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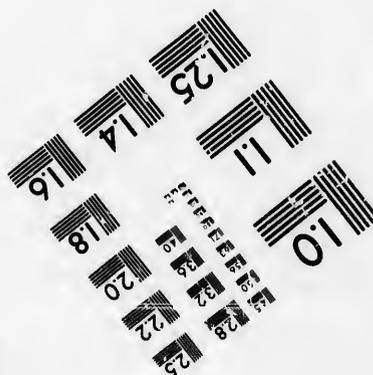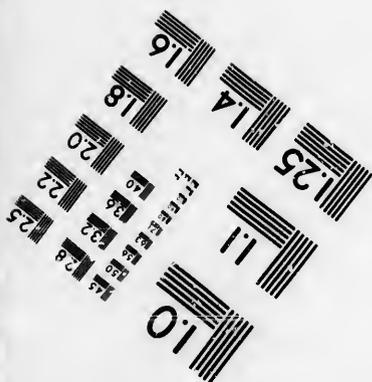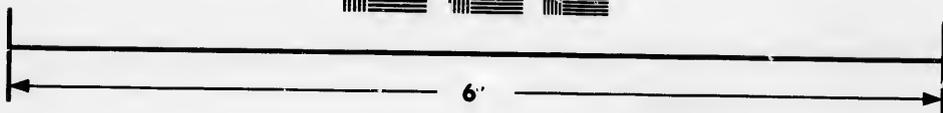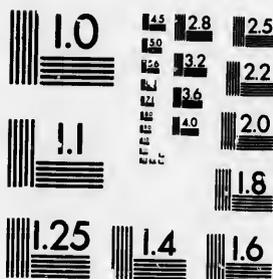# TEST TARGET (MT-3)

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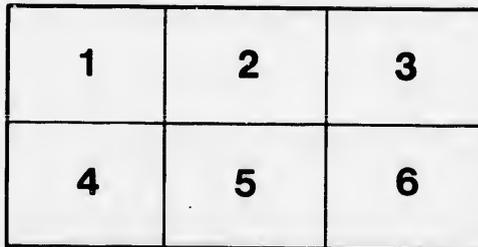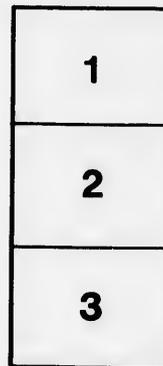
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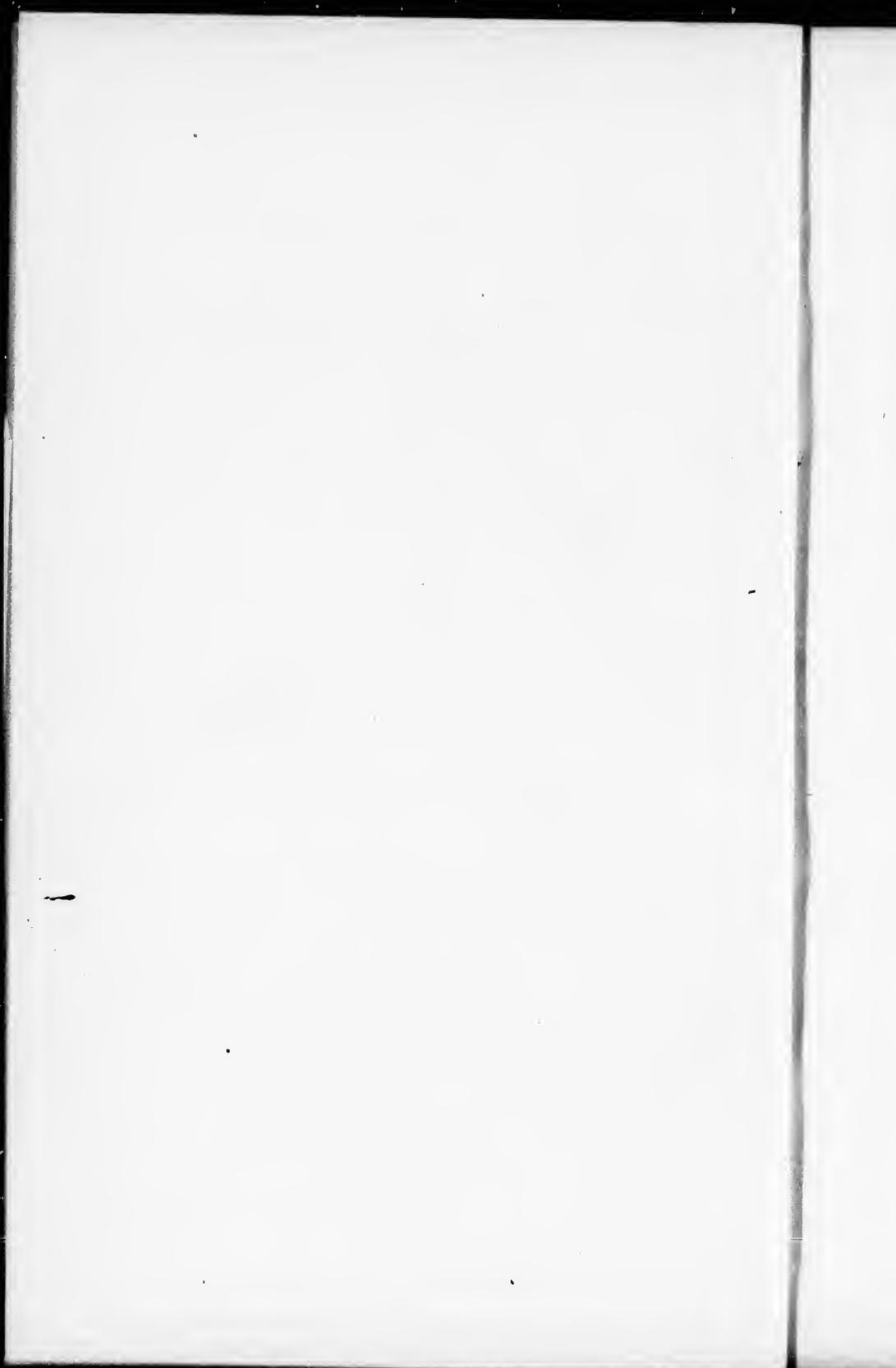
ON THE

