Trenton limestone; all of which are well characterized, both lithologically and paleontologically. The whole series, from the summit of the sandstone to the base of the limestone, here presents apparently one unbroken stratigraphical succession, corresponding to that already described as occurring in the central district of New York (§ 13), and to what is seen along the north shore of Lake Ontario, in Canada. A similar condition of things occurs in the Nippenose, the Nittany, and the other so-called coves or limestone valleys, which are found in central Pennsylvania, and, like that of Kishacoquillas, are eroded anticlinals. Accounts of these will be found in Rogers' "Geology of Pennsylvania," Vol. I., pp. 460–511; and also in Report T., on Blair County, by Franklin Platt, of the Second geological survey of the State. The latter tells us that "there is no appearance of non-conformability here between III. and IV."; that is to say, between the Loraine shale and the succeeding Oneida-Medina sandstones. Within these valleys, there appears, beneath the fossiliferous limestone, a great mass of magnesian limestones, several thousand feet in thickness, abounding in ores of iron and of zinc, and identical with the limestones of the Appalachian valley.

§ 20. When we pass from the central region of Pennsylvania to the east of the North or Kittatinny Mountain, we find, along the western border of the Appalachian valley, the sandstone, No. IV., which constitutes this monoclinal ridge, resting upon a great series of schistose rocks, declared by Vanuxem to belong to the Frankfort or lower division of his Hudson-River group, in which he included the roofing-slates of the region. The contact between the overlying sandstone and these rocks is not, however, as in the central valleys, one of conformable passage, through intercalations, into an underlying series of fossiliferous shales, but, as may be observed at the Lehigh Water-Gap, one of non-conformity. H. D. Rogers noted the fact that the conglomerates of the sandstone, No. IV., here include "many rounded pebbles and fragments of the three underlying formations which intervene between it and the Primary rocks at the bottom of the series."* He recognized among the pebbles portions of the Primal sandstone, of chert derived from the Auroral limestone, and of the Matinal slates. The presence of all these, which I have verified, is sufficient to show the complete stratigraphical break which here separates this Silurian sandstone from the subjacent argillites. These latter are seen along the banks of the Lehigh, resting in apparent conformity upon the Auroral limestone, — which, with its overlying and interstratified schists, and its subjacent quartzite, makes up the Lower Taconic of Emmons.

§ 21. As the result of my observations in these two regions of Pennsylvania, I stated, in 1878, that the passage in the central valleys "from the Upper Cambrian shales into the Silurian sandstones is gradual, and that there is no stratigraphical break; although, as shown by Rogers, such an interruption occurs between these same sandstones and the underlying slates along the northwest border of the great Appalachian valley."† This non-conformity has been questioned by Professor Lesley, but my own observations at the Lehigh Water-Gap are confirmed by those published by I. C. White, in 1882, in his Report G. 6, of the Second geological survey of Pennsylvania (pp. 150, 151), and I repeat his statement that "the proof seems conclusive" that the Silurian sandstone, IV., here rests unconformably upon the underlying slates. Of these, we have already spoken as entirely distinct from

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* Second Annual Report on the Geology of Pennsylvania, 1838, p. 36.

† Chem. and Geol. Essays, 2d ed., preface, p. xxi.

those fossiliferous shaly strata which underlie conformably the same sandstones in the valleys of central Pennsylvania.

§ 22. By Prof. H. D. Rogers, and his assistants on the First geological survey of Pennsylvania, the series of rocks found in the two regions just mentioned underlying the sandstone, No. IV., were regarded as stratigraphically equivalent. He rightly identified the fossiliferous shales and limestones which, in the central valleys, immediately underlie this sandstone, with the Loraine, Utica, and Trenton divisions of the Champlain series of New York, which in his nomenclature included three great divisions: I. Primal; II. Auroral; III. Matinal; the first, or silicious, corresponding to the Potsdam; the second, or calcareous, to the Calciferous, Chazy, and Trenton; and the third, or argillaceous, to the Utica and Loraine. This correlation, for the Trenton, Utica, and Loraine, was established by Rogers, alike on stratigraphical and paleontological grounds, for the central valleys. The rocks of the great southeastern or Appalachian valley, which were seen to be in many respects unlike the preceding, were spoken of by Rogers as belonging to a distinct or "southeastern type" of the same Primal, Auroral, and Matinal series. Herein, Rogers adopted the view of Mather, who, as we have seen (§ 11), had already declared these same rocks, in their extension to the northeastward, to be nothing more or less than modified representatives of the members of the Champlain series. In accordance with this view, Rogers called the quartzites and schists of the great valley, Primal, the granular limestones or marbles, Auroral, and the overlying schists and argillites, Matinal. Very great differences, both in thickness and in lithological characters, exist between this series and the Champlain division as seen in northern New York and central Canada; but the rocks in question lie, in both cases, between two well defined geological horizons, having the ancient gneiss below, and the Oneida, called by Rogers the Levant sandstone (which was IV. in his notation) above; and in both cases they present the same three-fold division of silicious, calcareous, and argillaceous strata.

§ 23. In support of the parallelism thus suggested, it was said that the peculiar markings to which the name of *Scolithus linearis* had been given — and which are characteristic of the basal or Taconic quartzite alike in Pennsylvania and in Massachusetts — were identical with a form found in the typical Potsdam sandstone of New York and Canada. The Potsdam form of Scolithus, however, as I have elsewhere shown, is very distinct, and does not resemble the Scolithus of the Taconic quartzite so much as it does the similar form found in the Medina sandstone.*

§ 24. There is, in fact, up to this time, no evidence that the typical Potsdam sandstone and Calciferous Sand-rock of northern New York exist in eastern Pennsylvania; but on the contrary there are many reasons for supposing that in this region, as in eastern Canada, and along the eastern side of the Champlain and Hudson-River valleys, the period of these two subdivisions of the New York system is represented by the First Graywacke of Eaton, the Upper Taconic of Emmons; which, as will be shown farther on, is now recognized as contemporaneous with the typical Potsdam and Calciferous subdivisions. Rocks supposed to represent this graywacke-series are found in the great valley of Pennsylvania, and these, together with the divisions immediately preceding them, — namely, the Primitive Quartz-rock, the Primitive Lime-rock, and the Transition Argillite, — which constitute the Lower Taconic of Emmons, — are, as we shall endeavor to show, represented by the so-called Primal, Auroral, and Matinal of the southeastern area.

§ 25. The Calciferous Sand-rock, together with the Chazy, Birdseye, and Black-River limestones of the Champlain division, was supposed by Rogers to be repre-

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* Azoic Rocks, pp. 135-139.

sented, in the area just mentioned, by the great masses of magnesian limestones and marbles, with intercalated schists, estimated by him at from 2500 to 5000 feet in thickness; while the succeeding schists and argillites were regarded as equivalent to the Trenton, Utica, and Loraine divisions. The large area occupied by these rocks of "the southeastern type," except in some few localities, had afforded no organic remains save the Scolithus, already mentioned; but the strata were supposed to have undergone a local alteration, or so-called metamorphism, effacing the evidences of organic life. The limestones of this series are in fact more or less crystalline, and often white or banded granular marbles. Moreover, there are intercalated both among the limestones and the quartzites of the series, peculiar schists sometimes containing hornblende, serpentine, talc, and chlorite, besides damourite, pyrophyllite, and other hydrous micaceous species, which have been mistaken for magnesian silicates, and have caused these rocks, as a whole, to be called talcose or magnesian. Many of these silicates, such as amphibole, serpentine, and mica, are also found in the limestones.

§ 26. These Taconic limestones and quartzites include, moreover, large masses of iron-ores, sometimes a peculiar type of magnetite, more rarely of hematite; besides beds or lenticular masses of pyrite and of siderite. The latter two species, in regions where the effects of sub-aerial decay are seen to considerable depths, are converted into the so-called brown hematite ores — limonite and turgite — which are found imbedded in soft clayey and generally highly inclined strata, the results of the decomposition and partial solution of the limestones and their associated schists. The limonitic ores of this horizon are extensively mined along the outcrop of these Taconic rocks, from Vermont to Alabama; and, as has been shown by the concordant observations of many investigators, have been derived by epigenesis, in some cases from the sulphid, and in other cases from the carbonate of iron; both of which, in the deeper workings, are found unaltered. Crystals of magnetite are sometimes disseminated through these schists, as well as thin layers of compact hematite, both of which are occasionally found in the clayey beds with the limonites. The massive granular magnetic ores of this horizon in Pennsylvania are generally associated with small quantities of pyrite and chalcopyrite, and frequently yield by analysis a little cobalt. They are distinguished from the magnetites of the older rocks by their generally finely granular texture and feebler cohesion, as well as by the characteristic imbedded minerals. The hematite is often a very soft unctuous micaceous variety, and both magnetite and hematite are occasionally found in grains disseminated in the soft granular sandstone layers. The limonites are often manganiferous, and are sometimes accompanied by manganese-oxyds, which are doubtless derived from corresponding manganesian carbonates.* Associated with the limestones of this series are sometimes considerable interbedded deposits of zinc-blende, and oxydized ores of zinc are found at the outcrops of these.†

§ 27. As regards the thickness of the strata which in the central region of Pennsylvania underlie the sandstone, No. IV., we find in the Kishacoquillas and Nittany

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* The few carbonated ores from this horizon in Pennsylvania, which have been analyzed, are more or less manganesian ; one of them yielding to McCreath 5.0 per cent of manganesian carbonate. A massive fawn-colored carbonate, with a specific gravity of 3.25, found in layers in the so-called Primordial slates of Placentia Bay in Newfoundland, gave me by analysis 81.6 per cent of manganesian carbonate, and 15.4 per cent of silica for the most part soluble in a dilute alkaline solution, besides traces of ferrous, calcareous, and magnesian carbonates. It was partially incrusted with black crystalline manganese-oxyd, evidently of epigenic origin. Amer. Jour. Science, 1859, vol. xxviii., p. 374.

† The chief facts in the mineralogical history of these rocks will be found in my volume already cited ; Azoic Rocks, etc., pp. 201, 206. See also a description of the Cornwall Iron-Mine, etc., Proc. Amer. Institute Mining Engineers, vol. IV., pp. 319-325, and two notes on the Taconic System, and on the Genesis of Iron Ores, published in the Canadian Naturalist for December, 1880 ; besides a farther discussion of this subject, pp. 261-268 of the present volume.

valleys, respectively — for the Loraine shales, a thickness of 1200 and 700 feet, for the Utica slate, 400 and 300 feet, and for the fossiliferous Trenton beds, 400 and 300 feet. Beneath the latter, in these central valleys, lies a great mass of magnesian limestones interstratified with schistose beds; the whole called by Rogers, Auroral, and supposed by him to be, like the similar rocks in the eastern part of the State, the representatives of the Chazy and Calciferous divisions of the New York system. To this succession of limestones, as observed at Bellefonte, Rogers assigned a thickness of over 5400 feet, of which the upper 600 are highly fossiliferous; while the great underlying portion is destitute of fossils, or contains but few and undetermined organic forms. The most complete section of the strata below the sandstone, No. IV., in the central region, is that lately measured by Mr. Saunders, in Blair County; where, beneath 900 feet representing the Loraine and Utica shales, are found not less than 6600 feet of strata, including, at the top, the fossiliferous Trenton beds, whose thickness is not separately given, and, near the base, intercalated sandstones and shales.* A summary of this section gives, in descending order: —

	Feet
Sandstone, No. IV.	—
Upper shales (Utica and Loraine)	900
Limestones and dolomites, including the fossiliferous Trenton	5400
White sandstone	40
Limestone with sandstone and shales	1160
	7500

§ 28. In none of the sections of these rocks exposed in the eroded anticlinal valleys of the west, has anything been found corresponding to the older crystalline groups which, along the border of the southeastern region, underlie the base of this series. For the rest, these lower non-fossiliferous strata present similar mineralogical characters

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[*] Second geological survey of Pennsylvania, Report T, by Franklin Pratt, pp. 18, 48–59.

to those of the great valley to the southeast, and include extensive deposits of limonite (imbedded in clays, which are decayed schists *in situ*), as well as ores of zinc; both of which are largely mined in Blair County.

§ 29. If we turn from these central valleys of Pennsylvania to what Rogers called the southeastern area, that is to say, the regions lying to the southeast of the Kittatinny Mountain, we find a very different condition of things. In place of the 900 feet of fossiliferous shales measured in Blair County between the limestone below and the overlying sandstone, we find not less than 6000 feet of unfossiliferous strata. As long since measured by Rogers, on the west side of the Delaware River, at the Water-Gap, there are 6102 feet between the base of the sandstone, No. IV., and the underlying Auroral limestone.* Mr. Chance, in a later section in this vicinity, makes them above 3900 feet, and Lesley concludes from observations on the Susquehanna that they have an aggregate thickness of not less than 6000 feet, which agrees with the early measurements of Rogers. The characters of this great group of strata in the Kittatinny valley, included both by Rogers and by the second geological survey in the Matinal division, are exceedingly variable, and they present important local differences. The roofing-slates already mentioned (§ 20) are confined to a small area in the northwest part of this valley, occupying a narrow zone lying from one to three miles south from the base of the Kittatinny Mountain, and extending from a point in New Jersey a few miles east of the Delaware Water-Gap, across the Delaware and Lehigh, and a few miles west of the latter river. These roofing-slates were assigned by Rogers to the lower part of the group in question. According to Chance also, who has lately examined them, they are very low in the series, and of no great thickness; but are affected by such sharp flexures that the dips on both sides of the anticlinals and synclinals are nearly parallel, so that the apparent

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* Second Annual Report, 1838, p. 35.

thickness of the roofing-slates is much augmented.* In the region to the west of the Lehigh, in the counties of Berks and Lebanon, these Matinal slates include a great amount of coarse arenaceous rock, and rise into bold hills. Some parts consist of heavy gray sandstones with conglomerates, and bluish or grayish shales with thin-bedded limestones. Large portions are characterized by a predominant reddish or reddish-brown color, with interstratified beds of yellow or fawn-colored shales, and are said by Rogers to resemble the strata of the Medina and Clinton, above No. IV.

Mention should also here be made of the existence of considerable masses of conglomerate made up of more or less completely worn pebbles of the Auroral limestone in a calcareous cement, which are found at several points in the great valley, and have been described by Rogers as resting upon the Auroral limestone.†

§ 30. From my observations in this region, in 1875, when I had an opportunity of seeing the rocks of this group at several points in the Appalachian valley between the Lehigh and Schuylkill Rivers, I was struck with their great resemblance to the First Graywacke of Eaton (the Upper Taconic of Emmons, or Quebec group), as seen from the banks of the St. Lawrence at Quebec, to the valley of the Hudson; which, it will be remembered, was, by Mather, confounded with the Second Graywacke (§ 12). It is apparent from a section to be seen a little west of the Lehigh, below Slatington, that the coarse red and gray sandstones, with red shales and conglomerates, overlie the roofing-slates of the valley; and their geographical relations are such as to suggest an unconformable superposition.

§ 31. Regarding the rocks of this valley, I expressed, in 1878, my belief "that besides the Auroral limestones,

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* Rogers, Geology of Pennsylvania, I., 247; also, Second Geol. Survey Penn., Report G 6; pp. 340, 363.

† Geology of Pennsylvania, I., 252.

with their succeeding argillites, and the unconformably superimposed (Oneida) Silurian conglomerates of the North Mountain, there are, to the west of the Lehigh River, portions of two intermediate formations. One of these, marked by red-colored sandstones, conglomerates, and slates, appears to be the same with the Upper Taconic or Cambrian belt; which has been traced by H. D. Rogers, Mather, Emmons, Logan and the writer, with some interruptions, from New Jersey to Canada, along the great Appalachian valley. The other is an impure black earthy limestone, becoming in parts a soft, thinly bedded flagstone, which was seen lying, at moderate angles, above the blue limestone of the valley, not far from Copley, and was then supposed to belong to a different series. It is apparently the same with the Trenton beds recognized by Professor Prime in that vicinity,"* as mentioned below (§ 34).

§ 32. We have noted the evidence of a stratigraphical break between the slates of the great valley and the overlying Levant (Oneida) sandstone in the Kittatinny Mountain, and have shown that the conglomerates of the latter include numerous pebbles derived alike from the underlying Primal, Auroral, and Matinal rocks. If now we turn to the central valleys we find, as already stated, no evidence of any stratigraphical break; but, on the contrary, a passage downwards from the Oneida sandstone to the underlying Loraine and Utica slates. We still, however, find in these sandstones similar conglomerates to those of the Kittatinny range. This is well seen in Jack's Mountain, on the eastern border of the Kishacoquillas valley, where the Levant division is described by Rogers as consisting in its lower part of four hundred feet of sandstone; of which he says, it contains "numerous pebbles of white quartz, of Matinal slate, and of the harder Primal strata, and is really a conglomerate." The upper member of the Levant, which is still thicker, is also a conglomer-

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[*] Hunt, Azoic Rocks, p. 215.

ate, holding in parts quartz pebbles, in addition to which, "flat lumps and pebbles of red shale occur throughout the whole mass."* The pebbles of these conglomerates, which I have examined *in situ*, have evidently nothing in common with the fossiliferous strata below them, but are derived from older rocks, like those of the Kittatinny valley, and include large quantities of the characteristic red shales which we have already noticed.

§ 33. The thickness of the Auroral limestones in the great valley is less than farther west, being, according to Chance, about 3000 feet on the Susquehanna; while at Bethlehem and Allentown, in Lehigh County, they measure about 2000 feet, according to Prime, who thinks their maximum thickness there may be 2500 feet. These Auroral limestones, with their immediately associated schists and limonites, have been carefully studied by Prime in the county just named, and are described by him in Reports D and D 2, of the second geological survey of Pennsylvania. Schistose layers, with limonite, are there occasionally intercalated in the limestone, but the principal bodies of clay, or decayed schist, holding this ore, are, according to this observer, found at two horizons, the one near the summit and the other at the base of the limestone, between it and the underlying quartzite; which, also, includes in this region, schistose bands with hydrous micas, limonite, and occasional layers of red hematite.

§ 34. These Auroral limestones and shales were, as we have seen, supposed by Rogers to be the equivalents of the New York series from the base of the Calciferous to the summit of the Birdseye and Black-River divisions; the Trenton limestone proper being, according to him, represented in the eastern area only by some beds of argillaceous limestone, which were by Rogers included in the Matinal division of his classification. According to Prime, "the Trenton or fossiliferous limestone seems to

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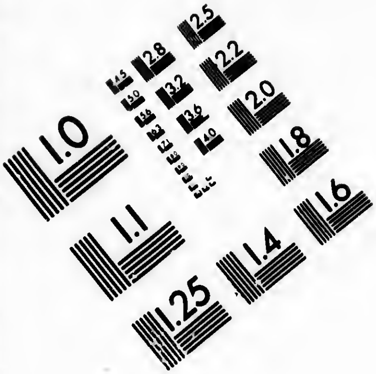
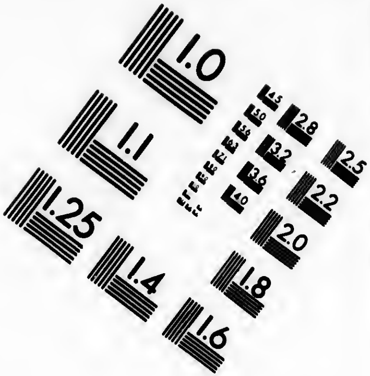
* Rogers, Geol. of Penn., Vol. I., p. 473.





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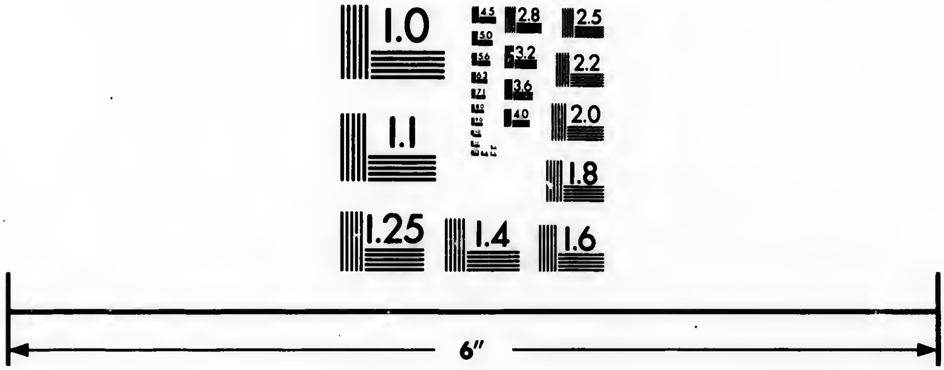

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occur only at a few points in the valley," having been recognized by its fossils at one locality only. It is here dark-colored, earthy, and uncrystalline, and associated with argillaceous beds which yield a hydraulic cement. These, which are supposed to belong to the same horizon, are found at several other places in the region, overlying the magnesian limestone. Prime also mentions one locality where forms referred to Euomphalus and Maclurea are met with, indicating the horizon of the Chazy; while in another an undescribed Lingula occurs. Peculiar funnel-shaped markings, not very unlike the Scolithus of the underlying quartzites, have also been found in the magnesian limestone in one place, and have been referred to the genus Monocraterion, which occurs in the Eophyton sandstone of Sweden. For farther notice of these organic forms see the author's volume on "Azoic Rocks," p. 206, and also Professor Prime's Report D 2.

§ 35. The Primal division of the series under consideration is, in the northeast part of the great valley, in Pennsylvania (where it rests unconformably upon the Laurentian gneiss), a thin and irregular deposit, and, according to Rogers, is sometimes wanting; in which case the Auroral limestone reposes directly upon the gneiss, as may be seen in Lehigh and Northampton Counties. In the North-Valley Hill, in Chester County, and farther to the northeast, in Lehigh County, the Primal quartzite, often with Scolithus, is seen to rest, with a thickness of from twenty to fifty feet, directly upon the Laurentian gneiss. These basal beds in Chester County include some micaceous and schistose layers, and are followed by the Upper Primal slates and the Auroral limestones. The rock is sometimes granular, and often detrital, while at other times it is a hard granular or even flinty quartzite. Farther to the southwest, in Berks County, the Primal quartzite becomes more continuous and thicker, rising into high ridges.

§ 36. The conditions above noticed show the deposition of these rocks over an uneven subsiding gneissic area, and a conformable overlapping of the Primal beds by the succeeding Auroral limestone. As described by the writer in 1876, "they were evidently deposited over a subsiding continent, with bold shores; so that while the Primal has in places a great thickness, it is elsewhere very thin, or entirely wanting beneath the Auroral, which rests directly upon the older crystalline rocks." * The characters of the Primal are best seen farther to the west, where, in the broader part of the basin, it is brought up by undulations from beneath the Auroral, and appears as a complex group of considerable thickness, with alternations of quartzites, argillites, and crystalline schists, beds of iron-ores, and intercalated limestone-layers; the latter constituting, as well described by Rogers, beds of passage into the overlying Auroral limestone. Rogers defined the group as a Primal sandstone, with slates above and below; but it is occasionally less simple, since what he called the Upper Primal slates may include interstratified sandstone-beds, sometimes of considerable thickness. Thus, in a section near Parkesburg, on the North-Valley Hill, described by him, a mass of 200 feet of yellow sandstone is found, with 300 feet of slates above, and 350 feet more below, lying between this upper sandstone and the white Scolithus-sandstone beneath, which here measures fifty feet; the section being as follows, numbered in descending order: —

		Feet.
0.	Auroral limestones	—
1.	Upper Primal slates with sandstone layers	300
2.	Yellow sandstone.	200
3.	Laminated slaty beds	350
4.	Middle Primal sandstone, with Scolithus	50
5.	Lower Primal slates	300–400

A section at Chickis, on the Susquehanna, also described by Rogers, gives a still greater thickness of strata referred

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* Harpers' Annual Record for 1876, p. xcvi.

by him to the Primal; the base of the series not being exposed. We have, as before: —

	Feet.
1. Upper Primal slates	1800
2. White sandstone	27
3. Slates	300
4. Sandstone with Scolithus	—

We shall notice farther on the characters of the Lower Primal slates as seen elsewhere in their distribution, both in Pennsylvania and in other States.

§ 37. Since the time when Rogers made his geological investigations in Pennsylvania, researches in various parts of the Atlantic belt, and elsewhere, have shown that between the ancient gneisses which were known to him, and the base of the Primal series, there are, in many localities, one or more groups of crystalline stratified rocks. Of these, portions of the Huronian, and of the younger gneisses and mica-schists which have been called Montalban, present certain mineralogical resemblances to the schists of the Lower Primal; which, as well as those interstratified with and overlying the Auroral, are, as was stated by Rogers, more or less distinctly crystalline schists. Misled by these resemblances, Rogers confounded these crystalline Primal strata with portions of the groups lying between them and the older gneiss: including both under the general name of "semi-metamorphic schists."

§ 38. No stratigraphical break separates the Scolithus-sandstone from the Lower Primal slates, and thus the whole of these so-called semi-metamorphic schists below this horizon were included in one great group. This was described as a downward prolongation of the Paleozoic series; but, from the absence of organic remains, was distinguished alike from this, and from the more ancient or so-called Hypozoic gneisses, by the name of the Azoic series. There was, according to Rogers, among the rocks of the Atlantic belt, but "one physical break, or horizon of unconformity, throughout the immense succession of altered crystalline sedimentary strata," namely, that at the summit of the ancient or Hypozoic gneiss; and "one paleontological horizon — that, namely, of the already discovered dawn of life among the American strata. This latter plane or limit, marking the transition from the non-fossiliferous or Azoic deposits to those containing organic remains, lies within the middle of the Primal series of the Pennsylvania survey; that is to say, in the Primal white sandstone, which, even where very vitreous, and abounding in crystalline mineral aggregations, contains its distinctive fossil, the Scolithus linearis."

§ 39. In the opinion of Rogers, the whole series of strata below the Levant sandstone had, in the southeastern area, been the subject of alterations, which had given to them the characters of crystalline rocks. I have elsewhere set forth at some length the views of Rogers on this point, and have shown that his conclusions with regard to the so-called Azoic rocks were not clearly defined, and that, in his opinion, it was often difficult, if not impossible, to distinguish between the upper portions of the Hypozoic and certain parts of the Azoic series. It would appear from his descriptions, and from my own examinations in the region, that portions of Huronian, and of Montalban, were by him included in the Hypozoic; and other portions of the same or of older rocks, in the Azoic, or even in the Upper Primal slates. Both these, and the Primal quartzite itself, were by Rogers supposed to have been changed into feldspathic rocks; and he has described as altered Upper Primal, a great group of such rocks seen in the South Mountain to the south of the Susquehanna, which we shall proceed to notice.

§ 40. Leaving the Mesozoic red sandstones at Gettysburg, and passing westward over the South Mountain, by Caledonia Spring to Chambersburg, we meet first with a belt, more than two miles wide, of crystalline rocks, regarded by Rogers as in part Upper and in part Lower

Primal slates; the latter represented by talcose, chloritic, and epidotic schists, with diorites, and the former by what were called by Rogers, "jaspery rocks," and "reddish jaspery slates." These, which I first saw with Dr. Persifor Frazer, in 1875, were found to consist of petrosilex or compact orthofelsite, often becoming porphyritic from the presence of crystals of feldspar or of quartz. I then compared them with the similar rocks found along the coasts of Massachusetts and New Brunswick, and on Lake Superior, all of which I at that time included in the lower part of the Huronian, but have since been led to regard as an independent series, identical with the Arvonian of Hicks; which, in Wales, appears to be interposed unconformably between the Laurentian (Dimetian) below, and the Huronian (Pebidian) above.

§ 41. To this series also belongs a great thickness of petrosilex-rocks, often porphyritic, and associated with small portions of soft, unctuous micaceous schists, occurring in central Wisconsin, where they overlie conformably a great mass of vitreous quartzites, which, from the intercalation of similar micaceous layers, apparently belong to the same series with the petrosilex. These rocks, originally described by Percival as altered Potsdam sandstone, were by James Hall, in 1862, referred to the Huronian, with which they are also classed by Irving, who has since described them.* I have recently examined these rocks, *in situ*, as seen on the Baraboo River in Wisconsin, and have found them indistinguishable from the petrosilex-beds of Pennsylvania and of our Atlantic coast, and from the typical Arvonian of Wales.

§ 42. These petrosilicious strata, presenting many varieties in color and in texture, have a great thickness in the South Mountain, west of Gettysburg, where they generally dip southeastward at high angles. With them are seen in some parts, apparently interstratified, thin

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* See Geology of Wisconsin, 1877, vol. ii., pp. 501–521; also Hunt, Azoic Rocks, p. 232.

bands of argillite, with chloritic and epidotic rocks, such as I have found with the similar petrosilicious rocks on Passamaquoddy Bay, on the Atlantic coast. This crystalline series is, to the westward, unconformably overlaid by a belt, about a mile and a half wide, of sandstone, with conglomerates, generally with a northwestern dip, constituting what is known as Green Ridge. This is followed by a repetition of the petrosilicious rocks, again with high southeast dips, and by a great mass of chloritic and epidotic strata, overlaid to the westward, as before, by a considerable thickness of Primal sandstone, which dips in that direction beneath the Primal slates and Auroral limestones of the Appalachian valley.

§ 43. In this remarkable section, it is evident that the crystalline rocks, upon which the Primal quartzite rests unconformably, belong to one or more older series, distinct from the Laurentian, and representing both the Huronian and the petrosilex or Arvonian series. I was thereby confirmed in my opinion, expressed in 1871, that the crystalline schists regarded by Rogers in this region as altered Lower Primal and Upper Primal, are both of them older than the Primal quartzites, and belong to one or more distinct series. These conclusions were announced in the Proceedings of the American Association for the Advancement of Science for 1876 (pp. 211, 212), and also in Azoic Rocks (pp. 18 and 193). Frazer, who has since devoted much time to the study of the region, agrees with me in placing the crystalline rocks of the above section in the Huronian, including under that name the accompanying petrosilex group; and regards the quartzites as there forming the basal member of the Primal series.*

§ 44. From the observations given in § 36, it is apparent that the Primal series of Rogers, where most largely developed in Pennsylvania, includes several repetitions of quartz-rocks, sometimes vitreous, sometimes granular, and

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* Thèse présentée à la faculté des sciences de Lille, etc., 1882.

occasionally detrital and conglomerate in character, alternating with softer schistose strata. This will be farther illustrated in a succeeding chapter, by observations in Virginia and elsewhere; when it will also appear that repetitions of these quartzites are met with below the horizon of the Scolithus-sandstone. In many cases, a quartzite, often a conglomerate, is found to constitute the basal member of the series, which rests unconformably upon different groups of the older crystalline rocks, — Laurentian, Arvonian, Huronian, or Montalban. Inasmuch as portions of the latter two groups were by Rogers confounded with the Lower Primal slates, it will require careful examination, in each case, to determine whether we have really to do with the older rocks, or with strata belonging to his Primal series.

Notwithstanding the division of the latter into Azoic and Paleozoic, based by Rogers upon the appearance, in the midst of the Primal, of the Scolithus-sandstone, it is to be remarked that the Primal slates, both above and below this horizon, really constitute, with the rocks of the Auroral, and a portion of the Matinal in the southeastern area of Pennsylvania, one great continuous series. Similar schistose and micaceous layers are found intercalated alike among the Primal quartzites and the Auroral limestones; while the accompanying masses of slate often include minor beds of quartzite, and others of granular limestone. The intimate relations of these various rocks were noticed by Rogers, who mentions what he calls "the alternations of Primal slate and Auroral limestone," and "the limestone at the passage of the Primal into the Auroral." The Lower Primal slates were elsewhere described by him as alternations of "talcoid silicious slate, talco-micaceous slate, and quartzose micaceous rocks," usually schistose, besides other strata which are nearly pure clay-slate. Portions of the Matinal, in like manner, were said by him to be "a semi-crystalline clay-slate, partially talcose or micaceous." Later studies have shown these strata to abound in hydrous micas, and more rarely to contain talc, chlorite, and related species. Some beds in the Primal slates are apparently feldspathic in composition, since they are changed by sub-aerial decay into clays resembling kaolin.

§ 45. The continuous belt of Primal and Auroral rocks stretching along the southeast base of the North or Kittatinny Mountain, is bounded on the south, in its extension between the Delaware and Schuylkill Rivers, by the so-called South Mountain. Beyond the Schuylkill, at Reading, this Laurentian range is, so far as known, represented only by one small mass, a little west of the town. Its disappearance at the Schuylkill, to rise again south of the mesozoic belt, in the northern part of Chester County, permits a great extension of breadth of the Primal and Auroral rocks to the southward, in the counties of Chester, Lancaster, and York, where they appear, both to the north and the south, from beneath the broad and somewhat irregular belt of mesozoic sandstone which, from the Delaware to the Susquehanna, crosses the State in an east and west direction. From the Susquehanna to the line of Maryland, however, the trend of this belt is to the southwest. The Primal and Auroral strata, along the south and east of the mesozoic, occupy the limestone-valleys of Lancaster and York Counties, with which the narrow limestone valley of Chester County, lying to the eastward, is, as Frazer has shown, continuous.

