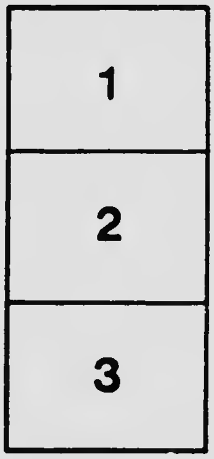
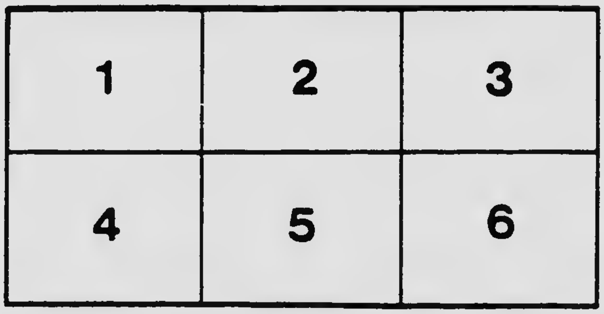

1
2
3


1
2
3


1
2
3
4
5
6

The Differentiation of a Secondary Magma trough Gravitative Adjustment

By REGINALD A. DALY
Ottawa, Canada

With 2 textfigures

Sonder-Abdruck
aus der Festschrift zum
siebzigsten Geburtstage
von Harry Rosenbusch
gewidm. v. seinen Schülern

E. SCHWEIZERBARTSCHE VERLAGSBUCHHANDLUNG, STUTTGART 1906.

[illegible] [illegible]

The Differentiation of a Secondary Magma through Gravitative Adjustment.

By Reginald A. Daly, Ottawa, Canada.*)

(With 2 textfigures.)

Introduction: the dependence of petrology upon structural geolog

Sooner or later experience must teach every careful field stu gneous rocks the truth of the principle of magmatic differentiation. principle is, indeed, so generally accepted by petrologists that it may

*) Published by permission of the Commissioner for Canada, International Bound Surveys.

considered as a permanent acquisition in the theory of their science. Yet it is a long step from the recognition of the doctrine to its application to the origin of igneous rocks as actually found in the earth's crust. The principle becomes really fruitful, in fact becomes first completely understood and realized, when certain chief problems have been solved.

Among those problems there are naturally three that are fundamental. Only after they are solved has petrology done that which it has set out to do, namely, determine, under the difficult conditions of earth study, the true nature and genesis of rocks. The first insistent question is, in every case, what was the magmatic mixture or matrix from which the material of the existing rock-mass or rock-masses was produced through differentiation? The second question is, how far did the differentiating process operate? The third insistent question is, what was the process of differentiation itself?

All three problems are interdependent and involve a study in structural geology. They cannot be solved simply by acquiring even the fullest information to be derived from single plutonic contacts, nor, as a rule, from such as may be derived from entire ground-plan contact lines. On the other hand, it is necessary that, more or less completely, the petrologist shall know his magma chamber as the chemist or metallurgist knows his crucible. No student of fused slags can obtain safe results from the profoundest examination of merely one surface or one section of the fused product. He must think in three dimensions. In the same way, the petrologist attempting to unravel the complex history of a magma chamber, should, ideally, know its general shape, size and contents as well as the method by which the chamber has been opened within the earth's crust. Until these conditions are fulfilled his problem of rock-genesis through magmatic differentiation must remain wholly or in part indeterminate.

The geologist knows how hard those conditions are. He is dependent upon erosion's rendering his contacts accessible; yet erosion destroys surfaces of contact. He can find no bottom to the chamber of stock or of batholith, though large-scale differentiation is most commonly evinced in stocks and batholiths. It is not to be wondered at that, notwithstanding the great number of described instances of magmatic differentiation, the phenomenon itself is so little understood or that the origin of the igneous rocks is still shrouded in the mists of hypothesis. In view of the difficulties surrounding the study, the discovery of single cases where the requisite field conditions are tolerably well fulfilled, merits special statement. Descriptions of bodies differentiated in [illegible]bers of known form are in the highest degree rare. Nevertheless, [illegible] precisely in the light of these rare cases that the laws of differentation can be most intelligently discussed.

Such an instance is described in this paper. It refers to an exceptionally clear example of differentiation within a magmatic chamber, the crystallized contents of which can now be examined from top to bottom of the chamber. The form and geological relations of the chamber are sufficiently well determined to serve for the discussion of the magmatic problem. The general nature of the magma whence differentiation has evolved the existing igneous rocks is believed to be deducible from the field and chemical relations. That compound magma was itself derived, owing its composition to the digestion [illegible] solution of acid sedimentary rocks in an original gabbro magma. Finally, [illegible]e facts seem indisputable as to the nature of the method by which the differentiation took place. The splitting of the magma may have ro[illegible]ly followed eutectic laws, but the actual segregation of the sub-magmas appears to have been directed by gravity, producing simple stratification in the chamber. The less dense sub-magma of splitting overlies the denser sub-magma of splitting.

A note on the Moyie Sill, the example to be discussed in the following pages, was published in the American Journal of Science, September, 1905, p. 185. In that paper stress was laid upon the repeated occurrence of similar phenomena in other regions. The comparison need not here be repeated, although its value is evidently of primary importance to the main conclusions regarding the mode of rock-genesis common to all the occurences. The present paper will be occupied more strictly with the Moyie Sill rocks of which Professor M. Dittrich and Mr. M. J. Connor have made chemical analyses additional to those published in the earlier paper. The new information derived from these analyses as well as from supplementary microscopic study goes far towards corroborating the views originally held by the writer.

General Geology of the Purcell Mountain Range.

During the field season of 1904 the writer developed a geological structure section along the 49th Parallel of latitude between Port Hill, Idaho, and Gateway, Montana, the two points where the Kootenay River crosses the boundary line between Canada and the United States. It was found that the mountains traversed by the section — the Purcell Range — are for the most part composed of two very thick siliceous sedimentary formations. The two are conformable and, while locally unfossiliferous, seem to be the stratigraphic equivalents of Cambrian and pre-Cambrian sedimentaries in the Rocky Mountains proper.