CHEMICAL AND MINERALOGICAL

RELATIONS

OF

METAMORPHIC ROCKS,

BY

T. STERRY HUNT, M.A., F.R.S.

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ON THE CHEMISTRY OF METAMORPHIC ROCKS,

BY

T. STERRY HUNT, M.A., F.R.S.

AT a time not very remote in the history of geology, when all crystalline stratified rocks were included under the common designation of primitive, and were supposed to belong to a period anterior to the fossiliferous formations, the lithologist confined his studies to descriptions of the various species of rocks, without reference to their stratigraphical or geological distribution. But with the progress of geological science, a new problem is present- ed to his investigation. While palæontology has shown that the fossils of each formation furnish a guide to its age and stratigraph- ical position, it has been found that sedimentary strata of all ages, up to the tertiary inclusive, may undergo such changes as to obliterate the direct evidences of organic life; and to give to the sediments the mineralogical characters once assigned to primitive rocks. The question here arises, whether in the absence of organic remains, or of stratigraphical evidence, there exists any means of determining, even approximately, the geological age of a given series of crystalline stratified rocks;—in other words, whether the chemical conditions which have presided over the formation of sedimentary rocks, have so far varied in the course of ages, as to impress upon these rocks marked chemical and mineralogical differences. In the case of unaltered sediments it would be difficult to arrive at any solution of this question without greatly multiplied analyses; but in the same rocks, when altered, the crystalline minerals which are formed, being definite in their composition, and varying with the chemical constitution of the sediments, may perhaps to a certain extent, become to the geologist what organic remains are in the unaltered rocks, a guide to the geological age and succession.

It was while engaged in the investigation of metamorphic rocks of various ages in North America, that this problem suggested itself; and I have endeavoured from chemical considerations, con- joined with multiplied observations, to attempt its solution. In the *American Journal of Science* for 1858, and in the *Quarterly Journal of the Geological Society of London* for 1859 (p. 488), will be found the germs of the ideas on this subject, which I shall endeavour to explain in the present paper. It cannot be doubted

* Read before the Dublin Geological Society April 10, and reprinted from advance sheets of the Dublin Quarterly Journal for July, 1863.

that in the earlier periods of the world's history, chemical forces of certain kinds were much more active than at the present day. Thus the decomposition of earthy and alkaline silicates under the combined influences of water and carbonic acid, would be greater when this acid was more abundant in the atmosphere, and when the temperature was probably higher. The larger amounts of alkaline and earthy carbonates then carried to the sea from the decomposition of these silicates, would furnish a greater amount of calcareous matter to the sediments; and the chemical effects of vegetation, both on the soil and on the other atmosphere, must have been greater during the Carboniferous period, for example, than at present. In the spontaneous decomposition of feldspars, which may be described as silicates of alumina combined with silicates of potash, soda and lime, these latter bases are removed, together with a portion of silica; and there remains as the final result of the process, a hydrous silicate of alumina, which constitutes kaolin or clay. This change is favoured by mechanical division; and Daubrée has shown that by the prolonged attrition of fragments of granite under water, the softer and readily cleavable feldspar is in great part reduced to an impalpable powder, while the uncleavable grains of quartz are only rounded, and form a readily subsiding sand; the water at the same time dissolving from the feldspar a certain portion of silica, and of alkali. It has been repeatedly observed, where potash and soda-feldspars are associated, that the latter is much the more readily decomposed, becoming friable, and finally being reduced to clay, while the orthoclase is unaltered. The result of combined chemical and mechanical agencies acting upon rocks which contain quartz, with orthoclase, and a soda-feldspar such as albite or oligoclase, would thus be a sand, made up chiefly of quartz and potash-feldspar, and a finely divided and suspended clay, consisting for the most part of kaolin, and of partially decomposed soda-feldspar, mingled with some of the smaller particles of orthoclase and of quartz. With this sediment will also be included the oxide of iron, and the earthy carbonates set free by the sub-aërial decomposition of silicates like pyroxene and the anorthic feldspars, or formed by the action of the carbonate of soda derived from the latter upon the lime salts and magnesia salts of sea-water. The debris of hornblende and pyroxene will also be found in this finer sediment. This process is evidently the one which must go on in the wearing away of rocks by aqueous agency, and explains the fact that

while quartz, or an excess of combined silica, is for the most part wanting in rocks which contain a large proportion of alumina, it is generally abundant in those rocks in which potash-feldspar predominates.