§ 46. The South Mountain, which, as we have seen, is effaced between the Schuylkill and the Susquehanna, reappears to the southwest of this river, in the broad ridge of crystalline rocks, already described in § 40 as found in Adams County, between the continuous limestone-valley on the northwest, and the mesozoic on the southeast. In this ridge of Huronian and Arvonian rocks, the Laurentian has not yet been recognized. It, however, as already remarked, appears in Chester County, between the mesozoic and the Chester limestone-valley. In addition to this, I pointed out, in 1876, the existence of a subordinate Laurentian axis, south of the limestone-valley just named, crossing the Schuylkill in Buck Ridge, near Conshohocken.* This ridge bears upon both flanks the Montalban gneisses and mica-schists; while between these and the Laurentian, on the south side of the axis, there is seen on the river an intermediate mass of hornblendic and chloritic schists, with serpentine, enstatite, and steatite, which may be an intervening outcrop of Huronian.

§ 47. Returning now to the Primal and Auroral rocks, the distribution of which has been defined, we remark that it is chiefly along the border of the mesozoic belt that the Primal schists, with their accompanying crystalline iron-ores, already noticed (§ 26), are best exposed. Examples of these ores are seen at Boyerstown, and near Reading, at Wheatland, Cornwall, and Dillsburg, on the north side, and at the Warwick and Jones mines, on the south side, of the mesozoic sandstone. Rogers, in his third annual report on the geology of Pennsylvania, in 1839, referred these iron-ores to the mesozoic or "middle secondary red sandstone" series, giving, as examples, besides the mines just mentioned on the south side of this belt, the Cornwall mine on the north side. In his final report, in 1858, however, he referred these crystalline iron-ores and their enclosing schists to the Upper Primal slates. He regarded the iron as an original constituent of the sediments, but supposed it to have been re-arranged "by some agency connected with the metamorphism of the strata." Lesley, in 1859, in his "Iron Manufacturers' Guide," described these same ores under the head of "Primary," with those of the gneisses and pre-paleozoic crystalline rocks; at the same time referring with approval to those who regard these ores "as of middle secondary, and not of primary age." Subsequently, in the same volume, he noticed the later view of Rogers

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* Azoic Rocks, page 200.

already stated, and apparently accepted it, at least for the ores of Warwick, of Cornwall, and of Chestnut Hill, where magnetite is closely associated, in adjacent strata, with limonite. Frazer, however, in 1876, still maintained the early view of Rogers for the ores of Dillsburg, in Adams County, which he describes as included in the mesozoic series,* and they are so classed in McCreath's Report M 3 (preface, page x) of the Second geological survey, in 1881.

§ 48. From my own somewhat extended studies of all the localities known along the two borders of the mesozoic belt in Pennsylvania, I am constrained to maintain the opinion expressed by me in 1875, that the ore-beds near Dillsburg form no exception, but that these, with the deposits of ore at Cornwall, at Wheatland, in the vicinity of Reading, and at Boyerstown, on the north, as well as those of the Warwick and Jones mines, on the south, all belong to the same ancient horizon. That they are met with chiefly along the borders of the mesozoic-sandstone belt, as I then said, "is due to the fact that these ancient ore-bearing rocks, from their decayed condition and their inferior hardness, have been removed by denudation, except where protected by the proximity of the newer sandstones, or by eruptive rocks, as is the case at the Cornwall mine." † There, as I have pointed out, the dikes from the neighboring mesozoic area have served as barriers, and have preserved from erosion a great mass of magnetic iron-ore.

§ 49. The stratigraphical relations of these ore-bearing rocks serve to show that they must be referred to the Primal schists which underlie the mesozoic sandstones. These latter, which are generally regarded as of triassic age, form a continuous belt from the banks of the Hudson southwestward across New Jersey and Pennsylvania into

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* Second Geological Survey of Penn., Report C, page 71; and Trans. Amer. Inst. Mining Engineers, v., 133.

† *Ibid.*, iv., 320.

Virginia. Throughout this region, as is well known, these newer rocks have everywhere a moderate and very uniform dip to the northwestward, of from ten to thirty degrees, and were deposited upon the worn surfaces of the previously folded Primal and Auroral rocks, which have contributed largely to the materials of the mesozoic. These older strata, unlike the latter, present everywhere considerable undulations, with dips, sometimes at high angles, alike to the northwest and the southeast. The unconformably overlying mesozoic rocks, now themselves affected by a gentle and pretty uniform inclination to the northwest, agree nearly with the older rocks in strike; and the coincidence which thus appears between the mesozoic and the northward-dipping outcrops of the older rocks readily explains how the two have been confounded.

§ 50. In the vicinity of Dillsburg, where numerous openings for iron-ore have been made, the dip of the enclosing strata, so far as observed, is to the northwest. The same condition is seen at Wheatfield, to the east of Cornwall, where several lenticular masses of magnetite have been mined; but at Fritztown, less than half a mile to the southward, the similar ore-bearing strata dip to the southeast. Again, at the Roudenbusch mine, near Reading, is a bed of magnetite which had, in 1875, been mined for a distance of 480 feet down the slope of the bed; the dip being thirty degrees in a direction S. 30° E. At the Island mine, also near Reading, is a similar opening for ore, which had been followed 240 feet on the incline, with a dip of forty-five degrees to the southeast; while immediately to the north of this opening is a slope with a still steeper dip to the northwest, on what appears to be the same ore-bed; indicating the presence of an anticlinal in the ore-bearing strata. At Boyerstown, still farther east, where the mesozoic lies along the southeast flank of the South Mountain, there is opened, at its margin, a mine in which the ore-stratum had, in 1875, been followed down the slope, 400 feet, at an angle of forty-five degrees to the east of south. At the great Cornwall mine, which, like all those above mentioned, lies on the northern border of the mesozoic, the ore-bearing strata are very slightly inclined; while at the Jones mine, on the southern border, they have a general inclination to the northward, and pass visibly beneath the adjacent mesozoic sandstone.

§ 51. The identity of mineralogical characters in all of the localities mentioned is very marked. The association with the granular magnetite, of pyrites, with portions of copper and cobalt, the admixture of a greenish, granular silicate, apparently related to pyroxene, and the constant proximity to the ores, of limestone and of serpentine, leave no doubt that we have to do with one and the same stratigraphical horizon; which, as the observations in many of the localities show, is unconformably subjacent to the contiguous mesozoic rocks. It may here be noted that the concretionary structure of some of the limestone-masses which accompany the ore-beds in these Primal slates, has led to their being confounded with the conglomerate of limestone pebbles often found in the mesozoic strata of the region. All of the rocks which, in the southeastern area of Pennsylvania (that is to say, to the southeast of the Kittatinny Mountain), belong to the Primal or Auroral divisions of Rogers, as well as those portions of the Matinal which are not included in the First Graywacke, or in the small Ordovician areas (§§ 31, 34), appertain to the Lower Taconic series of Emmons.

IV.— LOWER TACONIC ROCKS IN VARIOUS REGIONS.

§ 52. The Lower Taconic rocks, as seen in their typical locality, the Taconic hills in Williamstown and Adams, Berkshire County, Massachusetts, were described by Emmons as including, at the base, a conglomerate of varying thickness, resting upon the ancient gneissic rocks of the region, from the ruins of which it is derived;

and consisting of pebbles and fragments of quartz and feldspathic rock in a so-called talcose paste. Above this is found a rock described as a quartziferous talcose schist, sometimes including needles of tourmaline, and followed by the characteristic Granular Quartz-rock of Eaton. This, like the similar rock in Pennsylvania, has afforded Scolithus linearis: a specimen from Adams being figured, together with one from Chikis, Pennsylvania, by Hall, in his "Paleontology of New York," vol. i., pl. 1.* Above this Scolithus-sandstone, which is 100 feet thick, is a succession of so-called talcose slates, with two interposed beds of quartzite, one of which, fine-grained, massive, and jointed, measures 400 feet in thickness; the whole succession appearing in Oak Hill, arranged in a synclinal form, with moderate dips, and having a thickness of about 1200 feet.

§ 53. Immediately succeeding this, is found the Stockbridge limestone or marble, often dolomitic, and having its bedding-planes in many places marked by scales of a greenish micaceous mineral, called talc by Emmons; the presence of which gives rise to varieties of marble resembling the Italian *cipollino*. The limestone is white or gray in color, sometimes very dark, and more rarely reddish. To this mass, as seen on the western slope of Saddle Mountain, a thickness of 500 feet was assigned. Succeeding this is a mass of 2000 feet of soft slates, resembling those found below the limestone, and also occasionally interstratified with it. The limestone is said to be, in fact, intercalated in a great series of such slates, and to appear in similar relations throughout western New England and eastern New York. The aggregate thickness of

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* These two specimens, and a similar one, the locality of which is not given, are the only ones figured by Professor Hall for the Scolithus of the Potsdam. This form, however, is not known in the true Potsdam sandstone, as seen in the Champlain and Ottawa basins; nor, so far as I am aware, on the upper Mississippi; through all of which regions this sandstone is characterized by the very distinct form described by Billings as Scolithus Canadensis. See Azoic Rocks, pp. 135-139.

the whole series in Berkshire County, as above described, was estimated by Emmons at about 3700 feet.

§ 54. The roofing-slates of the series are, according to him, included in the great mass of so-called talcose slates above the Stockbridge limestone, and are found, with similar characters, from Massachusetts to North Carolina. Elsewhere, he mentioned that a band of argillites of variable thickness, adapted for roofing-slates, is also sometimes found in the schists beneath the limestone. Emmons was careful to distinguish between these Lower Taconic argillites, and those red and green roofing-slates which are found in the Upper Taconic. He farther affirms that the talcose slates, with their associated roofing-slates, are not found in the Upper Taconic series.

§ 55. It is well known that throughout this belt of Lower Taconic rocks east of the Hudson, as well as farther south, great deposits of limonite are found in the decayed schists of the series. Associated with this is an aggregate described by Emmons as an iron-breccia, made of fragments of quartz cemented by limonite, which, according to him, is characteristic of this horizon in Vermont, Massachusetts, Pennsylvania, Virginia, North Carolina, and Tennessee. Such a quartziferous limonite is also described by C. U. Shepard as found in the same belt at Kent, in Connecticut.* In an iron-mine, open in 1875, near Reading, Pennsylvania, I examined a similar aggregate, holding numerous pebbles of white quartz in a paste of limonite. At a depth of sixty feet, the ore-stratum being highly inclined, the limonite was replaced by granular pyrites, also holding quartz-pebbles, and it was evident that the alteration of this bed of pyrites had given rise to the limonite-conglomerate.

§ 56. The Lower Taconic series, according to Emmons, is as well developed in the southern as in the northern United States. "From the northern part of New England it is prolonged southward, and upon the line of

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* Geological Survey of Connecticut, 1837, p. 23.

prolongation it continues uninterruptedly for more than one thousand miles." It extends, in fact, through the whole length of the great Appalachian valley, and is well known from Pennsylvania southwestward through Virginia and East Tennessee to Georgia and Alabama. A section of these rocks from near Wytheville, in the valley of Virginia, and another near Harper's Ferry, will be found described by Emmons in his "American Geology," part II. These resemble closely both that of Berkshire County, Massachusetts, and those in Pennsylvania given in the preceding chapter. With all these we may compare a recent section along the western base of the Blue Ridge, in Virginia, described in a private communication from Prof. W. M. Fontaine. The granular quartz-rock with Scolithus, here 300 feet thick, is separated from the great mass of limestones above by about 600 feet of slates with limonite, and is underlaid by more than 1700 feet of argillites and sandstones, with intercalated strata of unctuous lustrous schists, apparently containing a hydrous mica, and sometimes decaying to kaolin. In the lower portions, which become more quartzose, are beds holding in a slaty matrix pebbles of quartz and of feldspathic rocks; and the base of the section is described as a conglomerate made up of pebbles from the eozoic rocks of the Blue Ridge, towards which the whole series dips, and beneath which it seems to pass. The strike of the Primal rocks is N. 60° E., while that of the eozoic is N. 30° E. The lower portions of the Taconic series are here sometimes concealed by faults.

§ 57. It is hardly necessary to repeat that the great Lower Taconic belt, as above defined, includes the Primal and the Auroral, together with a portion of the Matinal of Rogers, in Pennsylvania, where some localities were examined and described by Emmons. In our account of these rocks, in that State, in the last chapter, we called attention to the thinning-out of the slates and quartzites in some localities along the borders of the deposit, and even their concealment beneath the conformably overlapping limestone. We also noticed the appearance of these rocks of the Primal division, elsewhere, from beneath the limestones, with a volume not less than that measured by Emmons and Fontaine. The great thickness assigned to the limestones of the series in Pennsylvania is to be noted; and also the consideration that some of this apparent thickness of several thousand feet may possibly be due to repetitions. We have also remarked the fact that these Lower Taconic or Auroral limestones are brought up by undulations from beneath the overlying rocks in the central valleys or coves of Pennsylvania. The same condition of things is met with in Alabama, where the Auroral limestones or marbles, with their underlying slates and quartzites, abounding in limonite, as shown by Eugene A. Smith, are exposed on the great axis which divides the coal-basins of the Black Warrior and the Cahaba; and are also brought to view by a dislocation and uplift along the southeastern edge of the latter basin.*

§ 58. Lying to the eastward of the Lower Taconic belt of the Appalachian valley, and generally divided from it by the range of ancient crystalline rocks to which belong the South Mountain and the Blue Ridge, there are other areas of Lower Taconic strata found, at intervals, from Georgia to New Brunswick, often appearing as parallel interrupted belts. These are the remains of a mantle of these rocks once widely spread over the older crystalline strata of the Atlantic slope, from which, after folding and faulting, they have been in great part removed by erosion.

§ 59. One of these Taconic areas was, as long ago as 1817, defined and mapped by Maclure, who described it as "a Transition belt" extending from the Delaware to the Yadkin in North Carolina, having a breadth of from

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* See Hunt on Coal and Iron in Alabama; Trans. Amer. Inst. Mining Engineers, February, 1883.

two to fifteen miles, and a general dip to the southeast. He pointed out its course from the Delaware, passing by Norristown, Lancaster, York, and Hanover, in Pennsylvania, and Frederickstown, in Maryland, through Virginia; noted its passage beneath the mesozoic red sandstone, and its termination in Pilot Mountain, in Surry County, North Carolina. The rocks composing this belt were described by Maclure as consisting of granular quartzite, granular limestone or marble, and various slates.* Through the Lancaster valley, as already noticed (§ 45), the Taconic rocks of this eastern belt are connected with those of the Appalachian valley. Maclure also described another area of the same rocks found on the north branch of the Catawba, at the base of the Linville Mountains, in McDowell County, North Carolina.

§ 60. Emmons, who had examined this belt near the Schuylkill River, in Pennsylvania, was also acquainted with its extension into North Carolina, and in his report on the geology of that State, in 1856, mentions it as one of the five areas of Taconic rocks known within its borders, which are described in that report. Professor Kerr, who has since studied still farther the distribution of these rocks in that State, has delineated them on the geological map accompanying his report of 1875 These rocks present, according to him, "five principal outcrops, with two or three subordinate ones," which may be regarded as portions of these. Referring to his report for details, it may be said that the first or easternmost belt of these rocks in North Carolina, is in part concealed under the tertiary strata east of Raleigh, but is again seen west of the Raleigh granite-range. The second, a band with a breadth of from twenty to forty miles, extends from north to south across the State, along the western border of the mesozoic area.

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* Maclure, Observations on the Geology of the United States of America, with a Geological Map, etc., reprinted from the 1st vol. of the Trans. of the Amer. Philos. Soc., new series. Philadelphia: 1817; pp. 42, 43.

§ 61. The third, designated as the King's-Mountain belt, and including, besides the mountain of that name, the elevations known as Crowder's, Spencer's, and Anderson's Mountains, is in the southern part of the State, west of the Catawba River; stretching through Catawba, Lincoln, and Gaston Counties, and passing thence into South Carolina. This third belt is in the strike of that traced by Maclure from the Delaware into Stokes and Surry Counties, in the northern part of the State, and is regarded by Kerr as a continuation of it, though interrupted for some distance between the Yadkin and the Catawba.

§ 62. The fourth is a great belt which, like the second, is continuous across the State, along the Blue Ridge; the rocks in question passing from the east to the west side of that chain in the southwest part of their extension. This belt, at the Swannanoa Gap, is from six to seven miles broad, but has its greatest development in the Linville Mountains, where it includes the area of these rocks noticed by Maclure on the north branch of the Catawba, in McDowell County, and also an important section described by Emmons, on the French-Broad River, in Buncombe County, to be noticed farther on.

§ 63. The fifth or western area of the Taconic rocks is confined, according to Kerr, to the southwestern part of the State, into which it extends from Tennessee, including the mass of the Smoky Mountain of the Unaka range, and stretches from Madison County, widening southward, until it includes almost the whole breadth of Cherokee County, in the southwest corner of the State. To the Taconic of this region belongs the well known section near Murphy in that county. The rocks of this belt, as seen at Paint Rock on the French-Broad River, in Madison County, beginning at the Tennessee line, are by Kerr, and by Safford, identified as a continuous part of the Ocoee, Chilhowee, and Knox groups of the latter.* It is

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* Kerr, Report Geological Survey of North Carolina, 1875, vol. I., p. 131, and pp. 138, 139.

under these names that Safford has described the Lower Taconic series of the Appalachian valley, as found in eastern Tennessee, of which the belt in the southwest counties of North Carolina forms a part. The Ocoee slates, and the Chilhowee or Scolithus-sandstone of eastern Tennessee, both recognized by Emmons as Lower Taconic, represent the Lower Primal slates and quartzites, which, in this region, have a greatly augmented volume. In Alabama, according to Prof. Eugene A. Smith, the thickness of this sandstone is not less than 2000 feet, and that of the underlying slates, 10,000 feet.

§ 64. Professor Kerr, while recognizing in these rocks the strata described by Emmons under the name of Taconic, gave them, as he tells us in his report of 1875, provisionally, the name of Huronian, both designations appearing in the legend of the accompanying map. In explanation of this, it is to be remarked that he then included all of the more ancient crystalline rocks of North Carolina under the head of Laurentian, which he divided into Lower Laurentian (also called granite in his engraved sections) and Upper Laurentian. The latter name (at one time used by the geological survey of Canada to designate an entirely different group of rocks, the Norian) was by Professor Kerr applied to the series of younger gneisses and micaceous and hornblendic schists (with included beds of chrysolite or olivine-rock), which is the Montalban series of the author.

These rocks, in 1877, I found to rest in Mitchell County, North Carolina, directly upon the ancient granitoid gneisses of the Laurentian, the Huronian being absent. The true place of this, as appears from multiplied observations, is below, not above, the Montalban, and it moreover differs entirely in its lithological characters from the Lower Taconic rocks, which are found above the Montalban horizon. It remains, however, to be determined whether true Huronian and Arvonian rocks may not occur in parts of North Carolina, and may not be represented by some of the greenstones and the feldspar-porphyries noticed by Professor Kerr as found in parts of the Montalban (Upper Laurentian) area of the State.

§ 65. The Taconic strata of North Carolina are described by Kerr as resting in some places upon the granitic rocks, and in others upon the upper or Montalban series, and in part made up of its ruins. Pebbles of the older crystalline rocks, in which I have recognized both gneiss and mica-schist, are often met with in the conglomerates of the series. In the quartzites of the second belt at Troy, in Montgomery County, occur the silicious concretions regarded by Emmons as organic, and described by him under the name of Paleotrochis. Other beds of granular quartzite are flexible, constituting the variety known as itacolumite. With these, besides the usual argillites and unctuous schists, are found beds of pure massive pyrophyllite, which was by Emmons described as agalmatolite, and has been mistaken for steatite or compact talc, beds of which are also met with in this series. The schists are sometimes graphitic, and even include beds of graphite, as in the King's-Mountain belt. The quartzites of the series frequently contain cyanite and rutile, and also include, as in Pennsylvania, both magnetic and specular iron-ores, as will be noticed farther on, in the account of these rocks in South Carolina. The characteristic limestones — often becoming marbles — and the limonites of epigenic origin here, as in other regions, mark the series.

§ 66. I have elsewhere described these rocks as seen by me in the fourth belt in North Carolina, on the north branch of the Catawba, near Marion, in McDowell County, where they were first seen by Maclure; * and have noticed the granular quartz-rock, often becoming thinly bedded and flexible, the unctuous micaceous schists, the limonites, and the limestones, as having all the characters of

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* Proc. Boston Soc. Nat. Hist., 1878, xix., p. 277, and Azoic Rocks, pp. 207, 208.

these rocks as seen in Pennsylvania. A section in this same belt farther southwest, at Warm Springs, in Buncombe County, described by Emmons in 1855, may be compared with similar sections of the same rocks in the Appalachian valley in Virginia, in Pennsylvania, and in Berkshire County, Massachusetts, with which latter he especially compared it. The Taconic rocks, with a westward inclination, rest in Buncombe County unconformably upon the eastward-dipping crystalline rocks of the Blue Ridge. They present at the base a conglomerate with a talcose paste, followed by a succession of slates, with interposed masses of granular and vitreous quartzites and conglomerates, having an aggregate thickness of about 2400 feet. To these succeed 500 feet of limestone, followed by more than 150 feet of fine-grained slates, besides a farther mass of coarser schistose rocks, imperfectly exposed. Emmons notes in this section the larger development of quartzite and of conglomerates, which is shown in the greater thickness of the strata below the limestone; but declares, for the rest, that the rocks of the section, even in their details, are lithologically indistinguishable from the Taconic series in Williamstown, Massachusetts.*

§ 67. In connection with the unconformable superposition of the Taconic series to the older crystalline rocks, Emmons has noted, both in North Carolina and in New York, the appearance in some places among the Taconic strata, of granitic and primary rocks; and concludes that they are portions of the irregular underlying floor, exposed by the folding and denudation of the Taconic. Of certain interposed bands he says, "The geologist might regard them as interlaminated masses, but a careful examination of the relations of these rocks to each other will result in the conviction that the primary rocks are underlying and older masses, and have no connection with the sedimentary rocks which they geographically separate."†

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* American Geology, II., p. 24.

† American Geology, II., p. 26.

In a later book, his "Manual of Geology," published in 1860, Emmons reproduces the figures of the sections noticed above, but gives with them only very brief descriptions. He there states that the maximum thickness of the Lower Taconic rocks may be about 5000 feet. Above the basal conglomerate, which is sometimes absent, there are generally, according to his later statement, three masses of quartzite, divided by slates, the upper of these being often vitreous, and the lower granular in texture. The roofing-slates are said to occur in the upper part of the mass of slates which overlies the limestone.

§ 68. Passing southward from North Carolina, the Lower Taconic rocks were by Tuomey traced across South Carolina, and into Georgia and Alabama. He described them as a series of quartzites, with talcose slates and marbles, well displayed in the Spartanburg district, in the northern part of South Carolina. They are also met with in Pickens, the most western district of the State, in what is probably a continuation of the fourth belt of North Carolina, and extend across Pickens into the contiguous portions of Georgia. The belt just mentioned has there a considerable development in Habersham County, where it has been seen by the writer, and also in the adjacent counties of Hall and Union, a region in which a considerable number of diamonds, supposed to occur in this series, have been found. There appears also to be another and more eastern belt, which, according to C. U. Shepard, passes from South Carolina into the counties of Lincoln and Columbia in Georgia. In the former of these occurs Graves Mountain, known to mineralogists as a locality of pyrophyllite and cyanite, as well as of remarkable crystals of rutile and of lazulite, all of which are found with the granular quartzites of the series.*

§ 69. These rocks were the subject of extended and careful studies by the late Oscar Lieber, whose examinations were chiefly confined to the area in the northern

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* Amer. Jour. Science, 1859, xxvii., p. 36.

part of South Carolina, where, according to him, they are best seen at and near King's Mountain, in York District, and occupy a region about twenty-one miles long and from four to seven miles wide in York, Spartanburg, and Union districts. This region is the southward prolongation and terminus of the third, or King's-Mountain, belt of North Carolina, which we have described as passing southward from Gaston County, and as being, in the opinion of Kerr, the continuation of the belt which from the Yadkin River is traced northeastward to the Chester and Lancaster valleys of Pennsylvania, and thence into the great Appalachian valley.

§ 70. The rock most characteristic of this series is, according to Lieber, the granular, more or less schistose quartzite, which, with its associated iron-ores and slates, he compared to the similar rock described by Eschwege, from the province of Minas Geraes, in Brazil, as a chloritic or schistose quartz-rock. This, from its occurrence at Mount Itacolumi, near Villa Rica, was by Eschwege called "itacolumite," a name which was also adopted by Humboldt and Claussen for these and related rocks as a whole, but is now commonly given only to the flexible and elastic variety of the quartzite, the "elastic sandstone" of Martius. This variety, however, is exceptional alike in Brazil and in our Lower Taconic series; and the designation of itacolumite was by Lieber applied not only to the whole of the quartzite, but to its interstratified schists and limestones, which he described as the Itacolumitic group or series.

§ 71. These rocks, on lithological grounds, were conjectured by Lieber to be the stratigraphical equivalents of the Itacolumite or diamond-bearing series of Brazil, and of the similar rocks described by Jacquemont, and later by Claussen, as occurring in the diamond region of India, being the Lower Vindhyan series of the present geological survey of that country. He also noticed its probable relation to the rocks found by Helmersen and Hofmann in Russia, in the southern Urals, which they had described as identical with the Itacolumite series of Brazil, and which have since been found to be diamantiferous. I have elsewhere discussed at some length the history of these rocks,* which are again noticed farther on, in § 203.

§ 72. Lieber's studies are to be found in his four annual reports of the geology of South Carolina, published in 1856–60. With the third report there appears, as a supplement to the first three, an essay on the Itacolumitic series, resuming his conclusions and observations up to the year 1859.† This same essay was also published in German in 1860.‡

The studies by Lieber are the more interesting and instructive as they are the work of a student trained in a foreign school, and were made without any reference to the preceding investigations of Maclure, Eaton, Emmons, or Rogers, and apparently without the knowledge that these rocks extended to the north of the Carolinas. As his reports are very rare, and but little known, I have thought it desirable to give in the following pages an abstract of his observations. In the four annual reports already noticed, together with the included supplement, Lieber proposed to describe the ancient stratified rocks of the State, and successively corrected and enlarged his descriptions, by collating which we are enabled to frame a connected statement of his views. Lieber divides the

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* Report of the Smithsonian Institution for 1882; Review of the Progress of Geology.

† The Itacolumite and its associates, comprising observations on their geological importance and their connection with the occurrence of gold; a Contribution to the Geologic Chronology of the Southern Alleghanies, supplementary to Reports I., II., and III., by O. M. Lieber, state geologist, Columbia, S. C., 1859. This, though having a separate title, is paged consecutively (pp. 77–149) with Report III., published in 1858, with which it forms one volume. The relations of gold to the Itacolumite, and to other rocks, are considered in a subsequent part of the same volume, pp. 153–220.

‡ The German edition of Lieber's essay appears in the Gangstudien of Von Cotta and Herrm. Müller; dritter Band, drittes und viertes Heft, pp. 309–507. Freiburg, 1860

crystalline rocks of the State into three parts, namely, the Itacolumitic group and what he called sub-Itacolumitic and super-Itacolumitic rocks. For the first-named or middle one of these alone can be claimed the distinction of a natural group, inasmuch as it contains rocks closely allied and everywhere intimately associated.

§ 73. His descriptions apply to the King's-Mountain region, as seen in South Carolina, which we have defined in § 69, and of which a good geological map, with an ideal section, is given in Report II. (plate xii.). A description in Report I., of the series as there displayed, was afterwards corrected in Report II., and finally given, with some additions, in Report III. From these, substituting the word "quartzite" for "itacolumite," and adding some explanations, we get the following section, which represents the whole succession as described by Lieber, numbered in descending order: —

1. Banded blue crystalline limestone.
2. A bed of granular quartzite.
3. Talcose slate, with lenticular layers of catawbarite (an aggregate of magnetite and talc).
4. Granular quartzite (sometimes absent).
5. Granular limestone or marble, mottled or banded, sometimes with talcy interlaminations.
6. Granular quartzite; a great mass, with layers of the flexible, elastic variety.
7. Specular schists, consisting of micaceous hematite and quartz, passing into itabirite, in which magnetite replaces hematite.
8. Quartzite and quartzose conglomerate.
9. Talcose slates of loose texture, passing gradually into the quartzite above.

§ 74. Beneath these, Lieber placed in his sub-Itacolumitic division, clay-slate, talcose slate, mica-slate, hornblende-slate, gneiss, and granite, some of which were conjectured by him to be igneous rocks. He describes a stratiform granite, passing into a fine gray variety with thin hornblendic bands, which is distinct from the coarse porphyritic granites of other parts of the State, and is overlaid by a great mass of mica-schists holding brown iron-ores derived from pyrites. These various rocks have, in his opinion, no necessary relation to those above them, but are simply the strata which, in different parts, underlie the Itacolumitic series. Little is said about the underlying clay-slate and talcose slate, both of which may perhaps belong to the Itacolumitic series. To this all the others were referred, with the possible exception of the upper or blue limestone, which was provisionally designated as super-Itacolumitic, because it is unlike the marbles below, and also is apparently above the horizon of the gold-veins, which are common to the inferior rocks of the Itacolumitic series.

§ 75. No measurements of the several members of the series are given by Lieber, but as seen at King's Mountain, he says, "its thickness will probably equal nearly a mile." As represented in the engraved section in Report I. (plate v.), it is highly contorted, and in some places shows inverted dips, the strike being between north and northeast. No direct evidences of organic life are seen in the series, if we except the forms observed by C. U. Shepard in the upper blue limestone at the Broad-River quarry in York District, and by him supposed to be impressions of stems of Equiseta, with swelling nodes.* This description recalls the distinctly nodose character exhibited by the so-called Scolithus of the Primal quartzite of Pennsylvania, and the cylindrical forms in the Auroral limestone and its accompanying strata elsewhere, which I have compared with them (§ 34).†

§ 76. The quartzites of the series present the characteristics which we have recognized in those of the Primal series elsewhere, being sometimes conglomerate, and at other times massive, compact, concretionary, or granular; often with an admixture of a foliated mineral, which gives them a laminated character, and assimilates them to the

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* Shepard, Report to the Swedish Iron Manufacturing Company, Charleston, 1854; cited by Lieber, Rep. II., p. 88.

† Azoic Rocks, pp. 137, 138, 206.

older crystalline schists. This interposed mineral is, according to Lieber, sometimes a mica, and at other times chlorite or talc. We have seen that the schistose strata of this series in Pennsylvania, and in North Carolina, are sometimes chloritic, or contain the species venerite, a copper-chlorite (*ante*, page 357); while at other times they consist wholly or in part of a hydrous mica (damourite or sericite), pyrophyllite, or true talc. All of these species are probably confounded by the common epithet, "talcose," applied to these rocks, though true talc is comparatively rare. We have also noticed the occurrence in the schists of this series, in Pennsylvania, of serpentine, of amphibole, and of garnet. Cyanite and rutile, the latter in large and fine crystals, are not unfrequently found in the granular quartzites of the series, and staurolite is also met with. The lower limestone of Lieber's section sometimes contains tremolite. It is marked by dark bands, and frequently by talcose seams, which render it unfit for use as a marble. In King's Mountain, this limestone is traversed by auriferous veins, and the quartzites and schists of the series are also auriferous, and constitute the chief gold-bearing rocks of the southern States.

§ 77. The iron-ores of the series in South Carolina, other than the limonites, are by Lieber included under three varieties. First, an aggregate of magnetite with talc, called by him catawbarite, the talc in some cases disappearing; second, a schistose silicious hematite, described as a specular schist, in which foliated hematite takes the place of mica. This, by the substitution of magnetite for hematite, passes into a rock which, from a locality in Brazil, has been named itabirite. These ores occur in beds or lenticular masses; the latter two varieties in the quartzite, and the catawbarite in the talcose schists of the series.

§ 78. The hydrous iron-ore or limonite, so abundant in this series elsewhere, received but little notice from

Lieber. He mentions, however, its occurrence in the King's-Mountain region intercalated in decaying talcose slates, with red clays and an underlying stratum of kaolin. The limonite is here, as in parts of Pennsylvania (§ 26), associated with anhydrous red oxyd, and Lieber conceives this, and some other similar deposits in the region, to have originated from the hydration and alteration of specular iron-ore, or of magnetite. This view, which has been frequently advanced by others, is, however, inconsistent with the known permanency and unalterable character of the anhydrous oxyds of iron, and, moreover, with the well known origin of the hydrous ore by epigenesis from pyrites or from siderite. Lieber himself mentions elsewhere the occurrence of beds of limonite, intercalated in the talcose slates of the series, and due to the alteration of masses of pyrites, which is found unchanged in depth.

§ 79. We owe to Prof. Henry Wurtz a valuable paper, published in 1859, on the mineralogy of the northward extension of the King's-Mountain belt, as seen in Gaston and Lincoln Counties in North Carolina. He there noticed the itacolumite-rock, and its supposed relations to the diamond, described the anhydrous iron-ores under the names of magnetite-schist and hematite-schist, and moreover what he called a pyrites-schist. He farther observed great interstratified beds of limonite, which he regarded as derived from the alteration of a pyrites that is found unchanged in the deep workings of these ores. With them, and elsewhere in the talcose schists of the region, he observed the frequent occurrence of black earthy manganese-oxyd, containing much cobalt and some nickel.* It is worthy of notice in this connection that both the magnetites and the limonites of this horizon in Pennsylvania generally contain more or less cobalt, as shown in numerous analyses by Genth and McCreath. The pyrites found at the Cornwall iron-mine in Pennsylvania is also cobaltiferous.

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* Amer. Jour. Science, xxvii., pp. 24–31.