The lower formation has been called the Creston quartzite. It is a remarkably homogeneous, highly indurated, light-gray to medium-gray sandstone, generally thick-platy in structure but occasionally interrupted by thin intercalations of argillaceous material. The dominant rock is composed of quartz, feldspars and micas. The total thickness of the formation is at least 2670 meters in the vicinity of Port Hill; its base was not directly observed.

Immediately overlying the Creston quartzite is the conformable Kitchener quartzite which shows a minimum thickness of 1950 meters. This formation is distinguished from the Creston quartzite chiefly by the rusty colour of the outcrops, by thinner bedding, and by a greater proportion of micaceous cement once somewhat argillaceous. The old sandstone is also notably feldspathic and, like the Creston quartzite, often approaches a true arkose in composition.

Dark-coloured red, brown and gray shales with thin intercalations of gray quartzite conformably overlie the Kitchener quartzite. The series, totalling 1050 meters in thickness, has been grouped under the name of the Moyie argillite. The formation appears but twice in the section and then only in comparatively small areas.

This great group of formations has been strongly dislocated in the building of the mountains. A few open folds broken by faults appear in the eastern half of the belt, but the deformation has been due in general to the tilting of monoclinal blocks separated by normal faults and, more rarely, by thrusts. The tilting of the beds ranges through all angles up to verticality, but the average dip is less than forty-five degrees. In consequence of the deformation and subsequent denudation the edges of more than 5600 meters of well-bedded ancient sediments are now exposed. There have also come to light a number of thick sills of gabbro intruded at various horizons into the Kitchener quartzite and the upper part of the Creston quartzite.

The intrusion and crystallization of the gabbro are believed to have taken place before the upturning of the sedimentaries. One leading evidence for this is found in the existence of a conspicuous sheet of extrusive basic lava occurring at the upper limit of the Kitchener quartzite. The lava is clearly contemporaneous with that quartzite and flowed out over the ripple-marked surface of the sandstone while the latter lay flat on the sea-floor. There is field evidence that this lava flood was fed from one of the basic sills above mentioned. It is believed, therefore, that the intrusion of the sills occurred while the sedimentaries were still essentially in their original position.

The faulting and tilting have repeated the outcrops of certain of the sills. One of the thickest of them has been warped into one of the rare synclinal folds. The thickness of the sills varies from 30 meters to 840 meters.

Petrography of the sills in the Purcell Mountain Range.

The main body of each sill whether thick or thin was found to consist of a nearly constant type of hornblende gabbro. Macroscopically, it is a dark greenish-gray, medium grained rock of gabbroid habit. The principal variations in macroscopic character are due simply to the local coarsening of grain as so commonly seen in gabbros, or, secondly, to the local development of a more hornblendic phase in which feldspar is seen to be comparatively inconspicuous.

Microscopic examination confirmed the field impression of the relative uniformity of the material originally injected into the quartzites. The essential minerals proved to be hornblende and triclinic feldspar; the accessory constituents always include titanite, titaniferous magnetite and apatite with a more or less notable amount of interstitial quartz. Often biotite and, more rarely, orthoclase occur as additional accessories. Epidote, zoisite and chlorite are the chief secondary minerals.

None of these minerals presents unusual characteristics and their description warrants but few words. The hornblende is primary; its colour green, absorption strong ($\mathfrak{b} = \mathfrak{c} > \mathfrak{a}$). The extinction on the cleavage plate runs from 13° to 14°. These properties and the total analysis of the rock show that it is a type of aluminous hornblende. It is idiomorphic against feldspar. The dominant plagioclase crystals belong to the species Ab_5An_8, but some crystals are zoned with anorthite in the cores. The average feldspar is basic labradorite near Ab_1An_2. The anhedra and minute crystals of magnetite, like the minute apatite needles, are often strikingly rare; titanite with the habit usual in gabbros is abundant. No pyroxenic mineral has been discovered in any phase of the rock, even in that which is quite fresh.

The following analysis, "Phase B", illustrates the chemical composition of the comparatively fresh gabbro from a sill outcropping about 13 kilometers east of the Moyie River. It may be taken to represent closely the normal rock of the sills.

Phase B.

SiO_2	51.92 %
TiO_2	.83
Al_2O_3	14.13
Fe_2O_3	2.97
FeO	6.92
MnO	.14
MgO	8.22
CaO	11.53
Na_2O	1.38
K_2O	.47
H_2O below 110° C	.10
H_2O over 110° C	1.07
P_2O_5	.04
CO_2	.06
	99.78
Sp. Gr.	3.000

Analyst: Professor Dittrich.

A fairly accurate optical determination of the weight percentages among the principal mineral constituents gave the result:

Hornblende	58.7 %
Labradorite	34.8
Quartz	4.0
Titanite and magnetite .	1.4
Biotite	.9
Apatite	.2
	100.0

The two tables indicate that the rock is not a common type of gabbro. Calculation shows that the hornblende is of an unusually acid type and is low in alumina, with lime, magnesia and total iron oxides present in about equal amounts. The composition of the specially abundant amphibole and the presence of the accessory quartz chiefly explain the high acidity of the rock as a whole and also the comparative poverty in alumina. The rock is.