So long as this decomposition of alkaliferous silicates is sub-aërial, the silica and alkali are both removed in a soluble form. The process is often however submarine, or subterranean, taking place in buried sediments, which are mingled with carbonates of lime and magnesia. In such cases the silicate of soda set free, re-acts either with these earthy carbonates, or with the corresponding chlorids of sea-water, and forms in either event a soluble soda-salt, and insoluble silicates of lime and magnesia, which take the place of the removed silicate of soda. The evidence of such a continued reaction between alkaliferous silicates and earthy carbonates is seen in the large amounts of carbonate of soda, with but little silica, which infiltrating waters constantly remove from argillaceous strata; thus giving rise to alkaline springs, and to natron lakes. In these waters it will be found that soda greatly predominates, sometimes almost to the exclusion of potash. This is due not only to the fact that soda-feldspars are more readily decomposed than orthoclase, but to the well-known power of argillaceous sediments to abstract from water the potash salts which it already holds in solution. Thus when a solution of silicate, carbonate, sulphate, or chlorid of potassium is filtered through common earth, the potash is taken up, and replaced by lime, magnesia, or soda, by a double decomposition between the soluble potash salt and the insoluble silicates or carbonates of the latter bases. Soils in like manner remove from infiltrating waters, ammonia, and phosphoric and silicic acids, the bases which were in combination with these being converted into carbonates. The drainage-water of soils, like that of most mineral springs, contains only carbonates, chlorids, and sulphates of lime, magnesia, and soda; the ammonia, potash, phosphoric and silicic acids being retained by the soil.

The elements which the earth retains or extracts from waters are precisely those which are removed from it by growing plants. These, by their decomposition under ordinary conditions, yield their mineral matters again to the soil; but when decay takes place in water, these elements become dissolved, and hence the waters from peat bogs and marshes contain large amounts of potash and silica in solution, which are carried to the sea, there to be separated—the silica by protophytes, and the potash by algæ,

which latter, decaying on the shore, or in the ooze at the bottom, restore the alkali to the earth. The conditions under which the vegetation of the coal formation grew, and was preserved, being similar to those of peat, the soils became exhausted of potash, and are seen in the fire-clays of that period.

Another effect of vegetation on sediments is due to the reducing or de-oxidizing agency of the organic matters from its decay. These, as is well known, reduce the peroxide of iron to a soluble protoxide, and remove it from the soil, to be afterwards deposited in the forms of iron ochre and iron ores, which by subsequent alteration become hard, crystalline and insoluble. Thus, through the agency of vegetation, is the iron oxide of the sediments withdrawn from the terrestrial circulation; and it is evident that the proportion of this element diffused in the more recent sediments must be much less than in those of ancient times. The reducing power of organic matter is farther shown in the formation of metallic sulphurets; the reduction of sulphates having precipitated in this insoluble form the heavy metals, copper, lead, and zinc; which, with iron, appear to have been in solution in the waters of early times, but are now by this means also abstracted from the circulation, and accumulated in beds and fahlbands, or by a subsequent process have been redissolved and deposited in veins. All analogies lead us to the conclusion that the primeval condition of the metals, and of sulphur, was, like that of carbon, one of oxidation, and that vegetable life has been the sole medium of their reduction.

The source of the carbonates of lime and magnesia in sedimentary strata is two-fold:—first, the decomposition of silicates containing these bases, such as anorthic feldspars and pyroxene; and second, the action of the alkaline carbonates formed by the decomposition of feldspars, upon the chlorids of calcium and magnesium, originally present in sea-water; which have thus, in the course of ages, been in great part replaced by chlorid of sodium. The clay, or aluminous silicate which has been deprived of its alkali, is thus a measure of the carbonic acid removed from the air, of the carbonates of lime and magnesia precipitated, and of the amount of chlorid of sodium added to the waters of the primeval ocean.

The coarser sediments, in which quartz and orthoclase prevail, are readily permeable to infiltrating waters, which gradually remove from them the soda, lime, and magnesia, which they contain; and if organic matters intervene, the oxide of iron; leaving

at last little more than silica, alumina, and potash—the elements of granite, trachyte, gneiss, and mica-schist. On the other hand, the finer marls and clays, resisting the penetration of water, will retain all their soda, lime, magnesia, and oxide of iron; and containing an excess of alumina, with a small amount of silica, will by their metamorphism, give rise to basic lime and soda-feldspars, and to pyroxene and hornblende—the elements of diorites and dolerites. In this way, the operation of the chemical and mechanical causes which we have traced, naturally divides all the crystalline silico-aluminous rocks of the earth's crust into two types. These correspond to the two classes of igneous rocks, distinguished first by Professor Phillips, and subsequently by Durocher, and by Bunsen, as derived from two distinct magmas; which these geologists imagine to exist beneath the solid crust, and which the latter denominates the trachytic and pyroxenic types. I have however elsewhere endeavoured to show that all intrusive or exotic rocks are probably nothing more than altered and displaced sediments, and have thus their source within the lower portions of the stratified crust, and not beneath it.