The magnetic and specular ores found so abundantly in the Primal series of Pennsylvania, and already described at length, are evidently the equivalents of those described by Lieber and by Wurtz, and constitute an important and widely extended ore-bearing horizon. The silicate mingled with the magnetites in many of the Pennsylvania deposits, is probably more nearly related to pyroxene than to talc in composition. The mineralogy of all of these deposits demands careful study, inasmuch as they belong to a distinct and well marked horizon of crystalline rocks, the importance and geological significance of which has hitherto been to a great extent overlooked by American geologists.

The Itacolumitic series of Lieber, with its estimated approximative thickness of 5000 feet, being evidently the Lower Taconic of Emmons, it remains to be seen whether the upper blue limestone, provisionally regarded by Lieber as distinct, really belongs to a higher horizon, or is a member of the series. In the latter case, the upper schists and the roofing-slates of the Lower Taconic are unrepresented in this area, and have probably been removed by erosion. The best locality for the study of the whole series in South Carolina is, according to Lieber, at Limestone Springs, in the Spartanburg district.

§ 80. In this connection mention should be made of the occurrence of several narrow belts of Lower Taconic rocks folded in the gneiss of the Highlands east of the Appalachian valley, in northern New Jersey, where they have been carefully studied and described by Cook, and are well seen in the Pohatcong and Muscanetcong valleys. They also extend into southeastern New York, where little is known of their distribution, and where they have been confounded with the older Laurentian rocks, into which they were supposed, by Nuttall, Mather, and H. D. Rogers, to graduate.* In New Jersey, where Cook has shown the fallacy of this view, the Auroral limestones,

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* Hunt, Azoic Rocks, pages 40, 42.

associated with limonites, and often overlaid with slates, are found resting directly on the gneiss, or with a thin intervening layer of the Primal sandstone. These strata are much folded and faulted, and sometimes present overturned flexures, giving the whole succession an eastward inclination.* All of these rocks above the gneiss are, in accordance with the classification of Rogers in Pennsylvania, referred by Cook to the infra-Trenton portions of the Champlain division. The relations of the Green-Pond Mountain conglomerate, found in this region, will be noticed farther on.

§ 81. The parallel belts of Lower Taconic rocks found east of the Blue Ridge, in the southern States, and the final disappearance of these rocks beneath the tertiary to the east of Raleigh, show that they were once widely spread over the floor of the more ancient crystalline rocks which now form the Atlantic belt. To the north of New York, where this belt, greatly contracted between the James and the Hudson Rivers, again broadens, we might look for farther areas of Lower Taconic rocks in New England, and in the provinces lying farther to the north and east. We find, in fact, to the east of the Green Mountains, in Vermont, a series of limestones with soft micaceous slates, which have been compared with the Lower Taconic, and may perhaps represent it. To this horizon may also not improbably belong the considerable areas of argillites, often roofing-slates, found in the province of Quebec, to the north of Lake Memphremagog, extending to Melbourne, and occupying what I have called the Windsor basin. These argillites overlie the Huronian schists, and are themselves unconformably overlaid by Silurian limestones, which repose alike upon the argillites and upon the Huronian series.

§ 82. Farther east, in Maine, are areas of argillites, and others of quartzose conglomerates, limestones, and soft talcose schists, which were declared by Emmons to

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* Cook, Geology of New Jersey, 1868, pp. 70, 144.

resemble the Lower Taconic rocks of western Massachusetts, and to rest unconformably upon the ancient mica-schists and gneisses of the region. This series, which includes the limestones of Rockland and of Camden, has, according to Emmons, a thickness, in the latter locality, of 2000 feet, and is by him regarded as belonging to the Lower Taconic; to which, moreover, he refers, with much probability, many of the silicious and argillaceous schists of this part of Maine. The limestones and associated rocks of Cumberland, Rhode Island, are also supposed by Emmons to belong to the same horizon.* These, the present writer has not yet personally examined.

§ 83. In southern New Brunswick, as I have pointed out, there are found numerous exposures of rocks closely resembling those of Camden. They have been much eroded, but are seen at several points along the coast, as at Frye's Island, the peninsula of L'Etang, Pisarinco, and the mouth of the River St. John. At this last locality, a section along the Green-Head road, on the right bank of the river, is described in detail by Matthew and Bailey in the report of the geological survey of Canada for 1870. The strata, with a general southeast dip of about fifty degrees, have a breadth, across the strike, of 4100 feet, of which 1500 are limestones, and the remainder chiefly quartzites, often schistose, with argillaceous and somewhat micaceous schists, and occasional hornblendic layers. Considerable masses of conglomerate, with silicious and calcareous pebbles, are also included in the series, the members of which are not improbably repeated by dislocations. The limestones, of which there appear to be several masses two or three hundred feet in breadth, are in part distinctly crystalline and white, or banded with blue and gray colors, and in part finely granular, grayish, schistose, and sometimes concretionary. They are frequently magnesian, and occasionally contain small

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* Emmons, Agriculture of New York, I., 97-101, and Amer. Geology, II., 20-22; also Hunt, Azoic Rocks, 179.

masses of yellow serpentine, and a silvery-white mica. Portions of the limestone are apparently colored by a carbonaceous matter, and a bed of impure schistose graphite, which has not the crystalline aspect of the Laurentian graphites, is mined in these rocks near the city of St. John. These limestones have yielded to Sir. J. W. Dawson the remains of *Eozoön Canadense.* The argillaceous beds, sometimes schistose, and occasionally graphitic, which lie between the quartzite and the limestones, closely resemble those found in similar associations in the Taconian areas already noticed.

§ 83 A. [The rocks on the southern slope of the Cobequid Hills, at the head of the Bay of Fundy, belong to the same series as those of the St. John. Nearly vertical in attitude, and unconformably overlaid by carboniferous strata, they were long since described by Dawson as "a metamorphic series," supposed to be of paleozoic age.* They consist of a great underlying mass of quartzite, often granular, with massive beds of granular white limestone, black or olive-colored argillites, often lustrous, and a soft greenish or grayish, apparently argillaceous rock. These strata are intersected by great veins, often brecciated in structure, and filled with sparry ferrous carbonates of varying composition, sometimes nearly pure siderite, and including portions of crystalline hematite and magnetite. The carbonates of these veins near the surface are changed into limonite, and have been extensively mined at Londonderry, Nova Scotia. I have there found evidences of contemporaneous deposition of iron-ores in thin layers of crystalline hematite interbedded with the granular limestones.]

§ 84. This succession of crystalline limestones, quartzites and slates, in New Brunswick and Nova Scotia is clearly older than the uncrystalline sandstones and shales of Lower Cambrian (Menevian) age, which, with their characteristic fauna, are at St. John found to be in prox-

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* Dawson, Acadian Geology, 2d ed., p. 582.

imity. The latter strata appear to be in part made up of the ruins of the older schists, and in one section, beds of quartzite and conglomerate, believed to belong to the limestone series, occur between the Menevian and the underlying Huronian strata. A mile or two away, however, the limestone series is seen to rest upon red granitoid gneiss, regarded as Laurentian; and was itself described, in the report just mentioned, as an upper member of the Laurentian series. The evidence above adduced shows that we have here a great system resting unconformably alike on Laurentian and Huronian, and at the same time wholly distinct from the Lower Cambrian. From these facts, and from its close resemblance to the Lower Taconic of Maine, and of western New England, it was in 1875, by the present writer, referred to the Taconic series.* A great mass of similar limestones and marbles, with soft micaceous schists, described by Murray as occurring in Newfoundland between the gneisses and the fossiliferous Cambrian, may not improbably represent the Lower Taconic.†

§ 85. As we go northward in the Champlain valley, the Lower Taconic, which is seen in southern and central Vermont, at the western base of the Green Mountains, passes beneath newer strata. From thence northeastward, we have no certain evidence of the existence of this series between the latter and the belt of crystalline strata of Huronian age, which may be traced along the southeast side of the St. Lawrence valley, to a point a little farther east than the meridian of Quebec, where the crystalline rocks disappear beneath the surrounding paleozoic strata. If, however, we pass westward, we find in Hastings County, north of the eastern extremity of Lake Ontario, a considerable area occupied by quartzites, conglomerates, limestones, micaceous slates, and argillites, resembling closely those of the various Taconian areas.

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* Proc. Bos. Soc. Nat. Hist., xvi., 509; and Azoic Rocks, pp. 179-180.

† Hunt, Amer. Jour. Sci., 1870, vol. I., p. 86.

These strata, which rest unconformably alike upon the Laurentian and Huronian rocks of the district, are themselves arranged in several synclinals, with moderate dips, and are unconformably overlaid by the fossiliferous limestones of the Trenton; the lower members of the Champlain division being absent throughout this region. The conglomerates include pebbles from both of the underlying groups. Crystalline dolomites, constituting marbles, are found in the series, and above them, a mass of about 1000 feet of fine-grained, grayish and bluish, earthy and somewhat schistose limestones; the whole series being estimated at 3800 feet. These rocks, which were first particularly described by Thomas Macfarlane (then of the geological survey of Canada), in 1864, were subsequently known, in the reports of the survey, as the Hastings series; and were by Logan, in 1866, compared with the micaceous limestone-series of eastern Vermont (§ 81). In 1875, the writer, after an examination of the three regions, compared the rocks of the Hastings series with the similar rocks of southern New Brunswick, and of Berkshire County, Massachusetts, and described them as Lower Taconic.* It may here be mentioned that areas of Montalban gneisses and mica-schists occur in the vicinity of the Taconian rocks of Hastings County, in Ontario.

§ 86. These rocks are not destitute of direct evidences of organic life, having furnished remains of *Eozoön Canadense*, which have been described and figured by Dawson. Numerous specimens of this have been found in Tudor, "imbedded in an impure, earthy, dark gray limestone, with which, and with carbonaceous matter, the cavities of the white calcareous skeleton are filled"; unlike those of the Eozoön from the Grenville series on the Ottawa, which are generally filled with serpentine or pyroxene. Dawson farther noticed, in some of the impure dark-colored limestones of the Hastings series from Madoc,

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* Azoic Rocks, pp. 170–172, and p. 177.

"fibres and granules of carbonaceous matter which do not conform to the crystalline structure, and present forms quite similar to those which, in more modern limestones, result from the decomposition of algæ. Though retaining mere traces of organic structure, no doubt would be entertained as to their vegetable origin if they were found in fossiliferous limestones." He noticed also a similar limestone from the same vicinity, which is apparently "a finely laminated sediment, and shows perforations of various sizes, somewhat scalloped on the edges, and filled with grains of rounded silicious sand." Other specimens from the same region are said to present, on their weathered surfaces, indications of similar circular perforations, having the aspect of Scolithus or worm-burrows. Some of these markings from Madoc were subsequently figured by Dawson, and designated "annelid-burrows," with the remark that "there can be no doubt as to their nature." * These are as yet known only by a few transverse sections, and cannot, therefore, be compared with the cylindrical markings referred to Scolithus and to Monocraterion, in the Taconic quartzites and limestones of the Appalachian valley (§§ 34, 52).

§ 87. Brooks described in 1872 an area of rocks in St. Lawrence County, New York, lying along the northern base of the Adirondacks. They include the Caledonia and Keene iron-mines of that region, and appear as a series of folded strata, with a northeast strike, resting in apparent unconformity upon reddish Laurentian gneiss. The rocks in question consist of granular quartzite, crystalline limestone, and a greenish schistose rock described as magnesian. A bed of quartzite is interstratified with the limestones, which include tremolite and are overlaid by the soft, greenish, gray-weathering schists, to which succeed the micaceous and earthy red hematites in lenticular masses, intercalated with similar schists and masses of

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* Dawson; The Dawn of Life, pp. 110, 139; and Hunt, Azoic Rocks, pp. 171-177.

quartzite; a friable sandstone, sometimes conglomerate, overlying the whole. White quartzo-feldspathic veins occur in the lower portion of the limestone. Emmons, who described this locality in 1842, and did not observe the lower quartzite, referred the overlying conglomerate to the Potsdam, and supposed the hematite, the limestone, and the greenish rock (by him called serpentine) to be all alike erupted plutonic masses. The observed thickness of the series, as there exposed, is, according to Brooks, not less than 700 feet, and its entire volume probably much greater. Although they were by Brooks compared with the Lower Taconic of Emmons, I was disposed, in writing of these rocks in 1877, to regard them as a part of the Laurentian. They were, at that time, compared with the crystalline limestones, with interstratified quartzites and conglomerates, found in Bastard in Ontario.* Farther consideration leads me to suspect that these rocks of St. Lawrence County are really an outlier of Taconian.

In comparing these rocks in Maine, New Brunswick, Nova Scotia, Ontario, and northern New York with the similar rocks in the Appalachian valley, and elsewhere southwards, it should be remembered that in these latter regions the strata, in many cases, present, at their outcrops, soft materials, the results of sub-aerial decay; whereas only their harder underlying portions are seen in the eroded regions farther northward. These varying conditions of outcrops of similar crystalline rocks in different geographical areas have already been discussed at length in Essay VII.

§ 88. That the fauna of the Cambrian, as seen in the Menevian beds of our eastern coast, or in the so-called Potsdam which forms the base of the Cambrian in Minnesota and in Wisconsin, marks the dawn of organic life, will now scarcely be maintained, even by those ques-

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* Brooks; Amer. Jour. Science (3), iv., pp. 22-26; Hunt, Azoic Rocks, pp. 148 and 218; and Emmons, Geology of the Northern District of New York, pp. 92, 98.

tion the organic nature of Eozoön. Recent observations show the existence, beneath this horizon, to the westward, elsewhere, of fossiliferous strata occupying the place which we have assigned to the Taconic. There is found, along the northwest shore of Lake Superior, a series of quartzites, impure limestones, and slates, which the writer, in 1873, called the Animikie group. These had been, by Logan, regarded as the lower member of the great Keweenian or so-called Upper Copper-bearing series of the region. The writer, in 1873 and 1878, also attempted to show that the conglomerates, sandstones, and limestones of the so-called Nipigon group, overlying unconformably the Animikie, are not the Keweenian, but newer rocks; which, so far as the evidence afforded by the section examined by Logan and himself, at and near Thunder Bay, goes, might either be of Potsdam age, as maintained by some, or, as held by others, from lithological considerations, of a more recent period.*

§ 89. The Animikie group, the distinctness of which from the overlying Nipigon was then maintained, has since been traced westward by N. H. Winchell, and shown to underlie unconformably the horizontal sandstones of the St. Louis River, regarded as belonging to the Potsdam or Cambrian of the region. In this case, the Animikie quartzites and slates, which rest unconformably upon the Huronian series, would occupy the horizon of the Lower Taconic. The writer found, in 1883, in the argillites of this series, near Thomson, in Minnesota (in the vicinity of which they afford roofing-slates), numerous calcareous concretions, one of which has yielded to J. W. Dawson the remains of a keratose sponge. The granular quartzites or sandstones of this series are often mingled with magnetite; and constitute, in some cases, as described by Bell, an iron-ore. In this connection it should be mentioned that the quartzites and argillites of the Menominee River, in northern Michigan, were, in 1846, referred by

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* Azoic Rocks, pp. 238-241.

Houghton and Emmons to the Taconic system.* There is reason to believe that these rocks of the Menominee region which, as described by Brooks and Pumpelly, include great deposits of iron-ores and marbles, and apparently differ much from the Huronian in character, are, as supposed by Irving, identical with the Animikie rocks.

§ 90. [The publication, by the United States geological survey, in 1883, after the above was first printed, of Irving's report on the Copper-bearing rocks of Lake Superior, together with information since gathered from other sources, throws much additional light on the question of Huronian and Taconian in this region. Irving then announced his conclusion from the essential identity between the Animikie rocks (which have, according to him, a thickness of 10,000 feet) and those of the Penokie range in Wisconsin, and their close resemblance to the Iron-bearing strata of the Marquette and Menominee districts, that the whole of these constitute one great geological series.

[These conclusions I have been enabled to verify, having, by the courtesy of Prof. N. H. Winchell, examined his collections of rocks from Minnesota, and been allowed the same privilege for the collections from Minnesota and the northern peninsula of Michigan, got by Dr. Rominger, who has, moreover, permitted me to consult his unpublished report of geological work in these regions in 1881–84. The Granitic and Dioritic groups of his published report of 1878–80 are by him regarded as plutonic rocks, in the former of which he embraces alike gneisses and stratiform granites, and the transversal granitic masses found in the dioritic group. This latter includes both massive and schistose, more or less chloritic varieties, and is intimately associated with the serpentines of the region, which apparently form a part of his dioritic group.

[Resting in some cases upon this group, and in others upon the granitoid rocks, is a great system divided, in as-

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* Emmons, Agriculture of New York, i., p. 101.

cending order, by Rominger in 1880, into a Quartzite group (which includes a Marble series), an Iron-ore group, and an Arenaceous-slate group, all of which appear closely connected. The system comprises heavy beds of quartzite, often schistose and with conglomerates, interstratified and overlaid by argillites of various colors, with graphitic, hydro-micaceous or sericite slates, beds of jasper, of hematite, and magnetite, either pure or disseminated, and, in the upper portion, limonite and siderite. The limestones form, in the upper part of the quartzite division, great masses of white crystalline marble, sometimes with mica and tremolite and sahlite; at other times they are reddish, or dull and compact. The iron-ores appear to be in two horizons, one below and one above a great body of limestone. To the latter are referred the ores of the Gogebic and Menominee districts, and to the former those of Marquette and Felch Mountain, with which those of Vermilion Lake, in Minnesota, appear to be identical. The argillites which overlie the latter are those seen in the St. Louis River and at Thomson, Minnesota, which are by Rominger compared with argillites at L'Anse and Huron Bay. The iron-bearing series at Vermilion Lake, as described by Rominger, and shown in his collections, is very like that of the Taconian in the Appalachian region. Rominger there found no representative of the dioritic group; but, to the south, an area of rock described by him and by Irving as olivine-gabbro, which extends to Duluth. This, as seen by the writer at the latter point, where it is apparently overlaid by the Keweenian, has the characters of the granitoid norites of the Norian series in New York and Quebec.]

§ 90 A. [The mica-schists, sometimes with gray gneisses, long since referred by me to the Montalban series,* and by Brooks placed above the iron-bearing beds of the Menominee district, have since 1880 been found by Rominger to be an older and underlying series, occurring

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* Azoic Rocks, pp. 223–225.

in that area, which is there brought to overlie the iron-bearing schists by a fold in the stratification. It would appear from all these facts that, while the dioritic and serpentine group of Rominger is the true Huronian, the great series of quartzites, marbles, argillites, and iron-bearing strata of these regions, — the so-called Animikie group, — are wholly distinct therefrom, and, as long since declared by Houghton and Emmons, are Taconian.

§ 91. [The fact that the Taconian or Animikie series in northern Michigan rests sometimes upon the granitoid or gneissic group, sometimes upon the dioritic group of Rominger, and elsewhere upon a mica-schist series having the characters of the Montalban, goes far to show its stratigraphical distinctness from all three of these. Its separation from the dioritic group was early noticed by Logan, when he described the unconformable superposition of this series (the lower division of his Upper Copper-bearing series) on the ancient greenstone (Huronian) series, and the presence of portions of this in the basal conglomerates of the latter. There are, however, as I have elsewhere noticed,* certain mineralogical resemblances between the Taconian and the softer and more schistose beds of the Huronian, with which they were confounded by Murray at more than one locality along the north shore of Lake Superior. Hence, after visiting the Marquette district in 1861, he did not hesitate to call the Iron-bearing series of that region Huronian; a designation adopted by the geological survey of Canada. In this he was followed by J. P. Kimball in his study of the Marquette iron-ores in 1865, by Hermann Credner in 1869, by T. B. Brooks in 1873, and again by Irving in 1883. All of these include the two series under the common name of Huronian, and the estimates of the thickness of the Huronian have been based upon that of the two united. The distinctness of the underlying dioritic group with its serpentines and chloritic rocks, which together constitute the Huronian or

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* Azoic Rocks, p. 202.

pietre verdi—alike from the older granitoid and gneissic group, from the mica-schist or Montalban group, and from the great overlying Animikie or Taconian system, including the quartzites, marbles, iron-ores and argillites, is however manifest. The succession is thus brought into complete accordance with that which is found in many parts of the Appalachians, as well as in southern Europe, as pointed out in part iv. of Essay X.]

§ 92. Considering the pre-Cambrian age of the Lower Taconic of Emmons to be established, as well as its distinctness alike from the older crystalline rocks below and from the Cambrian series above, to which Emmons had given the name of Upper Taconic—it was proposed by the writer, in 1878, to restrict the term of Taconic,—for which the alternative name of Taconian was then suggested,—to the Lower Taconic of Emmons.*

The question as to whether the Cambrian is to be regarded as the base of the paleozoic series, or, in other words, whether the Taconian should be considered as belonging to eozoic or paleozoic time, was discussed by the author, in 1876, when he wrote as follows: "It will be found as difficult to draw the line between the eozoic and paleozoic as it is to define that between the mesozoic and paleozoic on the one hand, or between the mesozoic and cenozoic on the other. There are no hard-and-fast lines in nature; breaks are local, and there is nowhere an apparent hiatus in the geological succession which is not somewhere filled." Referring to the Lingula found by Prime in the Auroral limestone of Pennsylvania, it was said: "This seemingly imperishable type of brachiopods may serve, like the rhizopods, represented by Eozoön, as a connecting link between eozoic and paleozoic time." † Subsequently, in a paper read

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* On the Geology of the Eozoic Rocks of North America; Proc. Bost. Soc. Nat. Hist., xix., 278; and Azoic Rocks, p. 207.

† Proc. Amer. Assoc. Adv. Science, 1876, pp. 207-208; also, Azoic Rocks, p. 211.

before the National Academy of Sciences in April, 1880,* it was said of the Taconian series: "These older rocks are not without traces of organic life, having yielded in the Appalachian valley the original Scolithus, and related markings, besides obscure brachiopods; and in Ontario, besides similar Scolithus-like markings, a form apparently identical with the Eozoön of the more ancient gneisses. We may hope to find in the Taconian series a fauna which shall help to fill the wide interval that now divides that of the eozoic rocks from the Cambrian. We should seek, in the study of stratigraphical geology, not the breaks dividing groups from each other, so much as the beds of passage which serve to unite all these groups in one great system."

V. — THE UPPER TACONIC OR FIRST GRAYWACKE.

§ 93. We now return to the history of the First Graywacke, which, as has been shown, was by Mather, in 1842, assigned, contrary to Eaton's conclusion, to a horizon above the Trenton limestone, and to the position of the Second Graywacke of the latter. Mather regarded the Taconic quartzite, limestone, and slates of Emmons as forming one continuous series with the succeeding First Graywacke of Eaton, and referred the whole succession to the various subdivisions of the New York system from the Potsdam to the Medina, both included.

[Emmons, in his report on the Northern district of New York, in 1842, approached the discussion of this question with the remark that although the Taconic rocks do not appear within that district, a knowledge of them is requisite to a correct understanding of the relations of the Champlain division. While maintaining that the Quartzite, Limestone, and Argillite (which Eaton had placed beneath the First Graywacke) were inferior to the Trenton limestone, and, indeed, to the whole New York system, Emmons therein showed a divided opinion as

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* Canadian Naturalist for 1880, vol. ix., p. 430.

to the horizon of the Graywacke itself. In those chapters of the report in which he describes the Taconic system, he accepts the view of Eaton that it follows immediately the Argillite; while in the chapter on the New York Transition system, he adopts the notion of Mather that it is identical with the Second Graywacke, and above the Trenton — the Lower Secondary limestone of Eaton. These contradictions, which I have already elsewhere signalized,* have perplexed students, and demand farther notice. In describing the rocks of the Champlain division, in that volume (page 121), we are told by Emmons that a belt of red and purple slates with red sandstones, regarded as belonging to the Pulaski or Loraine shales, extends "through the higher parts of Columbia, Rensselaer, and Washington Counties," in New York, "and onward through Vermont into Canada." Again we are informed (pages 280–282) that shales and sandstones belonging to the horizon of the Loraine subdivision and the succeeding Gray sandstone, and seen in Addison and Charlotte, Vermont, belong to this belt, extending from Columbia County, New York, to the Canada line. They are farther said to be represented by the sandstones of Burlington and Colchester, Vermont, and by the sandstones in the fortifications of the city of Quebec (pages 124, 125).

§ 93 A. [When, however, he comes to describe the rocks of the Taconic system in this same report, he declares that these rocks also extend through the eastern counties of New York from the Highlands, beyond which "they are found stretching through the whole length of Vermont, and into Canada as far as Quebec" (page 136). This description in 1842 obviously applies only to the portion of the Taconic system afterwards distinguished by Emmons as Upper Taconic, since, it is known, the characteristic Quartzite, the Stockbridge limestone, and the Magnesian slates of the Lower Taconic, are not recognized

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* Azoic Rocks, p. 57.

anywhere along the line mentioned, northward of central Vermont. On the contrary, the typical Upper Taconic is traced throughout the whole distance to the city of Quebec, where the well known sections of it were by the geological survey of Canada described as belonging to the horizon of the Second Graywacke, until 1861, when there were referred by Logan to the First Graywacke or Upper Taconic, with the local name of the Quebec group.

[That the Taconic system as set forth in 1842 included the Upper Taconic or First Graywacke, is farther shown by the detailed descriptions of Emmons in chapter v. of his report of that year. He there includes besides the Granular Quartz-rock, the Stockbridge limestone, and the Magnesian slate, two other divisions, the "Sparry limestone, generally known as the Sparry Lime-rock," of Eaton, and the "Taconic slate." With regard to the latter limestone, he remarks that it is "quite even bedded, of a gray color, very sparry, and is underlaid by a fine argillaceous slate." He adds that the Stockbridge limestone, "being often sparry, and of a fine texture, is mistaken for the true Sparry limestone." The Taconic slate is more or less interstratified with limestone, and "often becomes a coarse graywacke." This Taconic slate belt was, according to him, distinct from the Magnesian slate, and had then been traced 150 or 200 miles north and south, without variation in characters.

§ 93 B. [The true succession of these divisions, or "the order in which the Taconic rocks lie, being unsettled, or, at least, not being as clearly established as is desirable" (page 150), Emmons tell us that in his descriptions he follows the geographic order, beginning with the most western mass of slate, the Taconic slate, succeeding which was the Sparry limestone. The question of the stratigraphical sequence was complicated by faults, with upthrows of the strata on the eastern side, the significance of which Emmons points out in 1846, as well as by the break at the base of the Graywacke noticed by Eaton (*ante*, page 526). He, however, informs us, in 1842, that the Taconic slate lies between the so-called Hudson-River or Loraine rocks on the west, and the Sparry limestone on the east, and, moreover, that "it is undoubtedly overlapped by the former rocks, and passes beneath the latter with a dip of 30° or 35°" (page 150). In 1846 Emmons gave us farther details with regard to these same Taconic slates, the limits of which, in the typical sections, he had already defined in 1842. He now tells us that "the Taconic slate, with its subordinate beds, occupies almost the whole of Columbia, Rensselaer, and Washington Counties," and is of immense thickness. He notes a section from Lansingburgh to the Sparry limestone on the east, as having a breadth of at least twenty miles, and, while conjecturing repetitions, still supposes that its volume "exceeds that of all the members of the New York system put together." He describes as subordinate divisions of this slate group, a black slate, with trilobites, and other slates with impressions resembling graptolites,* having already in 1842 declared that of these, his Taconic rocks, the upper portion is "the lower part of the Silurian system." †

§ 93 C. [That this great and continuous belt of slates with sandstones and interbedded limestones, overlaid by the Second Graywacke, and, together with the Sparry limestone, occupying the whole breadth between it and the other three named members of the Taconic system, belongs to the First Graywacke or Upper Taconic, as defined by Eaton (*ante*, p. 520), is too evident to require discussion. It may farther be said that notwithstanding the uncertainty as to sequence of these various members expressed by Emmons, the position of the Sparry limestone had been clearly and correctly fixed by Eaton, ten years before, when he placed it at the summit of the First Graywacke, and included it in the Lower Secondary

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* Agriculture of New York, pp. 65–72.

† Geology of Northern District of New York, p. 163. See also *post*, §§ 160, 161.

limestones, as the stratigraphical equivalent of the Calciferous Sand-rock and the Trenton limestone of the west side of Lake Champlain (*ante*, p. 520). James Hall, who in 1857 still held the view of Mather that this graywacke was no other than the Second Graywacke of Eaton, then wrote of "that part of the Hudson-River group which is sometimes designated as Eaton's Sparry limestone,—being near the summit of the group." *

§ 94. [In the report on the Agriculture of New York, in 1846, just cited, in which Emmons gives us in much detail his more matured conclusions on the Taconic system, he abandons the view of Mather as to the age of the Graywacke series which found a place in certain chapters of his report of 1842, already quoted, and holds to that laid down in chapters vii., viii., and ix., of that report. The complete discordance of these with the other portions of the volume, and their agreement with the report of 1846, show them to have been written at a later period than the rest, and interpolated therein. The great belt of slates, limestones, and graywacke designated the Taconic slates, and extending from the valley of the Hudson through Vermont into Canada as far as Quebec, was now regarded as the lower part of the Champlain division, and as a thickened and modified form of the Calciferous Sand-rock; which, in its eastward extension, was said to include a great variety of rocks, and to be "protean" in its characters. The Potsdam sandstone was then supposed by Emmons to be wanting in this eastern region, but he was afterwards led to regard certain strata in western Vermont as its representative. Eaton's three divisions of Quartzite, Limestone, and Argillite underlying this First Graywacke series, and constituting the lower part of the Taconic system, were still held by Emmons to be older than the base of the Champlain division. The stratigraphical discordance between the Argillite and the Graywacke, long before noticed

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* Report Geol. Survey of Canada, 1857, p. 117.

by Eaton, was, however, apparently disregarded by Emmons.]

§ 95. In 1855, returning to the subject in his treatise entitled "American Geology," Emmons, while still adhering to the views of its age and relations announced by him in 1846, proposed to consider the Taconic system as consisting of two parts, between which, according to him, "the line of demarcation is tolerably well defined." Of these, the lower division, or Lower Taconic, included the three lower members just mentioned, and the upper division, or Upper Taconic, the First Graywacke, or the great group of so-called Taconic slates, with the Sparry limestone. The same view is farther set forth in his "Manual of Geology," in 1860, and in his subsequent reports on the geology of North Carolina.

§ 96. We have now to consider more at length the history of the First Graywacke belt of Eaton, which, by his observations, and those of Emmons and Mather, was traced from below Quebec, on the St. Lawrence, southward through Vermont, and along the east side of the valley of the Hudson. Mather, who supposed this belt to be represented farther south, along the west side of the Hudson, by the Shawangunk range (a prolongation of the Kittatinny Mountain of New Jersey and Pennsylvania, which is of Oneida-Medina age, and consequently belongs to the Second Graywacke), referred the whole belt north and east of the Hudson to this period. In the opinion of Emmons, however, the First Graywacke, to the west and south of the Hudson, was represented, not by the Shawangunk, but by a parallel range a little to the eastward, to be mentioned below (§ 98). This Upper Taconic belt, according to him, is continued southwestward, with some interruptions, across New Jersey and Pennsylvania, into the valley of Virginia; where, near Wytheville, and again near Abingdon, he described sections of the Upper Taconic resting upon Lower Taconic rocks.

§ 97. We have not, however, as far as I am aware, any detailed account of these Upper Taconic rocks in the great valley from Virginia to the region east of the Hudson. In Pennsylvania they have received little notice from the two geological surveys of that State, though they are, as I have already stated, largely developed in the great valley in the interval between the Delaware and the Susquehanna Rivers (§ 30). They were here included by H. D. Rogers in the Matinal series, and placed by him below the Levant sandstone. He, at the same time, noticed their resemblance to the beds immediately above this sandstone; a likeness which led Mather to refer them, in eastern New York, to this higher horizon. It will be remembered that the roofing-slates of the Delaware, which succeed the Auroral limestones, and are supposed to be included in the Lower Taconic of Emmons, are assigned, both by Rogers and by Chance, to a position near the base of the series of about 6000 feet of so-called Matinal rocks (§ 29). This great series in Pennsylvania has thus the stratigraphical position, as well as the characters, of the Upper Taconic or First Graywacke, which is so conspicuous, both to the north-east and the southwest, along the Appalachian valley.

§ 98. The question now arises to what extent the rocks of this series are found to the eastward of the great valley; that is to say, east of the Blue Ridge, the South Mountain, and its northern prolongation from the Highlands of the Hudson into New England and Canada. So far as known, there is nothing to represent the Upper Taconic in this eastern area, farther north than the Highlands. Resting upon the ancient gneiss of the Highlands in Orange County, New York, there is, however, a range of rocks, formerly designated as graywacke, which were by Mather described as a parallel belt lying to the southeast of Shawangunk Mountain, of which he regarded it as a repetition. This graywacke-belt was said by Horton to constitute, in parts of Orange County, two or more narrow bands, the strata of which dip eastward at high angles, and lie directly upon the ancient gneiss, beneath which, in some cases, they seem to pass. The continuation of this belt in New Jersey is known as the Green-Pond Mountain range. This, while regarded by Mather as belonging to the Second Graywacke, was by Rogers conjectured to be an outlier of the great mesozoic area which lies farther to the southeast, but by Emmons was supposed to belong to the First Graywacke. More recently, it has been, by Professor Cook, in his geological survey of New Jersey, described as belonging to a still lower horizon, and, under the name of Potsdam, referred to the base of the Primal of Rogers. The lithological characters of this graywacke-belt, as I have observed it in New Jersey, are, however, very distinct from those of the Primal. This latter in the adjacent region of northeastern Pennsylvania, along the same gneissic belt, is, where it appears from beneath the Auroral, represented only by a small volume of quartzite, with soft schists: a development wholly unlike the Green-Pond Mountain conglomerate.

