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Mineralogical variations in a diabase sill near Nimrod Granite County Montana

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MINERALOGICAL VARIATIONS IN A DIABASE SILL NEAR NIMROD, GRANITE COUNTY, MONTANA

by

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MINERALOGICAL VARIATIONS IN A DIABASE SILL
NEAR NIMROD, GRANITE COUNTY, MONTANA

Paul Thomas Thiel

ABSTRACT

Samples collected from a diabase sill near Nimrod, Montana, were studied by means of the petrographic microscope and X-ray diffraction. Mineralogical compositions and approximate chemical compositions were computed for rock samples in vertical traverses in order to detect and describe variations. Wet chemical analyses were also made.

Major minerals present are plagioclase, clinopyroxenes, hornblende and unusually abundant iron ore (averaging 8 per cent). The absence of orthopyroxene is attributed to the original high iron/magnesium ratio.

The parent magma is deduced to have been of ferrogabbroic composition. It was an iron-rich tholeiitic magma slightly over-saturated in silica. The origin of the iron-rich magma was probably differentiation from an original tholeiitic magma which followed a Fenner-type course of differentiation with enrichment in iron and alkalis, but with otherwise little change in oxide content. A very low partial pressure of oxygen or a decrease in P_{O_2} during differentiation, total composition remaining constant, may be the cause of an enrichment in iron instead of silica

during differentiation. This trend is noted in non-orogenic regions.

Vertical variations were observed. The plagioclase ranges from An_{65} at the contact zones to An_{42} in the coarse zone near the top of the sill. There is some iron-enrichment in the later clinopyroxenes. Normal chemical variation for diabase occurred as the sill crystallized, except in the coarse zone, where the residuals were concentrated and an enrichment in iron, titanium and alkalis took place.

The Nimrod diabase sill is similar mineralogically and chemically to several sills and dikes in the area east of Missoula, Montana, which intrude Precambrian metasediments of the Belt Series. Cretaceous deformation of the diabases places age of intrusion between Precambrian and Cretaceous. The sills are similar to other (Purcell) diabases which intrude Precambrian sediments of northern Idaho, northwestern Montana and southeastern British Columbia.

ACKNOWLEDGEMENTS

I wish to thank Dr. John Hower for calling to my attention the possibility of work on this sill, and to thank both Dr. Hower and Mr. Ray Brodersen for their many helpful suggestions for studying the sill and correlating results. I am grateful to the Geology Department of Montana State University for providing the funds for three chemical analyses.

GENERAL GEOLOGY

The sill studied crops out near Nimrod, Montana, on the south side of the Clark Fork River for a distance of approximately six miles. (See Figure 1). Exposures are usually poor, for although the sill crops out on steep slopes, the vegetation (conifers, shrubs, and mosses) is dense and talus slides frequently conceal the bedrock. Extrusives cover the sill in several places. Samples were taken from spurs of bedrock jutting out of the hillside.

The region has high relief (3,000 feet in the township). Saddles have developed on spurs as a result of differential erosion of the sill and the more resistant quartzite above and below it. Two treeless slopes were observed where the sill crops out - one on the west side of Tyler Creek and the other one mile to the west. The outcrop pattern of the sill as mapped by Joel Montgomery (Montgomery, 1958, map in folder) has been checked and found to be accurate. Figure 1 shows this pattern and the location of sample traverses. Samples were collected approximately every six feet; positions of samples below the top of the sill are indicated on text diagrams and in Table III, page 62.

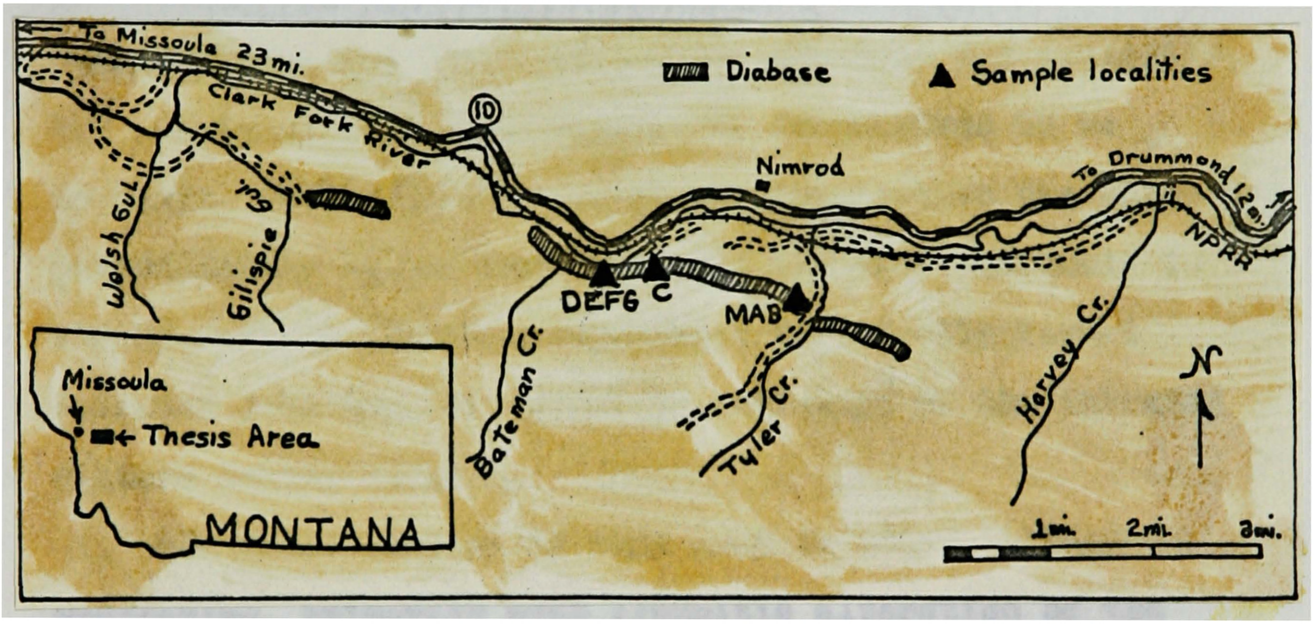


Figure 1. Map of Nimrod sill in Garnet Range formation (Belt Series) and location map of area (after Montgomery, 1958).

The sill was intruded into the bottom half of the Garnet Range formation of Precambrian (Beltian) age. The Garnet Range formation here is a gray quartzite which weathers pink. The formation as a whole is approximately 4,000 feet thick and was described by Montgomery as a thinly bedded, greenish brown, micaceous, sandy quartzite and argillite with interbedded gray quartzites.

The sill averages 470 feet in thickness, varying from 558 feet thick at the mouth of Tyler Creek to 374 feet at the western extremity. It strikes roughly N80°W. and dips, on the average, 32°S. Several joint orientations are present in the sill. In one system two sets of joints were developed, one roughly parallel to the contacts and one at 60° to the contacts, striking N20°W. and dipping 73°E. Because these same sets are also present in the quartzite, the origin of this joint system is interpreted to be tectonic. Other joints, which are confined to the sill, are perpendicular to the sill contacts and vary extremely in strike. These probably constitute imperfectly formed columnar jointing, developed by shrinkage of the intruded diabase during cooling.

The fresh diabase is dark gray in color. Chemical weathering, primarily with limonitic alteration of the ferromagnesian minerals, usually extends about 3 millimeters into the diabase. The rock has also been weathered along the many fractures which occur in it. Exfoliation was noted in the diabase near Bateman Creek.

Hydrothermal Zones

Several hydrothermal zones are found in the diabase, primarily near the mouth of Tyler Creek. These zones are pods of calcite and/or amphibole (primarily hornblende, with some actinolite). The pods are 20 to 60 feet in diameter and may be connected, because veins of calcite and quartz are found in the areas where the hydrothermal pods are found. The pods grade into normal diabase. The alteration of the diabase may have been a rearrangement of the elements into amphibole and calcite with the introduction of volatiles, principally water and carbon dioxide, and removal of silica. Chalcopyrite is sometimes found in the calcite of the pods.

The hydrothermal zones are quite coarse in the upper part of the sill, where hornblende crystals three inches long were found. The calcite in the upper part of the sill is often quite massive and polysynthetically twinned. In the lower part of the sill an altered zone was found containing fine grained calcite replacing pyroxene; plagioclase is more abundant than calcite in this zone. The abundant calcite (hence introduction of CO_2), the concentration of the zones near the mouth of Tyler Creek, and the presence of a calcite-plagioclase zone near the lower sill contact indicates a hydrothermal origin for the zones rather than a deuteric origin. Were the zones deuteric they would likely be more general throughout the coarse part of the diabase.

Contacts

The contacts of the diabase with the quartzite are generally very sharp. The diabase at the contact is of basaltic texture with small plagioclase laths in a glassy groundmass. Larger plagioclase laths and clinopyroxene grains are present as pheocrysts (see Figure 2). A study of the quartzite at the contact (see Figure 3) revealed a layer of plagioclase about 5 millimeters thick immediately adjacent to the diabase. Euhedral hornblende was introduced as far as two inches into the quartzite. However, on the whole, the quartzite, with its already sutured grains, was little affected by the intrusion of the diabase. Some quartzite fragments found in the diabase were remarkably unaltered.

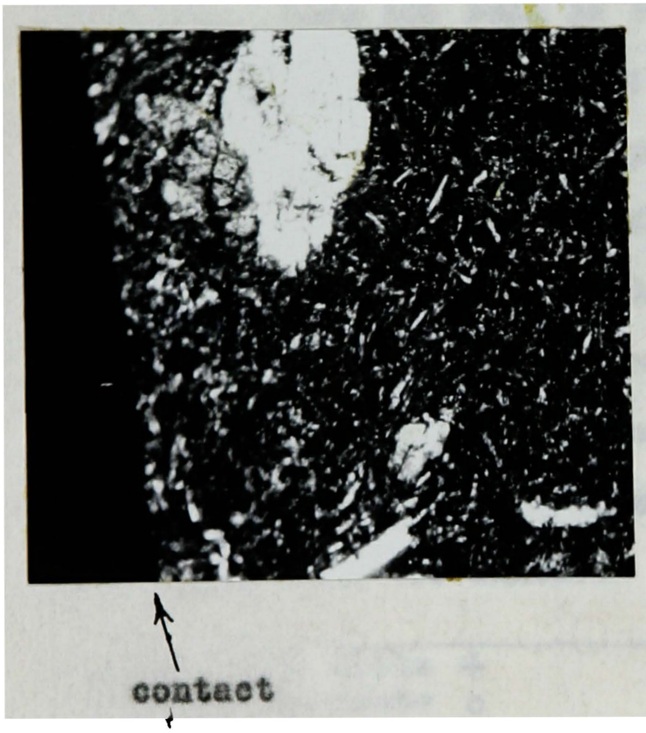


Figure 2. Photomicrograph of diabase at lower contact. (70X and crossed nicols).

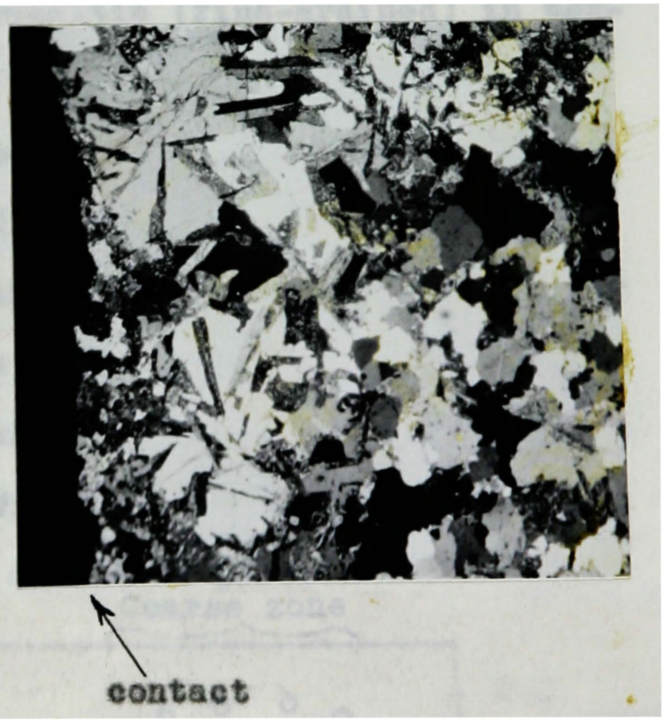


Figure 3. Photomicrograph of quartzite at upper contact. Note plagioclase laths introduced into quartzite near contact and sutured quartz grains. (25X and crossed nicols).

MINERALOGY

General Mineralogy and Texture

The diabase sill near Nimrod is a medium-grained, basic igneous rock. Its major constituents are pyroxene and plagioclase. However, in the lower part of the upper half of the sill, hornblende is more abundant than pyroxene. The hornblende resulted from deuteric alteration of the pyroxene.

Grain size is smallest in the chill zones, where the intruding magma was cooled rapidly by contact with the quartzite. Here the rock is basaltic (fine-grained) in texture with small phenocrysts of pyroxene and plagioclase (phenocrysts are less than 5 per cent of the diabase here). The grain size increases rapidly away from the chill zones and then increases less rapidly toward a coarse zone roughly 100 feet thick. Maximum grain size is reached in the coarse zone located 50 to 150 feet below the upper contact of the 450 foot thick sill (see Figure 4). Pyroxene prisms are much larger than the anhedral grains of pyroxene.