It may be well in this place to make a few observations on the chemical conditions of rock-metamorphism. I accept in its widest sense the view of Hutton and Boué, that all the crystalline stratified rocks have been produced by the alteration of mechanical and chemical sediments. The conversion of these into definite mineral species has been effected in two ways : first by molecular changes ; that is to say, by crystallization, and a re-arrangement of particles ; and, secondly by chemical reactions between the elements of the sediments. Pseudomorphism, which is the change of one mineral species into another, by the introduction, or the elimination of some element or elements, presupposes metamorphism ; since only definite mineral species can be the subjects of this process. To confound metamorphism with pseudomorphism, as Bischoff, and others after him, have done, is therefore an error. It may be farther remarked, that although certain pseudomorphic changes may take in some mineral species, in veins, and near to the surface, the alteration of great masses of silicated rocks by such a process is as yet an unproved hypothesis.

The cases of local metamorphism in proximity to intrusive rocks go far to show, in opposition to the views of certain geologists, that heat has been one of the necessary conditions of the change. The source of this has been generally supposed to be from below;

but to the hypothesis of alteration by ascending heat, Naumann has objected that the inferior strata in some cases escape change, and that in descending, a certain plane limits the metamorphism, separating the altered strata above, from the unaltered ones beneath; there being no apparent transition between the two. This, taken in connexion with the well-known fact that in many cases the intrusion of igneous rocks causes no apparent change in the adjacent unaltered sediments, shows that heat and moisture are not the only conditions of metamorphism. In 1857, I showed by experiments, that in addition to these conditions, certain chemical reagents might be necessary; and that water impregnated with alkaline carbonates and silicates, would, at a temperature not above that of 212° F., produce chemical reactions among the elements of many sedimentary rocks, dissolving silica, and generating various silicates (1). Some months subsequently, Daubrée found that in the presence of solutions of alkaline solutions, at temperatures above 700° F., various silicious minerals, such as quartz, feldspar, and pyroxene, could be made to assume a crystalline form; and that alkaline silicates in solution at this temperature would combine with clay to form feldspar and mica (2). These observations were the complement of my own, and both together showed the agency of heated alkaline waters to be sufficient to effect the metamorphism of sediments by the two modes already mentioned,—namely, by molecular changes, and by chemical reactions. Following upon this, Daubrée observed that the thermal alkaline spring of Plombieres, with a temperature of 160° F., had in the course of centuries, given rise to the formation of zeolites, and other crystalline silicated minerals, among the bricks and cement of the old Roman baths. From this he was led to suppose that the metamorphism of great regions might have been effected by hot springs; which, rising along certain lines of dislocation, and thence spreading laterally, might produce alteration in strata near to the surface, while those beneath would in some cases escape change (3). This ingenious hypothesis may serve in

1. Proc. Royal Soc of London, May 7, 1857; and Philos. Mag. (4) xv., 68; also Amer. Jour. Science (2), xxii., and xxv., 435.

2. Comptes Rendus de l'Acad., Nov. 16, 1857; also Bull. Soc. Geol. de France (2), xv., 103.

3. It should be remembered that normal or regional metamorphism is in no way dependent upon the proximity of unstratified or igneous rocks, which are rarely present in metamorphic districts. The ophiolites,

some cases to meet the difficulty pointed out by Naumann; but while it is undoubtedly true in certain instances of local metamorphism, it seems to be utterly inadequate to explain the complete and universal alteration of areas of sedimentary rocks, embracing many hundred thousands of square miles. On the other hand, the study of the origin and distribution of mineral springs, shows that alkaline waters (whose action in metamorphism I first pointed ou and whose efficient agency Daubrée has since so well shown), are confined to certain sedimentary deposits, and to definite stratigraphical horizons; above and below which saline waters wholly different in character are found impregnating the strata. This fact seems to offer a simple solution of the difficulty advanced by Naumann, and a complete explanation of the theory of metamorphism of deeply buried strata by the agency of ascending heat; which is operative in producing chemical changes only in those strata in which soluble alkaline salts are present. (4).

When the sedimentary strata have been rendered crystalline by metamorphism, their permeability to water, and their alterability, become greatly diminished; and it is only when again broken down by mechanical agencies to the condition of soils and sediments, that they once more become subject to the chemical changes which have just been described. Hence, the mean composition of the argillaceous sediments of any geological epoch, or

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amphibolites, euphotides, diorites, and granites of such regions, which it has been customary to regard as exotic or intrusive rocks, are in most cases indigenous, and are altered sediments. I have elsewhere shown that the great outbursts of intrusive dolerites, diorites, and trachytes in south-eastern Canada are found, not among the metamorphic rocks, but among the unaltered strata along their margin, or at some distance removed; and I have endeavoured to explain this by the consideration that the great volume of overlying sediments, which, by retaining the central heat, aided in the alteration of the strata now exposed by denudation, produced a depression of the earth's surface, and forced out the still lower and softened strata along the lines of fracture which took place in the regions beyond. See my paper "On some Points in American Geology," Amer. Jour. Science (2), xxxi. 414., and Can. Nat. vi. 81.