§ 99. The relations of this graywacke-belt to the Auroral limestone. often found adjacent, as well as to other and fossiliferous limestones and shales met with along the range, both in New Jersey and in Orange County, New York, are complicated by many stratigraphical accidents, and demand further investigation.* A summary of the facts regarding it, as gathered from the reports of Mather and of Horton, is given in the author's "Azoic Rocks," pages 35-37; while, for later observations by Cook, in New Jersey, the reader is referred to his volume on the geology of that State, published in 1868,

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* An area of fossiliferous argillites, found in the Peach-Bottom district in Lancaster County, Pennsylvania, some distance to the southeast of the second Taconian belt, and on the Susquehanna River, along the borders of Maryland, is perhaps to be regarded as an outlier belonging to the First Graywacke; since it has lately furnished to Dr. Persifor Frazer graptolites referred by Professor Hall to that horizon. I am indebted to Dr. Frazer for these facts, the results of Professor Hall's observations not being as yet published.

already cited, in § 80. In Bearfort Mountain, in this region, according to Cook, the conglomerate beds are overlaid by slates, which are followed by sandstones, called Oneida and Medina, while at Upper Longwood, fossiliferous limestone, regarded as Trenton, overlies the red slates of the conglomerate belt (loc. cit., pp. 149, 83).

[Later studies throw farther light upon the rocks of this belt. Thus Smock, in 1884, discovered in certain flagstones of the series remains of Devonian plants, while it has been found by Darton that the fossiliferous limestones at Upper Longwood, and near Newfoundland, in New Jersey, are not Trenton, as hitherto supposed, but approximately Niagara in age. Dwight, moreover, has found that the sandstones at the Townsend iron-mine, near Cornwall, in Orange County, New York, are of Oneida-Medina age, and are overlaid by Lower Helderberg limestones, the fauna of which has been described in detail by Darton.* The recent observations of the latter, in part unpublished, also show within the limits of this area the existence of strata holding Loraine, Trenton, and Calciferous forms, which, however, according to him, appear to be associated with a series of older schists and limestones, without observed fossils. While there is thus paleontological evidence in confirmation of the view of Mather that this belt includes the rocks of the Second Graywacke, it would also appear to embrace strata of lower horizons, as supposed by Emmons and by Cook. According to Darton, who is now engaged in the study of this region, and to whom I am indebted for these unpublished details, the structure is complicated by a considerable fault, along the west side of which the newer rocks predominate.]

§ 100. Passing now to the consideration of the Upper Taconic rocks in the regions north of the Highlands of the Hudson, where they have been chiefly studied, we

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* Dwight, Trans. Vassar Bros. Institute, ii., 1883-84, p. 75; Smock, Report on Geology of New Jersey, 1884, p. 35, and Darton, Amer. Jour. Science, 1885, xxix., p. 432, and 1886, xxx., p. 209.

remark, in the first place, that here, as farther south, they are found resting alike upon the Lower Taconic and the older crystalline rocks which appear on the western border of the latter. The base of the Upper Taconic, as described by Emmons, here consists of coarse greenish sandstones, with shales and conglomerates, holding materials derived from the underlying crystalline rocks. The higher part of the series was said to be very variable in character, including olive-colored sandstones, and so-called "brown-weathering calcareous sandstones," which are really arenaceous dolomites holding much carbonate of iron, beds of quartzite with green, purple, and red roofing-slates, followed by blue limestones, — the Sparry lime-rock of Eaton; while towards the summit are black shaly limestones, the series terminating with a black slate. The upper part of this series was declared to be fossiliferous, containing remains of graptolites, fucoids, and trilobites. In a section from near Comstock's Landing, eastward to Middle Granville, in Washington County, New York, in which the above-described rocks are found, there is, Emmons tells us, no representative of the granular quartzites, the limestones, the talcose slates, or the characteristic roofing-slates of the Lower Taconic. The rocks in this section have, according to Emmons, an apparent thickness of not less than 25,000 feet; a volume probably due to repetitions from numerous parallel dislocations, with upthrows on the east side; as a result of which the succession already described is apparently inverted, so that the black slates of the western part of the section seem to pass beneath all the other members, and the green sandstones of the eastern part appear to overlie them all.

§ 101. This condition of things, so far from being exceptional, is very frequent along the eastern base of the Atlantic belt, from the Gulf of St. Lawrence to Alabama, and is apparently general in similar disturbed regions. Emmons has described this with detail, and noted the parallel uplifts, increasing in vertical extent as we approach the mountain-chain of older rocks. I have discussed this matter, with many illustrations, in my volume on "Azoic Rocks," pages 54, 55. It is there shown that along the whole eastern side of the great Appalachian valley the newer rocks are found dipping to the eastward, towards the older rocks, and sometimes even beneath them. Thus, the Cambrian Graywacke appears to pass beneath the crystalline rocks of the Highlands of the Hudson and of the island of Newfoundland; the Ordovician beds beneath this First Graywacke; and farther southward, in Virginia, the carboniferous rocks beneath the older paleozoic. These relations result from dislocations, with uplifts on the eastern side, often connected with inverted folds.

§ 102. While the green sandstones in New England, according to Emmons, constitute, along its eastern border, the base of the series, there appears farther west in the valley, along the eastern shore of Lake Champlain, another mass of strata, the so-called Red Sand-rock of Vermont, which, towards the summit, becomes a reddish limestone or marble. These strata, which have yielded a Cambrian fauna, were by C. B. Adams referred to the horizon of the Medina and Clinton, and by Logan, in 1859, were said to belong to the summit of the Hudson-River group, or possibly to a still higher horizon. These rocks were, however, in 1855, assigned by Emmons to a position still lower than the green sandstones, and were supposed to represent the Potsdam horizon of the Champlain division; while the remaining portion of the Upper Taconic was regarded as the equivalent to the Calciferous Sand-rock. The Red Sand-rock in western Vermont is brought up by a dislocation, and the higher members of the Champlain division appear to pass conformably beneath it to the eastward. The same conditions are met with in the Cambrian beds at Troy, New York, studied by Ford, which there overlie the Loraine shales, and were by Billings assigned to the same geological horizon as the Red Sand-rock, with the name of Lower Potsdam. The outcrop of these strata in Georgia, Vermont, according to Logan, exposes a thickness of not less than 2200 feet, in the lower part of which are included the argillaceous beds holding Olenellus, with Conocephalites and Obolella. The late results of Walcott in the study of the Cambrian rocks in North America will be noticed farther on, after § 138.

VI.—THE UPPER TACONIC IN CANADA.

§ 103. We are now prepared to notice the studies of this Graywacke-belt in its extension through Canada, from Vermont to the St. Lawrence. Logan, who, in 1845, published a preliminary account of the geology of Canada, expressed therein the opinion that the contorted strata at and near the city of Quebec, which are those of the belt in question, were older than the adjacent horizontal (Trenton) limestones; but in a foot-note referred favorably to the view (which had been maintained by Emmons in 1842) that they were newer rocks. These contorted strata, consisting of argillites, sandstones, conglomerates, and limestones, were, during the next ten years, traced in Canada from Quebec northeastward along the right bank of the lower St. Lawrence, and southwestward to the valley of Lake Champlain; forming a belt from near Quebec southward along the northwest base of the crystalline schists of the Green Mountain range. They were recognized by the Canadian survey as forming a part of the Graywacke-belt of Eaton, and, in accordance with the view of Mather, and the earlier view of Emmons, were referred to the upper part of the Champlain division, and declared to embrace the so-called Hudson-River group, and the immediately succeeding strata; including the representative of the Oneida, to which the sandstones of Sillery were supposed to belong. The organic remains as yet found in the belt, in Canada, were in limestone-pebbles in a conglomerate at

Pointe Levis, which were erroneously supposed to be derived from the Trenton; and certain forms occurring in a limestone at Phillipsburgh, near Lake Champlain, also regarded as of Trenton age. In 1855, were first described, by James Hall, the graptolites of Pointe Levis, then spoken of by him as coming from "near the summit of the Hudson-River group"; to which horizon, considered as that of the Loraine shales, they were, on stratigraphical grounds, assigned by Logan.

§ 104. As early as 1846, however, as we have seen, Emmons had, on stratigraphical grounds, assigned this Graywacke-belt to the horizon of the Calciferous Sandrock, and had declared it to contain certain peculiar forms of graptolites and of trilobites. This view, which was essentially a return to that of Eaton, was, however, combated by all the other Americans geologists who had studied these rocks in Canada and in Vermont; C. B. Adams, W. B. Rogers, and W. E. Logan uniting, on alleged structural grounds, to place these rocks at the summit of the Champlain division, or in the Second, instead of the First Graywacke.

§ 105. It was not until 1856 that the present writer discovered in association with the graptolitic beds of Pointe Levis, limestones containing a hitherto unobserved trilobitic fauna, the examination of which by Billings led him to the conclusion that the strata in question were older and not younger than the Trenton limestone; or, in other words, that they belonged to the First and not to the Second Graywacke. It was in 1861 that Logan, in a letter to Barrande, published this conclusion, then reached, and at the same time admitted the correctness of the later view of Emmons, for which this geologist had contended alone during fifteen years, namely, — that the belt of disturbed rocks which in Canada and in Vermont had been called the Hudson-River group, was in reality the stratigraphical equivalent of the lower members of the Champlain division, and older than the Trenton limestones. These strata were the Upper Taconic of Emmons, which he had already in 1860 declared to be the equivalent of the rocks holding the first or Primordial fauna of Barrande. (§ 17, and *ante*, p. 586.)

§ 106. The contact of these rocks near Quebec with the underlying gneiss is concealed by the horizontal Trenton limestone of the region. The green sandstone of Sillery here lies upon the other members of the Graywacke series, and since this had been regarded as the Oneida sandstone, overlying Loraine shales, the whole series was supposed to be in its natural order of succession. Hence it was that, while admitting the change of horizon of these rocks from above to below the Trenton limestone, the Sillery sandstone, as it was henceforth called, was placed at the summit, and the limestones and graptolitic slates of Pointe Levis, to which the name of the Levis division was given, at the base of the series; an intermediate portion receiving the name of the Lauzon division. The real order, however, as described both by Emmons in Vermont, and by Murray in Newfoundland was the reverse of this, and the Sillery sandstone was, in truth, the oldest member of the series here displayed. Logan, as we have seen, maintained that the typical section of southeastward-dipping strata at Quebec, estimated by him to measure 7000 feet, was the southeast side of an eroded anticlinal, and represented the rocks of his Quebec group in their natural order; the Levis division at the base and the Sillery at the summit. I have long since endeavored to show, alike on structural and on paleontological grounds, that this view is erroneous, and that we have here an inverted succession. The true position of the Sillery is at the base of the series, and we here find exposed the eroded surface of the northwest side of an overturned anticlinal, by which the Sillery sandstone is made to overlie the younger members of the Graywacke series.[*] The succession is thus brought into harmony

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[*] Harper's Annual Record for 1876, p. xcviii., and for 1877, p. 167.

with that determined by Eaton, and by Emmons, in many sections farther south. This series, which had been previously called the Hudson-River group, was now by Logan, and the Canada geological survey, named the Quebec group, and was described as a great development of strata between the Trenton limestone and the Potsdam sandstone; which latter, Logan conceived to be represented by certain black shales, that in several localities appear to pass beneath the Levis division. The rocks of this series were now, by Logan and his assistants, traced down the St. Lawrence to Newfoundland, on the one hand, and to the valley of Lake Champlain, on the other; where, however, the Red Sand-rock was supposed to represent the Potsdam. The history of these investigations I have elsewhere set forth, in "Azoic Rocks," pp. 81–125. It should here be said that this view, which made the Sillery the youngest member of the series, was, in 1862, questioned by Billings, who inclined, with the writer, to place it at the base of the series; while its evident basal position in Newfoundland led Logan also to express doubts, and to look upon the order assumed by him as simply provisional.*

§ 107. It remained, however, to determine how far this identification with the First Graywacke applied to the rocks farther south, in the valley of the Hudson, to which the name of the Hudson-River group had first been given; and which had been declared, alike by Eaton, Emmons, and Mather, to be geographically and stratigraphically identical with the similar rocks in Vermont and in Canada. These rocks in the Hudson valley had been by Mather assigned to the horizon of the Second Graywacke, and from the occurrence in portions of them of the fauna of the Loraine or Pulaski shales, he, with Vanuxem, had, as we have seen, been led to employ the names of Hudson slates and Hudson-River group as synonymous

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* Billings, Paleozoic Fossils, 1865, p. 69, and Logan, Geology of Canada, 1863, p. 880.

with that of Loraine shales. The opposition between the view of Mather, on the one hand, and that of Emmons, now adopted by Logan, on the other, as to the horizon of the so-called Hudson-River group, was thus radical and complete.

§ 108. A question here arises whether it might not be possible to reconcile these two seemingly contradictory views by showing the belt of disturbed strata in question to include both the First and the Second Graywacke. These, as we have seen, were declared to resemble each other so closely as to be scarcely distinguishable save by the fact that the latter overlies the Trenton limestone (§ 7). If now, from any cause, this limestone should be absent, or should not appear in its usual character, it might very well happen that the Second should appear to succeed directly the First Graywacke. That such a condition of things occurs in the disturbed region east of the Hudson, had already been affirmed by Emmons in 1846. As I have elsewhere pointed out ("Azoic Rocks," page 49), he then asserted the existence in this region of three distinct series of rocks: I. The Lower Taconic or Taconian limestone and slates. II. The First Graywacke, or Upper Taconic, resting in apparent unconformity upon the former, and itself partially eroded before the deposition of III., which latter consists of shales and sandstones belonging to the upper portions of the Champlain division, or the Second Graywacke, and rests unconformably, in many localities east of the Hudson, both on I. and II.; having itself been subsequently disturbed and eroded.

§ 109. These observations accord with many others to show the existence of at least two important stratigraphical breaks, with unconformity, in this eastern region: the first between the Taconic and the First Graywacke, already pointed out by Eaton, and the second at the summit of the same Graywacke series; thereby dividing, in this eastern region, the Champlain division into two distinct periods, the second one of which began with the deposition of the Trenton, or, rather, with that of the immediately subjacent Chazy limestone.

The Laurentian regions of the Adirondacks and the Laurentides were not, at this early time, as has been so often said, the nucleus of a growing continent, but higher portions of a subsiding one. Upon its ancient gneiss we find reposing directly, in different localities, the Potsdam, the Calciferous, the Chazy, and the Trenton subdivisions. The deposition of the Trenton marks a time of subsidence, during which, along the Laurentides, the sea extended far and wide to the northward, and the marine limestones of the Trenton, overlapping the lower members of the Champlain division, were laid down (in the regions to the north of Lake Ontario and of the lower St. Lawrence, as far eastward as the basin of Lake St. John on the Saguenay), directly on the submerged primary or eozoic rocks. After this period, and before the deposition of the succeeding mechanical sediments, extensive movements took place in the region of the Ottawa and Champlain valleys, and still farther south, which serve to throw light upon the problem before us.

§ 110. A striking illustration of this disturbance is shown on Logan's larger geological map of Canada, in 1866, where, immediately south and east of the city of Ottawa, appears an outlier of Utica slate, overlaid by gray calcareous sandstone, holding the fossil remains of the Loraine, and associated with red slates; the two possibly representing the Oneida and the Medina. This outlier, with a length of about twenty miles from east to west, reposes transgressively alike upon the Trenton, Chazy, and Calciferous subdivisions. All three of these, with a slight eastward dip towards the centre of the Ottawa basin, appear successively, in passing from west to east along the southern border of this unconformably overlying area of newer strata, which are here preserved by having been let down along the north side of an east and west dislocation; thus testifying to a former extension of the Second Graywacke over this area, where it lies unconformably, not only on the Calciferous Sand-rock (the representative of the First Graywacke), but on the Trenton limestone itself. For farther references to the details of this region, which was carefully mapped by Logan, see "Azoic Rocks," page 50. We have here, in the valley of the Ottawa, evidences of the same conditions as were described by Emmons in that of the Hudson; namely, the unconformable superposition of the upper members of the Champlain division upon the lower ones; a break occurring at the summit of the Trenton. It is impossible not to connect these conditions in the Ottawa and Hudson valleys with those already noticed in eastern Pennsylvania, and in Orange County, New York, where the Oneida sandstone, which, as we have seen, is continuous with the upper part of the Loraine shales, is found to rest unconformably upon the strata of the First Graywacke.

§ 111. Considerable movements are thus seen to have marked both the beginning and the close of the Chazy-Trenton period, and it is evident that the absence, in any district, of the characteristic limestone of this time, between the First and Second Graywackes, might result either from non-deposition or from erosion. Evidence of the latter is afforded in the area just described in the Ottawa basin; while, at the same time, there is not wanting evidence that this limestone-mass, so well marked by its thickness, and the persistence of its lithological character over great areas in eastern North America, elsewhere thins out, and either disappears entirely, or loses its ordinary lithological characters. Thus while in Canada, at points as widely separated as Beauport, Montreal, Ottawa, Lake Simcoe, and the shores of Lake Huron, it appears with a thickness of from 600 to 750 feet (being everywhere followed by the Utica and Loraine shales), it is in Lewis County, New York, diminished to 300 feet, at Trenton Falls to 100 feet, and, it is said, to thirty feet in the Mohawk valley; thinning out and disappearing to the southeast, according to Conrad; but, as will subsequently appear, probably represented along this eastern border by argillaceous beds, which, but for their organic remains, would not be recognized as of Trenton age.

§ 112. The bearing of the paleontological investigations made by the geological survey of Canada on the question of the age of the eastern Graywacke, or so-called Hudson-River group of rocks, was discussed by James Hall, in a note to his "Geology of Wisconsin," in 1862 (page 443). He there alluded to the evidence furnished by organic remains found in the Hudson-River slates in Vermont and Canada, "which prove conclusively that these slates are to a great extent of older date than the Trenton limestone," though probably newer than the Potsdam. He moreover remarked that "the occurrence of well known forms of the second fauna . . . in intimate relation with, and in beds apparently constituting a part of the series, along the Hudson River, requires some explanation. Looking critically at the localities in the Hudson valley which yield the fossils, we find them of limited and of almost insignificant extent. Some of them are on the summits of elevations, which are synclinal axes . . . where the remains of newer formations would naturally occur. Others are apparently unconformable to the rocks below, or are entangled in the folds of the strata . . . while the enormous thickness of beds exposed is almost destitute of fossils." In view of all these facts, Hall, while still retaining the name of Hudson-River group as the designation of the fossiliferous strata which elsewhere are found to occupy a horizon between the Utica slate and the Oneida sandstone (otherwise called Pulaski and Loraine shales), concludes that the name of Hudson-River group cannot properly be extended to the great mass of strata which have hitherto borne that name, and which, according to him, "are separated from the Hudson-River group proper by a fault not yet fully ascertained."

§ 113. It should, however, be remembered that although the Hudson-River group was, through the paleontological publications of the New York survey, identified with the Loraine shales only, the name, as at first given by Vanuxem, was made to include two divisions, the lower of which, as he showed, was distinct from the upper, as appeared by its different geographical distribution. That these two divisions of the Hudson-River group were supposed by him to be associated with a still older series, lithologically resembling them, would appear from Vanuxem's language, when he wrote of "the difficulty of separating or distinguishing the slaty and schistose members of the Hudson-River group from those of greater age, with which, along their eastern border, the two (*sic*) are more or less really or apparently blended."

§ 114. Hall, while thus admitting the existence of an apparent unconformability between the older and the newer fossiliferous rocks in this disturbed region, fell back on Logan's explanation, and imagined the juxtaposition of the two series to be effected by a break of the strata, with an uplift on the eastern side, by which the rocks of pre-Trenton age were brought up, and were sometimes found in contact with the Trenton or Utica divisions, at others with the Loraine, and, perhaps, even with the still higher beds of the Oneida. I have elsewhere discussed at length this hypothesis of a single great fault, with an upthrow of 7000 feet, imagined by Logan to extend from Alabama to the northeast extremity of the continent, in Gaspé; and having shown its great improbability both geographically and stratigraphically, have maintained, for ten years past, the simpler explanation of an unconformity between the First Graywacke and the succeeding members of the paleozoic series. ("Azoic Rocks," pp. 121–125.) Evidences are there given that movements of the earth's crust in these regions immediately preceded the Trenton age, and that upon the folded, eroded, and submerged strata of the First Graywacke, as upon the Taconian and still older series, there were subsequently deposited the Trenton limestones. Where these limestones were afterwards removed by denudation, or where, to the eastward, they thin out and disappear, we may expect to find the Loraine, or the succeeding Oneida strata, in direct superposition upon these older rocks.

§ 115. In 1863, Logan, having followed southward into Vermont the Graywacke-belt, to which he had then given the name of the Quebec group, proceeded, in company with James Hall, to examine the same rocks in eastern New York; where they were now described by him, as they had been by Emmons, as sandstones and conglomerates, generally with argillites, sometimes red and green, and with limestones, often schistose or concretionary, including the Sparry Lime-rock of Eaton. All of these were now declared by Logan to belong to the Quebec group, which was said by him to occupy nearly the whole of Columbia, Rensselaer, and Dutchess Counties; the Sillery division being largely displayed in the first-named of these, but scarcely appearing south of it. To the westward, in approaching the River Hudson, these rocks were declared to be replaced by lithologically distinct and more recent strata, referred to the Loraine shales; a narrow belt of which was traced along the east side of the river to a point a little above Hyde Park, where the boundary of the two divisions crosses to the west bank. The strata on both shores from thence down to the gneiss of the Highlands were referred by Logan to the Quebec group.

§ 116. Logan, however, as we have seen, assumed the Sillery sandstone to be the summit instead of the base of the First Graywacke; and when he became, at this time, acquainted with the underlying Taconian marbles in Vermont, and, farther southward, imagined them to be his Levis and Lauzon divisions in an altered condition, and thus described them as members of the Quebec group. It yet remains to determine in this region the limits between the Taconic and the First Graywacke. We now know, moreover, from the discoveries of Dale, Dwight, and others, that still newer fossiliferous strata, of Ordovician age, are also included in this part of the Hudson valley; and that we have, in fact, in this region, the three groups of rocks long since pointed out by Emmons. (§ 108.) The testimony of Logan is valuable as confirming that of Emmons, and of Hall, as to the existence of portions of the Second Graywacke series resting, not upon the Trenton limestone, but upon the older schistose rocks of the region; and moreover, as showing the superposition of the First Graywacke to the Taconian.

§ **117.** The apparent absence of the characteristic limestone of the Trenton from the base of the Second Graywacke in this region may be due to a stratigraphical break and erosion at the close of the Trenton period, as we have seen in the Ottawa basin. Two other explanations are suggested by the thinning-out of the limestone-mass to the southeast, as already noticed (§ **111**); one, that the region was beyond the Trenton sea, and the other that the sediments of this sea over the area in question were argillaceous beds, resembling rather the succeeding shales than the limestone deposited elsewhere. That this latter was the case in parts of the eastern region, will be shown in the sequel, but we shall there also find many evidences of movements in paleozoic times, subsequent to the deposition of the Trenton.

I have elsewhere pointed out ("Azoic Rocks," page 123), besides the post-Trenton break in the Ottawa basin, the evidence in eastern North America of not less than five epochs, marked by movements of the strata, and by unconformities, subsequent to the deposition of the Trenton and Utica divisions. Of these the earliest, and the only one which now concerns us, is that of which we see evidences in the unconformable superposition of Silurian beds over older strata to the north and east of the Hudson valley. On St. Helen's Island, near Montreal, we find reposing on the eroded surface of the slightly inclined

Utica slates, a portion of fossiliferous limestone associated with a dolomitic conglomerate. The fauna in the limestone is referred to the age of the Lower Helderberg; while the accompanying conglomerate contains forms which belong rather to the Clinton and Niagara divisions of the Silurian, and holds at the same time pebbles of fossiliferous Trenton limestone, with others apparently of Potsdam sandstone, Utica slate, and red sandstone and shale, resembling those of the Medina; the whole mingled with pebbles of Laurentian gneiss, and of igneous rocks, giving evidence of a period of disturbance, and considerable erosion of the older rocks. Other masses of similar conglomerate are found elsewhere in the vicinity, in one case holding Silurian fossils, resting on various members of the Champlain division, and on the Laurentian gneiss.

Another mass of Lower Helderberg limestone is met with on the flanks of Belœil Mountain, an eruptive mass which breaks through the Loraine shales in the Richelieu valley. In the distribution of these, and of similar areas of fossiliferous limestones, we have the evidences of a Silurian sea, which extended from the Helderberg region in New York, not only through the valleys of the Hudson and Lake Champlain to that of the St. Lawrence, but also through those of the Connecticut, the St. Francis and the Chaudière, and thence to Gaspé; depositing its sediments, with their characteristic fauna, unconformably over rocks of very different ages. We have similar evidence that the Chazy-Loraine or Ordovician sea had already, in like manner, extended over parts of this region, leaving its fossiliferous sediments spread unconformably over Cambrian and pre-Cambrian strata.

§ 118. A section from Crown Point, New York, across the southern part of Lake Champlain eastward to Bridport, Vermont, which was studied in detail by Wing and by Billings, presents, in its western portion, the whole succession of the Champlain subdivisions, from the Potsdam to the Loraine shales. Farther eastward on this line, a great dislocation brings up the Red Sand-rock, with Olenellus, causing it to overlie, in seeming conformity, the Loraine shales. This sand-rock is followed to the eastward by limestones holding the fauna of the Calciferous Sand-rock, with other forms like those of the Levis limestone. To these succeed other limestones, with an abundant Trenton fauna, interrupted by a second fault, which again brings up the Levis beds; the Sillery sandstone being unrepresented, unless possibly by the Red Sand-rock to the west. For a summary of the observations on this section, and reference to the original paper, see "Azoic Rocks," page 119.

§ 119. Other examples of an extension of the Ordovician sediments eastward are found in the province of Quebec, in various localities along the disturbed region northeastward from Lake Champlain. Lying alike among the uncrystalline strata of the Graywacke series, and the older crystalline rocks to the southeast of them, there are met with, in many localities, carbonaceous shaly beds, more or less calcareous, containing organic remains of Ordovician age. These strata, probably never very considerable in amount, have, however, rarely escaped erosion, except in localities where, as the result of the folds and dislocations already noticed, they have been protected by the overlying or adjacent older strata, beneath which they often seem to pass with an eastward dip. As studied at Farnham, in the province of Quebec, they thus appeared to be more ancient than the Graywacke series, and were described by Logan as portions of Potsdam rocks underlying the Quebec group. The black slates of this locality, however, contain, according to Billings, besides undescribed graptolites, *Ptilodictya* and trilobites of the genera *Ampyx*, *Dalmanites*, *Lichas*, *Triarthrus*, and *Agnostus;* and were hence referred by him to the Trenton or the Utica division of the New York system. Similar black slates appear, in like manner, to pass beneath the crystalline schists which lie to the east of the Graywacke-belt in this region, and were by Logan adduced as proofs of the view then maintained by the geological survey of Canada, that the crystalline rocks in question were nothing more than portions of this same Graywacke in an altered condition.

The fallacy of this view I have long since shown, and have pointed out the nature of the stratigraphical accidents by which this seeming inversion has been brought about. Selwyn, of the geological survey of Canada, has more recently furnished additional facts regarding the distribution of these fossiliferous shales; outliers of which have been observed at various localities in eastern Canada, among the crystalline schists, especially along the west side of a line of fault, with an upthrow on the east side, extending through Stukley and Ely. Similar fossiliferous beds are found in Tingwick and Arthabaska, and also near Richmond; where a narrow belt of black shales, with Triarthrus and other organic forms, is found lying to the east of the crystalline schists of the region. The latter are a second time brought up on the eastern border of these shales, and soon pass beneath the argillites of the Windsor basin (§ 81). In this connection it may be noticed that Dodge has found, still farther to the eastward, in Penobscot County, Maine, black shales holding graptolites, which are regarded by him as species belonging to the Utica slate.*

§ 120. It was said at the commencement of this essay that the Upper Taconic rocks have been known both as the Hudson-River group and the Quebec group. This statement we have justified in the preceding pages, and are now prepared to state succinctly what has been the precise meaning attached to these two terms, which have been so conspicuous in the history of American geology. The Hudson-River group, by the admission of Vanuxem, who first proposed it, was a composite one, devised to include two, if not three divisions of strata, in part of

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* Amer. Jour. Science, 1881, vol. xxii., p. 434.

disputed age, but at the same time embracing in its upper portion the Loraine shales. As this was the only part of the group of which the fauna was known, the name of Loraine shales, in paleontological language, soon came to be regarded as the equivalent of Hudson-River group; and thus the fact of its heterogeneous character, clearly stated by Vanuxem, was lost sight of. Meanwhile, the name of Hudson-River group was applied stratigraphically to the whole of the First Graywacke of Eaton, with its succeeding Sparry Lime-rock. This is seen from the language of James Hall, who, in 1857, wrote of the graptolites found in slates with the limestone of Pointe Levis, at that time assigned by Logan to this horizon, that they are met with in "that part of the Hudson-River group which is sometimes designated as Eaton's Sparry limestone, — being near the summit of the group." This was the Levis limestone of Logan.*

§ 121. The Red Sand-rock of Vermont was also, at the same time, regarded as either forming a part of the same group or as closely related to it. Thus Hall, in describing, in 1859, the trilobites of the genus Olenellus found in shales intercalated in the Red Sand-rock in Georgia, Vermont, which he then referred to this horizon, wrote, "I have the testimony of Sir William Logan, that the shales of this locality are in the upper part of the Hudson-River group, or forming a part of a series of strata which he is inclined to rank as a distinct group, above the Hudson-River group proper."† We have farther to mention in this connection the notion of Mather, who supposed that the crystalline rocks of western New England, including the crystalline limestones, "and probably the associated micaceous gneiss, mica-slate, hornblende-slate, and hornblende-rocks . . . are nothing more than the rocks of the Champlain division greatly modified by metamorphic agency." This

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* Report Geol. Survey of Canada, 1857, p. 117.

† Twelfth Ann. Rep. Regents of the University of New York, 1859; cited by Barrande, Amer. Jour. Sci. (2), xxxi., p. 213.

view was adopted by Logan, and the similar crystalline rocks of the Green-Mountain belt in Canada were described as belonging to the altered Hudson-River group.

§ 122. The Quebec group, which, in 1861, succeeded to the Hudson-River group, inherited its traditions, with a few exceptions. Its horizon being now changed from above to below the Trenton limestone, it could, of course, no longer include within its limits the fauna of the Loraine shales, belonging to the Second Graywacke. The greater antiquity of the fauna of the Red Sand-rock of Vermont having in the meantime been recognized, these rocks were assigned, under the name of Potsdam, to a position beneath the so-called Quebec group. To this lower horizon, moreover, Logan, at the same time, referred certain black slates in Canada, which, though apparently underlying the Graywacke series, have since been found of Ordovician age (§ 119).

The Quebec group, as at first defined, was nothing more nor less than the First Graywacke of Eaton, with its overlying Sparry Lime-rock; which latter is really an upper member of that Graywacke series, and was included with it by Emmons in his Upper Taconic division. Emmons now read aright the relations of these rocks, and saw that the sections in which the limestones appear to underlie the massive green sandstones give an inverted succession. Logan, however, though recognizing therein the existence, in many cases, of overturned anticlinals, inverted the whole series, and regarded the basal or Sillery sandstone as the highest member, while the Levis limestones were made the lowest.

§ 123. This erroneous view as to the succession of the strata at Quebec, at first declared by Logan to be merely provisional, was the more acceptable to him for the reason that it could be made to accord with the hypothesis that the adjacent crystalline schists were, as Mather had taught, the altered equivalents of what was now called the Quebec group. When, as is sometimes the case, the Sillery sandstone was found alone (as long before described by Emmons), resting upon the crystalline schists, the higher and softer members of the Graywacke series having disappeared, Logan supposed that these schists were no other than shales of the Sillery (and Lauzon) in an altered and so-called metamorphic condition, — which, according to his view of the succession, should underlie these sandstones. Hence it was that the Huronian rocks of the Notre Dame range (the prolongation of the Green Mountains) were by Logan called "Altered Quebec group," long after it had been shown by the present writer that fragments of these same eozoic rocks occur in conglomerates with the fossiliferous strata of the Levis division near Quebec.

§ 124. In like manner, when the Sillery sandstone was found, farther southward along the Graywacke-belt, to rest upon the Taconian marbles and slates, these were by Logan declared to be limestones and shales of the Levis division in an altered condition (§ 116). But this was not all: as the Levis beds, sometimes through inverted faults, and sometimes through dislocations, came to be placed beneath the Sillery, so the black Ordovician slates, whether in direct contact with the Cambrian or with the older rocks, were, as the result of similar accidents, made to underlie the more ancient groups of strata, and were believed by Logan to be older than these. In either case, his argument was the same: in the former, these Ordovician strata were Potsdam beds passing beneath the unaltered Quebec group; and in the latter, they were the same beds underlying the altered strata of the same Quebec group.