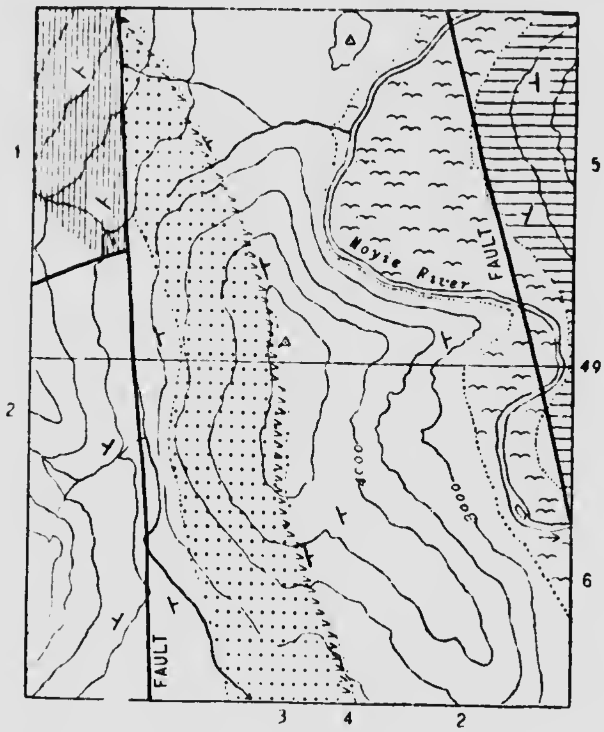


Figure 1.

Map of the Moyie Sill, taken from the plane-table sheet of the International Boundary Commission.

Explanation: 1 Moyie Argillite. 2 Kitchener Quartzite. 3 Hornblende gabbro. 4 Granite (acidified zone of sill). 5 Creston Quartzite. 6 Alluvium.

Conventional sign for strike and dip.

Isohypses in feet.

Scale 1 : 64000.

thus, to be classed among the hornblende gabbros and yet must be regarded as an abnormal variety in that class. As already indicated, this abnormality persists in the average rock of all these great intrusive bodies.

The Moyie Sill — its petrography.

Within each one of the thicker sills, however, there is a systematic variation in composition. It is most striking in the case of the greatest of all the intrusions, that of the Moyie Sill. Its situation and relations are shown in Fig. 1 and 2.

Though the thickness of this sill is so great — 840 meters — the body is best described as a true sill or intrusive sheet. It preserves a nearly constant thickness for the 9500 meters through which the respective contacts have been followed in the field. A sill of similarly great thickness outcrops on a large scale about 14 kilometers to the westward and it is very possible that it is the Moyie Sill merely repeated by the strong block-faulting characteristic of the region. In any case the Moyie intrusive body has not the local development, the ground plan or sections of a typical laccolith. If its whole extent were known, it might prove to be of a form transitional between sill and laccolith. It will be seen, however, that, for the purposes of the following argument, a decision as to this matter of classification is not necessary. Of much greater importance is the fact that from end to end of the part of the sill mapped in Fig. 1, the exposure of the intrusive body is exceptionally perfect. Two complete sections were made across it and the writer feels reasonably certain from less full observations made at yet other points that the phenomena to be noted are not only duplicated on the two complete sections but characterize the whole exposure of the sill.

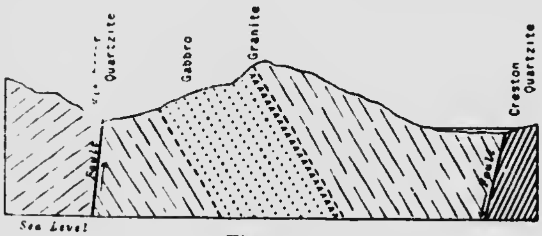


Figure 2.

Section of the Moyie Sill along line of the International Boundary.
Horizontal and vertical scales: 1 : 65000.

The one section was made exactly on the line of the international boundary (Fig. 2), the other along a wagon-road following the meridional valley west of the isolated mountain shown in Fig. 1. It was found in each case that, at the upper sill-contact, the igneous rock showed a remarkable variation from the usual type just described. For an average distance of about 45 meters measured perpendicularly from that contact, the sill-rock was, even in the field, at once referred to a species far removed from the gabbros. It evidently represented an acid, granitic zone in the sill

The acid rock is gray, much lighter in tint than the gabbro, and without the deep green cast of the latter. The grain varies from quite fine to medium. Very often roundish fragments of bluish, opalescent quartz interrupt the continuity of the rock. These are considered to be of exotic origin as they were seen to graduate in size into larger block-fragments of quartzite (xenoliths) shattered of from the sill-contacts.

In order to determine the average composition of the acid zone and to show the approximate limits of lithological variation within it, fresh specimens were taken at three points in the section following the wagon-road. They were collected at respectively 4.5, 12 and 15 meters from the upper contact with the quartzite.

The specimen taken at 4.5 meters from the contact, and representing what may be called Phase E, has the macroscopic appearance of a finely granular gray granite. In thin section it is seen to be a micropegmatite with a hypidiomorphic granular structure sporadically developed in many parts of the section. The crystallization is confused and does not show the regular sequence of true granites. The essential constituents are quartz, micropegmatite, microperthite, orthoclase, oligoclase-andesine and biotite; the accessories include titaniferous magnetite, a little titanite and minute acicular crystals of apatite and rarer zircons. The characters of all these minerals are those normally belonging to common granites. The chemical analysis of the rock shows the mica to be magnesian.

A striking feature of this, as of the other phases of the acid rock, is the advanced alteration of the feldspars which are usually filled with dust-like aggregates of epidote, kaolin and muscovite. This alteration is believed to be due to magmatic after-action, probably the result of the expulsion of vapours during the solidification of the underlying gabbro.

The calculation of the quantitative mineralogical composition of the rock has been attempted by the Rosiwal method. In the process the secondary products were neglected and the feldspars were arbitrarily regarded as fresh.

The inaccuracy of the result is manifest but it does not affect the value of the comparison among all the phases of the sill. Especially between the gabbro and the acid zone the contrasts of quality emerge with the same clearness and certainty as characterize the related contrasts established in the chemical analyses.

The total chemical analysis of this Phase E is here given:

SiO_2	71.69 %
TiO_2	.59
Al_2O_3	13.29
Fe_2O_3	.83
FeO	4.23
MnO	.09
MgO	1.28
CaO	1.66
Na_2O	2.48
K_2O	2.37
H_2O below 110° C	.14
H_2O over 110° C	1.31
P_2O_5	.07
CO_2	.13
	100.16
Sp. Gr.	2.773

Analyst: Professor Dittrich.