4. See Report of the Geological Survey of Canada, 1853–6, pp. 479, 480; also Canadian Naturalist, vol. vii., p. 262. For a consideration of the relations of mineral waters to geological formations, see " General Report on the Geology of Canada," p. 561; also chap. xix. on " Sedimentary and Metamorphic Rocks;" where most of the points touched in the present paper are discussed at greater length.

in other words, the proportion between the alkalies and the alumina, will depend not only upon the age of the formation, but upon the number of times which its materials have been broken up, and the periods during which they have remained unmetamorphosed, and exposed to the action of infiltrating waters. Thus for example, that portion of the Lower Silurian rocks in Canada which became metamorphosed before the close of the palæozoic period, will have lost less of its soluble bases than the portion of the same age which still remains in the form of unaltered shales and sandstones. Of these again, such parts as remain undisturbed by folds and dislocations, will retain a larger portion of bases than those strata in which such disturbances have favored the formation of mineral springs ; which even now are active in removing soluble matters from these rocks. The crystalline Lower Silurian rocks in Canada may be compared with those of the older Laurentian series on the one hand, and with the Upper Silurian or Devonian on the other ; but when these are to be compared with the crystalline strata of secondary or tertiary age in the Alps, it cannot be determined whether the sediments of which these were formed, (and which may be supposed, for illustration, to have been directly derived from palæozoic strata), existed up to the time of their translation, in a condition similar to that of the altered, or of the unaltered Lower Silurian rocks of Canada. The proportion between the alkalies and the alumina in the argillaceous sediments of any given formation is not therefore in direct relation to its age ; but indicates the extent to which these sediments have been subjected to the influences of water, carbonic acid, and vegetation. If however it may be assumed that this action, other things being equal, has on the whole, been proportionate to the newness of the formation, it is evident that the chemical and mi-.- eralogical composition of different systems of rocks must vary w .. their antiquity ; and it now remains to find in their comparative study a guide to their respective ages.

It will be evident that silicious deposits, and chemical precipitates, like the carbonates and silicates of lime and magnesia, may exist with similar characters in the geological formations of any age ; not only forming beds apart, but mingled with the impermeable silico-aluminous sediments of mechanical origin. Inasmuch as the chemical agencies giving rise to these compounds were then most active, they may be expected in greatest abundance in the rocks of the earlier periods. In the case of the per-

meable and more highly silicious class of sediments already noticed, whose chief elements are silica, alumina, and alkalies, the deposits of different ages will be marked chiefly by a progressive diminution in the amount of potash, and the disappearance of the soda which they contain.   In the oldest rocks the proportion of alkali will be nearly or quite sufficient to form orthoclase and albite with the whole of the alumina present; but as the alkali diminishes, a portion of the alumina will crystallize, on the metamorphism of the sediments, in the form of a potash-mica, such as muscovite or margarodite.   While the oxygen ratio between the alumina and the alkali in the feldspars just named is 3 : 1, it becomes 6 : 1 in margarodite, and 12 : 1 in muscovite. The appearance of these micas in a rock denotes then a diminution in the amount of alkali, until in some strata the feldspar almost entirely disappears, and the rock becomes a quartzose mica-schist. In sediments still farther deprived of alkali, metamorphism gives rise to schists filled with crystals of kyanite, or of andalusite ; which are simple silicates of alumina, into whose composition alkalies do not enter ; or in case the sediment still retains oxide of iron, staurotide and iron-alumina garnet take their place.   The matrix of all these minerals is generally a quartzose mica-schist. The last term in this exhaustive process appears to be represented by the disthene and pyrophyllite rocks, which occur in some regions of crystalline schists.

In the second class of sediments we have alumina in excess, with a small proportion of silica, and a deficiency of alkalies, besides a variable proportion of silicates or carbonates of lime, magnesia, and oxide of iron.   The result of the processes already described will produce a gradual diminution in the amount of alkali, which is chiefly soda.   So long as this predominates, the metamorphism of these sediments will give rise to feldspars like oligoclase, labradorite, or scapolite (a dimetric feldspar); but in sediments where lime replaces a great proportion of the soda, there appears a tendency to the production of denser silicates, like lime-alumina garnet, and epidote, or zoisite, which replace the soda-lime feldspars.   Minerals like the chlorites, and chloritoid, are formed when magnesia and iron replace lime.   In all these cases the excess of the silicates of earthy protoxides over the silicate of alumina is represented in the altered strata by hornblende, pyroxene, olivine, and similar species; which give rise by their admixture with the double aluminous silicates, to diorite, diabase, euphotide, eklogite, and similar compound rocks.

In eastern North America, the crystalline strata, so far as yet studied, may be conveniently classed in five groups, corresponding to as many different geological series, four of which will be considered in the present paper.

I. The Laurentian system represents the oldest known rocks of the globe, and is supposed to be the equivalent of the Primitive Gneiss formation of Scandinavia, and that of the Western Islands of Scotland, to which also the name of Laurentian is now applied. It has been investigated in Canada along a continuous outcrop from the coast of Labrador to Lake Superior, and also over a considerable area in northern New York.