§ 125. To complete this history, we must recall the fact that, not content with including in the newly organized Quebec group, besides the Cambrian Graywacke with its limestones, the Taconian and the Huronian of the Atlantic belt, Logan proposed to extend it to Lake Superior. Assuming that the horizontal sandstones there overlying unconformably the Keweenian or Copper-bearing series, were of the age of the Chazy or St. Peter's sandstone of the upper Mississippi, Logan was led, in 1861, to assign the whole of this series of 20,000 feet or more to the Quebec group, and thus to give it a position above the horizon of the fossiliferous Potsdam sandstone of Wisconsin and Minnesota; which, as seen on the St. Croix River, and elsewhere in that region, is well known to overlie the Keweenian unconformably, and is probably separated from it by a great interval of time. This view will be found represented on Logan's small map of Canada, dated 1864, and also in his larger map of 1866. The great Animikie or Taconian series,—the relations of which in this region we have considered in §§ 89–90, and which had been previously described by Logan as the lower division of his Upper Copper-bearing series,—was not distinguished from it on the maps in question, but was now supposed to represent the Potsdam.

§ 125 A. [As to the history of our knowledge of the Upper Copper-bearing or Keweenian series of Lake Superior, it was by Houghton, in 1841, regarded as more ancient than the Potsdam, and by Logan, in 1846, as inferior to the horizontal sandstones of Sault Ste. Marie, then supposed by him to be Potsdam. Logan, in the report of the geological survey of Canada for that year, included, under the name of "Volcanic formations," two divisions, a lower one of dark-colored argillites and quartzites, which is seen in a nearly horizontal attitude on Thunder Bay (where it was afterwards called the Animikie series by the present writer), and an upper division of sandstones, amygdaloids, and trappean rocks, regarded by Logan as equivalent to the series bearing native copper on the south shore, and elsewhere on the lake. Beneath this lower division on Thunder Bay were older crystalline rocks, then described as greenstones with epidotic rocks and chloritic slates, and noticed by Logan, in his report for 1846, as the "chloritic schists at the summit of the older rocks upon which the Volcanic formations rest unconformably,"* the lower division of the latter including, in a conglomerate layer, portions of these older rocks.

§ 125 B. [Two years later, however, in his report for 1848, Logan, overlooking these stratigraphical relations, and led by certain considerations set forth in that report, attempted to establish a parallel between the ancient greenstone and chloritic group and the so-called Volcanic formations, considering "their positive or approximate equivalence highly probable, if not almost certain." Much stress was then laid by him on the fact that the greenstone and chloritic series on the north shore of Lake Huron (extending nearly to Sault Ste. Marie, and often containing sulphuretted copper-ores), and the inclined sandstone and amygdaloid series of Lake Superior carrying native copper, were alike found resting unconformably upon an ancient granitic series, and unconformably overlaid by similar horizontal sandstones, then considered the equivalent of the New York Potsdam. The fact that what was regarded by him as the amygdaloid and trappean series had beneath it, on Thunder Bay, the dark-colored argillites and quartzites, which in their turn rested unconformably upon a greenstone and chloritic series like that of Lake Huron, was strangely overlooked. This new thesis of Logan was adopted by Rivot in 1855 and 1856, and by J. W. Dawson in 1857, Rivot even supposing that what had been regarded as igneous rocks in the amygdaloid and trappean series were but sediments altered in place.

§ 125 C. [This view of the equivalence of the two

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* The reports of the Canadian survey for 1845 (on the Ottawa valley) and for 1846 (on Lake Superior) were not published until 1847. In February of the latter year, the writer commenced his labors at Montreal as chemist and mineralogist to the geological survey of Canada, and, the publication of these reports having been delayed, he was thus enabled to examine and describe the various rocks and minerals from the region of the Ottawa, as well as those from Lake Superior. 'For the lithological and mineralogical notes and descriptions which occur in the reports for 1845 and 1846, and in the subsequent publications of the survey during twenty-five years, the present writer is responsible, inasmuch as they were all written by him or under his supervision." Azoic Rocks, p. 66.

unlike series was disputed in 1857 by J. D. Whitney, who maintained the distinctness of the greenstone and chloritic group from the cupriferous amygdaloid and trappean series of the south shore of the lake, and at the same time asserted that the latter "cannot be separated from the Potsdam sandstone with which it is associated; neither is there any reason whatever for placing it in the same line with the rocks of the north shore of Lake Huron." In the "Geology of Canada" in 1863, Logan returned to his former view of the distinctness of the greenstone and chloritic group (which, from its sulphuretted copper-ores, he sometimes called the Lower Copper-bearing group), to which, in 1855, the present writer had given the name of Huronian. Logan now described this as "unconformably overlaid by a second series of copper-bearing rocks," designated by him as the Upper Copper-bearing series, and including the two divisions of his Volcanic formations already distinguished in 1846. This second series, he however declared, in opposition to Whitney, to be distinct from the nearly horizontal sandstones of the east end of the lake, which he supposed, with Houghton, to overlie unconformably the Upper Copper-bearing series. Already, however, in 1861, Logan had conceived the notion that this series might be the stratigraphical equivalent of the First Graywacke or Upper Taconic, to which he had given the name of the Quebec group. The Animikie or lower division of his Volcanic formations, which is often absent (the upper division resting directly on the Huronian or the ancient gneiss), was henceforth called Potsdam, and the overlying sandstone, now known to be Cambrian of the Potsdam period, was supposed by Logan to be the equivalent of the St. Petèr or Chazy sandstone, and thus of Ordovician age.

§ 125 D. [Notwithstanding all this discussion, and the conclusions of Whitney and Logan, sustained by Kimball in 1865, as to the distinctness of the Huronian from the overlying Upper Copper-bearing series, Brooks and Pumpelly, in 1873, expressed the opinion that the latter was "formed before the tilting of the Huronian beds, upon which it rests conformably." It remains to be decided whether this observation refers to the true Huronian or to the younger Taconian series, so often hitherto confounded therewith, which itself is unconformable with the Huronian. The presence, already noticed by Thomas Macfarlane and myself, of boulders of crystalline rock in the conglomerates of the Upper Copper-bearing series, notably at Mamainse, where I had observed such masses having the characters alike of the Laurentian, Huronian, and Montalban series, was evidence of a great stratigraphical break between these and the former, and I was led to suppose that the same sub-aerial decay which had furnished these boulders had liberated the copper found in a metallic state in the younger rocks. Hence, conceiving the stratigraphical distinctness of the Upper Copper-bearing series, alike from the Huronian, from the Potsdam, and from the so-called Quebec group, to be unquestioned, I ventured to propose for it, in 1873, the name of the Keweenaw group. Two years later, in 1875, Brooks, having arrived at a similar conclusion, declared these rocks to constitute "a distinct and independent series, marking a definite geological period," and proposed as a designation the adjective Keweenawian. For this, the writer, in 1876, while recalling his own conclusions, and the name of Keweenaw series, already given by him, suggested the more euphonious adjective Keweenian.

[This is to be understood as marking a period distinguished by the deposition of a great thickness of uncrystalline sediments, and separated, in the Lake Superior region, by stratigraphical breaks alike from the overlying Cambrian (Potsdam) and the various underlying crystalline series from the Laurentian to the Taconian inclusive, upon each of which it may repose in turn. We shall notice farther on its probable relations to the Grand Cañon group of Arizona, and the Llano group of Texas, as suggested by Walcott. Meanwhile it is to be remarked that the Keweenian, on Lake Superior, affords apparent traces of organisms. I quote from a description in 1878 in "Azoic Rocks," p. 237: There are certain markings in the Keweenian which are probably of organic origin. Logan, in 1847, described the occurrence in some of the earthy or so-called tufaceous beds of the series, of numerous slender vertical tubes, filled with calcite, having a diameter of about a quarter of an inch, and a length, in some cases, of from eight to twelve inches. Two or more of these tubes were often found to coalesce in ascending, and they were supposed by Logan to have been formed by currents of gas rising through a pasty mass ("Geology of Canada," p. 71). From the observations of the writer, in 1872, on Michipicoten Island, where similar markings were found in an argillaceous stratum, he was led to compare them with some forms of so-called Scolithus, and to regard them as due to the burrowing of annelids. These were accompanied by large numbers of two curious forms, the one club-shaped, and the other hemispherical or dome-shaped; each recalling some sponges. These, like the tubes, were filled with calcite, agate, or crystalline quartz, and sometimes in part with a greenish chloritic mineral.]

VII. — PALEOZOIC HISTORY OF EASTERN NORTH AMERICA.

§ 126. To render more intelligible the relations of the Taconian, Cambrian, Ordovician, and Silurian rocks of eastern North America to each other, and to the older Primary rocks, we shall endeavor to present a sketch of the geological history of the region, based upon the facts already set forth. At the beginning of Cambrian time, marked by the earliest known trilobitic fauna, there stretched along the eastern border of the great paleozoic basin, a wide area of crystalline eozoic rocks; the remains of which are now seen in the Blue Ridge, and its eastern slope, from Alabama to Virginia, and in their northeastern prolongation through the South Mountain of Pennsylvania, the Highlands of the Hudson, the crystalline rocks of New England and of the whole region of Canada south and east of the lower St. Lawrence. To the north of the great paleozoic basin was a similar eozoic area, now represented by the Laurentides, stretching westward to the upper Mississippi, and beyond, and connected by low-lying portions with the insular mass of the Adirondacks. The evidences of similar eozoic islands are seen in parts of Newfoundland, northern Michigan, Wisconsin, Dakota, Missouri, Texas, etc. These eozoic lands, alike on the western, on the northern, and on the eastern shores of this early Cambrian sea, presented then, as now, portions of several great terranes, or series of crystalline stratified rocks, lying unconformably upon one another, or upon a more ancient gneissic floor, and telling a long history of successive depositions, elevations, and depressions, sub-aerial decay and erosion. These various groups we have briefly noticed in the second chapter of this essay. (§ 18.)

§ 127. The local geographical conditions presented by different portions of northeastern America during the long period when the depression of parts of the pre-Cambrian land permitted the deposition over its surface of Cambrian, Ordovician, and Silurian sediments, next demand our attention. Eaton had already, previous to 1832, divined that the Calciferous Sand-rock (which, underlying the Metalliferous or Trenton limestone, rests directly upon the Primitive gneiss) along the western shore of Lake Champlain, occupies the stratigraphical horizon of the Sparry Lime-rock found farther eastward, at the summit of the First Graywacke; and consequently that this great mass of strata, as well as the more ancient Transition Argillite, and the Primitive Lime-rock and Quartz-rock, was absent along the western side of the lake. Emmons, in 1846, sought to explain this deficiency, so far as the First Graywacke was concerned, by maintaining that this great group of strata, together with its overlying Sparry Lime-rock, is really the representative, or, as he expressed it, is "a protean development" of the Calciferous Sand-rock. In other words, this magnesian limestone, having, according to him, a maximum thickness of 300 feet between the Trenton or Chazy limestone and the underlying gneiss, on the west side of Lake Champlain, was represented to the eastward, along the western base of the belt of Primitive rocks, in New York, New England, and Quebec, by a vast accumulation of sandstones, conglomerates, argillites, and limestones, to which he assigned a thickness of not less than 25,000 feet. Subsequently, in 1855, he supposed that portion of this great series which had been known as the Red Sand-rock of Vermont, to be the representative of the Potsdam sandstone; which latter he had previously found to underlie, in some parts on the west side of the lake, the Calciferous Sand-rock of his Champlain division.

§ 128. These conclusions of Emmons as to the stratigraphical relations of the First Graywacke — called by him Upper Taconic — to the New York paleozoic system, were, as we have seen, adopted, in 1861, by the officers of the geological survey of Canada; who then gave to the Graywacke series the name of the Quebec group, and maintained, on paleontological grounds, that it might also represent the Chazy limestone, and thus correspond to the period between the Trenton limestone and the Potsdam sandstone. It was evident that these great differences of thickness, and in lithological characters, between the equivalent rocks in the two areas above referred to, must have been the result of widely unlike geographical conditions in the adjacent regions. Along the eastern border of the Cambrian sea, great subsidence and frequent changes permitted the deposition of a series of sediments variously estimated at from 10,000 to 25,000 feet in thickness, presenting an abundant and diversified fauna, with great variations in mineral character, often due in part to the materials derived from the contiguous Huronian, Montalban, and Taconian rocks.

§ 129. Meanwhile, it is apparent that over the more stable areas to the westward, along the base of the Adirondacks, and between these mountains and the Laurentides to the north, there was, during a great part of the period, dry land, and subsequently a region of shallow water, in which the only sediments were the silicious sands derived from the adjacent Laurentian, or perhaps Taconian rocks; giving rise to the Potsdam sandstone, with its ripple-marks, its tracks of crustaceans, and its very scanty fauna. To this succeeded lagoons in which were deposited the dolomites of the so-called Calciferous Sand-rock, holding bitterns, and occasionally gypsum. This deposit rests, in some parts, on the sandstone, and in others directly upon the ancient gneiss. The united thickness of the infra-Trenton members of the Champlain division in this region, even including the Chazy limestone, to be mentioned below, will not exceed 1000 feet, and is generally much less. The time occupied in the deposition of these, however, was but a small portion of the great Cambrian period. The so-called Lower Potsdam beds of the latter, from Troy to Newfoundland, not to mention the still more ancient Menevian (Paradoxides) beds of eastern Massachusetts, southern New Brunswick, and Newfoundland — are known by paleontologists to mark an earlier period than the typical Potsdam of the Champlain and Ottawa basins. The fauna of the Levis limestone, which was Eaton's Sparry Lime-rock, according to Billings (who rightly regarded it as the summit of the Quebec group), belongs to a horizon superior to that of the typical Calciferous Sand-rock. From all of these facts we conclude that the original Potsdam and Calciferous subdivisions are but local and partial representatives, alike chronologically and paleontologically, of the great Cambrian Graywacke period, anterior to the time of the deposition of the Ordovician (Trenton) limestones. [See for a more recent discussion of the American Cambrian strata §§ 127 A–127 B.]

§ 130. The fauna of the intermediate and non-magnesian Chazy limestone, as has been shown by Billings, serves to connect that of the Levis limestone with the fauna of the Trenton. This Chazy limestone is absent in some localities in central New York, where, according to Hall, the Trenton rests directly upon the Calciferous, as it does elsewhere, in the absence of this, upon pre-Cambrian rocks. The deposition of the Chazy in the Ottawa valley is distinctly marked as a period of disturbance, since it presents at its base a limestone-conglomerate, resting on the Calciferous, and followed by about fifty feet of sandstones and shales; to which succeed the fossiliferous beds of pure limestone, sometimes with dolomitic layers, which constitute the typical Chazy of the Ottawa basin.* The above facts with regard to the Chazy are additional evidences of the period of disturbance which, as already set forth, marked the close of the Cambrian period, and brought in the Ordovician. The continental movements of that time, while they plicated and uplifted the previously deposited fossiliferous strata along the southeastern border of the Cambrian area, caused elsewhere a subsidence which allowed the Ordovician sea to spread far and wide to the north, depositing its nearly pure limestones, with a thickness of 600 feet or more, along the St. Lawrence valley, not only over the Cambrian beds, but over the eözoic land.

§ 131. To the south and east, however, the uplifted and eroded Cambrian strata, with their adjacent eozoic rocks, the Taconian included, formed the eastern shores of the Ordovician sea, approaching which, as we have already seen (§ 111), the massive limestones of that period become thinner and disappear; being apparently replaced by the black shaly beds, which, at various points, are found lying among the older rocks. How far the

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* Azoic Rocks, pp. 124, 139.

subsequent movement — which, as has been shown, disturbed and eroded the Trenton limestone in the Ottawa valley before the deposition of the Loraine shale (§ 110) — was felt in this eastern region, is uncertain. It is also a question how far the higher strata, known as the Oneida sandstone, were laid down in this region over the Loraine shale. This latter is found preserved from denudation in regions to the east of Lake Champlain, along the lines of dislocation which have brought up on its eastern side the underlying Cambrian strata; and it is not improbable that portions of the upper sandstone of the Second Graywacke may, as some have supposed, there be found in the vicinity of the First Graywacke.

§ 132. We have already noticed the subsequent invasion of the Silurian sea, depositing its limestones over the lower levels from central New York northward and eastward as far as Gaspé and Newfoundland. Thus it happens that we find portions of these limestones overlying alike Ordovician, Cambrian, Taconian, and still older strata, and involved with all of these by subsequent movements of the strata. As a result of these geological accidents, successive observers have been led into many errors. Thus, the Taconian marbles have, within the last generation, been, by different geologists, declared to be of Cambrian, of Ordovician, of Silurian, and even of Devonian age; while similar views have been maintained with regard to the geological horizon of the still older crystalline schists of the region, of which we have already given examples (§§ 121, 123).

§ 133. The statement which has been made, and often repeated, that in Cambrian and Ordovician times the rocks of the Green Mountains were laid down as sediments beneath the sea, and that at the close of this latter period, these were hardened, crystallized, and uplifted as a mountain-range, is seen, from what has been set forth, to be a fiction based upon the hypothesis, first clearly formulated by Mather, and repeated by his successors, (including, during many years, the present writer), that the rocks of this mountain-range are altered paleozoic strata. Of this there is no evidence, while, on the contrary, the relations of the paleozoic strata to these crystalline rocks throughout the Atlantic belt, and the presence of fragments of these in the paleozoic conglomerates, demonstrate their greater antiquity. The same considerations apply, *a fortiori*, to the similar hypothesis of the crystallization, folding, and uplifting of Silurian and Devonian rocks at the close of paleozoic time, to form the White Mountain range.

§ 134. The White Mountains, the Green Mountains, the Taconic Hills, the Highland range, and in fact, all the crystalline stratified rocks of the Atlantic region, are parts of the great eozoic land which bounded, to the south and east, the Cambrian sea of North America. The same groups of rocks then, as now, moreover, stretched along the northern and western borders of that vast sea, which deposited its sediments alike over them all.

[Considerations set forth farther on, in § 137 B, show that the Keweenian rocks of Lake Superior, and the similar strata beneath the Cambrian in central Texas and in Arizona, mark a period in which, over the more western portions of our continent, a vast accumulation of sediments took place between the time of the Taconian and that of the deposition of the Upper Cambrian. These Keweenian sediments, though so far as we know distinct from the Cambrian, are, by their uncrystalline character, more closely related to it than to the Taconian.]

§ 135. The successive movements of the earth's crust, with foldings, often with inversions and with dislocations, which have at intervals affected the paleozoic rocks in the eastern portion of this great basin, in proximity to the Atlantic belt, throughout its entire length, have, it is true, been attended with uplifts of the strata on the eastern side of the dislocations; which have, to some extent, compensated for the loss of substance from these ancient crystalline rocks by sub-aerial decay and erosion. These movements, as we have had occasion to show in the preceding pages, have in many cases involved in their folds the superincumbent paleozoic strata, thus giving rise to a deceptive appearance of infraposition of these newer rocks. The fractures which often accompany these folds still afford passage, in some cases, to thermal waters; and such waters, in past times, by their action upon the strata along their course, have produced local changes, by the development of crystalline minerals; a phenomenon which has been invoked in support of the paleozoic age of the crystalline schists. The discussion of the evidences of this, and of various questions which arise in this connection, as well as that of the different hypotheses which have been put forth with regard to the age of the Taconian rocks, will be taken up in succeeding chapters.

VIII. — THE TACONIC HISTORY REVIEWED.

§ 136. In reviewing the preceding account of the Taconic question it is proposed to notice, in the first place, some of the characteristic differences of the Cambrian or Upper Taconic rocks as seen in different parts of North America, to follow the results of paleontological investigation from the disturbed region in eastern Canada southward into Vermont and New York, and thus to prepare the way for a consideration of the varying and contradictory hypotheses which have been from time to time put forth as to the age of both the Upper and Lower Taconic series.

§ 137. The Cambrian rocks of New York, as originally described by its geological survey, were known only in the stable and little disturbed region around the Adirondack Mountains, including the area west of Lake Champlain and a part of the Ottawa basin, where the series is represented by the quartzites and magnesian limestones of the Potsdam and Calciferous subdivisions, which are shallow-water deposits, corresponding, apparently, to small portions only of Cambrian time. The conditions of the Mississippi area are similar to those of the Adirondack region. In Wisconsin, where the Potsdam beds rest in a nearly horizontal position upon highly disturbed strata, often of Keweenian age, these sandstones and magnesian limestones of the Cambrian, lying in undisturbed succession, have about 1000 feet in thickness, and are overlaid by the St. Peter sandstone, which divides them from the succeeding Trenton, and may itself be regarded as the base of the Ordovician. When, however, we reach the Cordilleras, we find a great augmentation in the thickness of these lower rocks. In the Eureka district of Nevada, according to the late studies of Arnold Hague and Walcott, the fauna of the so-called Lower and Upper Potsdam ranges through more than 7000 feet of strata, and is succeeded by that of the Chazy and Trenton subdivisions.

§ 137 A. [In the Wasatch range in Utah there are known to be not less than 12,000 feet of conformable Cambrian strata, while in the Eureka district of Nevada 7700 feet have been observed, there overlaid by Ordovician, and including at their base 1700 feet of the upper part of the Wasatch section, so that by combining these two sections we have in the great American basin not less than 18,000 feet of fossiliferous Cambrian rocks. Walcott, who has carefully studied the very extensive fauna of this central region, and has compared it with that of the east, divides the American Cambrian into three parts. The Lower Cambrian, as far as yet known, is confined to the Atlantic coast, and represented by the small areas in Massachusetts, New Brunswick, and the island of Newfoundland, being the St. John's group of Hartt and Billings, which we have in the present essay spoken of as Menevian, and which, including the Menevian horizon of Wales, corresponds to the lowest Cambrian of Europe.

[The Cambrian rocks within our great continental area are by Walcott included in his middle and upper divisions. The first of these is the so-called Lower Potsdam of Billings, which is traced from the strait of Bellisle along the valleys of the St. Lawrence, Lake Champlain, and the Hudson, and thence southward along the great Appalachian valley, embracing a large part of the Upper Taconic of Emmons. The upper division of the Cambrian includes the typical Potsdam of the Adirondack area and of the upper Mississippi valley, in both of which regions the Middle Cambrian is unknown. The Middle and Upper Cambrian appear together in the sections in Utah and Nevada, where the latter is succeeded, as in the more eastern areas, by rocks carrying the second fauna of Barrande, which Walcott, following Lapworth and the present writer, designates as Ordovician (§ 17). This, it will be remembered, is synonymous with the Lower Silurian of Murchison, and with the Upper Cambrian of Sedgwick, which is thus distinct from and superior to the Upper Cambrian of Walcott.

§ 137 B. [In the Grand Cañon of the Colorado River 1000 feet of Upper Cambrian or Potsdam strata, locally known as the Tonto group, rest unconformably upon a great body of strata described by Powell as the Grand Cañon series, divided by him into the Grand Cañon and Chuar groups, and having an observed thickness of about 13,000 feet.* In like manner, a series of Cambrian sandstones and limestones, about 900 feet in thickness, closely resembling those of the Tonto group, and affording a abundant Potsdam fauna, already made known by Shumard, occur in central Texas, where they are overlaid by Ordovician. Here, as in the Grand Cañon of the Colorado, the Upper Cambrian strata rest unconformably upon a series of uncrystalline sandstones, shales, and limestones, several thousand feet in thickness, which are well seen in Llano county, and have been by Walcott called the Llano group. These, according to him were pene-

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* Powell, Amer. Jour. Science, 1883, xxvi., 437.

trated by granites before the deposition of the Potsdam.* This great series of uncrystalline sediments, found alike in the Grand Cañon and in Texas, is by Walcott compared with the Keweenian series of Lake Superior, and regarded as belonging to a Keweenian area of continental extent, over the upturned and eroded edges of which the Cambrian was laid down alike in Michigan and Minnesota, in Texas and in Arizona. Some evidences of organic remains have been observed by Walcott in these lower rocks in the Grand Cañon, and we have elsewhere noticed such evidences in the Keweenian of Lake Superior (*ante*, page 615). For the present, we agree with Powell and with Walcott in regarding these lower rocks provisionally as pre-Cambrian.] †

§ 138. A similar great development of Cambrian rocks exists in northwestern Newfoundland, where, from his studies of their organic remains, the late Mr. Billings was led to admit a succession of over 9000 feet of paleozoic strata below the Trenton horizon. The subdivisions there recognized by him, in ascending order, were: 1. Lower Potsdam; 2. Upper Potsdam; 3. Lower Calciferous; 4. Upper Calciferous; 5. Levis; and 6. Phyllograptus beds. The second and third of these were regarded by Billings as the representatives of the Adirondack Potsdam and Calciferous, while the Phyllograptus beds at the summit were considered the equivalent of the Welsh Arenig, which belongs to the base of the Bala group, or the second fauna. It is evident, as Billings declared, that we have, in this great thickness in northwestern Newfoundland, a much more complete sequence than in the Adirondack region, where the Upper Potsdam, Calciferous, and Chazy subdivisions represent the whole succession from the ancient gneiss up to the Trenton limestone.

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* Walcott, *ibid.*, xxviii., 431.

† For these generalizations by Walcott as to the American Cambrian, I am indebted to a yet unpublished paper read by him before the National Academy of Sciences at Washington, April 23, 1886, and to his private communications.

§ 139. Keeping in view the great development of the Cambrian alike in the Cordilleras and in Newfoundland, as compared with the Cambrian of the Adirondack and Mississippi areas, we are better prepared to understand the remarkable type assumed by this series in the Appalachian area, on the eastern margin of the American paleozoic basin, from near the Gulf of Mexico northeastward to the Gulf of St. Lawrence, and to Newfoundland, along the western base of the Atlantic or Appalachian belt. These Cambrian rocks throughout this extent, wherever preserved, are characterized by great thickness and considerable diversities in composition, due to the accumulation of mechanical sediments derived from the disintegration and decay of the various groups of pre-Cambrian rocks which made up the adjacent eozoic land. To this, and to repeated movements of the land during and after the Cambrian period, they owe their complex constitution, their great volume, their disturbed and faulted condition, and their unconformities. All of these characters serve to distinguish them widely from the horizontal and comparatively thin quartzites and magnesian limestones, their representatives along the northern border of the great basin, as seen in the Adirondack and Mississippi areas. It is this Appalachian Cambrian, many thousand feet in thickness, which, as we have already seen, constitutes the First Graywacke and the Sparry Lime-rock of Eaton, the Upper Taconic of Emmons, the Quebec and Potsdam groups of Logan, and a large part of the original Hudson-River group.

§ 140. That the Levis limestones and Phyllograptus shales, found at the summit of this series, mark the beginnings of the second fauna has already been noticed, as well as the fact that still higher strata, of Ordovician and Silurian ages, are found over portions of this Appalachian Cambrian series, among the strata of which they have sometimes been involved by subsequent movements. It will also be borne in mind: first, that this great mass of

10,000 feet or more of diversified and folded Cambrian strata is exchanged in the Adirondack and Mississippi areas for a far more simple type of horizontal strata, but a few hundred feet in thickness; and, secondly, that erosion has removed this great series wholly or in part from over large portions of its original area.

§ 141. With these explanations before us, we are now prepared to consider the relations of the Cambrian and Ordovician series, in their two unlike types of the Appalachian and Adirondack areas, to the Lower Taconic limestones. It has already been shown that Emmons, in 1842, in his final report on the geology of the Northern district of New York, defined, with the present names, the lower subdivisions of the New York paleozoic system, from the Potsdam to the Oneida sandstone, both inclusive, to which he gave the collective appellation of the Champlain division.

[He at the same time proposed for the Primitive Quartz-rock, the Primitive Lime-rock, and the Transition Argillite of Eaton, together with the First or Transition Graywacke — called by Emmons the Taconic slates — and the Sparry Lime-rock of Eaton, the general name of the Taconic system. The Taconic slates were then described by him as a great mass of argillites with interbedded limestones and coarse sandstones, limited on the east, in his original section, by the Sparry Lime-rock at the base of the Taconic hills, and on the west by "the Loraine or Hudson-River shales," by which the Taconic slates were declared to be undoubtedly overlapped, although the line of junction on the west was said to be obscure. This intermediate mass, whose limits were thus clearly defined to the west of the Taconic hills in 1842, was farther said in 1846 to have an immense thickness, and, in the typical section in Rensselaer County, a breadth of not less than twenty miles.

[All of these divisions from the Primitive Quartz-rock of Eaton to the Sparry Lime-rock, both included, were, by Emmons, in 1842, included in what he called the Taconic system, and described as "the rocks lying between the upper members of the Champlain group and the Hoosic Mountain." They were then regarded "as inferior to the Potsdam sandstone, or as having been deposited at an earlier date than the lowest members of the New York Transition system." The precise relation of this system to the Silurian and Cambrian systems, and, indeed, the limits of these in England, were not at that date clearly defined, but Emmons then supposed that the Taconic rocks in part might "be equivalent to the Lower Cambrian of Sedgwick," — "the upper portion being the lower part of the Silurian system,"* to which the Middle and Upper Cambrian of Sedgwick were then, on the authority of Murchison, very generally referred.]

§ 142. In 1843 appeared the final report by Mather upon the geology of the Southern district of New York, in which he rejected entirely the notion of the Taconic system, and the whole teaching of Eaton, asserting that the Taconic was nothing more than a modified form of the Champlain division of Emmons. The Granular Quartz-rock of the Taconic he declared to be Potsdam; the Granular Lime-rock, the Calciferous Sand-rock with the succeeding Chazy and Trenton limestones; while the overlying strata, including the Taconic slates or First Graywacke, were the Utica and Loraine shales. A similar suggestion had been put forth by Messrs. H. D. and W. B. Rogers, in 1841, for the like rocks in New Jersey and Pennsylvania, and was cited by Mather in support of his view. When, later, in 1858, H. D. Rogers published his final report on the geology of Pennsylvania, the Lower Taconic rocks of Massachusetts had been by Emmons traced southwestward through Pennsylvania, in the great Appalachian valley, and the adjacent and subordinate Lancaster valley. These rocks, under the names of

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* Emmons, Geology of the Northern District of New York, 1842, pp. 140, 144, 163.

Primal, Auroral, and Matinal, were now described by H. D. Rogers as local modifications of the Champlain series, — the great Auroral limestone being assumed to be the representative of the Calciferous, the Chazy, and the so-called Birdseye and Black-River subdivisions, while the Matinal slates were supposed to represent the upper part of the Trenton, with the Utica and the Loraine shales. For many details with regard to the facts noticed in this paragraph, and for other points in the Taconic history, the reader is referred to the author's volume on "Azoic Rocks." See also *ante*, pp. 533–535.

§ 143. Coupled with this view of Mather was that of a progressive alteration of these uncrystalline rocks of the Champlain division, supposed to be traced through the Taconic strata into the crystalline schists of western New England, designated by Mather as Metamorphic rocks; between which and the Taconic, it was said by him, "no well marked line of distinction can be drawn, as they blend into each other by insensible shades of difference." He was at length led to extend this same hypothesis to the more massive gneisses and crystalline limestones of southern New York, and to conclude that these also were, wholly or in great part, but altered rocks of the Champlain division, — a notion which has lately found an advocate in Dana, who has also revived Mather's view of the Champlain age of the Taconic quartz-rock and granular limestone, as will be noticed farther on.

§ 144. [As we have already seen, Eaton had long before announced the existence of a stratigraphic break at the base of his First Graywacke, — being the great group of strata called by Emmons the Taconic slates in 1842, when he already recognized its distinctness from the underlying portions of his Taconic system, and asserted that it was "the lower part of the Silurian," — that is to say, of the Silurian system as then defined by Murchison. This "upper portion" of the Taconic system, including the First Graywacke and the Sparry limestone, Emmons had found to be fossiliferous, in 1844, and in 1846 declared it to be the stratigraphical equivalent of the Calciferous Sand-rock of the Champlain division, of which he regarded it as a great and "protean development," and included with it the Red Sand-rock of Vermont, which he supposed to represent the Potsdam. It was not, however, until 1855 that Emmons gave to this paleozoic fossiliferous upper portion of his original Taconic system the name of Upper Taconic, but meanwhile the whole of what was afterwards called Lower Taconic, — including the Primitive Quartz-rock, the Primitive Lime-rock, and the Transition Argillite, — was assigned a position beneath the base of the New York system.]

§ 145. The above conclusion as to the age of the Red Sand-rock of Vermont was opposed by C. B. Adams and by W. B. Rogers. The former maintained, in 1846, after this announcement by Emmons, the opinion that this sand-rock was newer than the Champlain division, and referred it to "the period of the Medina sandstone and the Clinton group," while W. B. Rogers, in 1851, discussing the same subject, conceived that the reddish limestones which, near Burlington, Vermont, are associated with this sand-rock, were probably "a peculiar development of the upper portion of the Medina group." As regards the relations of this Red Sand-rock and its succeeding limestone to the granular quartz-rock and granular lime-rock of the Lower Taconic, Adams maintained that "the Taconic quartz-rock was probably but a metamorphic equivalent of the Red Sand-rock," and ascribed the change to a supposed "igneous agency." He farther conceived that the granular lime-rock, "or Stockbridge limestone of the Taconic system is the equivalent of the calcareous rocks which overlie the Red Sand-rock, rather than that of the lower limestones of the Champlain division, as has been commonly supposed." Allusion is here made by Adams to the views of Mather and the brothers Rogers, who, as already seen, had supposed this same limestone to be the equivalent of the Calciferous, Chazy, and Trenton. This opinion of Adams, which, in 1851, was, as we have shown, supported by W. B. Rogers, was again maintained by the latter in 1860, when, after the reading of an essay by C. H. Hitchcock before the Boston Society of Natural History, Rogers cited from his paper of 1851 the conclusions above mentioned, and announced his opinion "that there is no foundation for what Mr. Emmons called his Taconic system — a mixture of Silurian and Devonian — and that the Dorset limestone (the Stockbridge limestone of the Lower Taconic) is newer than the Lower Silurian, and probably Upper Silurian or Devonian.*

§ 146. The explanation of this new opinion as to the horizon of the Lower Taconic limestone is made apparent by reference to the report on the geology of Vermont, then in process of publication by the Messrs. Hitchcock. Therein Dr. Edward Hitchcock writes, with regard to the limestone in question, then named by him Eolian limestone, and said to be best displayed in Dorset Mountain: "We have found, mostly in strata from below the middle of the limestones, fossils which, though obscure from metamorphism, are clearly referable to genera characteristic of Devonian rocks, viz: Euomphalus, Stromatopora, Zaphrentis, Chaetetes, and encrinal stems." "Nor is it at all improbable, as we shall shortly show, that the Eolian limestone may be as recent as the Carboniferous rocks." † Accompanying this statement is a notice of these organic forms as determined by Prof. James Hall, who declared them to be of Upper Silurian and Devonian types. They are compared by Hitchcock to those found to the east of the Green Mountains, in the valley of Lake Memphremagog, the horizon of which is well known.