The most evident peculiarity is the low total for the alkalies: it accords with the relatively small proportion of feldspar present. Notwithstanding the abundance of free quartz the silica percentage is kept low by the comparative richness in biotite and by the magmatic alteration of the rock. The estimate of the mineralogical composition gave the following result in weight percentages:

Quartz	41.6 %
Sodiferous orthoclase	32.5
Biotite	15.2
Muscovite	4.6
Microperthite	3.9
Oligoclase	1.0
Magnetite	1.0
Apatite	.2
	100.0

The second analyzed specimen of the acid zone, Phase D, is that collected at the point 12 meters from the upper sill-contact. It is closely allied in composition to the phase just described and is chiefly distinguished from the latter by a coarser grain and a different structure. Microscopic examination shows this rock to be eugranitic (hypidiomorphic granular) with small isolated areas of the micrographic intergrowth of quartz and feldspar. The constituents are nearly the same as in Phase E. Here, however, muscovite is an accessory so rare as not to enter the table of quantitative mineral proportions. True soda-orthoclase replaces nearly all the microperthite of the micropegmatitic facies. Calcite enters the list of secondary minerals.

The chemical analysis of Phase D is as follows:

SiO_2	72.42 %
TiO_2	.68
Al_2O_3	10.47
Fe_2O_3	.83
FeO	5.50
MnO	.16
MgO	.41
CaO	2.53
Na_2O	1.93
K_2O	2.94
H_2O below 110° C	.06
	97.93

	97.93%
H_2O over 110° C	1.11
P_2O_5	.11
CO_2	.61
	99.76
Sp. Gr.	2.784

Analyst: Professor Dittrich.

The corresponding mineral composition in weight percentages was roughly determined thus:

Quartz	46.0%
Soda-orthoclase . . .	29.1
Biotite	22.0
Oligoclase	1.5
Magnetite	.5
Apatite	.5
Calcite	.4
	100.0

The high proportion of quartz, the very low percentages of the alkalies, yet lower than in Phase E, and the low percentage of alumina indicate that we have here again, as in Phase E, a quite abnormal kind of granite.

The Phase D′, collected at the point 15 meters from the upper sill-contact is unusually quartzose. It has nearly the same qualitative composition as Phase D but the structure is more like that of Phase E, being essentially that of a rather coarse-grained micropegmatite. The optical method gave the following weight percentages for the different constituents:

Quartz	57.1%
Sodiferous orthoclase .	24.9
Biotite	8.9
Muscovite	3.2
Calcite	2.5
Magnetite	1.9
Oligoclase	1.5
	100.0

It is clear that there is notable variation in the composition of the whole acid zone as represented in Phases E, D and D'. The apparently regular increase in acidity in the zone from above downwards is fortuitous. The zone is in reality irregularly streaked in many such phases carrying variable proportions of the mineral and oxide constituents. Whatever the cause, the magma of the acid zone was not homogeneous at the time of its solidification. To that fact is doubtless to be related the confused, rapid crystallization of the essential mineral constituents.

On the other hand, the rock of the acid zone in all its phases belongs to the granite family and stands at all points in contrast with the gabbro, the main constituent of the sill. Field and optical study show that the great body of this gabbro has the chemical composition already described as belonging to the sill gabbro occurring generally throughout the region i. e., Phase B. So evident was this fact that it was considered unnecessary to have the normal Moyie Sill gabbro specially analyzed. To appreciate the fundamental dissimilarity of the acid rock and the gabbro it is only necessary to glance at the tables of chemical and mineralogical analyses (Tables I. and II.).

Between the acid zone and the normal gabbro is an intermediate, transitional zone represented by Phase C, collected at a point 60 meters from the upper sill-contact.

Macroscopically, Phase C is quite closely similar to the normal gabbro. It is a dark greenish gray, granular rock of basic habit. Its essential minerals are hornblende, biotite and andesine; the accessories, quartz, orthoclase, titanite, titaniferous magnetite and apatite. The secondary minerals are zoisite, kaolin and epidote. The structure of the rock is in general the hypidiomorphic granular but local areas of micropegmatite are common in the section.

The total analysis of this phase gave the following result:

SiO_2	52.63%
TiO_2	.62
Al_2O_3	16.76
Fe_2O_3	2.86
FeO	10.74
MnO	.38
MgO	4.33
CaO	6.17
Na_2O	1.41
K_2O	2.29
H_2O below 110° C	.12
H_2O over 110° C	1.17
P_2O_5	.33
CO_2	.10
	99.91
Sp. Gr.	3.020

Analyst: Professor Dittrich.

The quantitative mineral composition by weight percentages was determined (orthoclase not separately estimated but included in the andesine) thus:

Hornblende	49.4%
Biotite	22.0
Andesine	16.5
Quartz	11.7
Apatite	.3
Magnetite	.1
	100.0

The abundant biotite and quartz go far to explain the differences between the chemical analysis here and that of the normal gabbro. It also appears from the analysis that the hornblende is here unusually aluminous. Chemically considered this intermediate rock has its nearest relatives among the diorites: yet the low feldspar content forbids our placing this rock variety in that family. Like both the gabbro and the granite it is an anomalous type.

Such are the conditions at the upper zone of contact within the great sill. Vastly different are those at the lower contact. In the field it is almost impossible to say that there is even the slightest systematic change, other than in a certain diminution of grain, as one passes downward in the sill. Crossing the thoroughly gabbroid rock for more than 700 meters of sill-thickness, the observer comes abruptly upon the quartzite without meeting any evident zone of acid igneous rock.

Yet microscopic and chemical study of the lower internal zone of contact shows that here, too, the rock is not quite the normal gabbro. Phase A was collected at a point 9 meters perpendicularly from the lower surface of contact. In macroscopic appearance and internal structure it is not markedly different from the normal gabbro. The essential minerals are hornblende and labradorite; the accessories, quartz, potash feldspar, titanite, magnetite. Zoisite, kaolin and much chlorite are the secondary constituents.