II. Associated with this system is a series of strata characterized by a great development of anorthosites, of which the hypersthenite, or opalescent feldspar-rock of Labrador, may be taken as a type. These strata overlie the Laurentian gneiss, and are regarded as constituting a second and more recent group of crystalline rocks, to which the name of the Labrador series may be provisionally given. From evidence recently obtained, Sir William Logan conceives it probable that this series is unconformable with the older Laurentian system, and is separated from it by a long interval of time.

III. In the third place is a great series of crystalline schists, which are in Canada referred to the Quebec group, an inferior part of the Lower Silurian system. They appear to correspond both lithologically and stratigraphically with the Schistose group of the Primitive Slate formation of Norway, as recognized by Naumann and Keilhau, and to be there represented by the strata in the vicinity of Drontheim, and those of the Dofrefeld. The Huronian series of Canada in like manner appears to correspond to the Quartzose group of the same Primitive Slate formation (5). It consists of sandstones, imperfect varieties of gneiss, diorites, silicious and feldspathic schists passing into argillites, with limestones, and great beds of hematite. Though more recent than the Laurentian and Labrador series, these strata are older than the Quebec group; yet from their position to the westward of the greatest accumulation of sediments, they have been subjected to a less complete metamorphism than the palæozoic strata of the East. The Huronian series is as yet but imperfectly studied, and for the present will not be further considered.

(5) See Macfarlane—Primitive Formations of Norway and Canada compared—Canadian Naturalist, vii., 113, 162.

IV. In the fourth place are to be noticed the metamorphosed strata of Upper Silurian and Devonian age, with which may also be included those of the Carboniferous system in eastern New England. This group has as yet been imperfectly studied, but presents interesting peculiarities.

In the oldest of these, the Laurentian system, the first class of aluminous rocks takes the form of granitoid gneiss, which is often coarse grained and porphyritic. Its feldspar is frequently a nearly pure potash orthoclase, but sometimes contains a considerable proportion of soda. Mica is often almost entirely wanting, and is never abundant in any large mass of this gneiss, although small bands of mica-schist are occasionally met with. Argillites, which from their general predominance of potash and of silica, are related to the first class of sediments, are, so far as known, wanting throughout the Laurentian series; nor is any rock here met with, which can be regarded as derived from the metamorphism of sediments like the argillites of more modern series. Chloritic and chiastolite schists, and kyanite are, if not altogether wanting, extremely rare in the Laurentian system. The aluminous sediments of the second class are however represented in this system by a diabase made up of dark green pyroxene and bluish labradorite, often associated with a red alumino-ferrous garnet. This latter mineral also sometimes constitutes small beds, often with quartz, and occasionally with a little pyroxene. These basic aluminous minerals form however but an insignificant part of the mass of strata. This system is farther remarkable by the small amount of ferruginous matter diffused through the strata; from which the greater part of the iron seems to have been removed, and accumulated in the form of immense beds of hematite and magnetic iron. Beds of pure crystalline plumbago also characterize this series, and are generally found with the limestones. These are here developed to an extent unknown in more recent formations; and are associated with beds of crystalline apatite, which sometimes attain a thickness of several feet. The serpentines of this series, so far as yet studied in Canada, are generally pale colored, and contain an unusual amount of water, a small proportion of oxide of iron, and neither chrome nor nickel; both of which are almost always present in the serpentines of the third series.

The second or Labrador series is characterized, as already remarked, by the predominance of great beds of anorthosite, composed chiefly of triclinic feldspars, which vary in composition from anorthite to andesine. These feldspars sometimes form mountain

masses, almost without any admixture, but at other times include portions of pyroxene, which passes into hypersthene. Beds of nearly pure pyroxenite are met with in this series, and others which would be called hyperite and diabase. These anorthosite rocks are frequently compact, but are more often granitoid in structure. They are generally greyish, greenish, or bluish in colour, and become white on the weathered surfaces. The opalescent labradorite-rock of Labrador is a characteristic variety of these anorthosites; which often contain small portions of red garnet and brown mica, and more rarely, epidote, and a little quartz. They are sometimes slightly calcareous. Magnetic iron and ilmenite are often disseminated in these rocks, and occasionally form masses or beds of considerable size. These anorthosites constitute the predominant part of the Labrador series, so far as yet examined. They are however associated with beds of quartzose orthoclase gneiss, which represent the first class of aluminous sediments, and with crystalline limestones; and they will probably be found, when further studied, to offer a complete lithological series. These rocks have been observed in several areas among the Laurentide Mountains, from the coast of Labrador to Lake Huron, and are also met with among the Laurentian rocks of the Adirondack Mountains; of which according to Emmons, they form the highest summits.