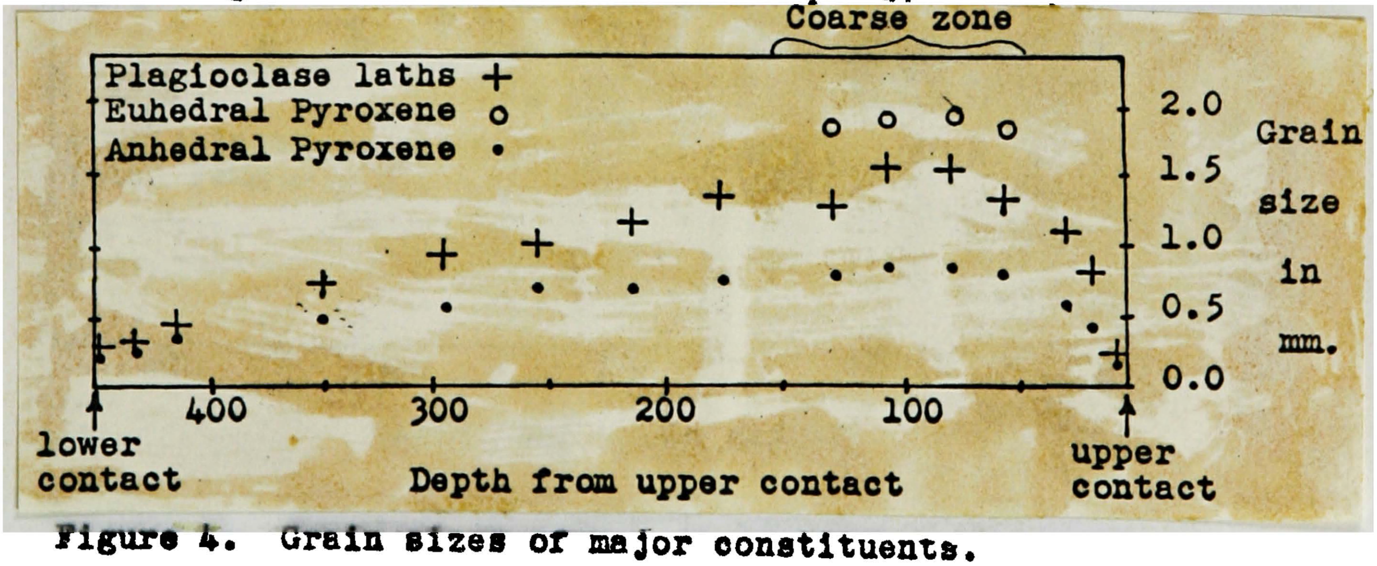


Figure 4. Grain sizes of major constituents.

The following average lengths were found for the minerals in the sill:

Plagioclase	1.0 mm.	Ore	1.5 mm.
Clinopyroxene	.9 mm.	Quartz	.7 mm.
Hornblende	1.2 mm.	Biotite	1.1 mm.
Myrmekite	1.4 mm.	Apatite	1.3 mm.

In comparing the per cent of the major minerals in the sill (see Figure 5), it is observed that the plagioclase content increases steadily toward the coarse zone from both contacts then decreases suddenly in the coarse zone. The pyroxene content is at a maximum close to the chill zones and decreases rapidly toward the coarse zone. However, the content of hornblende must also be considered, because it is an alteration product of the pyroxene. The two ferromagnesian minerals are also plotted together, along with biotite. Note that there is still a decrease in total ferromagnesian content toward the coarse zone.

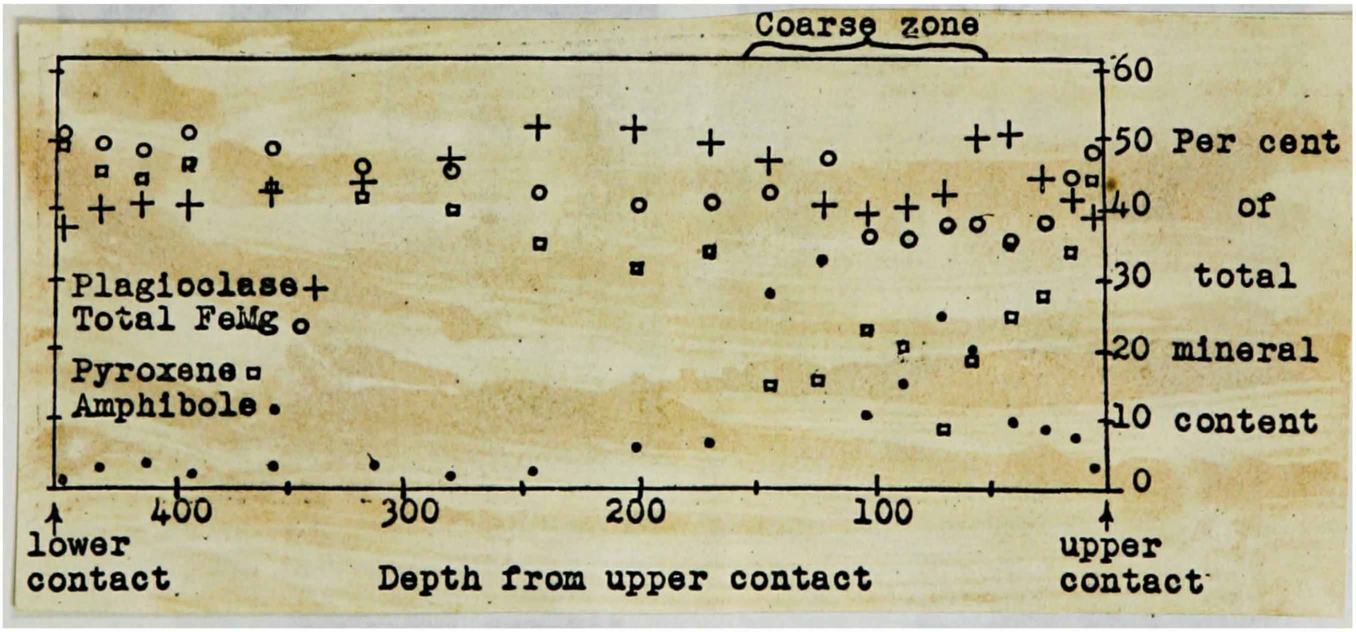


Figure 5. Vertical variation in mineral percentages.

Paragenesis

Plagioclase and pyroxene were the first two minerals to crystallize from the magma. The other minerals, with the exception of apatite (see page 10), occur as alteration products or as crystallization products from the residual melt. It may be inferred from the apparent piercing of clinopyroxene grains by plagioclase laths (see Figure 6) and conversely, the piercement of the laths by the anhedral grains of pyroxene, that the two minerals crystallized simultaneously from the magma. Interlocking grains of the two minerals are found, and, more rarely, ophitic texture is seen, with plagioclase laths enclosed in a pyroxene grain and vice versa. The diabasic texture thus supports an early, simultaneous crystallization of plagioclase and pyroxene.

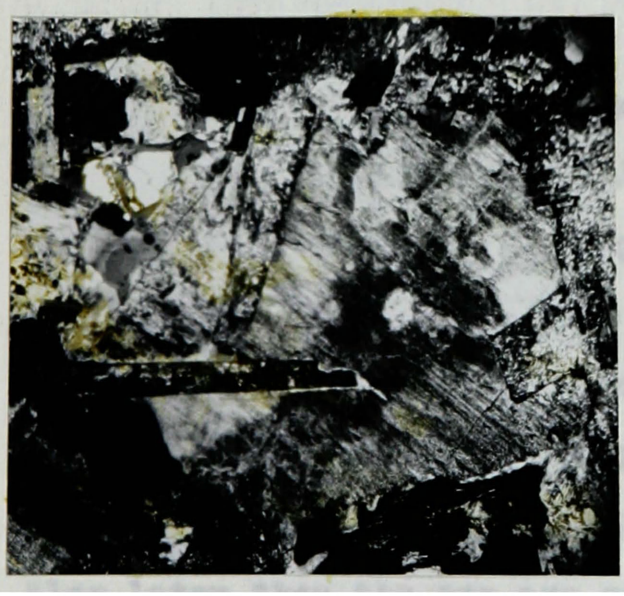


Figure 6. Photomicrograph of plagioclase laths piercing large pyroxene crystal (25X and crossed nichols)

Figure 7. Photomicrograph of hornblende (dark) rimming pyroxene crystal (70X and plain light)

It is quite common to find hornblende rims around pyroxene grains or aggregates of pyroxene (see Figure 7). Hornblende is abundant in the coarse zone, where large interstices might easily have held the residual melt which reacted with the earlier formed pyroxene to produce hornblende. Hornblende has replaced some large, almost euhedral crystals of pyroxene in the coarse zone. The hornblende also commonly occupies interstitial positions. The evidence cited above would place hornblende later in the sequence of crystallization than pyroxene and consequently later than plagioclase crystallization. After complete crystallization of pyroxene and plagioclase crystals, the residual melt occupied interstitial positions. Hornblende crystallized in the interstices and as a reaction of the residual liquids with the pyroxene.

Biotite and chlorite, where present, often occur as reaction rims around the hornblende, indicating the later crystallization of the two phyllosilicates. Ore sometimes occurs along biotite cleavage planes; these biotite crystals preceded the ore. However, brown biotite (a highly colored variety, lepidomelane) often rims the large skeletal ore masses, indicating that this biotite is later than the ore. Also later than the ore are sphene and leucoxene, which occur as alteration products of exsolved ilmenite.

Myrmekite is later in crystallization than plagioclase. It occupies interstitial positions and sometimes occurs in plagioclase-like laths (Figure 8). This suggests resorption of the plagioclase by the residual melt. Saussuritization dominated by sericitization probably occurred at this stage (deuteric), and isolated quartz grains formed in the interstices. Apatite crystals pierce plagioclase, quartz, pyroxene, and hornblende indiscriminately (see Figure 9), indicating that apatite possibly formed first with the other minerals crystallizing around the slender apatite needles. However, apatite is most abundant in the coarse interstices which crystallized late. It is probable that apatite formed early at any one place, but was concentrated in the latest forming phases.

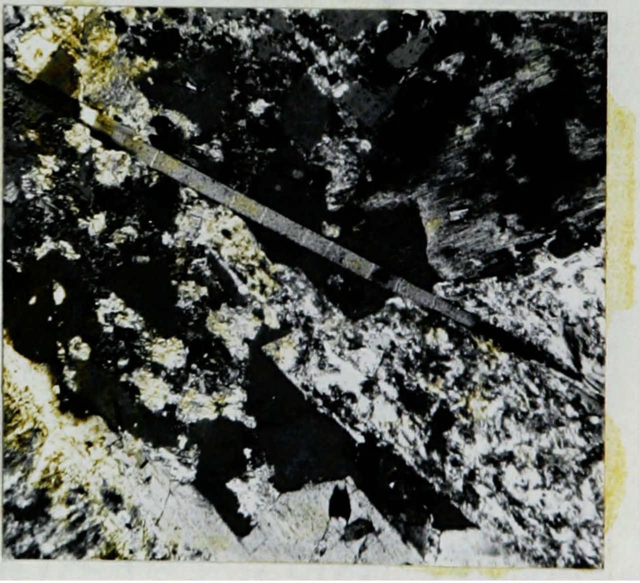


Figure 8. Photomicrograph of plagioclase laths apparently resorbed by myremekite (70X and crossed nicols).

Figure 9. Photomicrograph of apatite crystal piercing several other grains. Sericitized plagioclase is speckled white, pyroxene is dark gray. (70X and crossed nicols).

Plagioclase

Plagioclase is the most abundant mineral in the diabase. It averages 45 per cent of the minerals in the sill, varying from 38 per cent in the chill zone to 53 per cent in the coarse zone. This average is lower than the 50-60 per cent normal content of plagioclase in a diabase, according to Turner and Verhoogen (1960, p. 211).

This plagioclase occurs as subhedral to euhedral laths, twinned and slightly zoned. Most of the laths are twinned either in accordance with the albite law or the Carlsbad law. Simple Carlsbad twins in combination with albite twins are common. It is also common to find pericline or acline twinning (composition plane {001}) at almost right angles to the albite twinning (composition plane {010}) in a net-like pattern. All the plagioclase is zoned. The zoning present is continuous and normal, causing the extinction to advance rapidly from the center of the laths outward as the stage of the petrographic microscope is turned. In the coarse zone, where associated with the myrmekite, andesine is often replaced by rectangular and elongate blotches of albite (see Figure 10). This partial replacement appears to have followed cleavage planes.

A normal variation is found in the plagioclase in vertical sections of the sill. It ranges from An_{65} in the chill zones to An_{43} in the coarse zone. Thus, as plagioclase crystallized in the sill from the chill zone inward, it became progressively more sodic, changing from calcic labradorite to andesine. Absent in the chill zone, abundant in the coarse zone, and common in the sill proper is myrmekite, a worm-like intergrowth of sodic plagioclase and quartz. The plagioclase associated with and in the myrmekite is albite (composition about An_7). The anorthite content of all plagioclases was determined by means of the indices of refraction and optic sign, as well as by the extinction angle of albite twins, when present, using the Michel-Levy method.

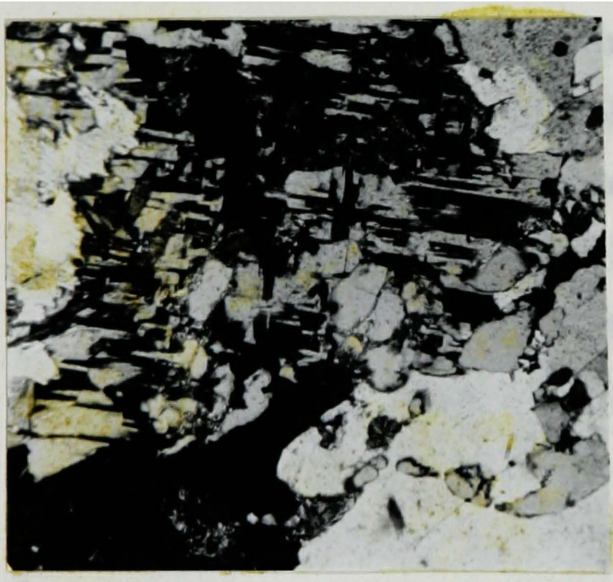


Figure 10. Photomicrograph of rectangular and elongate blotches of albite (black) replacing andesine (white). (70X and crossed nicols).

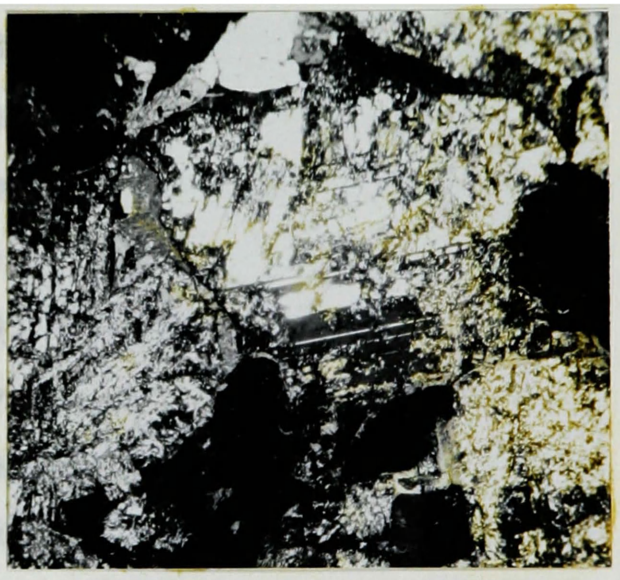


Figure 11. Photomicrograph of saussuritization of plagioclase. Note that twinning is still apparent in the plagioclase. (25X and crossed nicols).