Chemical analysis of Phase A gave the following result:

SiO_2	52.94 %
TiO_2	.73
Al_2O_3	14.22
Fe_2O_3	2.08
FeO	8.11
MnO	.35
MgO	6.99
CaO	10.92
Na_2O	1.40
K_2O	.49
H_2O below 110° C	.12
H_2O over 110° C	1.56
P_2O_5	.08
	99.99
Sp. Gr.	2.980

Analyst: Professor Dittrich.

The corresponding mineral composition in weight percentages is roughly as follows:

Hornblende	54.8%
Labradorite	25.6
Chlorite	11.0
Quartz	6.3
Titanite	2.0
Magnetite	.3
	100.0

On account of some alteration in the rock, it was found difficult to distinguish with certainty the small amount of alkaline feldspar; which has, accordingly, been entered in the total for labradorite.

At the perpendicular distance of 60 meters from [illegible]er contact a related specimen was collected which may be called Phase [illegible] It is somewhat fresher than Phase A and gave the weight percentages thus:

Hornblende	42.9%
Quartz	22.8
Andesine	18.5
Biotite	6.6
Sodiferous orthoclase .	5.5
Titanite	3.7
	100.0

The comparison of these two phases with the normal gabbro, Phase B, indicates the subordinate yet certain acidification of the sill-rock for at least 60 meters from the lower sill-contact. This lower contact zone thus tends to approach the intermediate rock, Phase C, in mineralogical and chemical constitution.

Résumé.

As a convenient summary of the foregoing descrip[illegible] the mineralogical and chemical analyses of the different phases have been assemb[illegible] Tables I. and II.

Table I.

Weight percentages of minerals as determined by the Rosiwal method.

	A	A'	B	C	D'	D	E
Hornblende	54.8	42.9	58.7	49.4	—	—	—
Biotite	—	6.6	.9	22.0	8.9	22.0	15.2
Labradorite, $Ab_1An_1 - Ab_1An_2$	25.6	—	34.8	—	—	—	—
Andesine, Ab_4An_3		18.5	—	16.5	—	—	—
Oligoclase, Ab_2An_1	—	—		—	1.5	1.5	1.0
Soda-bearing orthoclase . . .	—	5.5	—	—	24.9	29.1	32.5
Microperthite	—	—	—	—	—	—	3.9
Quartz	6.3	22.8	4.0	11.7	57.1	46.0	41.6
Muscovite	—		—	—	3.2	—	4.6
Apatite	—		.2	.3	—	.5	.2
Titanite	2.0	3.7	1.4	—	—	—	—
Magnetite	.3	—	—	.1	1.9	.5	1.0
Chlorite	11.0	—		—	—	—	—
Calcite	—	—	—	—	2.5	.4	—

The total is 100.0 in each case.

Phase A 9 meters from lower contact, Moyie Sill
" A' 60 meters " "
B Normal unacidified gabbro, equivalent of main mass of the Moyie Sill
C Intermediate rock, 60 meters from upper contact, Moyie Sill
D' Acid rock, 15 meters from upper contact, Moyie Sill
D Acid rock, 12 meters "
E Acid rock, 4.5 meters

Phases A and A' belong to a lowermost zone of slight acidification. The basic Phase B constitutes the bulk of the sill. Next above the basic zone is a shallow zone of intermediate rock, Phase C, itself overlain by the fourth principal zone of highly acid rock represented by Phases D', D and E.

Corresponding to the foregoing tables, item for item, is the table of specific gravities (Table III.)

Table II.

Chemical analyses, Moyie Sill phases.

	A	B	C	D	E
SiO_2	52.94	51.92	52.63	72.42	71.69
TiO_2	.73	.83	.62	.68	.59
Al_2O_3	14.22	14.13	16.76	10.47	13.29
Fe_2O_3	2.08	2.97	2.86	.83	.83
FeO	8.11	6.92	10.74	5.50	4.23
MnO	.35	.14	.38	.16	.09
MgO	6.99	8.22	4.33	.41	1.28
CaO	10.92	11.53	6.17	2.53	1.66
Na_2O	1.40	1.38	1.41	1.93	2.48
K_2O	.49	.47	2.29	2.94	2.37
H_2O below 110° C	.12	.10	.12	.06	.14
H_2O over 110° C	1.56	1.07	1.17	1.11	1.31
P_2O_5	.08	.04	.33	.11	.07
CO_2	—	.06	.10	.61	.13
	99.99	99.78	99.91	99.76	100.16

Table III.

	Spec. Grav. (15° C.)
Phase E	2.773
» D	2.784
» D′	2.800
Average for granite zone, about	2.790
Phase C	3.020
» B. average about	3.025
» A′	2.967
» A (too low, as rock is altered somewhat)	2.980

Origin of the Acid Zone.

The critical point of the present paper is the explanation of this peculiarly stratified condition of the Moyie Sill. The question is synonymous with that of the origin of the acid zone. As for the main body of the igneous rock, there is little doubt that its intrusion occurred quite in the manner usual for basic intrusive sheets. It may be assumed from such facts as the great horizontal extent of the sill and, secondly, the ease of diffusion within the gabbro, that the basic magma was fluid at the time of intrusion. The fluidity may have been of a high order.

Among all the conceived hypotheses as to the origin of the acid zone, the writer has been forced to retain one as the best qualified to elucidate the facts in this one case of the Moyie Sill. More important still, this hypothesis better than any of the others, affords a coherent, fruitful and, it seems, satisfactory explanation of similar occurrences in other parts of the world. The view adopted includes what has been called "the assimilation-differentiation theory". The acid zone is thereby conceived as due to the digestion and assimilation of the acid sediments at both upper and lower contacts with the concomitant segregation of most of the assimilated material along the upper contact. The statement of the hypothesis naturally falls into two parts: — first, as to the evidences for assimilation; secondly, as to those favoring the special kind of differentiation involved.

Evidences for Assimilation.