In the third series, which we have referred to the Lower Silurian age, the gneiss is sometimes granitoid, but less markedly so than in the first; and it is much more frequently micaceous, often passing into micaceous schist, a common variety of which contains disseminated a large quantity of chloritoid. Argillites abound, and under the influence of metamorphism sometimes develop crystalline orthoclase. At other times they are converted into a soft micaceous mineral, and form a kind of mica-schist. Chiastolite and staurotide are never met with in the schists of this series, at least in its northern portions, throughout Canada and New England. The anorthosites of the Labrador series are represented by fine grained diorites, in which the feldspar varies from albite to very basic varieties, which are sometimes associated with an aluminous mineral allied to chlorite in composition. Chloritic schists, frequently accompanied by epidote, abound in this series. The great predominance of magnesia in the forms of dolomite, magnesite, steatite and serpentine, is also characteristic of portions of this series. The latter, which forms great beds (ophiolites), is marked by the almost constant presence of small portions of the oxides of chrome and nickel. These metals are also common in

the other magnesian rocks of the series; green chrome-garnets, and chrome-mica occur; and beds of chrome iron ore are found in the ophiolites of the series. It is also the gold-bearing formation of eastern North America, and contains large quantities of copper ores in interstratified beds resembling those of the Permian schists of Mansfeld and Hesse. In some parts of this series pure limestones occur, which contain various crystalline minerals common also to the Laurentian limestones, and to those of the fourth series. The only graphite which has been found in the third series, is in the form of impure plumbaginous shales.

The metamorphic rocks of the fourth series, as seen in south-eastern Canada, are for the greater part quartzose and mica-ceous schists, more or less feldspathic; which in the neighboring States become remarkable for a great development of crystals of staurotide and of red garnet. A large amount of argillite occurs in this series; and when altered, whether locally by the proximity of intrusive rock, or by normal metamorphism, exhibits a micaceous mineral, and crystals of andalusite; so that it becomes known as chiastolite slate in its southern extension. Granitoid gneiss is still associated with these crystalline schists. Gold is not confined to the third series, but is also met with in veins cutting the argilites of Upper Silurian age. The crystalline limestones and ophiolites of eastern Massachusetts, which are probably of this series, resemble those of the Laurentian system; and the coal beds in that region are in some parts, changed into graphite. It is to be remarked that the metamorphic strata of the third and fourth series are contiguous throughout their extent, so far as examined, but are everywhere separated from the Laurentian and Labrador series by a zone of unaltered palæzoic rocks.

Large masses of intrusive granite occur among the crystalline strata of the fourth series, but are rare or unknown among the older metamorphic rocks in Canada. The so-called granites of the Laurentian and Lower Silurian appear to be in every case indigen-ous rocks; that is to say, strata altered *in situ*, and still retaining evidences of stratification. The same thing is true with regard to the ophiolites and the anorthosites of both series; in all of which the general absence of great masses of unstratified rock is especially noticeable. No evidences of the hypothetical granitic substratum are met with in the Laurentian system, although this is in one district penetrated by great masses of syenite, orthophyre, and dolerite. Granitic veins, with minerals containing the rarer elements, such as
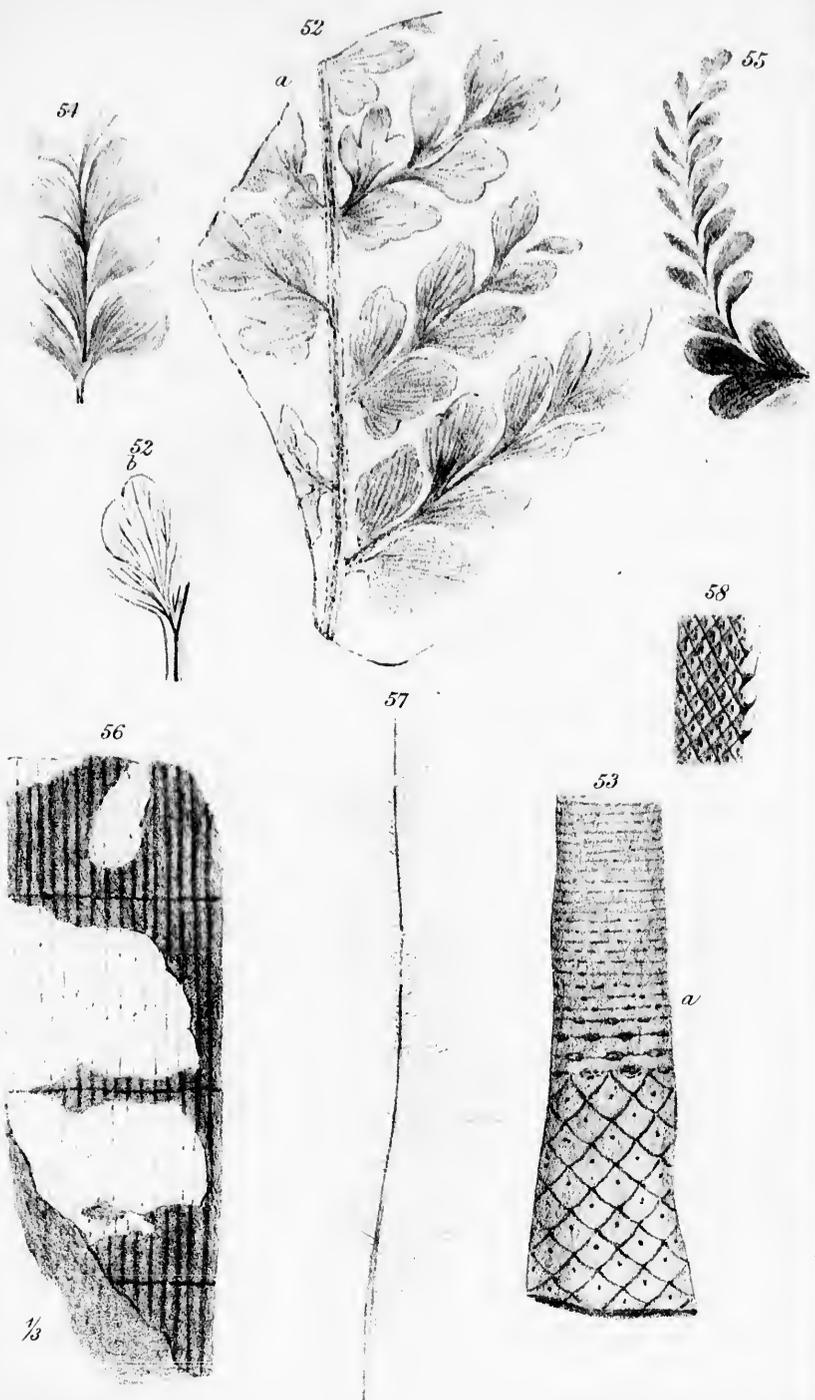
boron, fluorine, lithium, zirconium, and glucinum, are met with alike
in the oldest and the newest gneiss in North America.   These
however, I regard as having been formed, like metalliferous veins,
by aqueous deposition in fissures in the strata.