§ 147. We have already noticed the occurrence of outliers of Lower Helderberg limestone on St. Helen's

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* Proc. Bost. Soc. Nat. Hist., vii., 238.

† Geology of Vermont, 1861, pp. 421, and 418, 419.

Island, near Montreal, and on Belœil Mountain, a few miles farther east; in the first locality resting unconformably upon Ordovician strata, and in the second upon a mass of eruptive rock which breaks through similar strata (§ 117). In this connection may be recalled the like occurrence at Becraft's Mountain, near the town of Hudson, on the east side of the Hudson River, long known, and lately re-examined by W. M. Davis. Here, resting upon shales referred to the Hudson-River group and, from the locality, probably of Loraine age, there is found, in a small synclinal area, a mass of contorted strata, including 150 feet or more of fossiliferous Lower Helderberg limestones overlaid by as great a thickness of Cauda-galli shales, to which succeed a few feet of cherty limestone regarded as the equivalent of the Corniferous or Upper Helderberg.* In all of these localities, as well as at Rondout, also re-examined by Davis, we note the absence, beneath these Silurian strata, of the great mass of mechanical sediments, including the Oneida and Medina sandstones, which, farther west, are so conspicuous in the lower part of the Silurian series, and belong to the Second Graywacke of Eaton.

[The late observations of Dwight, Smock, and Darton (§ 90 A), showing the existence of portions of Silurian (Lower Helderberg) limestones, and even of Devonian sandstones, in the Green-Pond Mountain area in New Jersey and southeastern New York furnish farther illustrations of the eastward extent of these higher paleozoic sediments.]

§ 148. As already mentioned in § 118, Augustus Wing having detected in Vermont fossiliferous limestones of Trenton age, the locality was examined by Billings. In a section eastward from Crown Point, in New York, the latter found what was described as the Red Sand-rock, with Olenellus, brought up by a fault on the east side of the Loraine shales, and followed eastward by strata carry-

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* Amer. Jour. Science, xxvi., 381 and 389.

ing the fauna of the Calciferous Sand-rock, succeeded by some forms of the Levis, and then by the Chazy and Trenton; to the east of which another dislocation brings up again a limestone abounding in the typical fauna of the Levis limestone. The close association of the latter with the white marbles quarried in this region, led Billings to refer these to the Levis horizon.* It is worthy of notice that it was in the same vicinity which furnished Billings with Calciferous, Levis, Chazy, and Trenton forms, that the organic remains had been found which were referred by Hall to the Niagara and still higher horizons, and had caused Edward Hitchcock and W. B. Rogers to conjecture that the marbles of this region might be of Devonian age or younger. So perplexing were these facts to Wing, that we find him led to the conclusion, announced in a letter to J. D. Dana in 1875, and recently cited with approval by the latter,† that "the Eolian limestone of the Vermont geological report embraced not only the Trenton and the Hudson-River beds, but all the formations of the Lower Silurian as well, and even limestones and dolomites of the Red Sand-rock (Potsdam sandstone) series."

§ 149. Another hypothesis touching the age of the Taconic marbles was now offered to the perplexed geologist, and this time by the geological survey of Canada. We have already shown that, forced by the paleontological evidence which had previously been urged by Emmons, Logan, in 1861, adopted the views of the latter as regards the horizon of the Upper Taconic, long before traced from New York beyond Quebec on the St. Lawrence. This,

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* Hunt, On Some Points in the Geology of Vermont, 1868, Amer. Jour. Science, xlvi., pp. 222, 229. This paper, from data furnished by Billings, was written while the writer still accepted the untenable view of Logan, from the first opposed by Billings, which assigned the Levis or Sparry limestone to a position near the base of the Cambrian series, instead of its summit.

† Dana, The Age of the Taconic System, Quar. Geological Journal, xxxviii., 402.

in accordance with the conclusions of Mather, and the earlier published view of Emmons, had been described by Logan as consisting of the Hudson-River group with the addition of the Oneida sandstone. The study of its fossils by Billings now led Logan to see that its position was really below and not above the Trenton limestone; but instead of adopting Emmons' later name of Upper Taconic, he gave to the series, as seen near Quebec, the name of the Quebec group, then described by Logan as a stratigraphical equivalent of the Calciferous Sand-rock. Taking as a type the well known section there displayed upon the St. Lawrence, he called the apparently superposed sandstone the Sillery, and the underlying fossiliferous limestones and shales (the Sparry Lime-rock of Eaton) the Levis division. This was a reversal of the order described by former observers, and there can be no doubt that the section at Quebec is really an inverted one, the Sillery sandstone being the oldest and not the youngest member of the series as there displayed. This history has already been given at length, in chapter vi. of this essay.

§ 150. We have there also explained how Logan's view of the position of the Sillery sandstone was made to support the notion that the crystalline schists which have been found to underlie it were the altered representatives of the sedimentary strata found between the Sillery and the Levis, which he had called the Lauzon division. Following the rocks of his Quebec group southward into Vermont until he met the granular marbles of the Lower Taconic, Logan was led to include these also in the Quebec group, and to regard them as the Levis limestone in an altered condition. This, as already set forth in §§ 115–116, is seen in his large geological map of Canada and the Northern States, published in 1866, after he had spent some time in tracing these rocks through western Vermont and Massachusetts into eastern New York. Therein the Lower Taconic limestone in Massachusetts is represented as an uninterrupted continuation of the Levis limestone from the province of Quebec, brought up along an anticlinal, and having on both sides overlying it, successively, the Lauzon and Sillery divisions,—these, on the west side of the anticlinal, having the ordinary type of the uncrystalline First Graywacke or Upper Taconic, but being represented on the east side by the crystalline schists of the Green Mountain range, their supposed equivalents. Few will now question that Logan was wrong in this latter point, or will doubt the greater antiquity of these crystalline rocks. On the other hand, it is to be noted that, in thus asserting the infraposition of the Lower Taconic marbles to the First Graywacke or Upper Taconic series, Logan but confirmed the older observations of Eaton and Emmons, and only erred in having, by a false interpretation of the succession of the latter series near Quebec, assigned the Levis limestone to its base, by which he was led to confound it with the Lower Taconic limestone. In either view, he placed the latter below the series of several thousand feet of sandstones, conglomerates, and shales, which constitute the First Graywacke of Eaton and the Upper Taconic of Emmons.

§ 151. We have already seen that Emmons, as early as 1846, had recognized the fossiliferous character of the First Graywacke, which he afterwards called Upper Taconic; that he described and figured, in 1846, trilobitic forms found therein, and did not hesitate, in 1860, to declare that it corresponded with the Primordial zone of Barrande.* Thus it happened that Barrande, Marcou, and after him Perry, assumed the Taconic system to be the equivalent of the Primordial zone or Cambrian of Great Britain, Bohemia, and Spain, — they having failed to recognize the distinction which Emmons had made,

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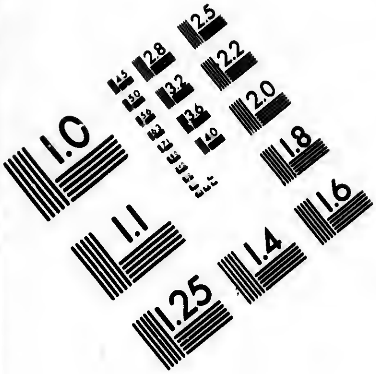
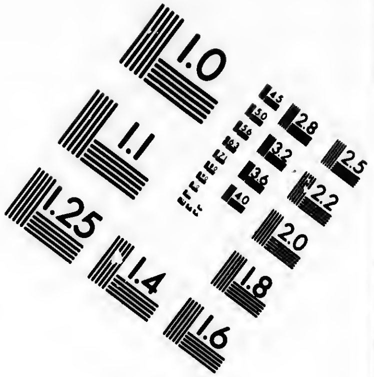
* See, in this connection, Barrande and Marcou on the Primordial Fauna and the Taconic System; Proc. Boston Soc. Nat. Hist., Dec., 1860, vol. vii., pp. 369–382.





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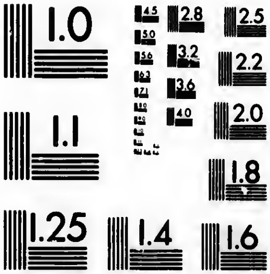

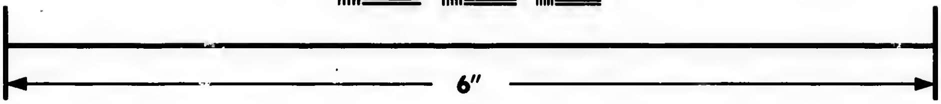

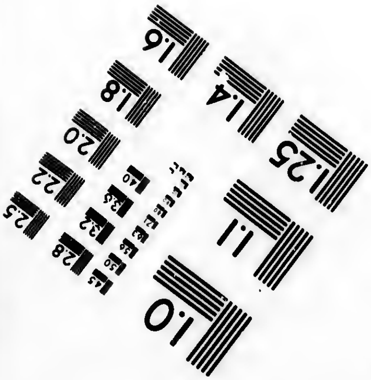

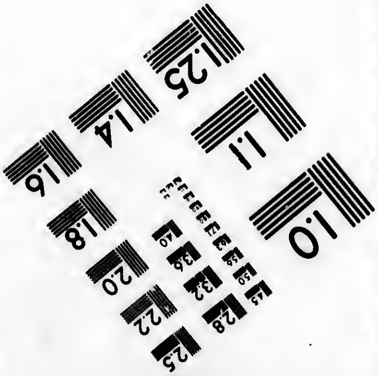

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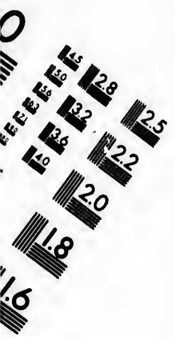

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as early as 1842, between the lower and upper divisions of his original Taconic, when he referred the upper portion to what he then called the Silurian system. In 1867, J. B. Perry described the Taconic system of Vermont as composed of three parts: 1. Lower, consisting of quartzites, marbles, and talcoid schists, the Lower Taconic of Emmons; 2 and 3. Middle and Upper, including the uncrystalline fossiliferous Scranton and Georgia slates, and the overlying Red Sand-rock, which he regarded as the equivalent of Potsdam. The succeeding graywacke, constituting a great part of the Upper Taconic of Emmons, was by Perry supposed to be separated by an unconformity from the Red Sand-rock, and he was disposed to divide it from the Taconic and connect it with the Champlain division.*

§ 152. Still more recently Marcou has given us his own later views of these rocks in Vermont. The true or typical Taconic is, according to him, the Upper Taconic of Emmons, and rests unconformably upon the Lower Taconic. This upper series he divides into four parts, in ascending order, designated the St. Albans, Georgia, Phillipsburg, and Swanton groups. In these are found, besides the Primordial fauna, fossils of the second fauna in included limestones, a fact which he explains as indicating centres of creation in which the forms of the second fauna first made their appearance; the whole of these being, according to him, below the horizon of the Red Sand-rock, which he supposes to overlie unconformably the Upper Taconic.† That the forms of the second fauna found in portions of this region belong to a lower horizon than the Potsdam, is in discordance alike with the facts of paleontology and of stratigraphy, and is opposed to the conclusions of all other observers in that region, including alike Emmons, Logan, and Perry. Marcou's

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* The Red Sand-rock of Vermont, etc., J. B. Perry; Proc. Bost. Soc. Nat. Hist., 1867, vol. xi.

† Marcou, Bull. Soc. Géol. de France 1880 (3), ix., pp. 18–46.

conclusions would seem to be based on some of the frequent cases of inversion of strata, or of dislocation and upthrow, to which we have elsewhere alluded, and which led Logan to place the Levis limestone near Quebec at the base of his Quebec group, and to represent the Taconic marbles of southern Vermont as passing below the crystalline schists of the Green Mountain range.

It should, however, here be said, at the same time, that in a disturbed region like eastern Vermont, where areas of the higher rocks of the second fauna exist, and have probably at one time been more widely spread than now, it is not impossible that there may be outliers of a sandstone of Oneida or Medina age, such as in Pennsylvania we have described as overlying unconformably Lower Taconic rocks, and also that such higher sandstones may have been confounded with the older Cambrian or Potsdam sandstone, and thus afford a seeming justification for the strange hypothesis advanced by Marcou, that the whole of the Appalachian Cambrian in Vermont is older than the Lower Potsdam. [The late discovery in the Green-Pond Mountain range, in New Jersey, in close association with older sediments, of Silurian limestones and Devonian sandstones, as mentioned in § 148, is significant in this connection.]

§ 153. The studies of the last few years have thrown much light on the character of the lower portions of the Cambrian in its development to the east and southeast of the Adirondack area. It has been noticed that the Red Sand-rock and its accompanying slates and limestones near Burlington, Vermont, referred by Emmons to the Potsdam, but by Adams and W. B. Rogers to the Medina, and by Logan to the summit of the Hudson-River group, were subsequently by Billings called Lower Potsdam, to indicate that the fauna of these rocks belongs to a somewhat lower horizon than the typical Potsdam of the New York system. The later studies of Logan in western Vermont, as given by him in 1863, showed that these ancient rocks are brought up by a north and south dislocation, with an upthrow on the east, from beneath rocks of Trenton, of Chazy, or of Levis age, which latter here occupy their natural position at the summit of the Upper Taconic or First Graywacke group.* Billings, also, in 1868, as already pointed out, had shown that farther southward in Vermont the Red Sand-rock, or Lower Potsdam, is in like manner brought up by a dislocation, so as to overlie on the east the Loraine shales.

§ 154. It was now clear to all, that much of what had been called Hudson-River group to the east of the Hudson valley and of Lake Champlain, consisted, not, as taught by Mather and his followers, of disturbed and altered strata newer than the Trenton limestone, and of the age of the Loraine shales, but of older rocks, carrying, in part, at least, the forms of the first fauna. We have already seen (§ 112) how, in view of these facts, Hall expressed his opinion, in 1862, as to the relations of these newer strata to the older ones. In 1877, he returned to the subject, and, after retracing the history of investigation, concluded that "we now know approximately the limits between the newer and the older formations, and there is now no longer any question that the newer series, or the rocks above the Trenton limestone, do occupy both sides of the Hudson River for nearly one hundred miles, and continue along the valley for many miles farther towards Lake Champlain. The term Hudson-River group has, therefore, a definite signification, from absolute knowledge of superposition and fossil remains. The error lay in extending the term to rocks on the eastward, at a time when their fossil contents had not been studied, and were, in fact, unknown, and their geological position had not been determined by critical examination." † The distinction between the two had however been clearly pointed out by Emmons as early as 1842 (*ante*, p. 586.) We

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* Geology of Canada, chap. xxii., pp. 844–860.

† Hall, Proc. Amer. Assoc. Adv. Science, 1877, p. 263.

have already shown in §§ 13–14 how Vanuxem had devised this term to include, besides the true Loraine shales, other disturbed and apparently non-fossiliferous rocks of controverted age, which he supposed might be included with the former, and thus introduced much of that confusion which has prevailed in the use of the name of Hudson-River group as the equivalent to Loraine shales.

§ 155. The eastern limit of the rocks of the second fauna, along the Hudson valley, being defined as stated by Hall, and as already shown by him for that region on Logan's geological map previously published, it was important to determine the age of the uncrystalline rocks along their eastern border, and to decide whether these were (as mapped by Logan) portions of the so-called Quebec group, or of the still older Potsdam which had been found in this position at several points in Vermont. Nothing has contributed more to the solution of this problem than the careful studies of Mr. S. W. Ford, who, in 1871, discovered the existence of fossiliferous rocks of this lower horizon at Troy, New York, and, following up his investigations, showed that these strata, containing an abundant fauna of Lower Potsdam age (corresponding to the Olenellus slates of Georgia, Vermont, and to the beds at Bic, Quebec, and at the Strait of Bellisle, in Labrador), are at Troy brought up on the eastern side of a fault, against the Loraine shales.* Continuing his studies, Ford has recently traced these Lower Potsdam rocks, under similar conditions, through various parts of Columbia and Dutchess Counties, the stratigraphical break and the upthrow of the Cambrian strata on its eastern side being well defined. He does not attempt to estimate the thickness of this series of Cambrian sandstones, shales, conglomerates, and limestones, but says that it "is manifestly very great in eastern New York,"† Emmons having already in 1846 declared its volume to be probably equal

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* Amer. Jour. Science, 1873, vi., p. 135.

† Amer. Jour Science, 1884, xxviii., pp. 35 and 206.

to that of all the members of the New York system in their ordinary development (*ante*, p. 586).

§ 156. It is hardly necessary to mention that this series of Cambrian fossiliferous rocks, traced by Ford through Rensselaer, Columbia, and part of Dutchess Counties, along the eastern side of a belt of Loraine shales, is a part of the First Graywacke belt of Eaton, the Upper Taconic of Emmons, which Logan, after his examination of the region with Hall, in 1863, described and subsequently mapped as Quebec group. These observers, as has been already stated (§ 115), and as may be seen on Logan's map of 1866, then traced a narrow but persistent belt of Loraine shales along the eastern side of the Hudson, from Washington County southward to a point a little above Hyde Park, where they found the boundary between these shales and the older group to cross to the west side of the Hudson. The accuracy of this delineation is confirmed by Ford, who, while remarking that the distribution of the upper rocks might entitle them to be called the Hudson-River group, suggests, in view of the perplexities which have attended its use, that it would be better "to discard altogether the designation, and go back to the old term, Loraine shales." Ford farther speaks of the "great dislocation," which, at so many points from western Vermont to the Hudson in Dutchess County, brings up the Cambrian rocks against newer strata of Ordovician age. A reference to the sections of Logan and Billings, already cited, will, however, show the existence, not of a single dislocation, but of parallel dislocations, with upthrows on the east side, towards the barrier of older rocks. Of such parallel faults we find, in fact, repeated examples, not only east of the Hudson, but farther southward in many places, along the eastern border of the Appalachian valley, as already pointed out, in § 101.

§ 157. The one continuous break, with an upthrow, on the south and east, of 7000 feet, extending from Gaspé to

Alabama, imagined by Logan, was required in his structural scheme, because he had assumed the Levis limestone, (which near Quebec is brought to adjoin the Loraine shales), to occupy a position at the base of his Quebec group, and to have been originally buried 7000 feet beneath the Loraine shales, in a great conformable series. The strata along the west side of these dislocations in Canada and in Vermont are, according to Logan, either Levis, Chazy, Trenton, or Loraine, the Lower Potsdam being on the east side. In a section described by Billings, and already noticed (§ 148), where the first dislocation brings up the Lower Potsdam — which is successively overlaid by Calciferous, Levis, Chazy, and Trenton — against the Loraine, a second parallel fault, a little farther to the east, brings up the Levis against the Trenton. We see, from the late studies of Ford, that the great belt along the eastern border of the Loraine shales, which Logan described and mapped as Quebec group, is in large part Lower Potsdam. The whole series must now be farther studied in the present light: we must know the real thickness of the Cambrian in the region in question; the interval therein which separates the Lower Potsdam from the Levis fauna; and how much of the Quebec group of Logan is to be included in the Potsdam.

§ 158. As regards the relations of the Cambrian and Ordovician rocks over this area, we have already shown that there is every reason to believe that there exists a stratigraphical break between them (as is also the case between the Lower Taconic and Cambrian) and farther, that the lower members of the Ordovician series (the limestones of the Trenton group) thin out and present irregularities to the south and east. Although to Hall and Logan it appeared that the line between the Loraine shales and the inferior series passed from the east to the west bank of the Hudson near Hyde Park in Dutchess County, subsequent studies * have shown the existence of

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* Amer. Jour. Science, xvii., 57.

the higher strata farther southward, on the east bank. Dale, in 1877, found fossils of the Loraine period in shales at Poughkeepsie, and Dwight soon after detected abundant forms of Trenton age in the limestone of the Wappinger valley, a little farther south, as well as at Newburg on the west bank of the Hudson. These discoveries were soon followed by that of a remarkable fauna of Calciferous age in other limestones in the Wappinger valley, thus showing the presence here, as in Vermont, to the east of the outcrop of the Cambrian, of strata carrying the fossils of the Calciferous, the Trenton, and the Loraine subdivisions. These observations by Dwight were made in 1877–1880,* and joined to those of Dale, and those of Ford, show the existence, in what has there been called both Hudson-River group and Quebec group, of fossiliferous strata ranging from the Lower Potsdam to the Loraine, both inclusive,— a result identical to that already arrived at in Canada for the area which had been successively mapped as Hudson-River group and Quebec group.

§ 159. Having thus recalled the latest results of paleontological research among the so-called Upper Taconic, and shown the association of areas of Ordovician rocks with the predominant Cambrian, we may proceed to notice the views of Prof. J. D. Dana on the Taconic question. He, in 1872 and 1873, published an extended series of papers on the rocks of the Taconic range, as seen in Berkshire County, Massachusetts, and reasoning from the organic forms found in association with similar limestones in Vermont, reached the conclusion that the Stockbridge limestone "is mainly Trenton," the overlying schists being of the Hudson-River group.† This latter statement, supported by a stratigraphical argument, may be found in his paper on The Geological Age of the Taconic System.

§ 160. [In the paper just named (communicated to

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* Amer. Jour. Science, xvii., 389; xix., 50; xxi., 78; and xxvii., 249.

† *Ibid.*, vi., 274.

the Geological Society of London in 1882),* Dana proposes to limit the question to the Taconic hills, and the area originally described by Emmons. He claims that the "true original Taconic schists" are those of the Taconic range, extending north and south along the boundary between Massachusetts and New York, including the counties of Rensselaer and Columbia in the latter State, to which he adds Dutchess County on the south. In the centre of the range are, according to him, these "Taconic schists," having on the east the Stockbridge limestone (the latter being three times repeated, with intervening Granular Quartz-rock and the Magnesian slates of Emmons), and on the west the Sparry limestone or Sparry Lime-rock of Eaton, all the strata having a general eastern dip. Dana declares that these three rocks — by which he means the Stockbridge limestone, the Magnesian slate, and the Sparry Lime-rock, neglecting the Granular Quartz-rock — "are all that need be considered," and that the only question is whether these limestones are the same rock, repeated, with alterations in character, to the eastward, or whether the Sparry Lime-rock, which seems to dip beneath all the others, is a newer rock or an older rock than they. Emmons, in 1842, was perplexed by the continuous eastern dip of the strata across a great breadth of country, and expressed doubts on this point, which he was, however, enabled to solve before 1846, and to assure himself that the position of the Sparry limestone was younger than the Stockbridge limestone, or the Magnesian slate which overlies this last, while Professor Dana continues to cherish the contrary opinion. That the Sparry Lime-rock is not only younger than the Stockbridge or Lower Taconic limestone, but belongs at the summit of the First Graywacke, had been clearly pointed out by Eaton, in 1832.

§ 160 A. [In an ideal section given in 1846 to show

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[*] Quar. Jour. Geol. Soc., xxxviii., 397, and, in abstract, Amer. Jour. Science, xxiv., 291.

their supposed order of deposition, Emmons thus arranges the members of the Taconic system:—1. Granular Quartz-rock; 2. Stockbridge limestone; 3. Magnesian slate; 4. Sparry limestone; 5. Roofing slate; 6. Coarse sandstones; 7. Taconic slate; 8. Black slate. In a companion section, showing the apparent succession of these in the Taconic region, from east to west, he gives: 1. 2. 3, successive alternations of the Granular Quartz-rock, Stockbridge limestone, and Magnesian slate; 4. Sparry limestone, followed by the higher members already noticed, and unconformably overlaid on the west by the Loraine shales. These numbers, 5–8, we are told, "refer to the Taconic slate in its subordinate beds."* This name of "Taconic slate" was, in fact, already employed by Emmons, in 1842, to designate the whole group of strata lying west of the Sparry Lime-rock, and between it and the Loraine shales (*ante*, p. 586). The name of "Taconic schists," employed by Dana, serves only to confuse his readers, and was not used by Emmons, who called the schistose strata of the Lower Taconic simply talcose slate, or Magnesian slate, and gave to the great mass of sedimentary strata of the Upper Taconic the collective name of the Taconic slate. The various subdivisions of this Taconic slate group are given by Emmons farther on (loc. cit., pp. 66–67) as coarse greenish sandstones, gray sandstones, red and chocolate-colored slates, green and black flinty slates, blue compact limestones, and gray silicious limestones, all of them lying to the west of "the great mass of the Sparry limestone." The order of these is variable, and the observer "will, in the space of fifteen or twenty miles, pass several times over the same beds, which are brought up by many successive uplifts" with a seeming thickness of 25,000 feet (loc. cit., p. 67). The nature of these movements of dislocation, by which the subdivisions of the Taconic slates are thus repeated, is farther shown by an ideal section in 1855. At the same

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* Agriculture of New York, i., pp. 60–61.

time the real order of succession in the Upper Taconic was declared to be,—greenish chloritic sandstones at the base, followed upward by a great mass of various colored slates and sandstones, and, towards the top, by the Sparry limestone, with quartzose and conglomerate beds, black shaly limestone, and fine black slates.*

§ 161. [Nothing of all this can be gathered from Dana's statements. In his latest communication on the subject, read to the American Association for the Advancement of Science, in August, 1885,† he refers to Emmons's description of the Taconic system in 1855, wherein, he would have us believe, the Sparry Lime-rock is made a part of the Lower Taconic. By referring thereto,‡ we, however, find it to consist of: *A*, Granular Quartz-rock, with repeated interstratifications of so-called talcose slate; *B*, Stockbridge limestone, and, *C*, overlying talcose or Magnesian slate, with included roofing-slate, 2000 feet thick. These "form by themselves a distinct physical group," in the Taconic range, about 5000 feet thick, and Emmons adds: "the sequence of the Lower Taconic rocks, which has been stated and illustrated in the foregoing pages, is essentially the same from Maine to Georgia." No mention is there made of "the Sparry limestone, with its associated slates," which Dana seems to say are included by Emmons in his Lower Taconic, and the only apparent ground for this interpolation is the statement of Emmons that the Stockbridge limestone "is seamy and sparry," or, as he elsewhere says, "occasionally sparry," a fact which, he tells us, had led others to mistake it for the Sparry limestone of Eaton (*ante*, p. 585). No place is left for the Sparry limestone in the Lower Taconic, and in the Upper Taconic this, as well as the other limestone-masses and fossiliferous slates, is placed towards the summit, and not at the base. This is in complete accord with

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* American Geology, ii., p. 49, 13.

† Amer. Jour. Science, 1886, xxxi., p. 241.

‡ American Geology, ii., pp. 15–20.

the remarkable section at Quebec, as interpreted by Billings and myself, as well as by James Hall, who, in 1857, spoke of the graptolitic shales of that vicinity as being near the Sparry Lime-rock of Eaton, towards the summit of the Hudson-River group, as it was then called (*ante*, p. 587). The horizon of this was declared by Billings to be considerably higher than that of the New York Calciferous, and at the base of the second fauna of Barrande (*ante*, p. 625). The recently announced discovery by Messrs. Ford and Dwight, of organic forms, believed by them to be of Trenton age, in the Sparry limestone found in the Upper Taconic area, in Canaan, New York,* is only another instance of the fact, so often insisted upon in these pages, of the recurrence of Ordovician strata at many points along this great Graywacke belt from Quebec to Pennsylvania.]

§ 161 A. [That the Sparry limestone was regarded by Emmons as related to the Taconic slate group, or rather a subordinate part thereof, is evident from his descriptions in 1846. After noting that this limestone, while generally persistent in its extent throughout the counties of Dutchess, Columbia, Rensselaer, and Washington, in New York, seems in parts of its distribution to be "engulfed, pinched out, or lost," for short distances, he farther tells us that, though the principal mass of this limestone occurs on the eastern border of the Taconic slate group, similar masses, often thinner, are found farther westward in the sections, and that, while some of these "are, undoubtedly, mere repetitions of the same mass" of Sparry limestone, others are distinct. He conjectures, therefore, that the production of limestones of this type "occurred at intervals during the whole period of the deposition of the Taconic slate," thus clearly showing that, in his opinion, it belongs to the Taconic slate group or Upper Taconic, and not, as Dana imagines, to the Lower Taconic. Emmons at the same time informs us that he

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* Amer. Jour. Science, 1886, xxxi., p. 240.

had found organic remains (including trilobites and graptolites) in three of the subordinate members of the Taconic slate group, namely, the green sandstones, the green slates, and the black slates, and remarks, with regard to the Sparry limestone, "no fossils have yet been discovered in this rock, though it must be confessed sufficient examination has not been made for microscopic bivalves."*

[The conjecture of Emmons as to the recurrence of similar limestones at different periods during the deposition of the Taconic slate group is so far true that there are many bands of limestones, both pure and magnesian, among the shales in the upper portion of the group. This is well shown in the section at Pointe Levis, near Quebec, where numerous bands of this kind were mapped by Logan in 1861. Of these repeated interstratifications of pure limestones, dolomites, sandstones, and argillaceous shales of Pointe Levis the author had already written in 1856: "Both limestones and dolomites are very irregular and interrupted in their distribution, the beds sometimes attaining a considerable volume while at other times they thin out or are replaced by sandstones." Some of these were then described as forming masses many feet in thickness, of pure limestone, without visible marks of stratification, and without organic remains, and were compared to travertines, while others were granular and fossiliferous, more or less magnesian, frequently conglomerate, and passing into dolomites and dolomitic sandstones. In this section "other organic forms, obscure and undetermined, occur in the calcareous beds both above and below" the belt of graptolitic shales.†

§ 162. The different views with regard to the geological horizon of the Lower Taconic or Stockbridge limestones of Emmons — the Granular Lime-rock of Eaton — may be resumed as follows: —

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* Agriculture of New York, vol. I., pp. 68–74.

† Azoic Rocks, pp. 101–104, 106, 133.

I. That they are pre-Cambrian, and occupy a position below the Potsdam sandstone or Red Sand-rock, and the Quebec group of Logan, which together constitute the First or Cambrian Graywacke of Eaton and the Upper Taconic of Emmons, as shown in the table, § 18. (Eaton, Emmons, Perry, Marcou.)

II. That, although lying beneath the greater part of this Graywacke series, they are not distinct therefrom, but are the altered representative of the Levis limestone or Sparry Lime-rock, imagined by Logan to lie between the Red Sand-rock below and the chief part of the Quebec group above. (Logan, in his geological map of 1866.)

III. That they are the altered representatives of the whole of the limestones which, in the New York system as seen in the Adirondack area, appear between the Potsdam sandstone and the Utica slate. (Mather, H. D. and W. B. Rogers, J. D. Dana.)

IV. Allied to the last is the view expressed by Wing, in 1875, that they include the representatives of the limestones of the Potsdam and Quebec groups of Logan, together with the Trenton and the Loraine or Hudson-River group, or, in other words, the whole of the Champlain division of the New York system, from the Potsdam to the base of the Oneida.

V. That they belong to a horizon above the Champlain division, and are true Silurian and Devonian. (C. B. Adams, Ed. Hitchcock, W. B. Rogers.)

§ 163. We have already briefly set forth the arguments on which these various and contradictory hypotheses have been based. While the fifth supposes the Lower Taconic limestone to hold a position above the Oneida sandstone, and consequently superior to the Second Graywacke, the third was devised at a time before the existence of the First Graywacke (maintained by Eaton and Emmons, but denied by Mather) had been again brought into favor by the conversion of Logan to the teaching of Emmons, and by his farther admission that the Lower Taconic limestones in Vermont and Massachusetts are inferior to a great mass of sandstones, conglomerates, and shales many thousand feet in thickness, constituting what he called the Lauzon and Sillery divisions of the Quebec group.