1. Of primary importance in this connection is, of course, the composition of the sediments invaded by the original magma. One of the most noteworthy features of the huge series of conformable strata in the Creston-Kitchener series in this particular district is the marvellous homogeneity of the whole group. Hence it is that the study of comparatively few type specimens from these rocks can give a very tolerable idea of the average constitution of the quartzites. As already indicated, even the division into the two great sub-groups, Creston and Kitchener, is founded on but subordinate details of composition. Single beds typical of the Creston occur interleaved in the Kitchener and occasionally rusty beds are intercalated in the Creston series. In both series the average rock is a quartzite, always micaceous and often decidedly feldspathic. Many of the (Kitchener) strata immediately above

and below the Moyie Sill are seen, under the microscope, to have a composition essentially identical with that of typical Creston quartzite. It is, therefore, justifiable to use the chemical analysis of this latter rock in the attempt to evaluate the constitution of the sedimentary group invaded by the gabbro.

Professor Dittrich has analyzed such a type specimen collected several kilometers to the westward of the Moyie River. It is a very hard, light gray, fine-grained to compact, metamorphic sandstone breaking with a subconchoidal fracture and sonorous ring under the hammer. The hand-specimen shows glints of light reflected from the cleavage-faces of minute feldspars scattered through the dominant quartz. A faint greenish hue is given to the rock by the disseminated mica. This rock occurs in great thick-platy outcrops, the individual beds running from a meter to three meters or more in thickness. Occasionally a notable increase in dark mica and iron ore is seen in thin, darker-colored intercalations of quartzite. Ripple-marked surfaces are sometimes found, though they are not so common as in the overlying Kitchener quartzite.

In thin section this characteristic Creston quartzite is found to be chiefly composed of quartz, feldspar and mica, all interlocking in the manner usual with such old sandstones. The clastic form of the mineral grains has been largely lost during the regional metamorphism. The feldspars are orthoclase, microcline, microperthite, oligoclase and probably albite. The mica is biotite and muscovite, the latter either well developed in plates or occurring with shreddy, sericitic habit. The biotite is the more abundant of the two micas. Subordinate constituents are titanite in anhedra, with less abundant titaniferous magnetite and a few grains of epidote and zoisite.

The chemical analysis (Table IV., Col. 1) shows a notably high proportion of alkalies, and therewith the importance of the feldspathic constituents, especially of the albite molecule which alone holds about 15% of the silica in combination.

Table IV.

	1.	2.	3.	4.	5.
SiO_2	82.10	76.90	74.23	79.50	72.05
TiO_2	.40	.35	.58	.38	.63
Al_2O_3	8.86	11.25	13.23	10.13	11.88
Fe_2O_3	.49	.69	.84	.59	.83
FeO	1.38	3.04	2.65	2.21	4.87
MnO	.03	.02	.07	.02	.12
MgO	.56	1.01	1.02	.78	.85
CaO	.82	.88	1.13	.85	2.10
SrO	—	—	Tr	—	—
Na_2O	2.51	3.28	2.78	2.89	2.20
K_2O	2.41	1.36	2.66	1.89	2.66
H_2O below 110° C	.05	.20	.08	.12	.10
H_2O above 110° C	.37	1.20	.81	.78	1.21
CO_2	—	Tr	.08	—	.37
P_2O_5	.04	.15	—	.02	.09
	100.02	100.33	100.16	100.16	99.96
Sp. Gr.	2.681	2.680	2.754	2.680	2.790

1. Type specimen of Creston Quartzite. Analyst: Prof. Dittrich
2. Type specimen of Kitchener Quartzite. Analyst: Mr. Connor
3. Specimen of Kitchener Quartzite from contact zone, Moyie Sill. Analyst: Prof. Dittrich
4. Average of analyses 1. and 2.
5. Average of analyses D and E, types of acid zone, Moyie Sill.

Mr. Connor has analyzed a specimen collected as a type of the Kitchener quartzite itself. It was taken from a point about 150 meters measured perpendicularly from the upper contact of the Moyie Sill and this specimen represents what appears to be the average quartzite both above and below the sill. The rock is rusty-brown on the natural outcrop and on joint-planes, but is light gray on the fresh fracture. It is rather thin-bedded, the thin individual strata being grouped in strong, thick plates sometimes rivalling in massiveness the beds of the Creston quarzite. Some cross-bedding and a few ripple-marks were observed.

The thin section discloses a fine-grained interlocking aggregate of quartz grains cemented with abundant grains of feldspar and mica. The feldspar is so far altered to kaolin and other secondary products that it is most difficult of accurate determination. One or two small grains only exhibit polysynthetic twinning and the preliminary study referred practically all the feldspar to the potash group. Mr. Connor's analysis shows conclusively, however, that soda feldspar is really dominant. The analysis was most carefully performed, the second complete determination of the alkalies agreeing very closely with the first. Supplementary optical study of the rock has pointed to the probability that pure albite as well as highly sodiferus orthoclase are present. Quartz makes up about 60% of the rock and feldspar from 25 to 30%. Biotite both fresh and chloritized is the chief mica; sericite is here quite rare. Colorless epidote is the principal accessory; titanite, magnetite, apatite, a few zircons and pyrite crystals are the remaining constituents.

The analysis is given in Table IV., Col. 2. Col. 4 of the same table shows the average of Cols. 1. and 2. and may be taken as nearly representing the average chemical composition of the quartzite invaded by the Moyie Sill. This average may be at once compared with that of the two analyses from the granite zone of the sill, represented in Col. 5. The general similarity of the two averages is manifest. There is clear chemical proof that the greater proportion of the elements in the granite could have been derived directly by fusion of the quartzite.

That conclusion has been enforced by an examination of the exomorphic contact-zone at the upper limit of the sill. For the perpendicular distance of at least 20 meters from the upper surface of contact, the quartzite has been intensely metamorphosed. The rock is here vitreous, lightened in colour-tint, and exceedingly hard. Under the microscope the clastic structure is seen to have totally disappeared. Recrystallization is the rule. It takes the form of poikilitic or of micrographic intergrowth of quartz with various feldspars, along with the development of abundant well crystallized biotite and (less)muscovite. The feldspar is chiefly microperthite and orthoclase the latter often, perhaps always, sodiferous. Albite in independent, twinned grains of small size seems certainly determined by various optical tests. Innumerable, minute grains of zoisite and epidote occur as dust clouding the feldspars, micropegmatitic intergrowths, and even the quartz. Scattered anhedra of magnetite and small crystals of anatase and apatite are rather rare constituents.

