

PETROLOGY OF A DIFFERENTIATED ANORTHOSITIC
INTRUSION IN NORTHWESTERN WISCONSIN

Thesis for the Degree of Ph. D.

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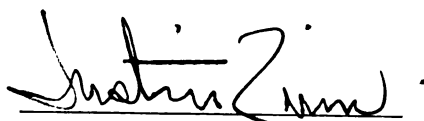
PETROLOGY OF A DIFFERENTIATED
ANORTHOSITIC INTRUSION IN
NORTHWESTERN WISCONSIN

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ABSTRACT

PETROLOGY OF A DIFFERENTIATED ANORTHOSITIC INTRUSION IN NORTHWESTERN WISCONSIN

by James F. Olmsted

The Keweenawan gabbros of the south side of the Lake Superior synclinorium are large sill-like bodies that intrude the Middle Keweenawan lavas. The Mineral Lake Intrusion is a single, very thick (16000 ft.) anorthositic body that has been concordantly emplaced near the base of the Keweenawan lavas. The intrusion is strongly differentiated and displays rock types ranging from ultramafics to granites. The middle levels of the intrusion contain rocks grading from olivine gabbro to anorthosite to ferrodiorite displaying the extent to which fractionation has taken place.

Detailed field studies indicate that the body was intruded as a partially crystalline mush. Movement of the magma during emplacement resulted in the development of a strong fluxion structure that is particularly well-developed in the anorthosite zone. Field occurrence of the different rock types indicate that movement of the magma was parallel to the floor in an updip direction. An absence of igneous layering, gradual decrease of mafic content from the base upward and

occasional masses of ultramafic rocks near the base all suggest differential settling combined with flowage in one direction parallel to the floor rather than convection currents as a mechanism of differentiation.

Mineralogical studies, accomplished both optically and chemically, show that plagioclase and olivine, for the most part, crystallized from a basaltic liquid and formed the solid fraction of the magma during emplacement while much of the pyroxene and part of the plagioclase crystallized from an interprecipitate liquid.

The mineralogical data combined with chemical studies of the lower chill zone show that the liquid which was chilled to form these rocks was the product of strong fractionation. Comparisons of the trends of this intrusion with those of the Skaegaard Intrusion suggest that the chill zone is the product of the fractionation of a basaltic liquid which was about 50 per cent solid at the time of emplacement. Comparisons of these trends with experimental studies show that the intrusion solidified under conditions of extremely low oxygen pressure and the process was one approaching perfect fractionation and constant total composition. The result of these conditions was to produce large amounts of early magnesian mafic phases which did not rise to the level of exposure. Much of the early plagioclase was carried to higher levels in the intrusion either by floatation or friction with the liquid to produce the anorthositic rocks which form most of the exposed part of the intrusion.

The distribution of iron and magnesium in the mafic phases suggests a drop of about 300° centigrade from the time of the earliest to the latest pyroxene and olivine to form. Petrographic studies of the highest acid residues indicate that they are subsolidus and therefore have crystallized below 660° centigrade.

An origin for the excessive amounts of anorthositic rocks is proposed which involves the normal fractionation process under the conditions outlined above combined with differential settling under conditions of unidirectional flow.

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By

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	ii
LIST OF TABLES	vi
LIST OF FIGURES	viii
LIST OF PLATES	x
Chapter	
I. INTRODUCTION.	1
Statement of the Problem.	1
General Geology.	6
Regional Setting	6
Stratigraphy of the Animikian Series.	8
Stratigraphy of the Keweenawan Series	10
Structure of the Area.	12
Mineral Lake Intrusion	15
Previous Investigations	16
II. FIELD RELATIONSHIPS	19
General	19
Shape and Attitude of the Intrusion	19
Rock Unit Descriptions	23
Anorthositic Olivine Gabbro.	24
Gabbroic Anorthosite and Anorthosite.	25
Ferrodiorite.	27
Transition and Granitic Rocks	28
Relationships with Enclosing Rocks	29
Basal Contact	29
Eastern Boundary	31
Upper Contact	35
Origin and Significance of the Fluxion Structure.	37