§ 164. It was not until after his change of view as to the geological horizon of this great sedimentary or Graywacke series, or, in other words, after he had recognized the fact that its place is below and not above the Trenton limestone, that Logan began to examine the Lower Taconic rocks in western New England. Having then, by a misconception, placed the Levis or Sparry Lime-rock at the base instead of the summit of the Graywacke, and still holding to the notion of Mather that the crystalline rocks along the eastern border of the great Appalachian valley are but a portion of the paleozoic strata in a so-called metamorphic condition, Logan was led to look upon the Lower Taconic limestone as an altered representative of the Levis limestone, and its underlying quartzite as Potsdam; the immediately overlying schists, and the succeeding sandstones, conglomerates, and shales of the Graywacke series, being referred to the Lauzon and Sillery divisions of his Quebec group. Hence the wide difference between the view of Logan, given under II., and that of Mather and his followers, which we have numbered III. While both would place the Lower Taconic limestones above the Potsdam and below the Oneida, Mather imagined the slates and sandstones overlying them to be Ordovician and Silurian (that is, Utica, Loraine, and Oneida) or the Second Graywacke of Eaton. Logan, on the other hand, conceived the same overlying beds, as seen by him in Vermont, Massachusetts, and New York, to belong to the Cambrian or First Graywacke. The error of Mather and of H. D. Rogers was that both failed to recognize the distinctness of this great series of sandstones, conglomerates, and slates, which are so conspicuous in the Appalachian valley, and confounded them with the Second Graywacke. This error it was which completely misled the geological survey of Canada up to 1861, and continues to obscure the subject in the minds of many American geologists to the present time.

§ 165. It should be remembered that, as already pointed out in chapters ii. and iii., the overlying Graywacke or Upper Taconic does not include the schistose rocks immediately above the Lower Taconic limestone, but that a considerable amount of crystalline schists and argillites occurs, both interstratified with and overlying this limestone, and forming an integral part of the Lower Taconic series. We have, moreover, set forth in chapter v. evidences of the distinction between the Upper and Lower Taconic, and have shown that the latter is not limited to the great Appalachian valley, which confines the former, but is met with in more or less interrupted belts lying upon the crystalline rocks of the Atlantic region south and east of the great valley, from New Brunswick to Georgia. Thus in North Carolina not less than four distinct and separate parallel bands of the Lower Taconic are met with between that of the great valley and the overlying tertiary strata of the coast, while similar narrow bands of the same rocks are found in southern New York and New Jersey, lying upon the ancient gneisses. With none of these Lower Taconic belts outside of the great valley, so far as is known, is the Upper Taconic to be found, its absence being due either to erosion, or, more probably, as suggested by Emmons, to the elevation of these areas above the sea during Cambrian time.

§ 166. On the other hand, it has been shown in chapter vi. that what Mather regarded as a continuation of the great Graywacke series from the east of the Hudson extends south-westward across Orange County and, according to Horton, there rests, with a high eastern dip, on the northwest side of the gneissic belt of the Highlands. From central Vermont, northeastward along the great valley, to the St. Lawrence below Quebec, the Lower Taconic is not known, and the Upper Taconic or Graywacke series rests directly upon older crystalline schists, as in Orange County, New York. The same condition of things is again seen in Newfoundland. These facts, already given in detail, serve to show the distinctness and independence of the crystalline Lower Taconic from the uncrystalline Upper Taconic or Cambrian series, which two were probably separated by a considerable interval of time, corresponding to the stratigraphical break, long since pointed out by Eaton, at the base of the First or Transition Graywacke.

§ 167. The student who refers to Dana's paper of 1882, already noticed, on "The Age of the Taconic System," will obtain no light on the question of this Graywacke series, nor, indeed, any evidence that the author has ever seriously studied the literature of the subject, or comprehended its relation to the complex problem before us. He will get no notion of the two opposing views as to this series of rocks, or its position as above or below the Trenton limestone, or even of its existence as a great succession of uncrystalline sediments, many thousand feet in thickness, and distinct from the Lower Taconic limestones, as maintained alike by Eaton, by Emmons, by Mather, and by Logan, and as set forth in the preceding chapters.

§ 168. The hypothesis of Mather and H. D. Rogers as to the Lower Taconic rocks was devised at a time when the progress of geology in New York had made known, in the Northern district of that State, a great series of nearly horizontal fossiliferous strata resting upon the upturned granitoid gneiss of the Adirondacks and including certain familiar subdivisions of the paleozoic, from the Potsdam sandstone upwards. The relations and succession of these various rocks were simple and evident. To the east and southeast of this region, however, beyond Lake Champlain and the Hudson River, there were found other crystalline rocks, unlike the ancient gneiss, and other uncrystalline sediments very different in physical character and in stratigraphical attitude from the paleozoic strata of the Northern district of New York. The question then arose as to the correlation of these unlike rocks in the two regions. Amos Eaton, by a grand generalization, had already arrived at a system of classification in which he recognized the existence in the eastern or Appalachian region of types of Primitive crystalline rocks other than the granitoid gneiss, and of great masses of sedimentary strata to which nothing similar was found in the contemporary series in the Adirondack region.

§ 169. Rejecting the teachings of Eaton, and falling back on the metamorphic doctrine, which was then so generally received, Mather maintained, in 1843, that whatever to the east of the Hudson differed lithologically from the ancient gneiss, on the one hand, and from the paleozoic rocks of the New York system, as seen in the Adirondack region, on the other, could be nothing else than these same paleozoic rocks folded and subjected to successive stages of so-called metamorphism, as seen in the Lower Taconic quartzites and marbles and the crystalline schists which accompany them, as well as those others that succeed them farther to the east. All of these were, according to Mather, nothing but the more or less altered equivalents of the members of the New York system, from the Potsdam sandstone to the Loraine shales, both inclusive; while the great Graywacke belt, extending along the east side of the Hudson from Dutchess County northward through Vermont was declared to be, not, as maintained by Eaton, older than the Trenton limestone, but newer than the Loraine shales.

§ 170. The considerations which lent probability to this scheme were, first, the general resemblance of this Graywacke series to the Oneida, Clinton, and Medina subdivisions of the New York system, to which it was by Mather referred; and, secondly, the fact that the argillites with unctuous schists, granular limestones, and granular quartzite, which he agreed with Eaton and Emmons in placing below the adjacent Graywacke, presented a certain resemblance to the Loraine and Utica shales, the Trenton and Chazy limestones, the so-called Calciferous Sand-rock, and the underlying Potsdam sandstone. This general parallelism from the top of the Graywacke downward, which, to the mind of Eaton, suggested only the great law of cycles in sedimentation (since generally recognized), was accepted by H. D. Rogers and by Mather as a proof of identity. In fact, the Lower Taconic, as seen along the Appalachian region, in its regular succession of granular quartzites with granular limestones and intervening and overlying soft schists and argillites, presents, notwithstanding its many mineralogical differences, its crystalline character, and its great thickness, a general parallelism to the Champlain division, like that so often remarked in groups of sedimentary strata at very various geological horizons. It is thus, in certain respects, more like the Adirondack Cambrian and Ordovician, with which it has been confounded, than their Appalachian representatives. These resemblances were coupled with the fact that along the base of the South Mountain, in Pennsylvania, this succession is found lying between the ancient granitoid gneiss beneath, and the Oneida sandstone above, precisely as the Potsdam-Loraine succession in northern New York intervenes between the same gneiss and the same sandstone.

§ 171. It was not, therefore, surprising that the geologists then engaged in the study of Pennsylvania, New Jersey, and southern New York, should have accepted this plausible and, at first sight, natural explanation of the apparent lithological parallelism presented between these regions and northern New York, or that Mather endeavored to extend it to the rocks east of the Hudson. This attempt led him to assign to the great Graywacke series which we now know to be of Cambrian age, a position above the Loraine shales, or, in other words, to thus to mistake the First for the Second Graywacke of confound it with the Oneida, Medina, and Clinton subdivisions of northern New York and of Pennsylvania, and

Eaton, and, in fact, to deny the existence of the former as a great series lying above the Lower Taconic and below the horizon of the Trenton limestone. The two brothers Rogers, with Mather, forty years since, reasoning from the paleozoic succession as displayed in the Adirondack area, were not prepared to admit that, in a region so near as the great Appalachian valley, the paleozoic sediments beneath the Trenton horizon could assume a type so unlike the well known Potsdam and Calciferous subdivisions of the Northern district of New York, or that these subdivisions could be represented in the Appalachian area by the vast and lithologically unlike series of the First Graywacke, which Eaton had already, ten years before, assigned to its true position below the horizon of the Trenton limestone. Hence came the great mistake in American stratigraphy, the denial by Mather and his followers of the distinctness of the First Graywacke of Eaton, and the assertion of its identity with the Second Graywacke of the same author. So long as this false position was maintained, there was a plausible argument to be made for the original hypothesis of the brothers Rogers and Mather as to the age of the Lower Taconic series; but with the recognition of the correctness of Eaton's view of the First Graywacke, the fallacy of this hypothesis became obvious, and those who would still advocate it can only do so by rejecting the results alike of stratigraphical and paleontological study for the last generation.

IX. — THE METAMORPHIC HYPOTHESIS.

§ 172. The absence from the granular quartz-rock, the granular marbles and their intercalated and conformably overlying schists and argillites of the Lower Taconic series, of the organic remains of the various members of the Champlain division, or, indeed, of any organic form save the peculiar Scolithus of the granular quartz-rock already noticed (§ 23), was explained by those who maintained the paleozoic age of the series by the convenient hypothesis of a chemical change, attended by crystallization or so-called metamorphism, which was supposed to have effaced the original characters of the sediments, and obliterated their organic remains. In accordance with this hypothesis, it was believed that great series of strata might, within short distances, assume a new aspect, not through any original differences in the sediments, but from transformations wrought in these after deposition, in virtue of which fossiliferous and earthy limestones, losing all traces of their organic remains, could be converted into granular limestones containing, instead, only crystalline silicates — while ordinary sandstones and argillites might become micaceous, chloritic, or hornblendic schists, and even gneisses and granite-like rocks.

§ 173. These views, a development of the Huttonian school in geology, were, as is well known to students, accepted a generation since by a large number of geologists, both in Europe and America, and were carried to an extreme in America. Mather, in his final report on the geology of the Southern district of New York, declared that "the Taconic rocks are of the same age with those of the Champlain division, but modified by metamorphic agency and by the intrusion of plutonic rocks." They were, however, designated by him as "imperfectly Metamorphic rocks," while the various crystalline schists of New York and western New England, included by him in his group of proper Metamorphic rocks, were declared to be the same series in a still more highly altered condition (§ 121). Respecting these, he asserted that where the Taconic and Metamorphic rocks come together, "no well marked line of distinction can be drawn, as they pass into each other by insensible shades of difference." Mather was disposed to admit, in addition to these, an older or so-called Primary series of crystalline rocks in the Highlands of the Hudson, but, in the course of his report, ended by declaring that the Primary limestones of southern New York and northern New Jersey, with their associated granitic and hornblendic rocks, were nothing more than modifications of the members of the Champlain division. He had been led to believe that the Primary limestones in question "can be easily traced through all the changes from a fossiliferous to a crystalline white limestone, containing crystallized minerals and plumbago." From the interstratification of these crystalline limestones, supposed by him to be paleozoic, with gneissic and hornblendic rocks, he was brought to maintain the paleozoic age of these, and thus to doubt whether a portion, at least, of what he had called Primary gneiss was not also paleozoic.

§ 174. Apart from the crystalline rocks of the Highland or South Mountain belt, whose primary character was in part questioned by Mather, the great area of crystalline rocks lying to the south and east of this range in New York, comprising those of Westchester and New York Counties, and embracing Manhattan Island, was by him included, with the adjacent rocks of western New England, in his Metamorphic series, and declared to be "nothing more than the rocks of the Champlain division, modified greatly by metamorphic agencies and by the intrusion of granitic and trappean aggregates." In this area of southern New York he noticed hornblendic rocks, gneiss, mica-schists, and crystalline limestones, besides granite, syenite, and serpentine, the latter three being regarded by him as intrusive rocks.*

§ 175. The doctrine of the Metamorphic school of forty years since, as then resumed and formulated by Mather, was briefly as follows: The different groups of crystalline stratified rocks in southeastern New York and western New England (with the doubtful exception of the

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* For the details of these views see Mather's Geology of the Southern District of New York, 1843, *passim*. A summary of Mather's somewhat diffuse statements will be found in the author's volume on Azoic Rocks, pp. 38-42.

gneissic belt which he had designated Primary), including the Lower Taconic series, the series of micaceous gneisses and mica-schists, as well as the massive granitoid and hornblendic gneisses with their crystalline limestones, all belong to one and the same geological period, and are contemporaneous in age with the paleozoic rocks of the Champlain division of northern New York, from the Potsdam sandstone to the Loraine shales, both inclusive. These various and unlike, though contiguous groups of crystalline rocks were, according to Mather, all produced from the same uncrystalline Cambrian and Ordovician sediments, through a mysterious process of transformation, by what he called "metamorphic agencies," and the intrusion of igneous rocks, in which category he included not only the interbedded serpentines, but apparently, under the name of granites, much of the granitic gneiss, which characterizes large areas of the region, as well as the abundant endogenous granitic veins, — true intrusive or exotic granites being rare in the region. In Mather's cosmogony there was nothing in the geological sequence, at least in northeastern America, between the New York paleozoic series, as seen in the Adirondack area, and the fundamental Laurentian gneiss which there underlies it. Consequently all crystalline rocks which could not be referred to the latter were, unless plutonic, the result of some unexplained transformation of this lower part of the paleozoic column, known as the Champlain division.

§ 176. This hypothesis, extravagant as it now seems, was, during the next few years, accepted by many geological students on the authority of Mather and the brothers H. D. and W. B. Rogers. These latter, in 1846, extended this view of Mather to the White Mountains of New Hampshire, and suggested that the gneissic, hornblendic, and micaceous rocks of this series, since named Montalban, instead of belonging, as hitherto believed, to the "so-called Primary periods of geological time," were probably altered paleozoic strata of Silurian age, including the

Oneida, Medina, and Clinton subdivisions of the New York system. These observers then proceeded to name many species of characteristic organic forms of the Silurian period, which they thought to recognize in certain crystalline aggregates in the mica-schists of the region. In 1847, however, the same observers announced that they no longer considered these forms of organic origin,* and, while they did not then formally retract their opinion as to the paleozoic age of the gneisses and mica-schists of the White Mountains, are known, from their subsequent writings, to have abandoned it as unfounded, although it was for some years afterward maintained, with some variations, by Logan, Lesley, and the present writer.†

§ 177. As regards the ancient crystalline series of the Highlands of the Hudson and of New Jersey, which differs in lithological characters from the last, we find that H. D. Rogers, while he did not accept the notion of Nuttall and of Mather that its gneisses are altered paleozoic sediments, imagined the crystalline limestones, which are really interstratified with them, to be portions of a younger limestone, altered by supposed igneous agencies. In the words of Lesley, Rogers, while maintaining the Primary age of the Highland gneisses, "mistook the crystalline limestone engaged among the Highlands for metamorphosed synclinal outliers of No. II., as at Franklin," in New Jersey, whereas Cook has since shown that the horizontal strata of this later period overlie the upturned crystalline limestones of Franklin.‡ As a consequence of this, H. D. Rogers was quoted by Mather as supporting the extreme notions of metamorphism maintained by Nuttall in 1824, which Mather himself accepted, and which, as I have elsewhere said, "were adopted by H. D.

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* Amer. Jour. Science [2], i., 411, and v., 116.

† See, for historical notes, Hunt, Amer. Jour. Science, vol. i., 84; also Azoic Rocks, pp. 62, 181, 182.

‡ Lesley, Amer. Jour. Science, 1865, xxxix., 222.

Rogers, as far as regards the crystalline limestones of the Highlands in New Jersey,"* — while he soon after applied the same doctrine, in its fullest extent, to the great gneissic series of the White Mountains.

§ 178. To sum up in a few words the views of the Metamorphic school forty years since (1840–1846), we find that H. D. and W. B. Rogers then maintained the paleozoic age of the Lower Taconic series, of the White Mountain gneisses and mica-schists, and also of the crystalline limestones found among the gneisses of the New York and New Jersey Highlands, though admitting the primary age of these Highland gneisses. Mather, again, while holding, in like manner, to the paleozoic age of the Lower Taconic, was not acquainted with the White Mountain series, but maintained that the whole of the gneisses, mica-schists, and crystalline limestones of southeastern New York, with the possible exception of the Highland belt, were paleozoic, and of one age with the Taconic series. It is worthy of note that on the geological map of the State of New York, published in 1842, "by legislative authority," of which the Southern district was prepared by Mather himself, there is no distinction of color between the gneissic rocks of the Highlands and those adjacent to them on the south and east, described by him in his final report, in the following year, as metamorphic paleozoic strata. The serpentine of the region, as seen in Staten Island, is colored on the map like the adjacent intrusive triassic diabase,† but no attempt is there made to designate other eruptive rocks than these.

§ 179. In opposition to the views of this Metamorphic school, there were not wanting some, like Emmons and Charles T. Jackson, who maintained the Primitive age of the whole, or a part, of these crystalline rocks of New England, though recognizing, as Eaton had done, their

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* Hunt, Azoic Rocks, p. 41.

† See, for details with regard to this and the other serpentines of the region, *ante*, pp. 435–442.

lithological distinctness from the gneiss of the Adirondacks and of the Highlands of the Hudson. Already, moreover, in 1824, Bigsby had discovered, around Lake Superior and beyond, the existence of two series of crystalline rocks, and distinguished the younger of these as belonging to the Transition series. More than twenty years later, the geological survey of Canada, while adopting for the crystalline rocks of New England, and their extension into Canada, the hypothesis of their paleozoic age, re-examined these Transition crystalline schists of Bigsby, as seen both on Lakes Superior and Huron, and on the upper Ottawa, and described them as forming a distinct group between the base of the paleozoic series and the ancient gneiss, upon which it was found to rest unconformably. This intermediate series, first described in 1847, was by the present writer designated, in 1855, by the name of Huronian, — the underlying gneissic series having, in 1854, received the name of Laurentian. With the Huronian, as we have endeavored to show (*ante*, pp. 414, 581), have since been included, in the region of the great lakes and elsewhere, areas of Taconian rocks.

§ 180. In 1858 appeared the final Report of H. D. Rogers on the geology of Pennsylvania, in which we find no recognition of the extreme doctrines of metamorphism maintained by Mather in 1843, and by W. B. Rogers and himself in 1846. Not having come to an understanding of the question of the First Graywacke, H. D. Rogers regarded the Lower Taconic series in Pennsylvania as an altered form of the Champlain division, and considered the granular quartz-rock with Scolithus to be the equivalent of the New York Potsdam sandstone.* The characteristic crystalline rocks of western New England and southeastern New York, described by Mather as altered paleozoic, pass beneath the mesozoic sandstone in New

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* For Lesley's doubts as to the precise equivalence of the Primal quartzite of Pennsylvania and the New York Potsdam, see Amer. Jour. Science, 1865, xxxix., 223.

Jersey and re-appear in southeastern Pennsylvania. These rocks were now, in 1858, described by H. D. Rogers as forming two great groups, an older or so-called Hypozoic gneiss system, and a younger one of crystalline schists, which he called Azoic and placed beneath the horizon of the Scolithus sandstone. The views of H. D. Rogers, in 1858, with regard to the crystalline rocks of the Atlantic belt, were thus, as I have elsewhere said, "a return to those held by Eaton and by Emmons, but were in direct opposition to that maintained by Mather, which had been adopted at that time by Logan and by the present writer" (*ante*, p. 406), and, so far as regards the White Mountains, were maintained by the Messrs. Rogers themselves, in 1846.

§ 181. Henry D. Rogers died in 1867, but his venerable brother, William B. Rogers, survived till 1882, and fully shared the views set forth by the former in 1858, as to the pre-paleozoic age of the great groups of crystalline rocks. His careful and extended studies in Virginia during many years had convinced him of the fallacy of the metamorphic hypothesis of Mather. In a sketch of the geology of that state, contributed by him as late as 1878 to James Macfarlane's "Geological Railroad Guide," Rogers makes it plain that the crystalline rocks of that region are all pre-paleozoic, and older than what he calls the Primal or Potsdam group. This he describes as lying on the western slope, and in the west-flanking hills of the Blue Ridge, "often by inversion dipping to the southeast, in seeming conformity, beneath the older rocks of the Blue Ridge, but often, also, resting unconformably upon or against them." These older rocks, he tells us, "comprise masses referable probably to Huronian and Laurentian age," and, farther, he informs us that the letters, A, B, C, and D, used in his tabular view, "mark four rather distinct groups of Archean rocks found in Virginia, of which the first three may probably be referred to the Laurentian, Huronian, and Montalban periods, respectively, and the fourth to an intermediate stage, — the Norian or Upper Laurentian."

§ 182. It should here be remarked that this Primal group of the valley of Virginia, also called by Rogers Lower Cambrian, is no other than the base of the Lower Taconic series, which he continued to regard as in some sense the representative of the Cambrian Potsdam of the Adirondack region. In this connection, as showing the relations of this group to the crystalline rocks, and the apparent inverted succession, I venture to make the following extracts from a letter from W. B. Rogers, written to me in 1877, for publication in the volume on Azoic Rocks, after an examination with him of some forty unpublished transverse sections, made across the Blue Ridge during his geological survey of Virginia. In many of these sections "illustrating the position of the Lower Cambrian (our Primal conglomerate, etc.), in their contact with the crystalline and metamorphic rocks of the Blue Ridge in Virginia," "the unconformity of the Cambrian upon and against these crystalline and metamorphic rocks is unmistakable and conspicuous; the lower members of the Primal being seen to rest upon the slope of the Ridge, with northwest undulating dips, on the edges of the steeply southeastward-dipping older rocks. In other cases, the Primal beds, thrown into southeast dips in the hills which flank the Blue Ridge, are made to underlie, with more or less approximation to conformity, the older rocks forming the central mass of the mountain." Here follow details as to localities, for which the reader is referred to the letter as published. *

§ 183. While, therefore, the brothers Rogers held, and others still hold, to the paleozoic age of the Lower Taconic rocks, the view put forward by Mather, that the great region of gneisses and crystalline schists with limestones, lying to the east of these, consists of more highly altered paleozoic strata, had become discredited. It was,

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* Hunt, Azoic Rocks, p. 198.

as we have seen, abandoned by H. D. Rogers for Pennsylvania, in 1858, and by W. B. Rogers for Virginia, where he recognized in the pre-Taconian rocks the same great divisions which I had elsewhere pointed out. The history of the studies of Thomas Macfarlane, and my own, which showed conclusively the pre-paleozoic age of the extension of the New England crystalline schists into the Province of Quebec, has already been told elsewhere.*

§ 184. It was, therefore, with some surprise that geological students found J. D. Dana, in 1880, attempting to resuscitate, in its completeness, the discarded view of Mather. In an elaborate paper on "The Geological Relations of the Limestone Belts of Westchester County, New York," which appeared that year, Dana, following up the reasoning already noticed (§ 161), by which he sought to sustain the paleozoic age of the Lower Taconic rocks, proceeds to assume that the crystalline marbles enclosed in the gneisses, as well as the gneisses and crystalline schists of the region named, are altered rocks of paleozoic age. To quote his conclusions: "The limestone of Westchester County and of New York Island, and the conformably associated metamorphic rocks, are of Lower Silurian age," and, farther, "the limestone and the conformably associated rocks of the Green Mountain region, from Vermont to New York Island, are of Lower Silurian age." † His argument in favor of these assumptions appears to be, briefly, this: — That the crystalline limestones of the gneissic series, the granular Lower Taconic marbles, and the fossiliferous Cambrian and Ordovician limestones found among the uncrystalline sediments of the Appalachian valley, along the western flank of the crystalline belt north of the Highlands, are but three different conditions of one and the same calcareous series, and, hence, that the great area of crystalline rocks south of the narrow range of the Highlands (of which he

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* Hunt, Azoic Rocks, pp. 182–188, and *ante*, pp. 406, 407.

† Amer. Jour. Science, 1880, xx., 455.

admits the eozoic age) consists of paleozoic strata, Cambrian or Ordovician in age.

§ 185. Dana, having announced his conclusions as above, adds: "The evidence which has been adduced, though then but partly discerned, led Profs. W. B. and H. D. Rogers, and Prof. W. W. Mather, nearly to the results here reached." In support of this assertion, he refers to Mather's report of 1843, in which, as we have seen, the hypothesis was advanced, and also under the head of "Professors Rogers," to a paper by them in 1841, in the Proceedings of the American Philosophical Society. as well as to a statement in the American Journal of Science for 1872 (vol. iv., page 363). This the reader will find to be nothing more than Dana's assertion that the Messrs. Rogers, in that same paper of 1841, maintained the Champlain age of the Lower Taconic series,— a view which, as we all are aware, one of them, some years later, abandoned for that of its Devonian age. These eminent geologists did, for a time, put forward the view (afterwards relinquished) that the gneissic series of the White Mountains consists of altered Silurian (Oneida-Clinton strata), and Mather, in his argument, made the most of the error of H. D. Rogers, who mistook, in 1840, certain interstratified crystalline limestones among the Primary gneisses of New Jersey for superincumbent limestones in an altered condition; but Dana fails to show that the Messrs. Rogers ever maintained the paleozoic age of the great series of crystalline rocks in southeastern New York, as he would have his readers infer. When, in 1858, H. D. Rogers had occasion, in his final report on the geology of Pennsylvania, to describe the continuation of these same rocks into that State, he distinctly assigned them to a horizon below the base of his paleozoic series, proposing, at the same time, a Hypozoic and an Azoic system to include them.

§ 186. The Highland range on the east side of the Hudson traverses Putman County, and, passing southwestward to the river, occupies but a small area in the northwest corner of Westchester County. Along its southeast base, at Annsville, and at Oregon, is met a narrow belt of scarcely crystalline limestone, accompanied by an argillite or talcoid slate, and resting unconformably upon the ancient gneiss. This belt, apparently a Lower Taconic outlier, is regarded by Dana as partially altered Lower Silurian, and "the grade of metamorphism" is declared by him to become more intense to the south and east, giving rise to the whole gneissic area of Westchester and New York Counties. The gneisses and conformably interstratified crystalline limestones of this large area are, as we have seen, supposed by Dana to be metamorphosed Lower Silurian, though they are really undistinguishable from the rocks of the adjacent Highland range, which he admits to be Archean or Primary. In support of his startling proposition, Dana might be expected to point out some distinctions between the rocks of the two areas. He begins by suggesting certain differences as to more or less micaceous or hornblendic gneisses in the two regions in question, but confesses that "there are gradations between the two, in both respects, which make the application of a lithological test very perplexing," * and admits that "the lithological evidence of diversity of age is weak," a criticism which is equally applicable to Dana's stratigraphical argument.

I am familiar with the rocks of many parts of Westchester County, and since the publication of Dana's paper in 1880 have taken repeated opportunities to examine the rocks called by him Metamorphic Lower Silurian, in various localities, as at Sing Sing, Tarrytown, Yonkers, Spuyten Duyvil, and Kingsbridge, along the Hudson. I have also studied the same rocks farther to the east, along the River Bronx and the Harlem Railroad, to Pleasantvale, as well as between this line and the Hudson, and have crossed eastward to Long Island Sound, and examined

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* Amer. Jour. Science, 1880, xx., 373.

the exposures on the shore at and near New Rochelle. Being already familiar with the Laurentian rocks throughout Canada, as well as in parts of the Adirondacks, and in the Highlands from Putman County, New York, through New Jersey and Pennsylvania to the Schuykill, and beyond, I do not hesitate to say that the gneisses and their associated crystalline limestones of Dana's so-called Metamorphic Lower Silurian, in Westchester County, cannot be distinguished from the typical Laurentian. I believe that the judgment of an impartial observer would be that the notion of any difference between the Laurentian gneisses and limestones of the areas mentioned, and the gneisses and their interstratified limestones of Westchester County, has no foundation in fact.

§ 187. Passing now from Westchester County to the adjacent Manhattan Island, the same Laurentian gneiss is seen in its northern portion, between Seventh and Eighth Avenues, especially in a cutting at One Hundred and Forty-fifth Street, and thence in a ridge some distance farther south, the strata being nearly vertical and of grayish hornblendic gneiss, and a band of crystalline limestone appearing a little farther to the east, on Harlem River. A quarter of a mile to the west of this ridge, in Mount St. Vincent, is seen a distinct type of highly micaceous gneiss, and mica-schists, and similar rocks are exposed at intervals in the western part of the island, as far south as Fifty-ninth Street. Farther eastward, in the southern part of Central Park, just above Fifty-ninth Street, the numerous rock-exposures are all of similar mica-schists, and micaceous gneisses, often at moderate angles. They include endogenous granitic veins, occasionally presenting in their structure a marked bilateral symmetry, and sometimes tranverse, but at other times interbedded. Several perched blocks here found are of similar endogenous granite, and are apparently boulders of decomposition, left in the sub-aerial decay of the rocks of the region. These micaceous rocks are unlike those of

Laurentian areas, but, on the contrary, closely resemble those of the White Mountains, and of Philadelphia, which I have called Montalban, and are like the younger gneissic series of the Alps and the Scottish Highlands. I therefore, as long ago as 1871,[*] noticed these rocks as belonging to this younger series, and have since expressed the opinion that the Laurentian "of Manhattan Island appears to be overlaid in parts by areas of younger gneisses and mica-schists, the remaining portions of a mantle of Montalban."[†] It is, however, by an error for which I am not responsible, that in James Macfarlane's "Geological Railroad Guide," in 1878, the Montalban of Manhattan Island has been represented as extending upward along the Hudson River Railroad by Spuyten Duyvil, Yonkers, Tarrytown, and Sing Sing, as far as Croton, before meeting the Laurentian of the Highlands. There appears, nevertheless, to be an outlier of Montalban rocks at Cruger's Station, just above Croton, and there may be others in various parts of Westchester County.

§ 188. It has been deemed necessary to notice thus at length, in this connection, Dana's resuscitation of the ancient views of Mather, for two reasons: first, because therein, both the Lower Taconic rocks and various crystalline rocks just noticed, are supposed by him to be contiguous portions of the same Cambrian and Ordovician (Lower Silurian) sediments in different stages of transformation; and secondly, because the manner in which the names of the brothers Rogers are cited by Dana in conjunction with that of Mather is such as to lead the reader to the false conclusion that those eminent geologists supported Mather's hypothesis of 1843 as to the Cambrian and Ordovician age of these same crystalline rocks, as well as that of the Lower Taconic series; which latter view, as we have shown, W. B.

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[*] Hunt. President's Address before the Amer. Assoc. Adv. Science, 1871; in Chem. and Geol. Essays, pp. 248 and 197.

[†] Smithsonian Report for 1878, Progress of Geology.

Rogers repudiated a few years afterwards, in 1851, and again in 1860.

§ 189. The rise and fall of the doctrine of regional metamorphism, which is but an extravagant development of the Huttonian hypothesis of the origin of crystalline rocks, forms a curious chapter in the history of geology. I have elsewhere related the early application of this doctrine to the crystalline rocks of Mont Blanc by Bertrand, about 1797, and its subsequent restatement by Keferstein in 1834, until it was taken up and popularized by Lyell, Murchison, and various continental geologists, so that the view became generally accepted that the gneisses and mica-schists of the Alps are but altered secondary and tertiary strata. The story of the refutation of this hypothesis for the Alps by the studies of Favre, Pillet, Gastaldi, and others, has also been told.* A similar view was extended to crystalline rocks in other parts of continental Europe, in the British Islands, and in eastern North America, save that to all of these a paleozoic age was generally assigned. The opinions of Mather on this subject were adopted by Logan and others, including the present writer. The brothers Rogers, in 1846, advanced a similar view for the rocks of the White Mountains, but abandoned it before 1858. It was not until 1870 and 1871 that the present writer, rejecting entirely the views of this school, asserted the pre-Cambrian age of all the great areas of crystalline rocks, alike in North America and in Europe. Nearly coinciding in time with this, came the independent action of numerous continental geologists, including those already named, and the result has been such an advance of the views of the new school that, in 1881, Callaway could say that "every case of supposed metamorphic Cambrian and Silurian has been invalidated by recent researches," and in 1883 Bonney wrote that the hitherto accredited "instances of metamorphism in

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* Amer. Jour. Science, 1872, iii., 9, and Chem. and Geol. Essays, pp. 338–342 and 347, 348. Also, *ante*, Essay X., part iv.

Wales, and especially in Anglesey, in Cornwall, in Leicestershire, and in Worcestershire, have utterly broken down on careful study;" * as had already been the case in the Alps and in North America.

§ 190. The last stronghold of the metamorphic school in the British Islands was in the northwest of Scotland, where Cambrian and Ordovician fossiliferous sandstones, limestones, and shales, resting upon the ancient granitoid gneisses to the west, are, towards the east, overlaid. in apparent conformity, by a great series of unlike gneisses and mica-schists, which form the Scottish Highlands, and were declared by Murchison and Archibald Geikie, from their studies, to consist of still newer rocks in a so-called metamorphic condition. The structure of this northwestern part of Scotland was, in fact, according to their teaching, the precise counterpart of that of New England, as formerly taught by Mather and his followers, and still supported by Dana. The late Professor Nicol, however, constantly opposed this view of the structure of the Highlands maintained by Murchison and by Geikie, while the present writer, from his lithological studies of the Highland rocks, declared in 1871 his conviction that the upper gneisses of "the Scottish Highlands will be found . . . to belong to a period anterior to the deposition of the Cambrian sediments, and will correspond with the newer gneissic series of our Appalachian region," † then described as the White Mountain series, — an opinion which was reiterated, after farther examination of specimens of the rocks, in a communication in 1881 to the Geological Society of London, when these Highland gneisses were designated as Montalban.‡

§ 191. The studies by Hicks of the geology of parts of this region, from 1878, and the later and independent

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* Callaway, Geological Magazine, Sept. 1881, p. 423, and Bonney, *ibid.*, Nov., 1883, p. 507.

† Hunt, President's Address before the Amer. Assoc. Adv. Science, 1871, and Chem. and Geol. Essays, p. 272.