The above observations upon the metamorphic strata of a wide
region seem to be in conformity with the chemical princiciples
already laid down in this paper; which it remains for geologists to
apply to the rocks of other regions, and thus determine whether
they are susceptible of a general application.   I have found that
the blue crystalline labradorite of the Labrador series of Canada
is exactly represented by specimens from Scarvig, in Skye ; and
the ophiolites of Iona resemble those of the Laurentian series in
Canada.   Many of the rocks of Donegal appear to me lithologi-
cally identical with those of the Laurentian period ; while the ser-
pentines of Aghadoey, containing chrome and nickel, and the
andalusite and kyanite-schists of other parts of Donegal, cannot
be distinguished from those which characterize the altered palæo-
zoic strata of Canada.   It is to be remarked that chrome and
nickel-bearing serpentines are met with in the same geological
horizon in Canada and Norway ; and that those of the Scottish
Highlands, which contain the same elements, belong t) the
newer gneiss formation ; which, according to Sir Roderick
Murchison, would be of similar age.   The serpentines of Cornwall,
the Vosges, Mount Rosa, and many other regions, agree in contain-
ing chrome and nickel ; which on the other hand, seem to be absent
from the serpentines of the Primitive Gneiss formation of Scandina-
via.   It remains to be determined how far chemical and mineral-
ogical differences, such as those which have been here indicated,
are geological constants.   Meanwhile it is greatly to be desired that
future chemical and mineralogical investigations of crystalline rocks
should be made with this question in view ; and that the meta-
morphic strata of the British Isles, and the more modern ones
of Southern and Central Europe, be studied with reference to the
important problem which it has been my endeavour, in the present
paper, to lay before the Society.

MONTREAL, January 25, 1863.

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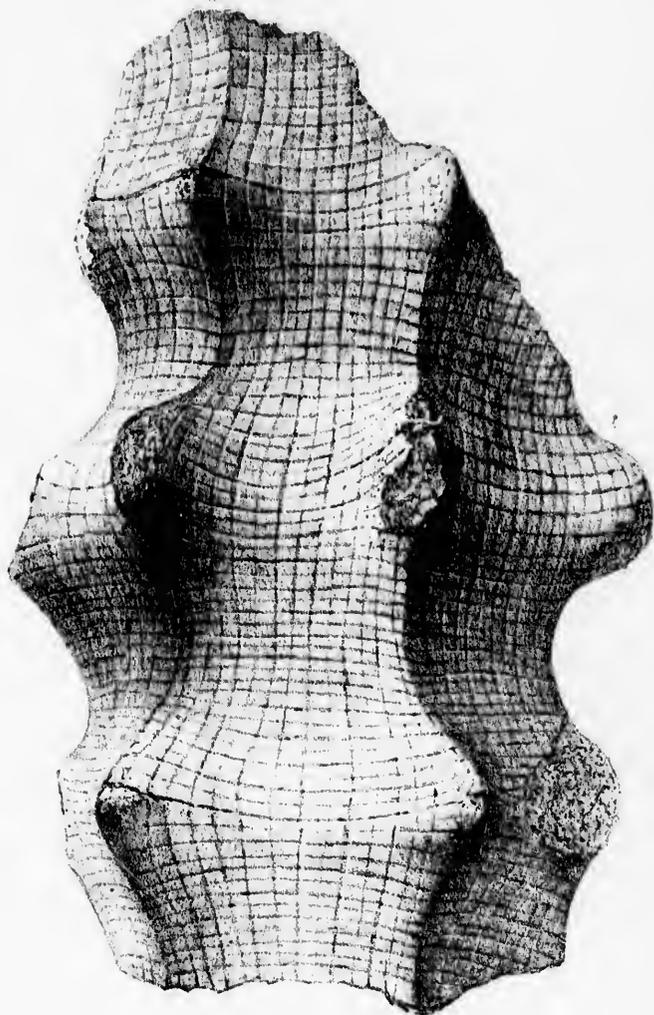rocks
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