The plagioclase is altered in the coarse zone to saussurite (Figure 11), in which sericite is the most common constituent. The very sodic plagioclases associated with the myrmekite are altered little, as are the calcic plagioclases toward and in the chill zone. Even in the coarse zone sericite and other minerals form less than 5 per cent of the plagioclase. The saussurite fogs up the plagioclase badly, but where grains are oriented perpendicular to the cleavage, it can be seen that the plagioclase is altered only along thin cleavage planes. X-ray diffraction patterns of separated plagioclase failed to indicate the presence of any other minerals in the plagioclase (peaks of quartz from the myrmekite were, of course, present along with the albite and more calcic plagioclase peaks).

X-ray diffraction was also employed to determine the modes of formation of the sodic plagioclases. A graph of exact mole per cent anorthite against the difference in 2θ values for the $1\bar{3}1$ plane and the 131 plane, according to the method suggested by Smith and Yoder (1956, pp. 632-645) has been used to determine whether the albite was a high-temperature or low-temperature polymorph. The results (see Figure 12) show that the albite is the low temperature type, indicating either a deuteric or hydrothermal origin for the sodic plagioclase. The andesine-labradorite from the sill plots on the curve for shallow intrusives.

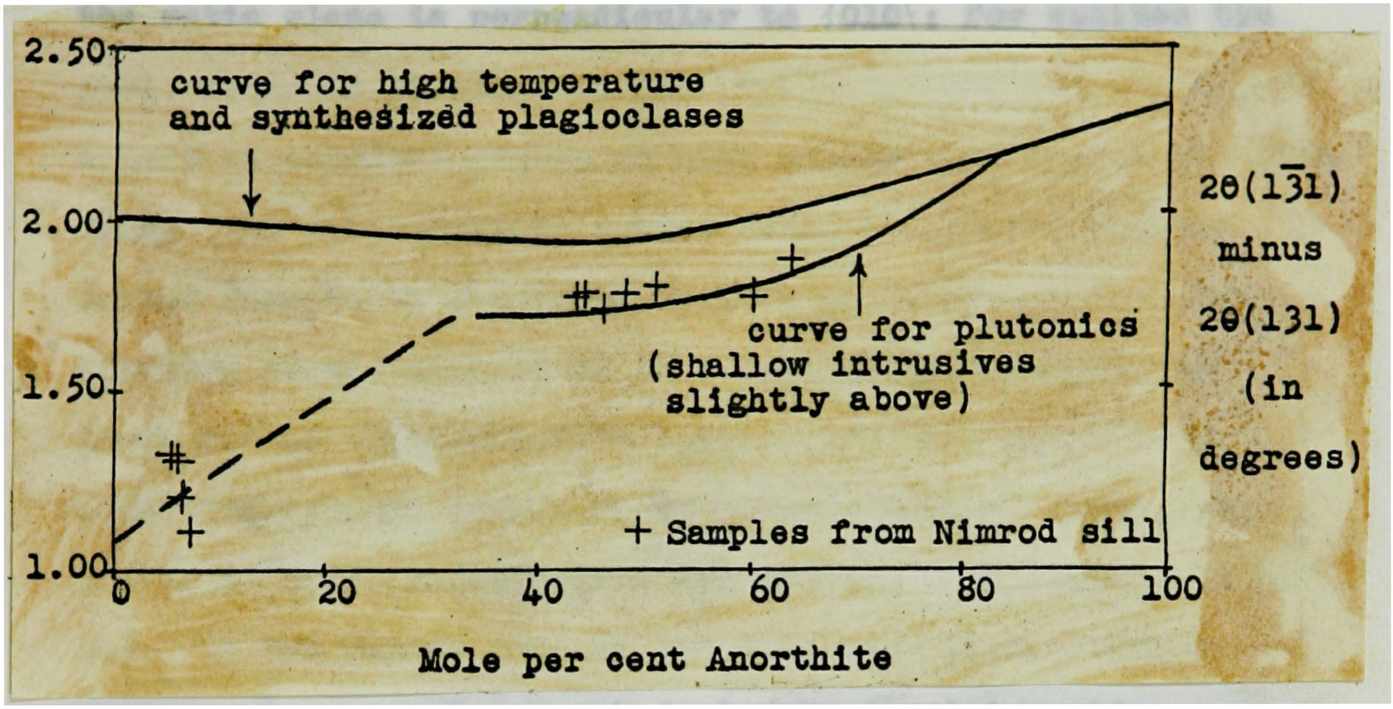


Figure 12. Curves for determining mode of formation of plagioclases (from Smith & Yoder, 1956, p. 641).

Pyroxene

Clinopyroxenes are the only pyroxenes present. On the average the diabase contains 35 per cent pyroxene, varying from 49 per cent in the chill zones to 8 per cent in the coarse zone. Over 90 per cent of the clinopyroxene is pigeonite; the other 10 per cent or less is augite. The augite/pigeonite ratio increases slightly in the coarse zone, but the dominance of pigeonite with its low 2V is striking throughout the sill.

Augite and pigeonite are distinguished from each other by the difference in the optic angle values and by the different orientation of the optic plane; for pigeonites the optic plane is perpendicular to $\{010\}$; for augites the optic plane is parallel to $\{010\}$. In transmitted light both appear as anhedral grains of high relief with a pinkish brown tint. The clinopyroxene grains occur in large irregular masses resembling glomerporphyritic aggregates, often surrounding plagioclase laths in a subophitic texture. In these masses the boundaries between pyroxene grains are indistinguishable except under crossed nicols, where the different optic orientations are obvious (see Figures 13 and 14). In the coarse zone of the sill part of the clinopyroxene becomes almost euhedral; the remaining clinopyroxene occupies interstitial positions as joined anhedral grains, as in the sill proper. No mineralogical distinction can be made here between the large euhedral prisms and the anhedral grains, for both pigeonite and augite occur as anhedral aggregates and as euhedral prisms.

Simple pinacoidal twinning on the $\{100\}$ plane was observed on many of the clinopyroxene grains. Continuous zoning occurs due to progressive enrichment in iron at the expense of magnesium from the center of the grain outward (Moorhouse, 1959, p. 166).

An approximate chemical composition of the different pyroxenes was obtained by plotting the index of refraction (Ny or Nx) against optic angle values on the ternary diagram of H. H. Hess, (1941, p. 585). The resulting diagram shows

Figure 13. Photomicrograph of glomeroporphyritic pyroxene (px). Note high relief of pyroxene. (25X and plain light)

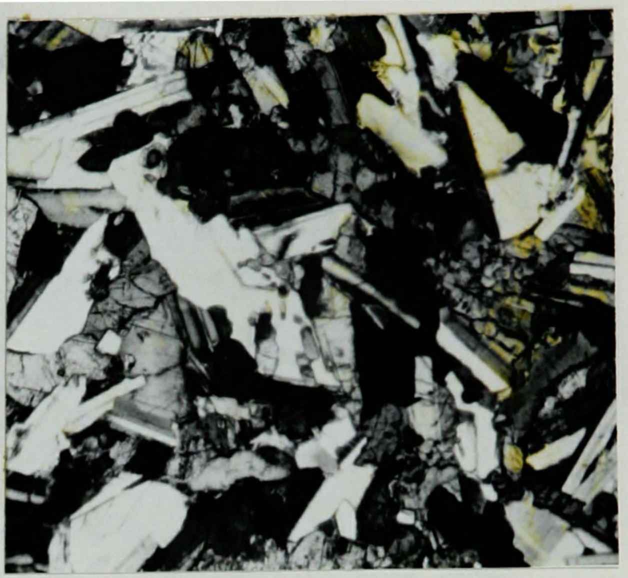
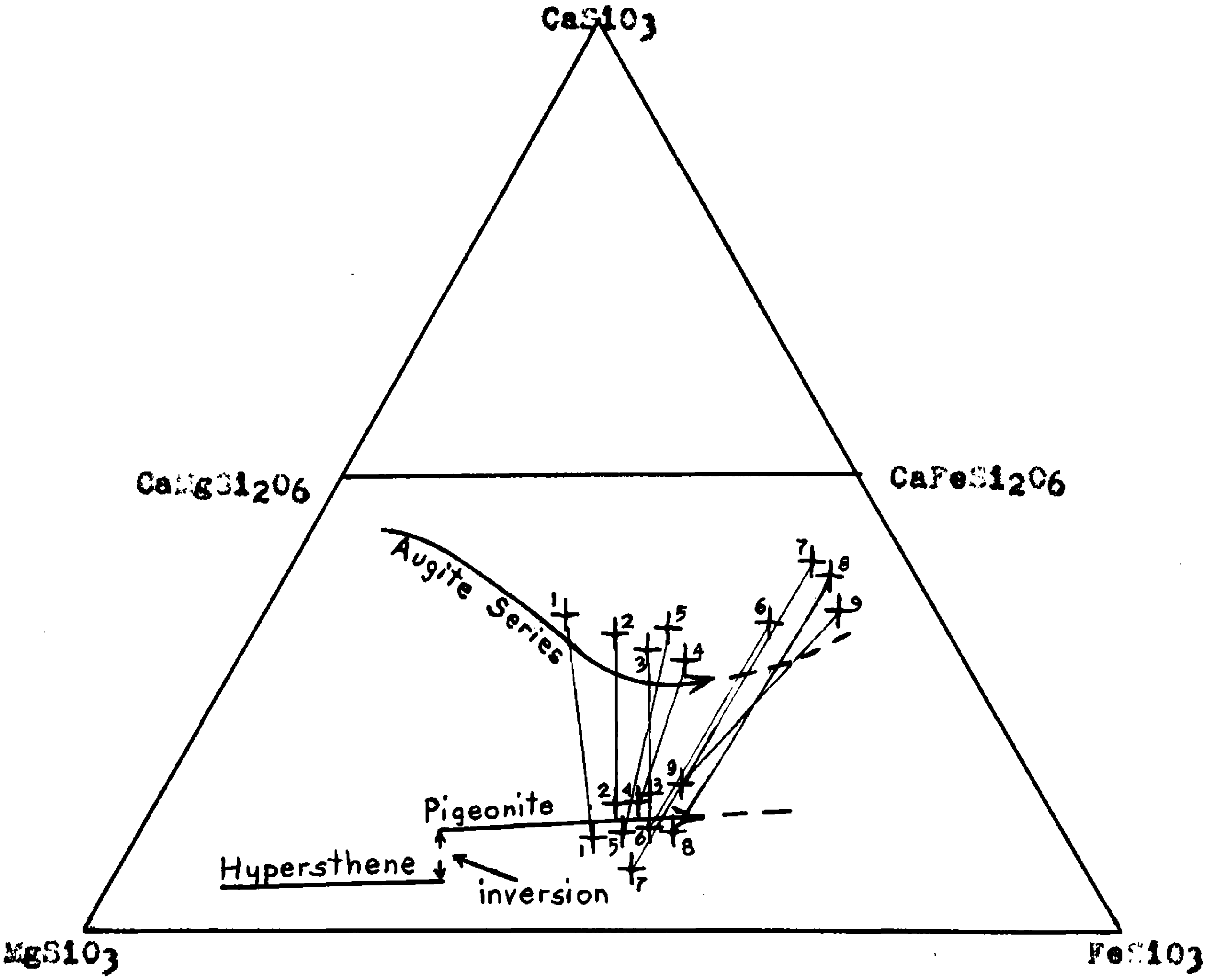
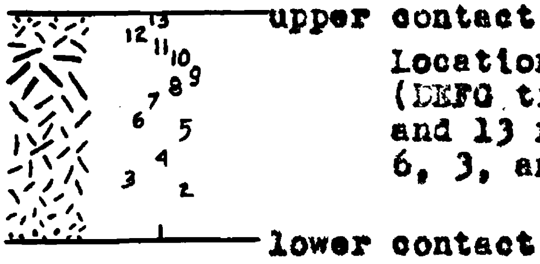


Figure 14. Photomicrograph of same area as Figure 13 with nicols crossed. Note division of pyroxene aggregates into separate grains by polarized light. (25X and crossed nicols).

an enrichment of the pyroxene in iron from the chill zones to the coarse zone. The augite approaches a ferroaugite in the coarse zone. The curves are compared to those of H. H. Hess for normal crystallization in pyroxenes (Hess, 1949). See Figure 15.

Muir (1954, p. 384) states that the pyroxenes do not form a complete solid solution relation with a minimum eutectic point, but the ferroaugites associated with pigeonites become progressively more lime-rich as well as more abundant in the coarse zones of diabases. Note that in





Location of pyroxene pairs in sill (DEFG traverse). Nos. 10, 11, 12, and 13 roughly correspond to Nos. 8, 6, 3, and 1, respectively.

Figure 15. Samples from Nimrod sill with tie lines connecting co-existing augite and pigeonite plotted on a diagram of the normal crystallization course in pyroxenes (after Hess, 1941, p. 585).

Figure 15 points from the Nimrod sill do not approach a minimum eutectic point. There is a slight increase in the augite/pigeonite ratio in the coarse zone of the Nimrod sill.

The absence of an inversion of pigeonite to orthopyroxene in the Nimrod sill is unusual, for in most diabases orthopyroxene is a major constituent in the zones crystallizing early (Turner & Verhoogen, 1960, p. 211). No orthopyroxene has been found in this sill or in the several iron-rich diabases in the area east of Missoula. Eisenbeis, in his work on the Milltown Dam sill, suggests that the original high iron/magnesium ratio of the pigeonite prevented the inversion of pigeonite to orthopyroxene and augite even in the early stages of crystallization (Eisenbeis, 1958, p. 24).

According to Barth (1952, p. 109) pigeonite in hypabyssal rocks which crystallized at a temperature above, at, or slightly below the inversion temperature for clinopyroxene to orthopyroxene (see Figure 16), will invert to orthopyroxene with augite inclusions. This is true for pigeonites rich in magnesium or even with relatively equal amounts of iron and magnesium available for incorporation into the pyroxene lattice. However, in iron-rich magmas, the crystallization will commence at the right hand side of the diagram where the temperature of the magma at crystallization is considerably above the inversion roof. Pigeonite will crystallize out, gradually being enriched in iron. However, until almost all of the magma has crystallized, the temperature of the hypabyssal body may be kept relatively constant by the continual addition of heat to the mass by the heat given off by formation of the crystals. Heat loss occurs constantly, of course, into the surrounding cooler rocks. Finally, with almost complete crystallization, the temperature may drop suddenly past the inversion temperature. The pigeonite, chilled relatively rapidly, does not invert, and remains as a metastable phase. Kuno (personal communication, 1961) stated that even in some plutonics where cooling is relatively slow, pigeonite will not invert if the iron/magnesium ratio is high in the parent magma.