Chapter	Page
III. PETROGRAPHY	41
Introduction	41
Petrologic Discussion	45
Fine Grained Gabbro.	45
Pyroxenite.	51
Anorthositic Olivine Gabbro	52
Gabbroic Anorthosite and Anorthosite	59
Ferrodiorite	62
Transition Rocks and Granite	64
IV. MINERALOGY.	73
General Statement	73
Plagioclase	74
Alkali Feldspar	80
Olivine.	82
Pyroxene	84
Geothermometry from Pyroxene Data	89
V. PETROGRAPHIC DISCUSSION	100
Introduction	100
Composition of the Intrusion.	104
Mineralogy.	110
Trend of Differentiation	113
Average Composition of the Exposed Section of the Mineral Lake Intrusion	122
Form of the Intrusive and Mechanism of Differentiation	125
VI. CONCLUSIONS	134
General.	134
Suggestions for Further Work.	138
REFERENCES	140
PLATES	144

LIST OF TABLES

Table	Page
1. Stratigraphic succession of Precambrian rocks of the Lake Superior region.	7
2. List of sections mapped in this study	20
3. Modal compositions of two chill zone gabbros .	46
4. Modal compositions of five anorthositic gabbros	55
5. Modal compositions of five anorthosites or gabbroic anorthosites.	60
6. Modal compositions of four ferrodiorites . .	63
7. Modal compositions of six transition or granitic rocks	65
8. Chemical analysis of chill zone plagioclase and computations showing composition of the plagioclase and inclusions	78
9. Optical properties of olivine, orthopyroxene, and clinopyroxene	86
10. Chemical analysis of clinopyroxene from sample 6-5-65	90
11. Chemical analysis of clinopyroxene from sample 25-42.	91
12. Chemical analysis of clinopyroxene from sample 11-9	92
13. Chemical analysis of orthopyroxene from sample 11-9	93
14. Chemical analysis of orthopyroxene from sample 6-5-65	94
15. Comparison of analyses of chill zone of Mineral Lake Intrusion with other chilled basaltic rocks	105

Table	Page
16. Normative compositions of chilled rock from Mineral Lake Intrusion and Cornwall's initial liquid from the Greenstone flow	108
17. Partial chemical analyses of four rocks of the Intrusion showing the trend of differentiation	114
18. Fe_2/O_3 ratios of Mineral Lake rocks compared with rocks from the Skaergaard Intrusion . .	121
19. Average modal composition of the Mineral Lake Intrusion.	123
20. Chemical analyses calculated from modes of Mineral Lake Intrusion by two different methods	124
21. Settling velocities of plagioclase and pyroxene crystals in a viscous melt. . . .	128

LIST OF FIGURES

Figure	Page
1. General geologic map of northwestern Wisconsin	3
2. Pole diagram of fluxion structure in anorthosite of the Mineral Lake Intrusion . .	22
3. Mode of emplacement of Mineral Lake Intrusion showing bulging of overlying flows .	36
4. Sketch showing distortions of fluxion structure due to flow	39
5. Plagioclase equilibrium diagram showing range of zoning of two chill zone feldspars.	50
6. Modal rock compositions in relationship to distance above base of the intrusion . . .	54
7. Albite-anorthite-diopside diagram showing plagioclase liquidus and solidus slopes as an additional phase is introduced (Wyllie, 1963)	69
8. Variation of plagioclase composition with height in the intrusion	75
9. Ternary diagram of Ab.-An.-Or. system showing approximate location of solvus for high water content conditions (Tuttle and Bowen, 1952, p. 135).	81
10. Plot of olivine orthopyroxene compositions versus average Fe/Fe + Mg ratio of the co-existing pair.	83
11. Equilibrium diagram of part of the FeO-MgO-SiO ₂ system (Bowen and Schairer, 1935) .	85

Figure	Page
12. Pyroxene composition showing trends of Mineral Lake Intrusion and trends of pyroxenes of other intrusions	88
13. Pigeonite orthopyroxene inversion curve (Hess, 1960, p. 40)	95
14. Plot of Fe^{++}/Mg^{++} ratios from pyroxene pairs showing distribution coefficients.	97
15. Subtraction diagram using composition of Mineral Lake Intrusion in comparison with an average basalt	106
16. Comparisons of mineralogical compositions versus height in intrusion	111
17. Differentiation trends of the Mineral Lake Intrusion compared with the Skaergaard and Duluth trends	115
18. Section from the tetrahedron $FeO-Fe_2O_3-MgO-SiO_2$ at $P_{O_2} = 0.21$ atm. (Osborn, 1959)	117
19. Comparison of magma compositions of the Skaergaard Intrusion and the chill zone rocks of the Mineral Lake Intrusion	119
20. Hypothetical cross section of Mineral Lake Intrusion showing possible mechanism for the production of anorthosite	130