The chemical analysis of this highly metamorphosed quartzite is entered in Col. 3., Table IV. In the preliminary study of the sill it was considered as probable that the quartzite had been somewhat feldspathized during the metamorphism, but the critical analyses seem hardly to bear out any certain conclusion on that point. The analysis shows that in several respects the metamorphosed rock is intermediate in composition between the granite of the sill and the unaltered quartzite. It should not be forgotten, however, that there is a perfectly sharp line of contact between the granite and this metamorphosed zone of the quartzite. The former rock has been in complete fusion; the latter rock still preserves its bedded structure.

The net result of the foregoing mineralogical and chemical comparisons affords good grounds for believing that the striking similarity of granite and quartzite is really due to a kind of consanguinity; that the igneous rock is due to the fusion of the sediment.

2. Granting that conclusion, there seems no other course open than to attribute the heat of fusion to the sill gabbro. A second test of the assimilation theory is suggested. This theory involves the assumption of sufficient heat to perform the work of fusion. It is, hence, an indication of great value that there is some acidification of the respective upper-contact zones in all of the six different sill-outcrops optically studied in the 85 kilometer stretch from Port Hill to Gateway: yet that this acidification is in

general in a direct proportion to the thickness of the sills. The Moyie Sill has at least four times the thickness of any other of the intrusive bodies. Presumably, therefore, its store of heat was much the greatest and its capacity fo. energetic contact-action much the largest. As a matter of fact, the Moyie Sill is the only sill bearing the truly granitic phase. The other sills are also somewhat more acid at their upper contacts than at their respective lower contacts, but the rock throughout is of gabbroid habit. The acidification in these cases has led to the development of abundant interstitial and poikilitic quartz, abundant biotite and less abundant alkaline feldspar in the hornblende-plagioclase rock. The rock of the acidified zones is here very similar to, if not identical with, the intermediate rock, Phase C, of the Moyie Sill. The acidification is relatively slight because these sills have been more rapidly chilled than the huge Moyie body. This point is based on deductive reasoning but it is no less positively in favour of the assimilation theory than the testimony of chemical comparison between the acid zone and the sediments.

3. There is, finally, direct field evidence that the Moyie gabbro has actually digested some of the quartzite. Along both the lower and upper contacts and, less often, within the main mass of the sill, fragments of the quartzite are to be found. These blocks have sharp contacts with the gabbro, but, none the less, they have the appearance of having suffered loss of volume through the solvent action of the magma. This phenomenon is quite familiar at intrusive contacts; its significance is only properly appreciated if one remembers that the visible effects of digestion are in but a small ratio to the total solvent effects wrought by the magma in its earlier, more energetic, because hotter, condition. It is not a violent assumption to consider that many quartzite blocks have thus been completely digested in the original gabbro magma. The product of this digestion is not now evenly disseminated through the crystallized gabbro, which except near its upper and lower contacts is very nearly identical in composition with the unacidified gabbro

occurring elsewhere in the district. No conclusion seems more probable than that the material of the dissolved blocks is now for the most part resident in the acid zone at the upper contact. The same view holds for the perhaps much more voluminous material dissolved by the magma at the main contacts themselves. The excess of acid material at the lower contact was held there because of the viscosity of the magma in its final, cooling stage. For the greater bulk of the digested material there has been, it appears, a vertical transfer upwards, a continuous cleansing of the foreign material from the basic magma.

The Differentiation.

In a word, there are reasons for concluding that the peculiar granitic zone at the top of the Moyie Sill is the immediate result of a special kind of differentiation. The composition of the original basic magma has been temporarily changed by the assimilation of quartzite; yet simultaneously gravitative adjustment has nearly restored the original composition, as the acid, assimilated material rose through the denser gabbro magma to the top of the sill. That the required differences of density were [illegible]ent is reasonably deduced from the specific gravities taken at critical [illegible]s in the sill cross-section (Table III.) The table shows that the sill is quite systematically stratified in the sense required by this hypothesis. The crystallized phases of the sill show contrasts of density which undoubtedly existed in the final molten stage of the sill's history. (Cf American Journal of Science, Vol. XV., April, 1903, p. 279).

Yet the process of differentiation may not have been purely physical, i. e., due simply to density stratification. The granite seems to carry more ferrous iron and lime and probably a little more alumina than the average quartzite. By the simplest supposition the increase in these oxides is to be attributed to robbery from the original magma. The volume of the gabbro is so immense that its total constitution has been but slightly, perhaps quite indiscernibly, affected by such abstraction.

Tests of the Assimilation-Differentiation Hypothesis.

Apart from its intrinsic merits, the foregoing solution of the Moyie Sill problem should obviously be tested in two ways. Other explanations need valuation and comparison with that hypothesis. Secondly, if the solution is correct, it might be expected to explain other similar rock-occurences if any such exist and to undergo either rejection or corroboration as the hypothesis matches all the facts concerning those other examples.

Alternative Hypotheses.

The various possible suggestions as to the origin of the acid zone in the Moyie Sill include, besides the favoured one, the following:

a) The zone may be conceived to have been an independent intrusion, either younger or older than the gabbro. This view is negatived by the field relations. There is an entire absence of any clear-cut contact surface between the granite and gabbro which, on the contrary, are completely transitional to each other through the zone of intermediate rock. This intimate relation is of a different order from that sometimes observed in a belt of welding between two masses of successive igneous intrusion. That the intermediate rock is due to an interaction between gabbro and quartzite is plainly indicated by the existence of zones of similar rock along the contacts of the thinner sills where there is no intervention of a granite zone.

b) The acid zone may be conceived as due to the simple differentiation of matter originally injected as one thick sill; or

c) to the simple fusion and recrystallization of the quartzite (with or without assimilation by the gabbro magma) along the upper contact only.