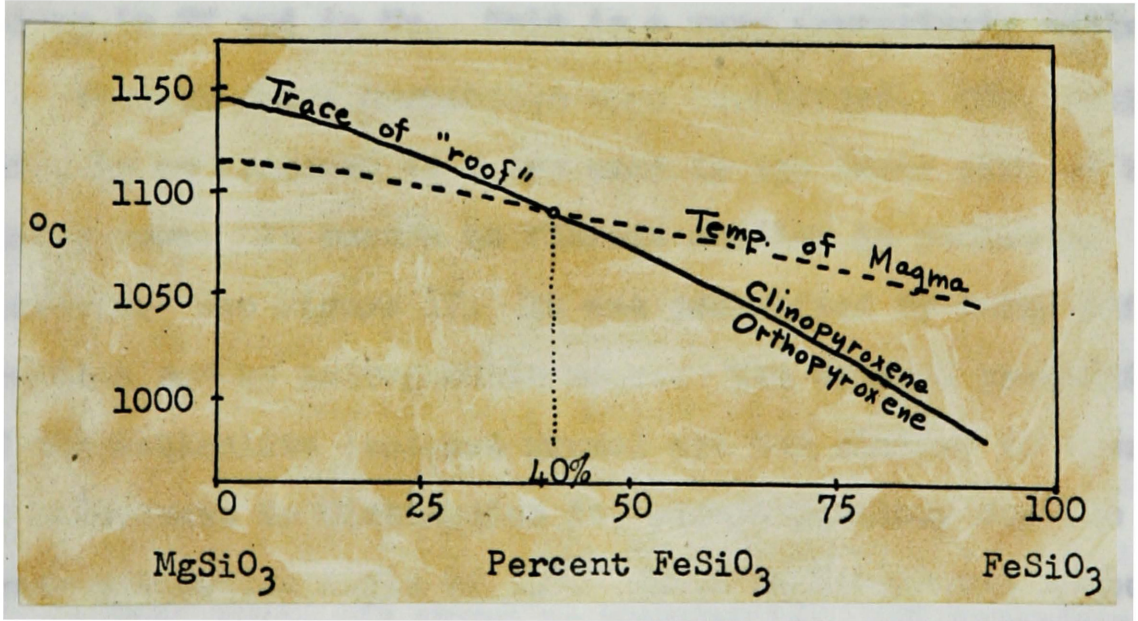


Figure 16. Inversion roof trace compared to temperature of magma (Barth, 1952, p. 109, adapted from H. H. Hess, 1941, p. 583).

Amphibole

Several varieties of amphibole are present, of which hornblende is the most common. Hornblende occurs throughout the sill except in the chill zones. However, it is only a major constituent in the coarse part of the sill where the pyroxene has been partially altered. Hornblende was identified by its $\{110\}$ cleavage, negative sign, large optic angle (averaging 75°) and indices of refraction ($Nz = 1.679$). It is pleochroic from dark olive green (Z) to a very light green-yellow (X), and the extinction angle $Z \wedge C$, averages 23°. The approximate composition of the hornblende $(Ca_{1.4}Na_{0.6})(Mg_{2.1}Fe_{2.1}Al_{0.8})\ Si_{7.8}Al_{0.2}O_{22}(OH)_2$ was found by using the curves of Moorhouse (1959, p. 78) for variations in 2V and in Nz. This is a very approximate estimate.

Several other amphiboles were identified. One, actinolite, is as abundant as 8 per cent in the lower part of the coarse zone. It occurs as fibrous needles in radiating clusters. See Figure 17. It was identified by X-ray diffraction and by petrographic means. The optical properties of the actinolite (colored green) are too similar to those of hornblende to distinguish it, except possibly for its lower extinction angle of 14°. Sodic amphibole was detected by a very blue coloration grading into the more olive color of the hornblende. It occurs in interstices in the coarse zone of the sill. The $X \wedge C$ angle of about 20° and the bright turquoise blue (X) to dark olive green (Z) pleochroism suggest arfvedsonite, a Na-Fe amphibole. However, the cleavage was indistinct, so that the determination was not definite.

Figure 17. Photomicrograph of fibrous actinolite crystals in radiating clusters. (70X and crossed nicols).

Biotite and Chlorite

Biotite occurs in minor amounts in the coarse part of the sill. Occasionally large masses of the highly pleochroic biotite are present. The pleochroism is from faint yellow (X) to dark red-brown (Z). The biotite which often rings ore is very dark. It shows no pleochroism, and interference figures are difficult to obtain. It is lepidomelane, which forms from a reaction of the residuals with ore and characteristically encircles ore (Fenner, 1929, p. 246).

Chlorite is much less common than biotite in the sill. It is associated with actinolite most commonly, both being products of late deuteric alteration of pyroxene and hornblende. The chlorite is recognized by its lower 2V (differentiating it from the green hornblende) and by its lower birefringence and green color (differentiating it from biotite). An anomalous blue interference color is often observed in the chlorite.

Ore

Ore in the sill is most abundant in the chill zones and in the coarse zone. In the latter the ore content exceeds 10 per cent. The ore has been found by X-ray diffraction to consist of approximately 60 per cent magnetite and 40 per cent ilmenite by volume. The ore occurs as large skeletal masses. Often an alignment of many linear plates or triangular-shaped bodies of ore is seen along cleavages of biotite, pyroxene or hornblende. These phenomena are attributed to the deuteric action of an iron and titanium-rich residual liquid on the aforementioned ferromagnesian minerals (Moorhouse, 1959, p. 169).

More rarely, many closely-spaced parallel plates of magnetite can be seen; sometimes two sets of plates cut across each other at an angle of about 120° (see Figures 18 and 19). The material between the plates is either sphene or rutile, alteration products of ilmenite. The thin plate-like grid structure is due to exsolution of originally homogeneous ore with alignment of magnetite plates parallel to the octahedral planes of magnetite (Buddington, 1955, p. 499). The intervening ilmenite then altered to sphene and rutile. According to Buddington (1955, p. 527) a high TiO_2 content of ore is indicative of deuteric activity. The sphene and rutile in the grid structure of the Nimrod sill would, therefore, be late deuteric.

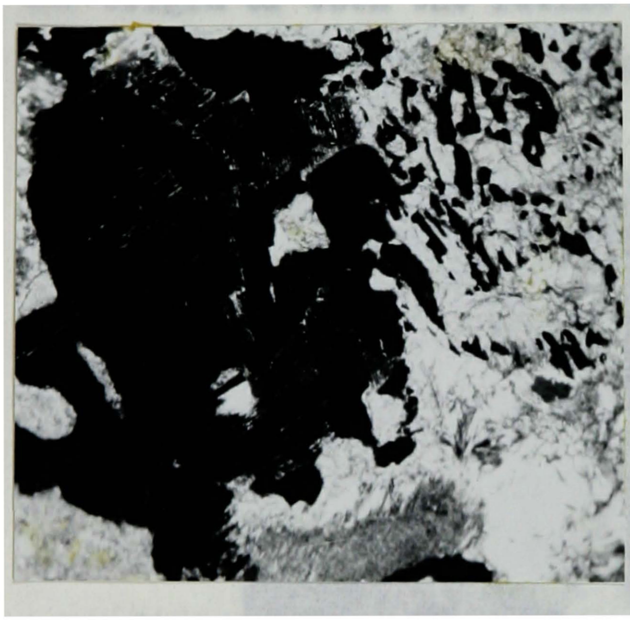


Figure 18. Photomicrograph showing relation of plate-like grid to unaltered ore. Magnetite and unaltered ore are black. Sphene and rutile occupy the lighter part of the grid.

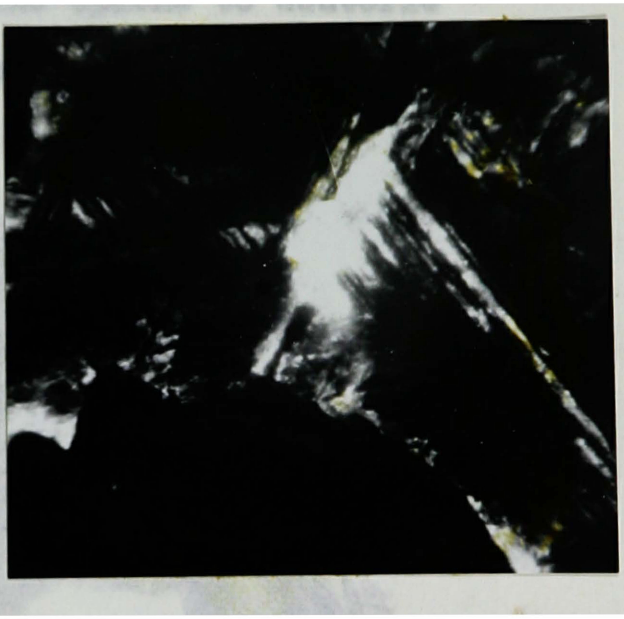


Figure 19. Photomicrograph of plate-like grid in higher magnification. (300X and plain light).

Sphene

Sphene is present in fairly large bodies (1 mm. or so) associated with the ore. It occurs next to an ore bleb or as a mass in which small ore bodies are disseminated in a semi-parallel alignment. It is recognized by extremely high birefringence and relief, a positive biaxial interference figure, relative transparency, and frequent wedge-like form (see Figure 20). According to Kuno (personal communication, 1961) the association of ore with sphene and rutile (often as leucoxene) is not uncommon in diabase sills. Kuno attributes the origin of both the rutile and sphene to deuteric alteration of exsolved ilmenite.

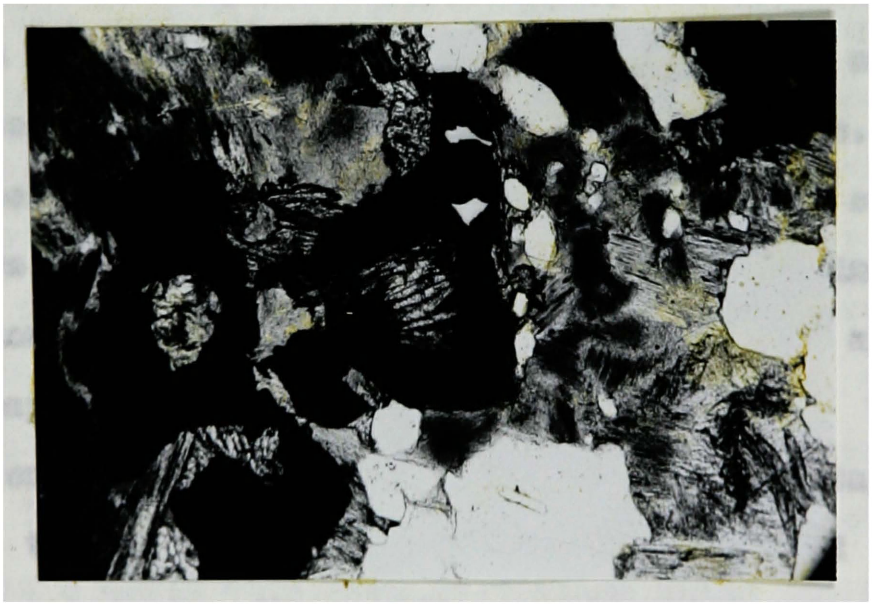


Figure 20. Photomicrograph of wedge-shaped crystals of sphene associated with ore. Note aggregate of wedge-shaped crystals surrounded by ore. (70X and plain light).

Rutile

Rutile was recognized by its uniaxial positive interference figure, a deep red-brown color, and high relief. It occurs as cloudy brown masses between magnetite plates associated with sphene.

Quartz

Quartz appears intergrown with sodic plagioclase in myrmekite or, less commonly, as isolated anhedral grains. It is recognized by its low relief, positive uniaxial interference figure, and a maximum interference color of first order yellow. The quartz is unaltered.

Apatite

Apatite is ubiquitous in the sill. It becomes more common in the coarse zone, approaching 2 per cent of the mineral content in some thin sections of that zone. Apatite occurs as long needles of hexagonal cross section. It appears as inclusions in all of the silicate minerals, most commonly in plagioclase and quartz, and long apatite needles may penetrate several different crystals. The terminations are rarely well developed and often taper to a point; the hexagonal basal section is sharp and decidedly euhedral. The apatite was identified by its uniaxial negative interference figure and its low birefringence. Small apatite peaks were found on diffraction patterns of the non-magnetic minerals of the coarse zone.

PARENT MAGMA

The composition of the parent magma of the Nimrod sill was approximated by using a "wet" chemical analysis (Table I, #1) and the average chemical composition from modes (Table I, #2). The "wet" chemical analysis was one of three performed by Technical Service Laboratories on samples from the Nimrod sill. A sample of chilled diabase, 3 inches from the lower contact, was used to approximate the chemical composition of the magma before fractional crystallization changed the composition.

From the modes of samples of diabase the approximate chemical compositions were found. Minerals have been identified by petrographic and X-ray means, and approximate chemical compositions of the individual minerals were found using different curves of chemical variation as a function of optical properties, as cited in text (see pages 15 and 20). Mineral volume percentages were obtained by point count methods. The weight percentages and chemical composition of the rock as a whole were then calculated using the method suggested by Wahlstrom (see page 56). The average chemical composition of the sill (Table I, #2) was computed by averaging the composition of equidistant points along traverse DEFG.

The chemical analysis and composition from mode agree favorably (see Table I). Several discrepancies can be explained. The higher percentage of iron and magnesium and

TABLE I. Chemical compositions of Iron-rich Tholeiitic Rocks

	1.	2.	3.	4.	5.	6.	7.
SiO_2	48.61	46.84	45.44	46.9	45.73	45.87	50.83
Al_2O_3	14.23	12.61	13.69	14.1	14.68	10.66	14.07
FeO	14.33	15.81	15.12	15.0	15.83	15.59	9.00
Fe_2O_3	2.97	4.41	6.06	3.6	2.85	4.11	2.88
MgO	3.27	5.52	7.60	4.0	4.18	3.50	6.34
CaO	9.90	7.56	6.15	9.5	8.38	8.28	10.42
Na_2O	2.00	2.61	2.20	3.00	3.71	2.84	2.23
K_2O	0.71	0.32	0.70	0.40	0.27	0.96	0.82
TiO_2	2.90	3.25	2.43	2.65	3.90	1.89	2.03
H_2O	0.32	0.54	0.31	*	0.55	4.65	0.91
P_2O_5	0.31	0.23	*	0.50	0.09	1.70	0.23
MnO	0.19	*	*	0.20	0.22	*	0.18
Total	99.74	99.70	99.70	99.75	100.39	100.05	99.94

1. Chemical analysis (by Technical Service Laboratories, Toronto, Ontario) of sample G-34 taken 3 inches from lower contact of Nimrod sill (location given in Figure 23, page 63). Probably close to composition of Nimrod sill magma.
2. Average chemical composition of samples from Nimrod sill as calculated from 20 modes.
3. Average chemical composition of samples from Milltown Dam sill as calculated by Eisenbeis (1958, p. 38) from modes.
4. Composition of Skaergaard liquid at middle point of zone L.MZ where 88 per cent of magma had already solidified (Wager, 1960, p. 386).
5. Ferrogabbro from Skaergaard intrusion (Wager,1960,p.370).
6. Iron-rich diabase, Beaver Bay, Minnesota (Muir, 1954, p. 285).
7. World average of normal tholeiitic basalt (Nockolds, 1954, p. 1021).