LIST OF PLATES

Plate	Page
I. Geologic map of the Mineral Lake Intrusion . (in pocket)	
II. Photomicrographs of chilled gabbros . . .	144
III. Photomicrographs of olivine gabbros . . .	146
IV. Photomicrographs of anorthosite.	148
V. Photomicrographs of ferrodiorite, transition and granite	150
VI. Photomicrographs showing mineralogical features	152
VII. Photographs showing gross appearance and textures	154

CHAPTER I

INTRODUCTION

Statement of the Problem

The Keweenawan intrusives of northwestern Wisconsin are a series of thick sill-like bodies that range from nearly ultrabasic to granitic in composition, but are mostly gabbros. The maps of this region published with Bulletin #71 of the Wisconsin Geological and Natural History Survey indicate that the intrusives extend from the Michigan-Wisconsin boundary near the village of Hurley, southwesterly along the strike of the Keweenawan structure for nearly fifty miles. These maps indicate that the intrusives vary from about a mile to as much as five miles in width (Fig. 1). The gabbros intruded the older Keweenawan volcanics and are generally concordant with them, although Aldrich (1929, p. 120) noted that over distances of several miles some crosscutting is evident.

In the vicinity of English and Mineral Lakes, T. 44 and 45, R. 3 and 4 west, the belt of intrusive rocks is approximately five miles in width. From a brief study of Figure 1, the volcanics appear to have been bulged to the north by the intrusives in this area. Leighton (1954) has found that these intrusives form a multiple complex with at

least two and possibly more separate intrusions which have been emplaced along the bedding of the enclosing volcanics.

The lowermost intrusive unit in this area is a very thick, tabular body which has been differentiated to a considerable degree. This unit, the Mineral Lake Intrusion, is on the order of twelve to fifteen thousand feet thick, and is the principal subject of this study.

A search of the literature reveals little petrologic information concerning the intrusive rocks of this area, however, published maps made by Aldrich (1929) clearly indicate the presence of a large mass of anorthositic gabbro north of Mineral and English Lakes. Aldrich dealt specifically with the underlying Huronian series and therefore made only general reference to the Keweenawan units. A later paper by Leighton (1954) deals with the gabbro-redrock association which is stratigraphically above the Mineral Lake Intrusion. Leighton made only brief reference to the presence of anorthositic rocks, although, it now is apparent that Leighton's southern unit is the upper part of the Mineral Lake Intrusion.

On the basis of the above information and a brief visit to the area in the fall of 1962, it became apparent to the writer that the Mineral Lake Intrusion may be a large, single, differentiated intrusion similar in many respects to other large tabular igneous complexes. With this somewhat vague information, a study was proposed with the following objectives in mind:

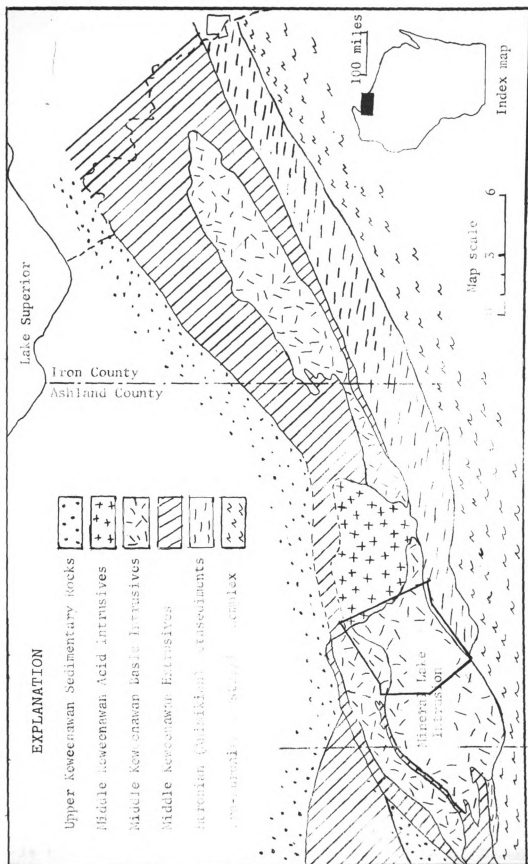


Fig.1.--General geologic map of northwestern Wisconsin.