‡ Proc. Geol. Soc. London, in Geological Magazine, 1882, ix., 39.

ones of Callaway and of Lapworth in other districts, had already, in the beginning of 1883,* shown the fallacy of the views maintained by Murchison and Geikie as to the geological structure of the Highlands. The united testimony of these observers made it clear that in the region in question were portions of two gneissic series,—an older or granitoid gneiss, like that of the western coast, and a younger, very distinct in type, which has been variously designated as Upper Pebidian, Grampian, and Caledonian, and is that described by me in 1871, and again in 1881, as of the White Mountain or Montalban type. This, the younger gneissic series of Murchison and Geikie, was clearly established to be of great thickness, and older than the fossiliferous Cambrian, which it is brought to overlie by a series of great folds, overturned to the west, and accompanied by parallel faults, with upthrows on the east side, as shown by Hicks in Ross and Inverness shires, as well as by Callaway in Assynt, and by Lapworth in Eriboll (*ante.*, p. 423).

§ 192. The concordant and independent results of the eminent observers just named having thus demonstrated the fallacy of the view of Murchison and Geikie that the gneiss, which in the Highlands overlies the fossiliferous strata, is a still younger paleozoic series in an altered condition, the geological survey of Great Britain, of which Geikie is now director, undertook, in 1883 and 1884, a reexamination of the region in question. The result of this has completely disproved the former statements of Murchison and Geikie, and has confirmed those of the new school. Geikie, in a note recently published,† tells us

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* Hicks, Quar. Geol. Jour., 1878, xxxiv., 816; Geol. Mag., 1880, vi.; also Quar. Geol. Jour., 1883 (with appended notes by Bonney), in abstract in Geol. Mag., March, 1883, x., p. 137. Callaway, *ibid.*, x., pp. 139 and 336; and Lapworth, *ibid.*, x., pp. 120, 192, 337; also Callaway on Progressive Metamorphism, *ibid.*, May, 1884; and summaries in accounts of the Progress of Geology in the Reports of the Smithsonian Institution for 1882 and 1883.

† Nature, Nov. 13, 1884, xxxi., 22-35.

that he has "found the evidence altogether overwhelming against the upward succession, which Murchison believed to exist in Eriboll, from the base of the Silurian strata into an upper conformable series of schists and gneisses," and adds: "That there is no longer any evidence of a regular conformable passage from fossiliferous Silurian quartzites, shales, and limestones, upwards into crystalline schists, which were supposed to be metamorphosed Silurian sediments, must be frankly admitted." The same conclusions are also reached by Geikie from the re-examination of the similar sections in Ross-shire, previously described by himself in accordance with the views of Murchison. The preliminary report of the surveyors, Messrs. Peach and Horne, which is subjoined to the director's note, shows the same structure as was already described by the late observers, namely, overturned folds and great faults, with lateral thrusts westward, by which the gneisses are made to overlie the fossiliferous strata,—the horizontal displacement of the gneisses to the west, which are superimposed on the Cambrian rocks, being, in some cases, according to Geikie, not less than ten miles.

[Judd, who, in 1885, reviewed before the British Association the early work of Nicoll in this region, writes that in a paper by the latter, published by the Journal of the Geological Society in 1861, he "must be admitted to have established the main facts concerning the geology of the Highlands as accepted by all geologists at the present day." He adds that the conclusions arrived at by Nicoll in early as 1860, those of the later investigations named, previous to 1883, and those of the British geological survey in 1883 and 1884, "are in all their main features absolutely identical, and the Murchisonian theory of the Highland succession is now, by universal consent, abandoned.*]

§ 193. Geikie notices the distinction between the older or granitoid gneiss, portions of which also appear in the

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* Nature, xxxii., 455, 456.

Highlands, and the upper gneissic and mica-schist series, the pre-paleozoic age of which was shown by the observations alike of Hicks, of Callaway, and of Lapworth. He calls attention to the laminated and schistose structure developed by the great pressure and friction along the lines of movement in gneissic and hornblendic rocks, and also to similar changes produced by the same agency in detrital rocks, such as arkose. Both of these structural alterations are apparently included by Geikie under the head of what he calls a "regional metamorphism,"—a misapplication of the term likely to confuse the reader, since local structural changes, induced by mechanical movements in ancient crystalline rocks, have nothing in common with that mysterious process which has been supposed by the metamorphic school to generate similar crystalline rocks from uncrystalline sediments. As regards the changes wrought by the same agency on detrital masses, it may be repeated that "the resemblance between primitive crystalline rocks and what we know to be detrital rocks compressed, recemented, and often exhibiting interstitial minerals of secondary origin, is too slight and superficial to deceive the critical student in lithology, and disappears under microscopical investigation" (*ante*, p. 108.)

§ 194. We have already elsewhere in this essay (§ 135) referred to the local development of crystalline silicates in sedimentary rocks by infiltration, and have in another place considered the relation of such a process to the question of the origin of Primitive crystalline rocks. These we believe to have been formed anterior to the existence of detrital sediments, and by a process which excludes alike all so-called metamorphic, metasomatic, and plutonic hypotheses of their origin. At the same time, we reject the Wernerian or chaotic hypothesis; and its modification by De la Beche and Daubrée, which we have called thermochaotic, in favor of a new aqueous or neptunian hypothesis, which supposes the elements of these rocks to have been dissolved, and brought to the surface from a disintegrated layer of igneous basic rock, the superficial and last-solidified portion of a cooling globe, through the action of circulating waters. The soluble and insoluble products of the sub-aerial decay alike of igneous and aqueous rocks are, however, conceived to have intervened in the process, especially during the period of the later crystalline or Transition rocks. This explanation of their genesis, which we have called the crenitic hypothesis, is discussed at length in Essay V. of the present volume.

IX.—CONCLUSIONS.

§ 195. The task attempted in the preceding chapters, of discussing the history of the Taconic question, has involved a review of much of the work done in American geology for more than sixty years, going back to the labors of Eaton, and even to those of Maclure. Of the somewhat extensive literature* of the subject I have made use, so far as has seemed of importance, in the controversies which have arisen on this question, and have supplemented the researches of various investigators by personal observations extending over a wider field and a greater number of years than those of any of my predecessors. From all of these sources, I have here sought to bring together whatever has appeared to be of value for the elucidation of the important problems before us. In the following sections, the conclusions which have already been set forth at length are summed up.

§ 196. There exists in eastern North America a great group of stratified rocks, consisting of quartzites, lime-

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* Dana, in the Amer. Jour. Science for 1880, xix., 163, has given "a list of the principal papers" on the Taconic System, in which, while professing to bring together those adverse to the pre-Cambrian age of the Taconian, he omits all reference to the opinions of Adams, of Ed. Hitchcock, and the later conclusions of W. B. Rogers as to the (Upper) Silurian or Devonian age of the Taconian limestones. The list is in other respects very incomplete, and serves to mislead the student.

stones, argillites, and soft crystalline schists, which have together a thickness of 4000 feet or more, and are found resting unconformably upon various more ancient crystalline rocks, from the Laurentian to the Montalban inclusive. This series, called Transition by Maclure, includes the Primitive Quartz-rock, the Primitive Lime-rock, and the Transition Argillite of Eaton, and is the Lower Taconic of Emmons, and the Itacolumitic group of Lieber. The series, which I have preferred to call Taconian, is essentially one of Transition crystalline rocks. The quartzites, which predominate in the lower portion, contain much detrital matter, and are sometimes conglomerates. They are, however, often vitreous or granular, the latter variety being sometimes flexible and elastic, and constituting what is called elastic sandstone or itacolumite. These quartzites, like the limestones of the series, often contain an indigenous micaceous substance, which is in most cases a hydrous muscovitic mica, related to sericite or to damourite. A similar mineral predominates in certain layers of soft unctuous lustrous schists, which, from their aspect, have been called talcoid or magnesian, and are found intercalated alike with the quartzites and the limestones of the series. The latter, often more or less magnesian, are generally finely granular, and yield marbles for statuary and for architecture. They are often variegated in color or banded with green or gray, constituting cipolins. The mineralogy of the limestones and their associated crystalline schists has been noticed in §§ 51, 65, 68, 76–79, and farther, on page 184 of the present volume, and it has been shown that the Taconian is an important ore-bearing horizon, including, besides great deposits of magnetite, and of hematite, others of siderite and of pyrite. Both of the latter species, by epigenesis, give rise to hydrous iron ores, which, throughout the Appalachian region, characterize the outcrops of the series, and are generally imbedded in clays, the result of the sub-aerial decay of the enclosing schists, which, it may thence be conjectured, include, in many cases, large proportions of a feldspathic mineral. The argillites of the Taconian, often yielding roofing-slates, are interstratified with more or less silicious beds, and occur chiefly in the upper part of the series.

§ 197. These Taconian rocks are not confined to the Appalachian valley. Extending southward therefrom, they are traced in Pennsylvania along the eastern base of the Blue Ridge into North Carolina, and are found in outliers to the east, over the Atlantic belt from Georgia to New Brunswick and Nova Scotia. To the west of the great valley, they are known to underlie the eastern part of the paleozoic basin, and appear in eroded anticlinals from beneath the coal-measures, alike in Alabama and Pennsylvania, where they are overlaid by Ordovician strata. They are seen in similar conditions, lying unconformably beneath the Ordovician limestones of the Ottawa basin, in Hastings County, Ontario, and are represented by the great series of quartzites, limestones, argillites, and crystalline schists, with iron-ores, around Lake Superior, which, as we have endeavored to show on pages 579 and 581, have been generally confounded with the Huronian, but were designated by the writer in 1873 as the Animikie series, and had long before been by Houghton and Emmons referred to the Taconian system. This, according to information got from Houghton, was declared by Emmons in 1846 to be largely developed in the central and western parts of the upper peninsula of Michigan, the slates being well exposed on the line of the Menominee River; while farther east, near to Lake Superior, the Granular Quartz-rock was said to appear, with a northeast strike, in hills several hundred feet high. In 1855, it was farther stated by Emmons that collections of the rocks from this region presented all the lithological characters of those from eastern New York.* They were, more-

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* Agriculture of New York, i., p. 101; American Geology, ii., p. 118, and Manual of Geology, p. 89.

over, found by Houghton to be overlaid by the Potsdam sandstone, and, as we now know, are also inferior to the Keweenian. Taconic rocks, we were subsequently told by Emmons, occur "in Arkansas, in the vicinity of the Hot Springs." * The argillites and quartzites which in the Black Hills of Dakota intervene between the lower crystalline rocks and the Cambrian, resemble those of the Taconian, and the same must be said of the quartzites with argillites, lustrous schists, and crystalline limestones, which the writer has noticed in a similar position in the Tintic Hills in Utah.

§ 198. The Taconian series is not destitute of evidences of organic life, but contains, in the granular quartzites near its base, the typical *Scolithus linearis* at many points throughout the Appalachian valley. Similar markings in the silicious beds of the series in Hastings County, Ontario, have been noticed as probably worm-burrows by J. W. Dawson, who has also described the *Eozoon Canadense* found in the associated limestones, while the argillites which I have referred to this series, from the western end of Lake Superior, have afforded the remains of a sponge. The Taconian, as I have suggested, may constitute a link between the older eozoic groups and those of paleozoic time.

§ 199. The Upper Taconic, which is the First Graywacke and the Sparry Lime-rock of Eaton, and the Potsdam and Quebec groups of Logan (including a large part of what was described by Mather, and by Logan previous to 1861, as Hudson-River group), we have seen to be the Appalachian representative of the Cambrian period. It sometimes overlies the Taconian, but, in the absence of this, rests directly upon the older crystalline groups along the eastern border of the great Appalachian basin. Unlike the Taconian, however, it does not, so far as known, extend eastward of this limit, while to the west, as we recede from this border,

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* Manual of Geology, p. 89.

it is soon replaced by the Adirondack type of the Cambrian.

This Appalachian Cambrian series is wholly uncrystalline, and is separated from the Taconian by a stratigraphical break, and by a great interval of time, which includes the Keweenian period. From the distribution of the Cambrian and the Ordovician in eastern North America, there was evidently another great stratigraphical break, with erosion (followed by a considerable continental depression), which preceded the deposition of the Ordovician limestones. Similar disturbances seem to have intervened at the beginning of the Silurian period, in this eastern region, for we find the Silurian limestones resting directly upon somewhat inclined and eroded Ordovician strata near Montreal, and apparently, also, in the valley of the Hudson, while throughout this eastern border the great mechanical sediments of the Oneida, Medina, and Clinton, which to the west of the River Hudson constitute the chief part of the Second Graywacke of Eaton, at the base of these limestones, are apparently absent, — a fact pointing to the emergence of this eastern region during the early part of Silurian time. The local disturbances which at this period prevailed in the eastern part of the great basin are farther shown in the conglomerate character of these Silurian sandstones in parts of New York and Pennsylvania, though it should be noted that in these regions, as well as in Ontario, there appears to be an unbroken succession from the Loraine shales to the Oneida, Medina, and Clinton subdivisions.

§ 200. As a result of all these various movements which affected the eastern border of the Appalachian basin, we find that the Taconian is there in some parts directly overlaid by Cambrian, in others by Ordovician strata, and in parts, it would seem, by limestones belonging to the upper portion of the Silurian, or to Devonian time. The strata of all of these periods are more or less involved with each other, and with still older crystalline groups, by the successive movements of folding and dislocation which continued to affect the Atlantic belt, at intervals, until after the close of paleozoic time. From the complex stratigraphical relations which have thus resulted, various observers have, during the past forty years, conjectured that the Taconian limestones are strata of Cambrian, of Ordovician, of Silurian, or even of Devonian age, which, by a process of so-called metamorphism, have been changed into granular non-fossiliferous marbles, often holding crystalline silicates.

§ 201. These various conjectures are not only in contradiction with each other, but, as we have seen, are in direct conflict with the facts of stratigraphy, and are, moreover, based upon the unproved and now generally discredited hypothesis of progressive and regional metamorphism. This hypothesis, as long since maintained by Mather for the rocks of eastern North America, and later by Dana, asserts successive changes, — called by the latter "grades in metamorphism,"— from uncrystalline sediments, through the Taconian and other more massive crystalline schists, to the granitoid gneisses. These various and dissimilar groups of strata, as I maintained in 1878, and as will to-day be admitted by nearly all geologists, "are not the result of different and unlike changes which one and the same uncrystalline paleozoic series has suffered in different geographical areas, but, on the contrary, belong to successive periods in paleozoic and eozoic time. The great divisions of the latter . . . present in ascending order a progressive change in mineral character, the nature of which has been shown; . . . thus constituting a veritable passage in time from the granitoid Ottawa gneiss at the base of the Laurentian, through the intermediate Huronian and Montalban divisions, to the less markedly crystalline schists of the Taconian."* Such a succession, I have since endeavored to show, is the necessary result of the secular process by which, from an undifferentiated primeval

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* Hunt, Azoic Rocks, 1878, p. 253; see also *ibid.*, p. 210.

chaos, the various groups of Primitive and Transition crystalline rocks have been generated, as set forth in the crenitic hypothesis* already explained at length, in Essays V. and VI.

§ 202. The Taconian crystalline rocks were deposited over a large part of eastern North America upon the eroded surfaces of more ancient eozoic groups, and in their turn suffered greatly from movements of the earth's crust, and from erosion, previous to the beginning of Cambrian time. Over the more depressed portions of the worn surfaces the uncrystalline sediments of Keweenian, Cambrian, Ordovician, Silurian, and later periods, were next successively laid down, alike on the Taconian and the more ancient crystalline groups, not, however, without intervening movements of the earth's crust, which along the eastern portion of the great paleozoic basin caused stratigraphical breaks, foldings, and partial erosions of these later groups of sediments. Beyond the limits of this basin, to the south and east, the sparse distribution of areas of paleozoic sediments, and their absence from the higher levels among the crystalline rocks of the Atlantic belt, permit us to suppose that the paleozoic seas did not invade these higher regions; while the deposits made by some of them at lower levels among these same crystalline rocks have been in great part removed by subsequent agencies. As a final result of this process, we find, within the great basin, the Taconian rocks resting on various older crystalline groups, and themselves overlaid directly by various paleozoic sediments; while outside of the limits of the basin, areas of the same

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* "All physical theories properly so called are hypotheses, whose eventual recognition as truths depends upon their consistency with themselves, upon their agreement with the canons of logic, upon their congruence with the facts which they serve to connect and explain, upon their conformity with the ascertained order of Nature, upon the extent to which they approve themselves as trustworthy anticipations or previsions of facts verified by subsequent observation or experiment, and finally upon their simplicity, or rather their reducing power," —Stallo, in The Concepts and Theories of Modern Physics, p. 85.

Taconian rocks are in parts overlaid by mesozoic and by tertiary strata.

§ 203. As regards the existence in other lands of a similar series of rocks to the Taconian of North America, we have seen that Lieber, whose independent and careful studies of this series in South Carolina we have resumed on pages 564–569, supposed it to be the stratigraphical equivalent of the Itacolumite or diamond-bearing series of Brazil, of the similar rocks of Bundelkhand in India, long since described by Claussen and by Jacquemont, and of those in Russia, where several areas of Itacolumite rocks, diamond-bearing like those of Brazil and India, were discovered in the southern Urals by Helmersen and Hoffman.*

These diamond-bearing rocks in Bundelkhand have since been described by the geological survey of India as the Lower Vindhyan series.† The studies of Hartt, of Gorceix, and of Derby have thrown farther light on the Itacolumite series of Brazil, which, according to the latter, rests unconformably upon the older crystalline rocks, and consists in great part of quartzites, often granular and sometimes flexible, with unctuous talcoid schists containing hydrous micas, chloritic and argillite beds, specular schistose iron-ore (itabirite), and great masses of crystalline limestone. The resemblances, long since noticed by Lieber, between this Brazilian series and the American Taconian were made very evident by a collection of these rocks from the province of Minas Geraes, examined by the writer in 1876. This ancient series in Brazil has afforded no organic remains, but, being unconformably

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* The following bibliographical references are cited from Lieber: Eschwege, Beitrage zur Gebirgskunde Braziliens, Berlin, 1832, p. 174; Spix and Martius, Reise in Brazilien, II. Theil; also, Humboldt, Gisement des roches dans les deux hemisphères, pp. 89–92; Jacquemont, Voyage dans les Indes, 1828–32, Sur les grès schisteux de Panna in Bundelkund, etc.; Cotta, Gesteinslehre, 1855, p. 212, and Zerrenner, Gold, Platin, und Diamant Waschen, etc., Leipzig, 1851.

† Manual of the Geology of India, Medlicott and Blanford, i pp. xxi. and 69–92.

overlaid by older paleozoic rocks, has been by Derby supposed to be altered Cambrian, while others have assigned it to a pre-paleozoic age. The diamonds (which are also met with in derived rocks), are found in the province of Diamantina in unctuous banded clays of varying colors, which are derived from the sub-aerial decay of eastward-dipping schistose beds of the Itacolumite group.*

§ 204. A close resemblance between the older rocks of Brazil and those of Guiana has been pointed out by Jannetaz, who, as remarked by Crosby, "has recognized in the latter country the itacolumite, with the hydromicaceous and other schists of the former, which have been connected with the Taconian system. The itacolumite of Guiana has also been observed by Schomburgk." † Farther to the northwest, beyond the mouth of the Orinoco, we meet a great development of a similar series. Crosby, writing in 1880, says these rocks "constitute the main mass of the great eastern branch of the Andes, or at least that part of it which skirts the Caribbean sea from Caracas eastward, and is known as the Littoral Cordillera of Venezuela." The Cordillera forms the Northern Mountains of Trinidad, which have an altitude of 3000 feet, and terminates in the neighboring island of Tobago. These semi-crystalline rocks of the Spanish Main and Trinidad were studied some twenty years since by Messrs.

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* O. A. Derby, On the Diamond and the Itacolumite Rocks in Brazil, 1881 and 1882, Amer. Jour. Science, xxiii., 97, 178, and xxiv., 34–42; and, in abstract, Rep. Smithsonian Inst., 1882, p. 332; also, Gorceix, Gisement des Diamants, etc., Bull. Soc. Géol. de France, 1884, xii., 538–545. Derby supposed the Itacolumite group might be altered Cambrian; Gorceix thinks it may be Huronian.

† W. O. Crosby, Notes on the Geology of Trinidad, 1878, Proc. Boston Soc. of Natural History, xx., 44–55; also farther, on the Crystalline Formations of Guiana and Brazil, 1880, *ibid.*, xx., 480–497, in which these rocks in Trinidad are described at greater length, and the relations of the Taconian and the more ancient crystalline series in North and South America are well brought out. See, for an analysis of these two papers, Hunt, in Report of Smithsonian Institute for 1882, pp. 330–333.

Wall and Sawkins,* by whom they were designated as the Caribbean group, more recently by R. J. Lechmere Guppy, and in 1878 were examined by Crosby.

§ 205. The structure of the Northern Mountains in Trinidad is monoclinal, high southerly dips being universal. The thickness of the strata exposed is not less than 10,000 feet, included in three divisions; a lower, consisting of a quartzite, granular, and usually more or less micaceous, followed by and alternating with hydrous micaceous schists and argillites, often lustrous; a middle one of several thousand feet of crystalline limestones in massive beds, varying in color from white to nearly black, and often somewhat micaceous; and an upper division consisting of several alternations of argillites like those of the first, frequently graphitic, and often passing into hydromicaceous schists, with layers of quartzite, sometimes detrital, and, towards the summit, thin beds of limestone. The whole succession, according to Crosby, strongly resembles the Taconian as seen in western Massachusetts. Overlying unconformably this ancient series, which appears to be unfossiliferous, is a dark-colored compact fossiliferous limestone, with interbedded shales, in which, among many obscure forms, Guppy recognized *Murchisonia Anna* and *M. linearis*, both found in the Calciferous Sand-rock in Canada.

§ 206. Subsequent observations of Crosby,† in 1882, made in the mountains of eastern Cuba, between Baracoa and the southern coast, show that there exists to the south of the dividing ridge a belt six or eight miles wide of highly inclined strata, having an east and west strike, and consisting of hydromicaceous and chloritic schists, with immense beds of white crystalline limestone, often micaceous. This group is entirely distinct from one made

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* Wall, Geology of Trinidad, etc., 1860, Quar. Geol. Jour., xvi., 660.

† W. O. Crosby on the Probable Occurrence of the Taconian in Cuba; Science, December 7, 1883, p. 740; also in abstract, Hunt in Report of Smithsonian Institute for 1883.

up of fissile slates, soft sandstones, and impure earthy limestones, found chiefly on the northern slope of the same mountains, and regarded by him as probably equivalent to the cretaceous and tertiary strata of San Domingo and Jamaica. Of the first-named group he says: "These rocks bear a strong resemblance to the Taconian system of western New England, and are essentially identical with the great series of semi-crystalline schists and limestones of Trinidad and the Spanish Main, which I have elsewhere correlated with the Taconian." From the published accounts of the geology of San Domingo and Jamaica, Crosby conceives that these islands have a similar structure to that of southeastern Cuba. Their crystalline schists which, according to him, have been generally confounded with the cretaceous beds, he believes to be like those of Cuba, and of Taconian age. Cleve, in 1870, noticed in Porto Rico, Santa Cruz, and the Virgin Islands an unfossiliferous series which he conjectured might be metamorphosed cretaceous. These strata, which are vertical, or have a high northern inclination, consist chiefly of argillites and crystalline limestones like those of Cuba and Trinidad.*

§ 207. There exists in the Alps, besides the ancient or central granitoid gneiss (Laurentian), the great *pietre-verdi* series proper (Huronian) and the younger gneiss and mica-schist series (Montalban), a fourth great group, very widely distributed, made up in large part of crystalline schists,—the argillo-talcose schists of Favre, the gray lustrous schists of Lory, the sericite-schists and the *glanzschiefer* of others. This schistose series, to which a great thickness is assigned, includes quartzites, dolomites, micaceous limestones, banded and statuary marbles, serpentine, talc, karstenite, and gypsum. These rocks,

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* P. T. Cleve, Kongl. Svenska Vetenskaps-Akademiens Handlingar; Bandet 9, No. 12. The cretaceous age of the crystalline schists and limestones of San Domingo was maintained by Gabb in his memoir on the Topography and Geology of the Island, etc., in 1873; Trans. Amer. Philos. Soc., vol. xv.

which, among other localities, are well displayed on the line of the Mont Cenis tunnel, have been by many Alpine geologists regarded as altered jurassic or triassic. This view was, however, in 1872, combated by the present writer, who then referred them to primitive or eozoic time; a view which has since been accepted by Favre, who had previously regarded them as mesozoic.* Their pre-paleozoic age was afterwards maintained by Gastaldi, by Pillet, and by Jervis. I have since called attention to the fact that these lustrous schists greatly resemble those of the Taconian of North America, to which I have compared this whole Alpine series. In it are included, by Gastaldi and Jervis, the schists of the Apuan Alps, with their crystalline marbles, all of which, as seen in the mountains of Carrara, I have found to resemble closely the Taconian. These marbles, it may be remarked, have, like those of the American Taconian, been referred to very different geological horizons, having been successively called altered cretaceous, liassic, rhætic, infra-carboniferous, and pre-paleozoic, to which latter position they were assigned by Gastaldi in 1874.

§ 208. To the same horizon, apparently, belongs the Hercynian Primitive Clay-slate series, which, according to Gümbel, intervenes in Bavaria between the Hercynian mica-schist group and the fossiliferous Cambrian strata, by which it is overlaid. This clay-slate series includes beds of crystalline limestone, sometimes magnesian, attaining in places three hundred and fifty feet in thickness, which contain hornblende and serpentine, and a form of Eozoon named by Gümbel *E. Bavaricum.* It also includes siderite, which, by epigenesis, gives rise to valuable masses of limonite. The history of the group of lustrous schists in the Alps, and their related rocks, is discussed at some length in the fourth part of Essay X., to which the reader is referred for details and for authorities.

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* Hunt, The Geology of the Alps, Amer. Jour. Science, vol. iii., pp. 1–15; also Chem. and Geol. Essays, pp. 336, 347, 348.

In some parts of central Norway, the fossiliferous Cambrian, or so-called Primordial zone, is described by Kjerulf as resting directly upon the ancient gneiss, but in other parts it is underlaid by a series which, from the presence therein of detrital beds, is designated as the Sparagmite group, and sometimes attains a thickness of over 2100 feet, as in Ostdalen. This underlying series, which itself rests upon the gneiss, includes red and gray sandstones and conglomerates, with considerable masses of limestone and of dolomite, besides various fissile rocks, described as black argillites, lustrous schists, sometimes talcoid, and schistose quartzites. It is without observed fossils, and has been by Kjerulf compared with the Lower Taconic.*

§ 209. The recent studies of Barrois in Spain, published in 1882, appear to throw a further light on the Alpine series which we have compared with the Taconian. The paleozoic rocks, containing at their base an abundant Cambrian fauna, are found in the province of Toledo resting, according to Cortazar, directly upon the ancient gneissic rocks, but in the Asturias, between these Cambrian strata and the ancient gneisses, there intervenes a volume of not less than 3000 metres of strata, described as argillites and quartzites, with dolomites and limestones, sometimes saccharoidal and cipolin marbles, with beds of specular iron-ore. As there is no apparent stratigraphical break between this younger crystalline series and the strata holding the first fauna of Barrande, the name of Cambrian is applied by Barrois to the whole.† The student of American geology, however, recalls the interposition between the Appalachian Cambrian and the ancient gneisses, of a similar great series, which suggests that in this region of Spain, as in parts of the Alps and in

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* Hunt, Azoic Rocks, p. 131, and Kjerulf, Udsigt over det Sydlige Norges Geologi, 1879, pp. 128–138, and the accompanying Atlas, plates xxvi., xxvii.

† Barrois, Recherches sur les Terrains Anciens des Asturies et de la Galice; Lille, 1882; 4to, pp. 623.

Norway, we have a pre-Cambrian group corresponding to the American Taconian.

§ 210. It has been thought well, in concluding this essay on the present state of our knowledge of the Taconian series in North America, thus to bring together, in a condensed form, the principal facts with regard to certain rocks in the West India Islands, in South America, in Hindostan, in Russia, in the Alps, in Bavaria, in Norway, and in Spain, which tend to show that in all these various regions there exists a series analogous to the Taconian alike in mineral and lithological characters and in stratigraphical position. Should further studies confirm this view, it will appear that the Taconian is a great and wide-spread group of strata which cannot henceforth be overlooked in geognostical history.

APPENDIX.

Mineralogical Classification. It has been shown in the essay on A Natural System of Mineralogy that differences in hardness and specific gravity — the first data in the natural-history method — are intimately connected with, and dependent upon, greater or less complexity of chemical constitution. The arbitrary chemical method of modern mineralogists is thus superseded, and a new chemistry is made the basis of a natural system of classification, in which the chemical and natural-history methods are united and harmonized. The crystallographic mineralogists have assigned to crystalline individualization, which is but an accident of certain mineral species, an importance in classification that has often been misleading. The principle that for related species "*the hardness and chemical indifference are inversely as the value of* V.; or, in other words, that they increase with the condensation" (*ante*, p. 304), is shown, as regards their chemical relations, in the case of meionite and zoisite, and of wollastonite, amphibole, and pyroxene, as well as in the various carbon-spars, when treated with chlorhydric or nitric acid, and in tridymite and quartz with solution of sodium-carbonate, but still more strikingly in the behavior of silicates with fluorhydric acid. It has been noticed (*ante*, p. 214) that while many silicates are readily attacked thereby, zircon, staurolite, amphibole, pyroxene, and chrysolite are found to resist, more or less completely, its action. Mr. J. B. Mackintosh of the School of Mines, Columbia College, New York, having tried this reagent to distinguish between certain gems, called my attention to the indifference thereto of garnet, which I ascribed to its great condensation, and suggested comparisons between the spathoids, iolite and petalite, on the one hand, and the adamantoids, epidote and spodumene, on the other, predicting that the first two would be attacked and the last resist the action of fluorhydric acid. This was at once verified by the trials of Mr. Mackintosh, communicated to me April 9, 1886, since which time he has greatly extended his inquiries in this direction. He finds that while not only the pectolitoids and the zeolitoids, but various spathoids, such as wollastonite, the feldspars, scapolite, and leucite, as well as iolite and petalite (together with titanite and some chloritic species) are more or less corroded by the acid, the adamantoids, pyroxene, enstatite, danburite, garnet, epidote, zoisite, axinite, beryl, tourmaline, spodumene, andalusite, topaz, and cyanite are not attacked by it. He has farther, at my suggestion, determined the rate of attack with equal weights of various silicates in a granulated state by excess of dilute fluorhydric acid. By this, in an hour's time, there were dissolved of 100.00 parts: of albite, 23.00, of petalite, 28.97, of iolite, 47.34, of orthoclase, 43.45, and of leucite 63.30

parts; while of chrysolite but 5.40, and of quartz but 1.56 parts were dissolved. Of opal, under similar conditions, 77.68 parts, and of a yellowish noble serpentine (sp. gr. 2.532) 80.67 parts were dissolved; showing, apparently, a great susceptibility of these colloid or porodic species to the action of the acid. Labradorite and oligoclase were, like the other feldspars, readily attacked, but the separation of calcium-fluorid in these, as in other calciferous silicates, is a disturbing factor in quantitative experiments. Mackintosh has found that, while the natural faces of quartz-crystals resist the action of the concentrated acid, their cut surfaces are readily attacked by it. Of these important investigations, now in progress, a note by Mackintosh appears in the School of Mines Quarterly for July, 1886; while a more detailed account was given by the writer in a "A Supplement to a Natural System in Mineralogy" read to the Royal Society of Canada, May 26, 1886, and published in vol. iv. of its Transactions.

MINERALOGICAL NOMENCLATURE. It is evident that there are relations between the species in any given tribe which serve to unite them in families and genera, but which our present trivial nomenclature fails to indicate. Thus the large family of the feldspathides includes several genera, one of which — the true feldspars — embraces the albite-anorthite series, and another — the adularia genus — with a less condensation, orthoclase, microcline, and hyalophane. In the same tribe, besides the scapolite genus, which comprehends the meionite-marialite series, is a group of related silicates, including melilite, humboldtilite, gehlenite, sarcolite, milarite, and barylite, which will form a cognate genus. To show these relations aright, a Latin binomial nomenclature is needed, which, with the new system of classification, will, it is believed, give to mineralogy a form and a completeness hitherto wanting.

MINERALOGICAL EVOLUTION. The laws which have presided over the differentiation of the primeval chaos, and produced the various groups of rocks, alike exotic, endogenous, and indigenous, which have determined the progressive changes in chemical constitution from the ante-gneissic granite down to the youngest crystalline schists and the detrital sediments of later times, are, as we have sought to show, not less certain and definite than those which preside over astronomical and biological development. The great successive groups of stratiform crystalline rocks mark necessary stages in the mineralogical evolution of the planet (*ante*, pp. 113, 184, 253, 678). The facts already discussed, of the continued generation, down to the present time, of certain silicates in the channels of thermal springs, in deep-sea ooze, in fossiliferous limestones, in the interstices of detrital rocks, and often in proximity to intrusive igneous masses, afford no justification of the hypothesis of regional metamorphism, which seeks the origin of the unlike groups of crystalline eozoic strata in some unexplained and inexplicable transmutation of different portions of one and the same series of ordinary detrital sediments of paleozoic or more recent times. The supposed examples of such a process have one by one been disproved and abandoned by their former advocates, who had substituted the intervention of miracles for the orderly and established process of mineralogical development.

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