* Not given

lower percentage of calcium in the calculation from the mode (#2) compared with the chemical analysis (#1) may well be partly due to errors in the mode pigeonite/augite ratio. The clinopyroxenes were indistinguishable under the petrographic microscope except for those grains oriented such that 2V measurements could be made. Only one-fourth of the grains could thus be distinguished. Determination of 2V on the universal stage was even more difficult, as the high dispersion of the clinopyroxene greatly limited the number of grains that could be used. Calculation of the norm from the chemical analysis (see Table II) indicates the single clinopyroxene $Wo_{24}En_{28}Fs_{48}$. The average single clinopyroxene present using the 85/15 pigeonite/augite ratio from thin sections is $Wo_{12}En_{36}Fs_{52}$. A 60/40 pigeonite/augite ratio would result in a single pyroxene quite close in composition to the normal pyroxene calculated from the chemical analysis.

The pyroxene ratio can thus partly account for the lower Ca and higher Mg and Fe in calculations from the mode. The common substitution of aluminum for silicon in pyroxenes and the substitution of Mn^{+2}, Ti^{+2}, and Fe^{+3} in the pyroxene lattice also contribute to the difference between calculations from mode and chemical analyses. The higher K_2O and lower Na_2O in the chemical analysis than in calculations from the mode may be partly due to the presence of orthoclase molecules in solid solution in albite.

The accuracy of chemical calculations from modes is not high (see page 57). Therefore, reasonable differences are to be expected between calculations from modes and chemical analyses.

The chemical composition of the Nimrod sill is compared to the composition of other tholeiitic type rocks in Table I. The Milltown Dam sill (Table I, #3) is an iron-rich diabase 100 feet thick, which intruded Precambrian Belt metasediments twenty miles west of the Nimrod sill. Note the similarity in chemical composition. The mineralogy of the two sills is strikingly similar (see page 51). The two sills are probably genetically related. A striking similarity may be noted between the oxide percentages of the Nimrod sill magma and those of the Skaergaard liquid at zone L.MZ (Table I, #4). This Skaergaard zone represents the composition of the residual magma after 88 per cent of the initial magma had crystallized. Wager (1960, p. 386) estimated the composition of the successive residual magmas formed as a result of the crystal fractionation of the initial Skaergaard magma. The rock type which most closely follows the chemical composition of the residual Skaergaard liquid at L.MZ stage and the Nimrod magma is a ferrogabbro. The ferrogabbro from the Skaergaard intrusion which most closely follows the chemical composition of the Nimrod magma is one which crystallized from the liquid left after 96 per cent of the initial magma had crystallized (Table I, #5). An iron-rich diabase in Minnesota (Table I, #6) is also compared to the Nimrod sill magma.

Comparing the Nimrod, Milltown and Beaver Bay diabases and the later Skaergaard residual magma and ferrogabbro with the world-wide average for normal tholeiitic basalt (Table I, #7), one can observe a pronounced difference in the FeO and SiO_2 content but otherwise general concordance in composition.

The 5 per cent difference in iron oxide in the iron-rich diabases and the later Skaergaard magma compared to average tholeiitic diabases is balanced, on the average by a lower SiO_2, MgO, and CaO content. The high H_2O content of the Beaver Bay diabase is due to later alteration (Muir, 1954, p. 286). The iron-rich diabases and the ferrogabbros of the Skaergaard intrusion are thought by Muir (1954, p. 376) and Wager (1960, p. 364), respectively, to be derivatives of tholeiitic magma. Calculations of norms of the Nimrod magma support the presence of normative quartz (see page 48), despite SiO_2 content lower than normal tholeiitic magma. Because normal pyroxene and calcic plagioclase with slight SiO_2 excess are the principal mineralogical features of tholeiitic normative calculations, I would consider the parent magma of the Nimrod sill to be an iron-rich tholeiitic melt.

Fenner (1929, p. 245) believed that the result of crystallization of basalts was a final liquid rich in iron and alkalis and poor in silica, magnesia, and lime. This was contrary to Bowen's earlier hypothesis of evolution of tholeiitic magma into rhyolitic and granophyric differentiates (Bowen, 1928, p. 318). Wager (1960, pp. 382-387) has shown that the successive residual magmas of the Skaergaard complex become increasingly enriched in alkalis and iron oxide (reaching 30 per cent total iron oxide in the late UZ zone), with SiO_2, MgO, and CaO steadily decreasing. The close chemical affinity in composition of a late residual Skaergaard magma and the parent magma of the Nimrod sill has already been demonstrated. The Nimrod parent magma would then seemingly have been derived from an original tholeiitic magma which, by fractional crystallization, followed a course of differentiation similar to that followed by the Skaergaard intrusion, that is, an iron-enrichment, Fenner-type course. The residual magma (Nimrod parent magma) was tapped at a stage where probably 90 per cent of the original normal tholeiitic magma had crystallized.

Kennedy (1955, p. 501), by remelting and crystallizing natural basalts in crucibles, discovered that the same basalt could be made to follow a Bowen trend of differentiation (enrichment of residual liquids in alkalis and silica), or follow a Fenner trend with iron enrichment, depending on the partial pressure of oxygen under which the melt is crystallized. If the basalt crystallized under a modest P_{O_2} much of the iron in the melt would be converted from Fe^{+2} to Fe^{+3} and the first phase appearing would be spinel. Spinel crystallizes early and in great abundance, thus impoverishing the liquid in both Fe and Mg, consequently enriching the melt in

SiO_2. The basalt thus differentiates toward a diorite and granite (Bowen-type differentiation). If the basalt has an extremely low P_{O_2}, the FeO is not oxidized, and spinel does not form. The first phases to crystallize are Mg-rich olivine and anorthite (Mg-rich diopside could also appear); consequently very little iron is extracted by the early forming phases, and thus Fe is concentrated in the residue magma. The trend toward production of an iron-rich (Skaergaard-type) residue is established.

Kennedy emphasizes the FeO/Fe_2O_3 ratio as the deciding factor in the trend of differentiation (whether or not spinel appears in abundance as an early forming phase). Osborn (1959, p. 609), emphasizes the constancy of water pressure and thus of P_{O_2} in determining the trend of differentiation. With fractional crystallization occurring at constant total composition the liquid moves toward and finally down the magnetite surface in the quaternary system, $MgO-FeO-Fe_2O_3-SiO_2$. The liquid decreases in amount and its iron oxide content increases relative to other components, with magnetite as one of the crystallizing phases. At the same time P_{O_2} decreases. On the other hand, with fractional crystallization at constant oxygen partial pressure, the liquid must remain on the isobaric surface and change in composition when magnetite begins to crystallize. The liquid moves along the magnetite surface increasing in SiO_2 and decreasing in FeO until it reaches the pyroxene-magnetite-silica univariant line where it completes its course of crystallization. The initial FeO/Fe_2O_3 ratio does not affect the direction of differentiation after the magnetite surface is reached.

Osborn also distinguishes the two courses of differentiation by environment of differentiation (1959, p. 645). The "Bowen" course of differentiation occurs in an orogenic region where the magma picks up water easily from geosynclinal sediments to maintain a constant partial pressure of oxygen, and because of depth magma differentiation can occur more readily due to the slower rate of cooling. The basalt, andesite, dacite and rhyolite suite occurs in orogenic regions as a result of the increasing content of silica in residual magmas with differentiation. In non-orogenic regions the partial pressure of oxygen decreases as the total magma composition remains constant. There would generally be no continual source of water to maintain a constant P_{O_2} as in orogenic regions. The trend toward iron enrichment with little change in total silica as differentiation proceeds results in the production of ferrogabbro-type magmas, as in the Nimrod sill.

The Nimrod sill was probably emplaced in a non-orogenic environment prior to the late Cretaceous orogeny of the region. Deformation of a similar sill near Clinton (Hintzman, 1961, p. 12) and tectonic fractures in the diabase indicate that these sills were emplaced prior to the late Cretaceous orogeny which produced the major structures in the region.

Maxwell (1959, p. 1783), noting differences in bedding point diagram patterns between Belt and Paleozoic rocks, suggests that the Belt Series near Drummond, Montana, was tilted and warped prior to deposition of Cambrian sediments. The age of tilting and tectonic jointing in the Nimrod sill may thus possibly be late Precambrian, Cretaceous, or both. There are extrusive basalt, dactite, and rhyolite flows in this region, which covers the sill in places. These extrusives are Tertiary in age according to Montgomery (1958, p. 58). This extrusive rock suite is Osborn's orogenic type.

CHEMICAL VARIATIONS WITHIN THE SILL

A complete traverse (DEFG) was taken perpendicular to the attitude of the sill, mainly to discover if there were any vertical chemical variations in the residual melt as the sill crystallized from the chill zones inward. Thin sections and mineral grains from traverse C and traverse M (located one-half and two miles east of DEFG respectively) were compared to the DEFG modes to see if there were any significant lateral changes in the sill. Significant lateral variations were found only in areas of hydrothermal pods described above.

Figure 21 shows percentages of separate element oxides plotted against vertical position in the sill along traverse DEFG. The left hand side of the diagram represents the lower contact; the right hand side represents the upper contact. The middle of the coarse zone would be located one-fourth of the way down from the top of the sill, hence one-fourth of the distance from the right hand side of the diagram. Crosses represent oxide per cent as calculated from modes. (1.125 inches on the chart represents 100 feet measured perpendicular to attitude of sill). Circles with centers are averages of two wet chemical analyses on each of three samples. (See Table IV, page 63 for the analyses performed by Technical Service Laboratories.) The chemical analysis of a sample at the lower contact is considered roughly the average composition of the sill. A dashed line is carried from the per cent value of this analysis across each chart. A rough curve could be formed by connecting the crosses. The area between the curve and the dashed line is considered a positive area if above the curve, negative if below. The algebraic sum of the positive and negative areas for a given chart is herein designated the area difference. When the area difference is significant a consistent error in calculating composition from mode may exist. The most obvious explanation would be an error in the assumed composition of one or several minerals.

The following generalizations may be noted from the vertical chemical variations:

The SiO_2 content increases from contacts toward the coarse zone due to an increase in the per cent of plagioclase, quartz, and hornblende and reduction in pyroxene, which is more SiO_2-poor, and iron ore. In the coarse zone itself the SiO_2 content is low. This is due to the lower content of plagioclase and other silicates and the quite high ore content. The area difference is approximately zero.

The Al_2O_3 content increases from the contacts toward the coarse zone, and drops suddenly in the coarse zone. Its path roughly parallels that of SiO_2, and is a good indicator of the variation in plagioclase because it is only a minor constituent of the ferromagnesian minerals compared to SiO_2. The area difference is negative. Al_2O_3 in pyroxene was not calculated, although some is certainly in the lattice.

The exact content could not be determined by petrographic or X-ray means. Hence, the Al_2O_3 content from modes is lower than it should be.

The Fe_2O_3 content is an immediate indicator of ore content because it was only calculated from ore. It decreases from the contacts, then increases to over 7 per cent in the coarse zone where the extremely iron-rich residual liquids concentrated in the larger interstices and finally crystallized, producing large skeletal masses of ore. The area difference is positive. In point counting there is a tendency to term most opaque substances "ore" whereas some may be highly colored lepidomelane (opaque at times) and rarely sulphides.

The FeO content decreases from the contacts as ore and ferromagnesian content decreased. It is high in the coarse zone due to high ore content there. The area difference is positive. Probably less FeO and more CaO and Al_2O_3 should be calculated from pyroxene because of discrepancies in augite composition and content.

The MgO content decreases from the contacts toward the coarse zone due to the decreasing amount of ferromagnesian minerals toward the coarse zone and the increasing Fe/Mg ratio which exists in the pyroxene crystal lattices as the temperature of crystallization falls. Mg^{+2} has the greater lattice energy at higher temperatures, while Fe^{+2} has greater lattice energy at lower temperatures. Therefore, Fe^{+2}

Figure 21. Vertical variations of element oxides in Nimrod sill.