1. To determine if the Mineral Lake gabbro is a single intrusive.
2. To determine the origin and petrologic nature of the large mass of anorthosite.
3. To provide a detailed outcrop map of a well-exposed section across this intrusive sequence.

Very early in the course of the field studies it became apparent that the plagioclase of the anorthositic portion of the intrusive possessed a pronounced parallel orientation. Such textures are often interpreted as evidence of flow (Wager and Deer, 1939) and hence imply a mechanism of differentiation. Leighton (p. 410) used the terms igneous lamination and fluxion structure as synonyms and this use of the terms is followed here. The very large volume of anorthosite without a complimentary mafic rich zone such as Hess (1960) described in the Stillwater Complex posed a challenging problem. Taylor (1964) noted that the anorthosites of the Duluth Complex likewise show evidence of transport and lack their mafic compliments. Unfortunately, the base of the Duluth anorthosite was itself intruded by later gabbros rendering complete study impossible. This problem does not exist in the Mineral Lake Intrusion, therefore an opportunity is presented to investigate an uncomplicated example of a large body of anorthosite to determine the mechanism by which it was separated from its parent magma.

Another problem that was investigated to some extent is the relationship between the trend of the differentiation

and the partial oxygen pressures at varying stages of cooling of the magma. This has been accomplished by comparing the ratios of ferrous to ferric iron in samples taken from different levels in the intrusion.

Finally, a rather detailed study of the textures, particularly near the base of the intrusion, was undertaken for the purpose of gathering information concerning mineral habits and textures in relationship to composition of the rock, and location within the intrusion. It is felt that such data is of value to the further definition and understanding of igneous textures, particularly the ophitic variations of basic rocks.

Early in the study an investigation of the distribution of minor elements throughout the intrusion was planned. As the project progressed it became apparent that; (1) such a study could only follow a thorough understanding of the mineralogical and major element variations, and, (2) these latter variations are sufficient to describe the trend of differentiation of the intrusion. The fact that all of these undertakings could not be completed within a reasonable amount of time made it necessary to postpone the minor element study until a thorough understanding of the petrology of the intrusion has been gained.

General Geology

Regional Setting

The Keweenawan rocks of northwestern Wisconsin constitute the southern limb of the Lake Superior synclinorium (Van Hise and Leith, 1911, p. 234). This belt of Keweenawan rocks ranges in width from 10 to about 40 miles, extending from Keweenaw Point, Michigan on the east to the Wisconsin-Minnesota boundary on the St. Croix River (Van Hise and Leith 1911, p. 376). The general trend of the structure is northeasterly with dips to the northwest. In Wisconsin, the Keweenawan succession is underlain to the south by the Gogebic series of Animikian (Huronian) age. The trend of this group is also northeasterly so that the major unconformity between the two groups is not apparent, a relationship which has been the subject of some controversy. According to Van Hise and Leith (1911, p. 376) the Keweenawan succession is composed of a basal conglomerate, a thick (Middle Keweenawan) igneous sequence and a very thick sequence of coarse to fine clastics that make up the Upper Keweenawan part of the succession. The Mineral Lake Intrusion is later than the Middle Keweenawan volcanics but there is no clear evidence that it is earlier or later than the Upper Keweenawan. Traditionally, the igneous rocks of the region are classed as Middle Keweenawan so that the rocks intrusive into the volcanics must be considered as the latest of this group.

TABLE 1.--Stratigraphic succession of Precambrian rocks of Northwestern Wisconsin (modified from Leith, Lund, and Leith, 1935 and Goldich *et al.*, 1961).