These two latter hypotheses have been rather fully examined by the writer in the earlier note on the Moyie Sill. It is unnecessary to restate the grounds of their rejection which must be considered as yet more clearly advisable as those hypotheses are viewed in the light of the new information supplied by the chemical analyses. The strongest alternative view is, in the writer's opinion, that which attributes the granite-micropegmatite zone to contact fusion along the upper contact only. This view rests on the possibility that original magmatic waters were concentrated along the upper contact and, aided by the heat of the magma, could there specially favour the conversion of the quartzite into a local sheet of secondary magma. The chemical analyses seem to invalidate this hypothesis which is also subject to objection on account of the great rarity of quartz veins or other true mineral veins within the quartzite at the upper sill-contact. Nevertheless, the distribution of "juvenile" waters in intrusive magma offers an important field for investigation.

Other Illustrations.

Similarly, the more positive test of the assimilation-differentiation hypothesis, the witness of other examples in the world, especially those in Minnesota and Ontario, has been rather fully treated of in the former paper.

Summary.

A brief summing up of the whole case may, however, be of service in placing the hypothesis more clearly before the reader of the present sketch.

1. The Moyie intrusive is an enormously thick sill composed in greatest part of a peculiar hornblende gabbro slightly acidified at the lower contact. An equally abnormal biotite granite merging irregularly into micropegmatite forms a zone in the uppermost part of the sill, while a fourth zone of rock intermediate in composition between the granite and gabbro and, on the respective sides, transitional into those rocks, occurs between the thick basic zone and the much thinner granite zone.

2. The sedimentary formation cut by the sill comprises a very thick series of ancient sandstones highly quartzose but generally containing alkaline and soda-lime feldspars and always carrying mica.

3. At the time of intrusion the quartzitic strata lay flat.

4. At both contacts of the sill, the igneous rock contains foreign blocks shattered off from the quartzites. These blocks often show evidence of magmatic corrosion.

5. The field-relations and the chemical and optical study of sill-rocks and quartzites suggest that the material of the granite-micropegmatite zone is of derived origin. Most of that material resulted from the solvent action of the gabbro magma on the quartzite blocks and on the main sill-contacts. Some of the constituent elements of the granite may have been taken from the gabbro which, on account of its superior and great volume, shows no appreciable modification by such loss.

6. The asymmetry of the intrusive body is believed to be owing to the stratification of the sill by the action of gravitative adjustment. The product of assimilation whether at the lower main contact or about quartzite blocks immersed in the gabbro, possessed less density than the gabbro magma, rose through that magma and collected at the top of the sill. The intermediate rock represents a zone of incomplete differentiation.

7. The assimilation and concomitant differentiation are exhibited in other sills of the region, but, on account of the relatively small thickness and consequently smaller share of heat energy possessed by those sills, the action did not develop true granite.

8. Following the solidification of these sills, they were faulted and tilted to their present position in the fault-blocks of the Purcell Mountain Range.

9. More or less perfect parallels to the Moyie Sill have been described by various workers in Minnesota and Ontario. In all of these instances there is the same genetic relation of gabbro, granite and siliceous sediments or schists. An important special feature of the extraordinarily thick and extensive intrusive sheet of the Sudbury district in Ontario is an apparent case of the gravitative differentiation of the famous sulphide ores of that district.

General Application.

The Moyie Sill does not teach much that is absolutely new among the principles of petrology. The main purpose of the writer has been, on the other hand, to emphasize through the witness of an unusually well exposed example in nature, the importance of both magmatic assimilation and magmatic differentiation. The most significant single feature of the Moyie and neighboring sills as of the Minnesota and Ontario intrusives is their evidences of gravitative adjustment in magma. That is the most practical result of the investigation. If the principle is once thoroughly established, it must take a prominent place in petrological theory. This is true whatever be the origin of the magmas from which igneous rocks have been derived. The principle will evidently apply whether a magma were the compound product of assimilation by an earlier magma or whether it were the compound product of fusion through the rising of the isogeotherms in sediments, schists or ancient igneous terranes.

"In the foregoing discussion the secondary origin of certain granites has been deduced from the study of intrusive sills or sheets. It is clearly by no means necessary that the igneous rock body should have the sill form. The wider and more important question is immediately at hand: does the assimilation-differentiation theory apply to truly abyssal contacts? Do the granites of stocks and batholiths sometimes originate in a manner similar or analogous to that outlined for sills?" The writer has briefly noted general reasons affording affirmative answers to these questions. (Cf. American Journal of Science, Vol. XV., 1903, p. 269, Vol. XVI., 1903, p. 107).

"The difficulty of discussing these questions is largely owing to the absence of accessible lower contacts in the average granite body of large size. All the more valuable must be the information derived from intrusive sheets. The comparative rarity of such rock-relations as are described in this paper does not at all indicate that the corresponding petrogenic events are exceptional. It is manifest that extensive assimilation and differentiation can take place in sills only when the sills are thick, well buried, and originally of high temperature. All these conditions apply to the Moyie case. The phenomena described are relatively rare because thick basic sills cutting acid sediments are comparatively rare.

On the other hand, there are good reasons for believing that a sub-crustal gabbroid magma, actually or potentially fluid, is general all around the earth; and, secondly, that the overlying solid rocks are, on the average, crystalline schists and sediments more acid than gabbro. Through local, though widespread and profound assimilation of those acid terranes by the gabbro, accompanied and followed by differentiation, the batholithic granites, syenites etc. may in large part have been derived. True batholiths of gabbro are uncommon, perhaps because batholithic intrusion is always dependent on assimilation.

The theory is applicable to plutonic rocks other than granite, to lavas as well as to intrusive bodies. Demonstration of the truth or error of the theory will doubtless be found in the study of intrusive igneous bodies rather than in the study of volcanoes either ancient or modern. Finally, the fact of "consanguinity" among the igneous rocks of a petrographical province may be due as much to assimilation as to differentiation."