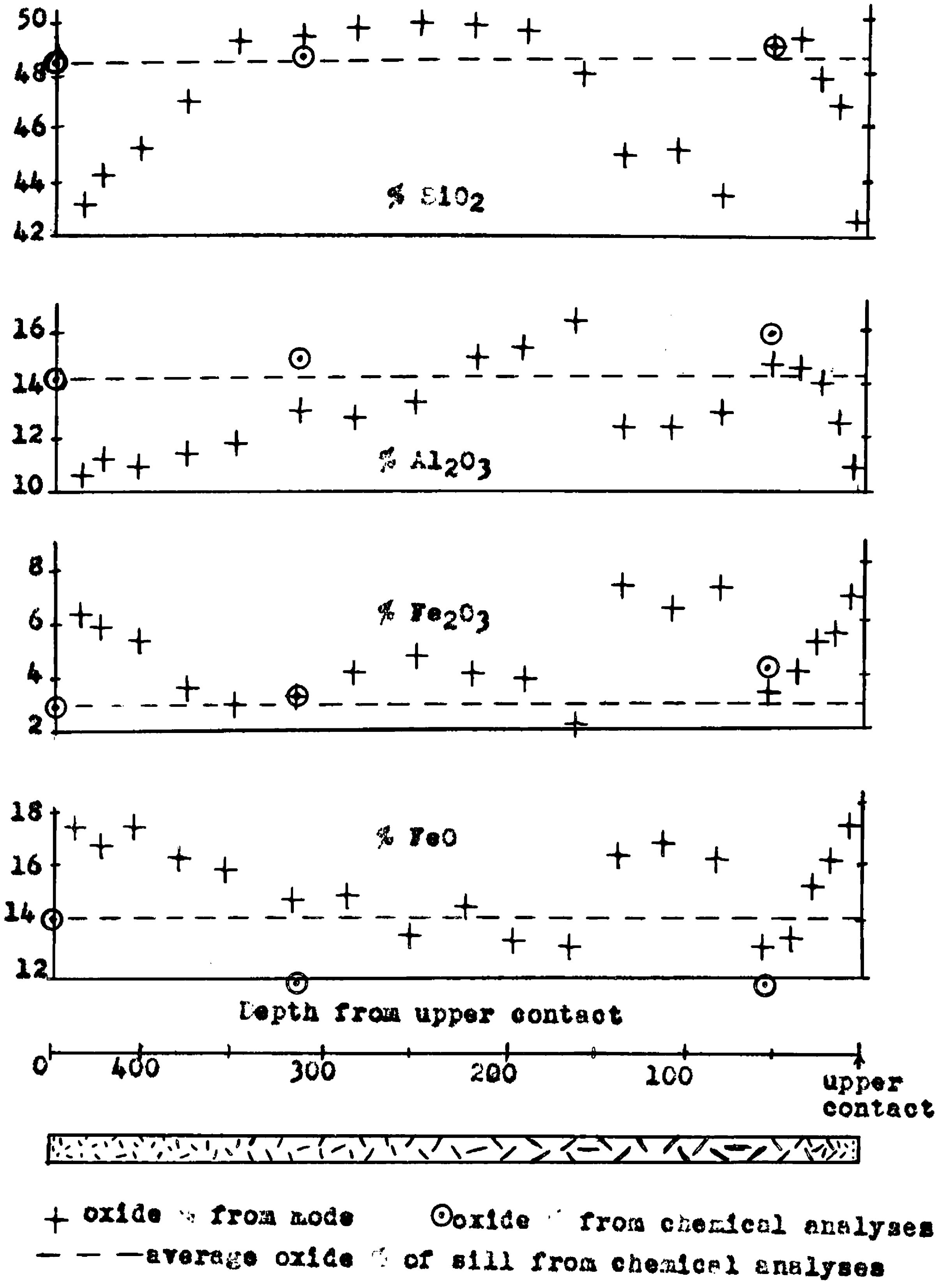


Figure 21 (contd.) Vertical variations of element oxides in Nimrod sill.

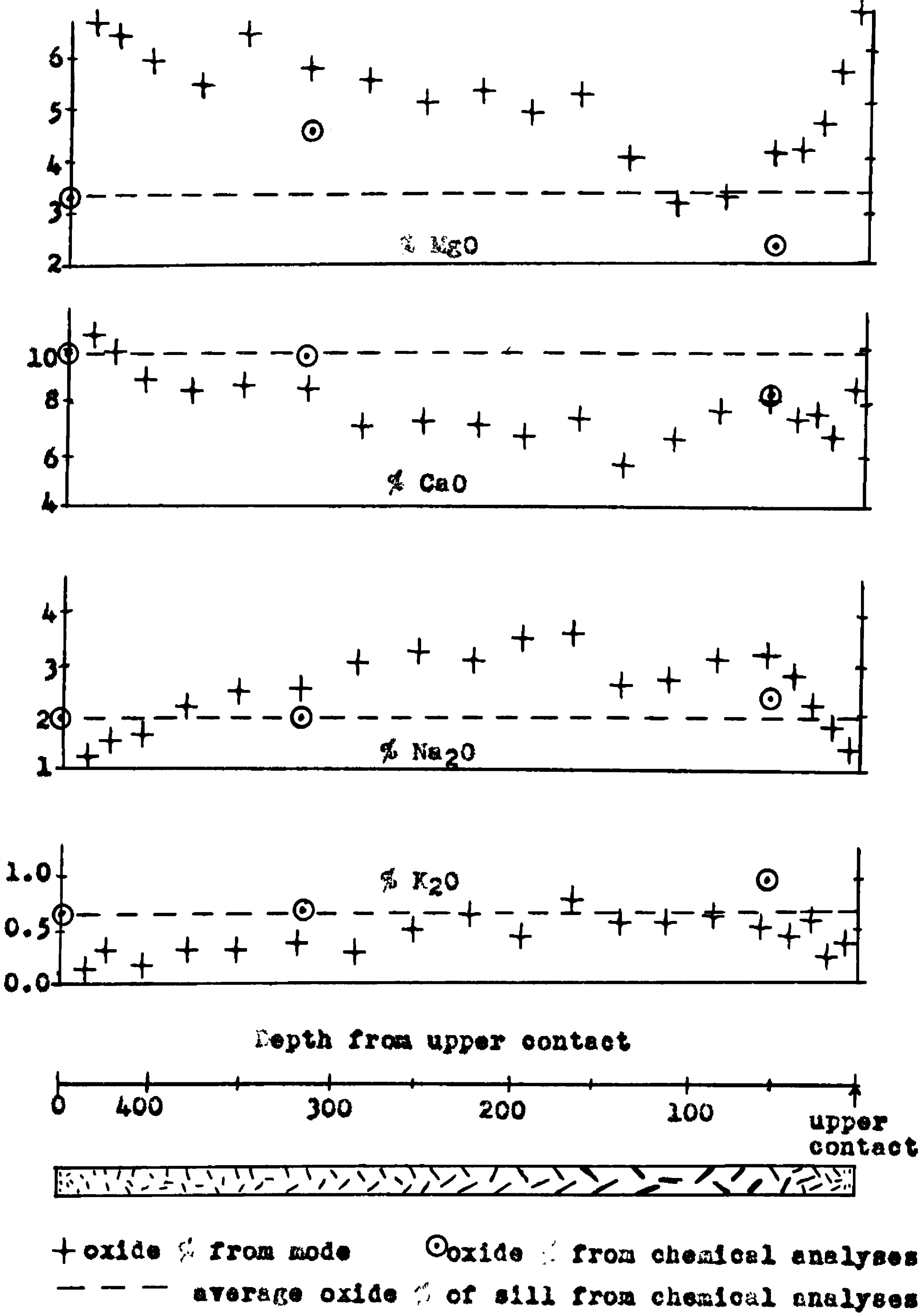
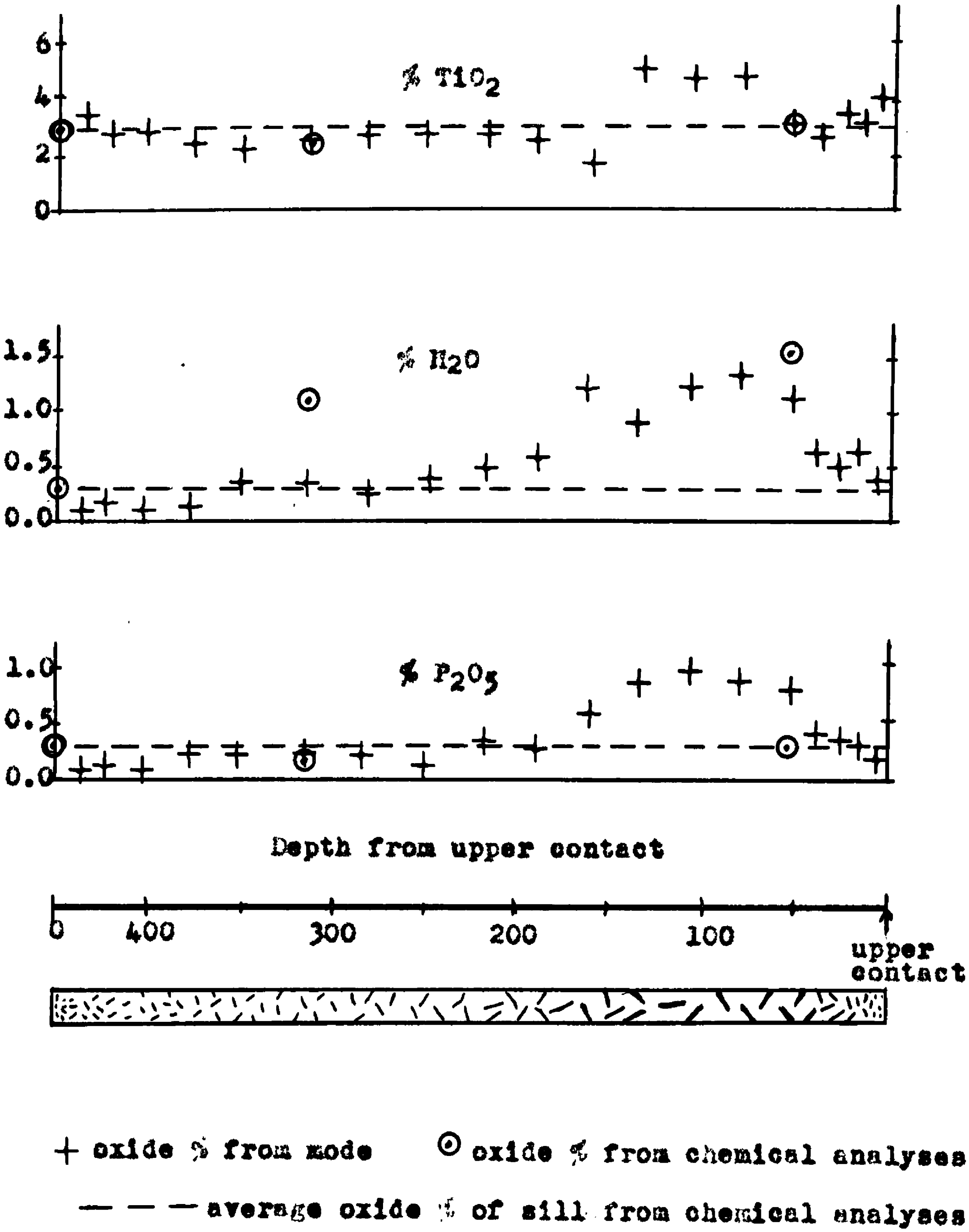


Figure 21. (contd.) Vertical variations of element oxides in Nimrod sill.



increasingly substitutes for Mg^{+2} as temperatures of crystallization fall. The area difference is positive. The excess MgO accounted for in calculations from mode may well be due to an error in estimating the ratio of augite to pigeonite (see page 28) as well as errors in determining the pyroxene. In the ferroaugite field fairly exact determinations by optical properties are difficult because of the small differences in 2V in those pyroxenes. The average pyroxenes may well be much more calcic, less ferrous, and much less magnesium-containing than assumed for calculations.

The CaO content decreases from contacts to coarse zone due to a decrease in the anorthite content of the plagioclase and a decrease in ferromagnesian minerals. The area difference is negative. Higher CaO content in pyroxenes than was assumed for calculations from the mode would partly account for the difference.

The Na_2O content increases steadily from the contacts toward the coarse zone. In the coarse zone it is somewhat lower than in the diabase above and below it. The increasing per cent of the albite molecule in solid solution in plagioclase from the contact to the coarse zone and the decreasing amount of total plagioclase in the coarse zone would account for variations. This variation may also be partly due to presence of the orthoclase molecule in albite of myrmekite. The area difference is somewhat positive.

The K_2O content increases somewhat toward the coarse zone due to an increasing amount of biotite and sericitization of plagioclases toward the coarse zone. The area difference is somewhat negative. Additional K_2O not used in calculations may be accounted for by the partial substitution of the orthoclase molecule for the albite molecule in the myrmekite and the greater per cent of opaque lepidomelane instead of ore.

The TiO_2 content decreases somewhat toward the coarse zone then increases in the coarse zone, again due to the decrease in ore toward the coarse zone and higher ore content in the zone itself. The area difference is approximately zero.

The H_2O content gradually increases toward the coarse zone. The higher content of biotite, sericitization of plagioclases, and alteration of pyroxene to hornblende toward, and in the coarse zone would account for the increasing H_2O. The area difference is positive. Sericitization in the coarse zone may have been over-emphasized in calculations from modes (see page 13). However, chemical analyses of the ferrogabbros indicate an even greater amount of water. If these analyses are correct, then the average in the Nimrod sill must be too low.

The P_2O_5 content increases gradually and becomes high in the coarse zone. This is attributed to the increasing amount of P_2O_5 in residual liquids in the sill and the final concentration of these residuals in the larger interstices of the coarse zone. Wager (1960, p. 386) uses the P_2O_5 content as a means of estimating the proportion of trapped liquid to the rest of the material of the rock. The more trapped liquid, the greater the deuteric action. The great deuteric activity in the coarse zone of the diabase (sericitization of plagioclase, alteration of pyroxene to hornblende, and the larger ore and myrmekite content) attests to the validity of using increasing P_2O_5 content as a measure of deuteric activity. The area difference is approximately zero.

It may be observed that the above variations follow the normal trend for diabases from the chilled zone toward the coarse zone. According to Walker (1942, pp. 1067-1076), Turner and Verhoogen (1960, pp. 209-217), and Hess (1941, pp. 584-591), during the normal course of crystallization of a basalt the later formed crystals of pyroxene have a greater Fe/Mg ratio than the earlier formed crystals near the chill zones, and the later formed plagioclase (according to Walker, and Turner and Verhoogen) is enriched in sodium relative to calcium. The latter two sources also point out that plagioclases increase and ferromagnesian minerals decrease toward the coarse zone. Such mineralogical trends would tend to cause chemical variations as found in the Nimrod sill from the contact toward, but not in, the coarse zone.

In the coarse zone of the Nimrod sill, the decrease in silica and general decrease in other oxides, except iron and alkalis are deviations from the normal crystallization in diabases according to the above authors. This suggests a Fenner-type trend resulting from the greater size and amount of interstices where the final residuals were concentrated and then crystallized as iron ore, myrmekite, apatite, biotite, and hornblende which occurs also as an alteration of pyroxene.

Plotting a Fe-Mg-alkali diagram (see Figure 22) one notes that owing to the greater iron content of the diabase it does not follow the diabase to granophyre curve but runs parallel to it. In that position it follows the trend of differentiation of the Skaergaard intrusion which tended toward iron enrichment, except in the very last stages. Note that point A, the approximate composition of the magma, lies between points B and C. Point B is from differentiated diabase in the lower half of the sill. Point C is near the coarse zone and represents a later stage of differentiation than point B.

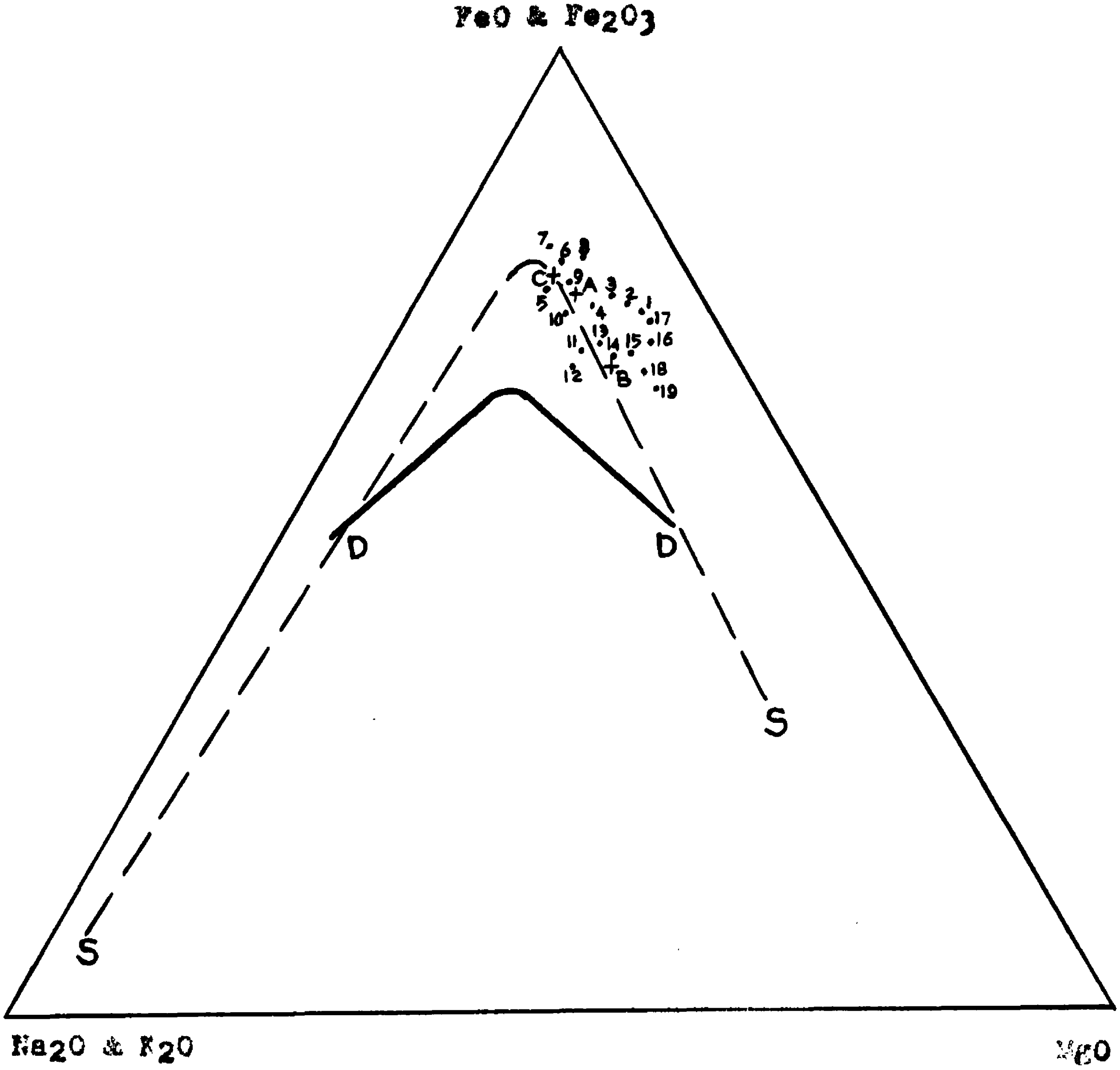


Figure 22. Variation in Skaergaard ferrogabbro series (SS) and in diabase to granophyre series (DD). Numbered points 1 through 19 represent chemical calculations from modes of samples D-1 through G-31 respectively (see page 62). Points 6 through 9 are from the coarse zone of the sill, 1 is near the top of the sill, and 19 is near the bottom of the sill. Point A is from a chemical analysis of the chilled contact (G-34); point B is a chemical analysis of G-11 (point 14) and point C is a chemical analysis of D-11 (point 5). Curves are from Turner and Verhoogen, 1960, p. 234.

VOLATILE PRESSURES

The temperature and pressures of volatiles of the Nimrod magma at crystallization can be estimated. McFarlane's work on the metamorphism of coals by sills in Colorado suggests that the temperatures of basaltic (diabase) intrusions was above 1000°C. (McFarlane, 1929, p. 11). According to Lovering (1955, p. 262), the temperature of diabase could well have been at essentially the temperature of basaltic lavas on extrusion at the surface. Measured temperatures on the earth's surface of crystallizing basalt are in the range 1050°C. to 1200°C. The probable temperature of the Nimrod magma at crystallization is considered to be within this range, and probably close to 1150°C.

The pressure of volatiles was computed using Kennedy's work on equilibrium between volatiles and iron oxides (Kennedy, 1948, pp. 529-549). The ratio of Fe^{+3}/Fe^{+2} depends on P_{O_2} with which the melt is in equilibrium. In the equation

$$2Fe_2O_3 \rightleftharpoons 4FeO + O_2$$

the dissociation constant (Kd) is equal to the activity of the right hand side divided by that of the left hand side:

$$Kd = \frac{(\mu FeO)^4 \ (\mu O_2)}{(\mu Fe_2O_3)^2}$$

For solutions dilute in iron the activities of molecules in the melt are proportional to the mole fraction. The activity of O_2 is directly proportional to the external pressure of O_2. The value of P_{O_2} may then be determined using the revised equation below, the value of Kd at various temperatures having been determined experimentally for iron oxides in a melt of basaltic composition (Table in Kennedy, 1948, p. 536).

$$Kd = \frac{(\text{mole frac. FeO})^4 \; (P_{O_2})}{(\text{mole frac. Fe}_2\text{O}_3)^2}$$

Because the partial pressure of O_2 is a function of total volatile pressure, total volatile pressure can be computed extrapolating in Kennedy's table of partial pressure versus total volatile pressure (Kennedy, 1948, p. 547).

Calculations were made using the above formulas on the iron oxide content from chemical analyses of two fresh samples of Nimrod diabase. The sample (G-34) from the chilled contact indicated a pressure of approximately 30 atmospheres. A sample (G-11) 135 feet above the lower contact indicated a pressure of 250 atmospheres. Sample (D-11) was not used because it contains a large amount of ore and pyroxene which crystallized under different conditions. It would thus be inaccurate to use FeO/Fe_2O_3 total ratios, as the individual ratios would be quite different. Temperatures assumed were 1150°C. Kennedy (1948, p. 548) estimated the pressure of fresh gabbro from southern California to be of the order of 250 atmospheres. Although G-11 is not gabbroic in texture, it is fairly coarse grained diabase. According to Kennedy (1948, p. 548), errors in chemical analyses of iron oxide are common due to oxidation of FeO to $Fe2O_3$. No generalization could be made concerning the depth of crystallization due to the great differences of total volatile pressures within the sill.

NORM CALCULATIONS

Norm calculations were performed according to Niggli's modifications of the CIPW method (Barth, 1952, pp. 76-82). Table II consists of norms from different parts of the sill calculated from chemical compositions obtained by "wet" chemical analyses and by calculations from modes. These are compared to the norm of the world average of normal tholeiitic basalt and dolerite. Note that despite the low SiO_2 content of the sill, it has normative quartz except in the lower part of the sill. No modal olivine was found; however, modal olivine and probable normative olivine are not uncommon as a minor constituent in the lower part of differentiated diabase sills (Turner and Verhoogen, 1960, p. 210). The parent magma, although iron rich, was thus slightly over-saturated in silica. The high iron content is used in ore and ferrosilite rather than in fayalite. In the coarse zone the ore is quite abundant. Therefore, despite a silica content in the coarse zone lower than most alkali olivine basalts, no normative olivine is found (see Table II, #5).

Discrepancies may be noted between norms from "wet" chemical analyses and from calculations from modes. The orthoclase and anorthite contents are higher due to higher K_2O and Al_2O_3 percentages in the chemical analyses. This is partly due to orthoclase in solid solution in albite, a probable higher content of lepidomelane (to account for more K_2O) and the presence of the Al_2O_3 molecule in pyroxene.

TABLE II. Norms of Diabase

	1.	2.	3.	4.	5.	6.	7.
Apatite	0.6	0.5	0.8	0.5	0.9	0.4	0.5
Ilmenite	4.5	4.2	4.4	4.8	7.2	4.6	3.8
Orthoclase	1.5	4.5	1.8	6.0	2.5	1.5	5.0
Albite	23.0	19.0	29.0	23.0	27.0	17.0	18.9
Anorthite	24.4	29.0	26.5	31.9	24.0	22.3	25.9
Magnetite	5.4	3.4	4.2	4.8	8.4	6.6	4.2
Wollastonite	6.2	8.6	3.8	3.8	4.6	8.2	10.3
Enstatite	17.5	9.8	12.0	6.8	10.0	19.8	15.8
Ferrosilite	15.7	16.8	14.4	11.4	13.8	18.6	11.2
Quartz	1.1	4.3	3.1	7.2	1.4	-	3.5
Olivine	-	-	-	-	-	0.9	-

1. Norm from average of Nimrod sill chemical composition as calculated from modes.
2. Norm from assumed Nimrod sill magma (from "wet" chemical analysis of sample G-34, taken 3 inches above lower contact)
3. Norm from average medium grained diabase high in the sill as calculated from composition from modes.
4. Norm from "wet" chemical analysis of sample D-11 which is included in #3.
5. Norm of coarse zone of diabase calculated from composition from modes.
6. Norm of average fine grained diabase; mid-point 30 feet from lower contact. From composition based on modes.
7. Norm of world average of normal tholeiitic basalt and dolerite (calculated by Nockolds, 1954, p. 1021).

The lower content of albite and enstatite in norms from the chemical analyses is due to lower sodium and magnesium in the analyses than in compositions from modes (see pages 37 and 41). Note in the norms the difference between the Nimrod sill and normal tholeiitic magma in the ferrosilite/enstatite ratio. According to the norms most of the excess iron in the iron-rich sill is taken up as ferroaugite. This is only partly true, because the sill has an unusually high ore content, averaging 8 per cent, and varying from 3.9 to 13.7 per cent.

RELATION TO SIMILAR INTRUSIVES

The Nimrod diabase sill is one of several similar diabase sills and dikes in the area east of Missoula, Montana. These rocks intrude Precambrian metasediments of the Belt Series. The Nimrod sill is similar chemically and mineralogically to a sill 20 miles west studied by Richard Eisenbeis (Eisenbeis, 1958). This latter sill, located at the Milltown Dam near Bonner, Missoula County, Montana, has a high total iron content (see Table I, 53), and is, therefore, quite high in ore content; its major pyroxene is pigeonite. The sill intrudes argillite of the McNamara formation.

A brief study was made of thin sections of a diabase sill 6 miles northwest of the western extremity of the Nimrod sill. The mineralogical composition and texture of this sill in the Clinton area, described by Hintzman (1961, p. 26), leads the writer to conclude that the sill is very similar to the Nimrod sill. It is 500 feet to 1500 feet thick and has a high ore content in the form of large skeletal masses. The plagioclase is partially altered to sericite in the coarse zone, and pyroxene is almost wholly altered to hornblende in that zone. Both pigeonite and augite were found in all thin sections, but orthopyroxene was not found. The sill intrudes the lower part of the Garnet Range formation. Although a complete study of the sill should be made before valid conclusions can be drawn, it is not unlikely that the sill is a western extension of the Nimrod sill since it is quite thick and also intrudes the lower Garnet Range formation. Extrusives and erosion could have covered or removed the sill in the intervening area.

The sill in the Clinton area described by Hintzman is folded and the Nimrod sill has tectonic jointing, indicating that the sills were present in the Belt rocks at the time of late Cretaceous or late Precambrian tectonic activity in the region. Therefore, the diabases may be Precambrian to late Cretaceous in age.

Attempts to correlate the Nimrod sill to diabase sills in the Cretaceous Colorado formation near Garrison failed. A sill which crops out three miles east of Garrison, Montana, on United States Highway No. 12 was briefly studied. It is low in iron ore content (less than 3 per cent) and is consistently porphyritic with augite phenocrysts. Glomeroporphyritic pyroxene is not common, nor are large skeletal masses of ore. The plagioclase laths in this sill seem crushed and borders are somewhat "fused," whereas the plagioclase laths in the Nimrod sill are strikingly euhedral in comparison. Because of the differences of this sill in mineralogy and texture compared to the Nimrod sill, it is impossible to imply a direct genetic relationship.

The Missoula area diabases (Nimrod, Clinton, and Milltown dam sills) are distinctly iron-rich, averaging nearly 20 per cent iron oxide. The excess iron is found in the form of ore, which averages 8 per cent of the rock and in the ferrosilite molecule. The high iron content in the original tholeiitic melt is thought to account for the lack of a pigeonite to orthopyroxene inversion in the diabases. Pigeonite is the dominant pyroxene (occurring with augite) and orthopyroxene is absent.

Other diabases occur in the Rocky Mountain area several hundred miles north of Missoula in Glacier National Park, in northern Idaho, and in the Kootenai area in British Columbia. Ross (1959, p. 56) describes gabbroic sills and dikes largely confined to the Siyeh formation (middle Belt Series) in Glacier National Park. The sills and dikes consist of titaniferous augite largely altered to hornblende, zoned plagioclase which is decidedly calcic, and interstitial micropegmatite. Ross believes there is a genetic relation between the sills and the Purcell basalts. Kirkham and Ellis (1926, p. 38) describe diabase sills altered by uralization to a dioritic type in Boundary County, Idaho. These sills were intruded into flat lying Belt (Purcell) Series rocks and have subsequently taken part in all the orogenic movements which built the Cabinet and Purcell ranges. Kirkham and Ellis consider the parent magma of the sills to have been produced in the same reservoir as the Purcell lava magma with some differentiation. The Purcell lavas, which consist of altered basalt and andesite flows of late Precambrian to early Cambrian age, occur in the same region as the sills. Rice (1937, p. 18) considers that the diabase sills (altered to diorite) and the Purcell lavas in southeast British Columbia are related. He cites as evidence the similar composition, the absence of sills or dikes of that nature above the lavas, and the greater coarseness of sills in older (hence deeper buried) sediments. Work by Hunt (1950, p. 1893) indicates that the minimum age of two Purcell sills in southeastern British Columbia from A^{40}/K^{40} of biotite is 558 to 669 million years, indicating that they are ~~probably~~ certainly older than late Cretaceous; he obtained a maximum age of 835 million years for one of the sills.

It appears possible that the Nimrod sill and Missoula area iron-rich diabases belong to a major basic intrusive epoch that affected the Belt Series in the northern Rocky Mountain area during late Precambrian to early Cambrian time.

APPENDIX

The Nimrod diabase sill was studied using samples from several traverses perpendicular to the attitude of the sill (see Figure 1). Samples from the upper to the lower contact were obtained only from traverse DEFG. Traverses A and B are across hydrothermal pods. Traverse M is across the lower half of the sill and traverse C is across the upper two-thirds of the sill. Both M and C are perpendicular to the attitude of the sill.

Thin sections were made of the DEFG traverse and of traverse A. Thin sections from traverse M made by Montgomery for his work on the sill were used to correlate with traverse DEFG. No appreciable difference was found in modes from equivalent points in the two localities.

After minerals were identified using the petrographic microscope and X-ray diffraction, the modes were calculated using a point counter, counting 500 to 1500 points per slide depending on the uniformity of distribution and grain size of the minerals.

To obtain more accurate estimates of the chemical composition of the minerals, rock samples were crushed and screened to obtain particles of 60-120 mesh. These were optimum sized particles, large enough to be identified by use of the petrographic microscope and small enough to be almost monomineralic. Magnetic constituents (ore) were first separated by using a hand magnet. The non-magnetic minerals (plagioclase and quartz) were separated from the paramagnetic ferromagnesian minerals (pyroxene, hornblende, and biotite) by using the Franz Magnetic Separator.

The composition of the plagioclase, pyroxene, and hornblende was determined by using immersion oils to find the indices of refraction and the appropriate diagrams on which index of refraction is plotted in relation to chemical composition (for plagioclases, Wahlstrom, 1955, p. 118; for pyroxenes, Wahlstrom, 1955, p. 160; and for hornblende, Moorhouse, 1959, p. 78). The mineralogic composition of the ore was found by using the X-ray diffractometer. Magnetite and ilmenite peaks were found, and the relative intensity of strong magnetite peaks were compared to strong ilmenite peaks to determine the relative percentages of the two minerals. Standard peaks of 100 per cent magnetite and 100 per cent ilmenite were used to determine the ratio of intensities of a 100 intensity magnetite peak and a 100 intensity ilmenite peak.

The approximate chemical compositions of the different samples from the sill were computed by using model analyses of thin sections. A sample calculation is shown below. The volume percentages obtained from point counting of the thin sections were converted to weight percentages by multiplying volume percentage by mineral density for the separate minerals and then computing the mineral percentage by weight. The separate oxide percentages of each mineral were then multiplied by weight percentage. Mineral compositions had been determined by optical means -(index of refraction, 2V, etc.) Oxide totals for the rock were then tabulated.

The accuracy of the chemical composition calculations is rather low due to several factors. Variations occur in chemical composition that cannot be determined by optical means; extensive solid solution is common in almost all of the minerals encountered. Albite invariably contains some molecules of potassium feldspar. Magnetite and ilmenite may not be completely exsolved. The ferromagnesian minerals have some manganese in their crystal lattice (see Table I). Hornblende composition determinations are rather inaccurate owing to the possible percentage variations in the several cations that may be present. In the coarse zone, especially where hornblende may be abundant and plagioclase and pyroxene are partially altered to cloudy aggregates of many minerals, chemical composition calculations are not to be considered totally valid.

Sample Chemical Calculation

Thin section G-24 from diabase sill 59' above lower contact:

Mineral	Mode Volume %	Mineral Density	Partial Density	Weight %
Plagioclase	40.1	2.7	1.08	33.1
Pyroxene	46.4	3.4	1.60	48.5
Hornblende	2.7	3.3	.10	2.8
Biotite	0.5	3.0	.02	0.5
Ore	8.7	5.0	.43	13.7
Quartz	1.3	2.7	.03	1.1
Apatite	0.3	3.2	.01	.3
		Density of G-24	3.26	

Plagioclase - 33.1% $Ab_{43}An_{57}$

Ab= $2NaAlSi_3O_8$

Oxide	Grams/mole	Wt. % of oxides		% Ab. in Plag.		% Plag.		% oxide in rock contributed by Ab
Na_2O	62	11.8	X	43	x	33.1	=	1.68
Al_2O_3	102	19.5	x	43	x	33.1	=	2.77
$6SiO_2$	360	68.7	x	43	x	33.1	=	9.77

524 gms for 1 mole Ab.

An= $CaAl_2Si_2O_8$

Oxide	Grams/mole	Wt. % of oxides		% An. in Plag.		% Plag.		% oxide in rock contributed by An
CaO	56	22.1	x	57	x	33.1	=	4.19
Al_2O_3	102	35.7	x	57	x	33.1	=	6.92
$2SiO_2$	121	43.2	x	57	x	33.1	=	8.15

279 gms for 1 mole An.

Pyroxene - 48.5% 15% Augite $Wo_{32}En_{36}Fs_{32}$ $Ca_{32}Mg_{36}Fe_{32}SiO_3$

85% Pigeonite $Wo_{13}En_{42}Fs_{45}$ $Ca_{13}Mg_{42}Fe_{45}SiO_3$

Augite

Oxide		Vol. %		Gms/mole		Weight Fractions	Wt. % of oxides		% Aug		% Px		% oxide in rock contributed by Augite
CaO	=	.32	X	56	=	.179	15.3	x	15	x	48.5	=	1.11
MgO	=	.36	x	40	=	.144	12.4	x	15	x	48.5	=	.90
FeO	=	.32	x	76	=	.243	20.8	x	15	x	48.5	=	1.51
SiO_2	=	1.00	x	60	=	.600	51.5	x	15	x	48.5	=	3.75
						1.166							

Pigeonite

Oxide		Vol. %		Gms/mole		Weight Fractions	Wt. % of oxides		% Pig		% Px		% oxide in rock contributed by pigeonite
CaO	=	.13	x	56	=	.075	6.8	x	85	x	48.5	=	2.86
MgO	=	.42	x	40	=	.168	14.0	x	85	x	48.5	=	5.47
FeO	=	.45	x	76	=	.342	28.9	x	85	x	48.5	=	10.90
SiO_2	=	1.00	x	60	=	.600	50.7	x	85	x	48.5	=	20.90
						1.183							

Hornblende - 2.8%

$(Ca_{1.4}Na_{0.6})(Mg_{2.1}Fe_{2.1}Al_{0.8})Si_{7.8}Al_{0.2}O_{22}(OH)_2$

Oxide	Gms/mole				Weight Fraction	% oxide in Hb.		% Hornblende		% oxide in rock contributed by hornblende
CaO	56	x	1.4	=	.078	9.0	x	2.8	=	0.25
Na_2O	31	x	0.6	=	.019	2.2	x	2.8	=	0.06
MgO	40	x	2.1	=	.084	9.7	x	2.8	=	0.27
FeO	72	x	2.1	=	.151	17.4	x	2.8	=	0.49
Al_2O_3	51	x	1.0	=	.051	5.9	x	2.8	=	0.17
SiO_2	60	x	7.8	=	.468	53.9	x	2.8	=	1.51
H_2O	9	x	2.0	=	.018	2.1	x	2.8	=	0.06
					.869					

Biotite - 0.5% $K(Mg_{0.9}Fe_{1.5}Al_{0.6})(Si_{3.7}Al_{0.3})O_{10}(OH)_2$

Oxide	Gms/mole				Weight Fractions	% oxide in Biotite		% Biotite		% oxide in rock contributed by biotite
K_2O	47	x	1.0	=	.047	.100	x	0.5	=	0.05
MgO	40	x	0.9	=	.036	.071	x	0.5	=	0.04
FeO	72	x	1.5	=	.108	.229	x	0.5	=	0.11
Al_2O_3	51	x	0.9	=	.046	.098	x	0.5	=	0.05
SiO_2	60	x	3.7	=	.216	.459	x	0.5	=	0.23
H_2O	9	x	2.0	=	.018	.038	x	0.5	=	0.02
					.471					

Ore - 13.7%

Magnetite Fe_3O_4 60%

Oxide	Gms/mole				Weight Fraction	Wt. % of oxides		% Mag. in ore		% Ore		% oxide in rock contributed by magnetite
FeO	72	x	1	=	72	31.0	x	60	x	13.7	=	2.55
Fe_2O_3	160	x	1	=	160	69.0	x	60	x	13.7	=	5.67
					232							

Ilmenite $FeTiO_3$ 40%

Oxide	Gms/mole				Weight Fraction	Wt. % of oxides		% ilmenite in ore		% Ore		% oxide in rock contributed by ilmenite
FeO	72	x	1	=	72	47.4	x	40	x	13.7	=	2.60
TiO_2	80	x	1	=	80	52.6	x	40	x	13.7	=	2.88
					152							

Quartz - 1.1% SiO_2

Apatite - 0.3. $Ca_5 (PO_4)_3 (F_1Cl)$ not considered

Oxide	Gms/mole				Weight Fraction	Wt. % of oxides		% Apatite		% oxide in rock contributed by apatite
CaO	56	x	5	=	.280	.568	x	0.3	=	.17
P_2O_5	71	x	3	=	.213	.432	x	0.3	=	.13
					.493					

Total oxide % to nearest 0.1%

Oxide		
SiO_2	45.41	45.4
Al_2O_3	10.91	10.9
FeO	17.76	17.8
Fe_2O_3	5.07	5.7
MgO	6.48	6.5
CaO	8.68	8.7
Na_2O	1.74	1.7
K_2O	0.05	0.1
TiO_2	2.88	2.9
H_2O	.08	0.1
P_2O_5	.13	0.1
	99.89	99.9

TABLE III. Modes (Volume Per cent)

Sample	Depth from upper contact	Plag.	Px.	Hb.	Act.	Bio.	Ore	Qtz.	Ap.	Sph.	Ch.
D-1	2'	39.8	44.4	3.0	-	0.5	10.1	2.0	0.2	-	-
D-3	12'	42.7	33.1	6.8	-	1.1	8.7	7.3	0.3	-	-
D-5	22'	46.2	29.0	8.1	0.1	1.8	7.5	6.9	0.4	-	-
D-8	36'	50.9	24.6	8.2	-	1.3	6.9	7.6	0.4	0.1	-
D-11	53'	50.2	18.0	12.6	6.1	1.0	5.2	5.4	0.8	0.7	-
D-16	82'	42.4	8.4	16.7	8.0	6.6	11.9	4.7	0.8	0.5	-
D-20	105'	41.6	18.2	11.5	3.1	3.5	12.2	8.4	0.9	0.6	-
D-25	133'	40.8	21.3	10.6	0.1	2.9	12.8	10.8	0.5	0.2	-
F-5	168'	41.2	15.1	31.7	0.4	2.8	4.0	4.5	0.3	-	-
F-10	196'	46.3	14.8	28.0	0.5	2.3	4.5	3.6	0.7	0.2	-
F-15	224'	50.6	31.9	5.8	-	1.8	6.1	3.0	0.5	0.1	0.2
G-1	251'	52.9	30.1	4.5	0.3	0.5	6.7	4.2	0.8	-	-
G-6	282'	51.8	33.8	1.7	-	0.6	7.2	3.9	0.4	-	0.6
G-11	313'	48.0	38.6	1.1	-	1.2	7.3	3.0	0.8	-	-
G-16	344'	44.8	40.9	3.3	-	1.8	5.0	3.1	0.7	-	0.4
G-20	368'	42.0	41.8	3.1	-	1.2	8.0	3.4	0.5	-	-
G-24	391'	40.1	46.4	2.7	-	0.5	8.7	1.3	0.3	-	-
G-28	414'	40.7	43.5	2.3	-	0.6	9.5	2.9	0.5	-	-
G-31	431'	38.8	36.4	8.3	-	1.1	10.4	4.7	0.3	-	-
*G-34	448'	38.4	28.1	0.2	-	.2	5.1	0.3	0.1	-	-

*Includes 24.6% basaltic glass. Sample is located 3 inches above lower contact.

TABLE IV. Wet Chemical Analyses

	G-34		G-11		D-11	
	(A)	(B)	(A)	(B)	(A)	(B)
SiO_2	48.76	48.46	48.72	48.70	49.18	48.76
FeO	14.32	14.34	11.97	11.84	11.71	11.87
Fe_2O_3	2.98	2.95	3.41	3.19	4.26	4.29
Al_2O_3	14.40	14.06	14.92	15.18	15.98	15.94
CaO	9.94	9.86	9.76	9.94	8.02	8.22
MgO	3.16	3.37	4.72	4.72	2.26	2.29
TiO_2	2.95	2.84	2.37	2.27	3.12	3.20
MnO	.18	.20	.17	.18	.17	.19
P_2O_5	.31	.31	.21	.21	.31	.32
Na_2O	1.94	2.06	1.94	2.06	2.29	2.38
K_2O	.69	.72	.68	.68	.98	.99
H_2O	.30	.33	1.15	1.13	1.51	1.46

G-34 is chilled diabase 3 inches from lower contact.

G-11 is differentiated diabase in the middle of the lower half of the sill (135 feet above lower contact).

D-11 is differentiated diabase in the top of the coarse zone of the sill (53 feet below upper contact).

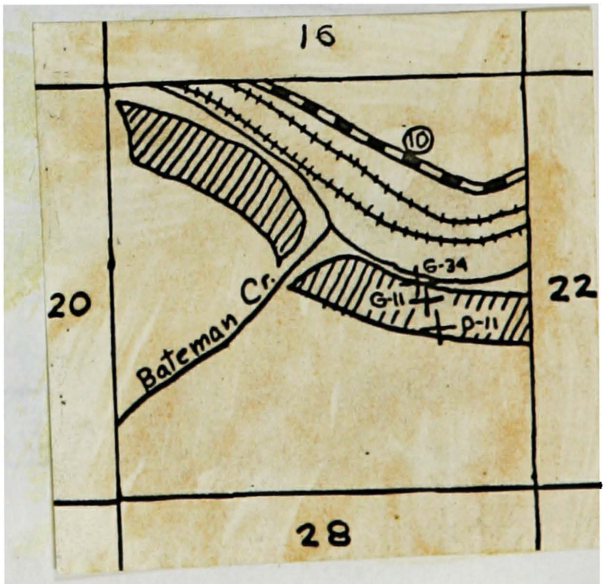


Figure 23. Location of samples taken for wet chemical analyses. They are a part of traverse DEFG located in E½NW¼SE¼ of section 21, T.11N., R.15W., Prime Meridian, Montana. Traverse G is located by proceeding straight up the middle of the only large talus slope of diabase at the bend of the river. Traverse F is one spur left of spur G. Traverse E is one spur left of Traverse F. Traverse D is one spur left of Traverse E. Sample localities are indicated in indelible ink on the outcrops.

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