Era	Period-System	Sequence	Formation
Late Precambrian	Keweenawan	Upper	Conglomerates, Sandstone and shales

			Basic and Acid In- trusives
		Middle	Conglomerates?
			Basic and Acid Flows

Middle Precambrian	Huronian	Lower	Quartzite and Conglomerate

			Unconformity
			Tyler Formation
			Basic Igneous
		Animikie Group	Ironwood Formation
			Palms Formation
			Unconformity
			Bad River Formation
			Sunday Quartzite
Early Precambrian	Timiskaming	Not Represented	Unconformity
			Laurentian Granite
			Intrusive Contact
	Ontarian	Kewatin	Greenstone and Schist

Stratigraphy of the Animikian Series

In the course of the field studies rocks of Animikian age were mapped in only two exposures. Although these rocks are poorly exposed in the map area, there is little doubt as to their occurrence and gross structure. Previous maps by Aldrich (1929) and the Bear Creek Mining Company (unpublished) show the relationships that are reflected in the two outcrops examined. Other exposures out of the map area have been examined for the purpose of familiarization, but no detailed studies were attempted.

Aldrich (1929) thoroughly reviewed the stratigraphy of the Animikian series so that only brief mention need be made here of the various units. The lowermost Huronian formation is the Bad River dolomite which directly overlies the Archean schists, gneisses, and metavolcanics. Aldrich (1929, p. 79) assigned this somewhat discontinuous formation to the Lower Huronian which is separated from the overlying units by a well-defined unconformity.

The Palms slate and quartzite and the Ironwood iron formation are next in this order and together with the Tyler formation they constitute the Upper Huronian. The combined thickness of the Palms and Ironwood is at least 1000 feet. Exposures of both of these units near the basal contact of the Keweenaw gabbro may be seen in Sec. 14, T. 44 N., R. 4 W. As implied by the name above, the Palms formation is somewhat variable in composition, ranging from conglomerate to arkose and feldspathic greywacke. Near the top of the

formation a continuous bed of vitreous quartzite marks the contact with the Ironwood formation. This quartzite member may be seen in outcrop in Section fourteen south of Mineral Lake.

The Ironwood is a typical bedded iron formation composed of fine-grained chert and various iron minerals, namely hematite, magnetite, iron silicates, or carbonates. The formation has been divided into five members depending on the mineralogy and proportions of the minerals (Aldrich, 1929). The total thickness of the Ironwood is about 650 feet and is quite constant except where folding has thickened the formation. Aldrich (1929) discussed the stratigraphy and petrology of the Ironwood formation in considerable detail so additional description is not necessary.

Aldrich has indicated that the contact between the Ironwood formation and the underlying Tyler formation is not exposed, but that where the contact has been examined in drill cores there is no evidence for any unconformable relationship. The Tyler formation is about 10,000 feet thick, however, because of either faulting or erosion it is often thinner and at the west end of the Penokee Range is missing. From the descriptions presented by Aldrich, the Tyler is probably best called a greywacke although its composition varies from quartzite to a thin-bedded shale.

Stratigraphy of the Keweenawan Series

As indicated earlier, the exact nature of the contact between the Animikian and the Keweenawan series is not completely clear. Van Hise and Leith (1911, p. 234) reviewed the field relationships and concluded that the Animikian series had undergone moderate metamorphism and subsequent uplift and erosion prior to the beginning of Keweenawan time. They note that at either end of the Penokee Range the Keweenawan rocks overlie older rocks than in the central part of the range suggesting the presence of an unconformity representing a considerable lapse of time.

The views presented by Aldrich (1929, p. 122) are somewhat different. Briefly, Aldrich has concluded that the units are unconformable, but that the break is insignificant and where there are crosscutting relationships the contact is a fault plane along which rocks of the two units have been brought into contact in an angular relationship. If this is indeed the case, then there is no time lapse between the series and the rocks that are assigned to the Animikian in this area are somewhat younger than usually considered. These crosscutting relationships are such that in T. 44 N., R. 4 W., southwest of the map area of this study, the Keweenawan intrusives bevel completely across the Animikian rocks and are in contact with the pre-Animikian or Archaean complex. This crosscutting is what Van Hise and Leith (1911) consider as evidence of a deep erosion surface and Aldrich

(1929), uses as proof of a fault surface separating the two series.

The Lower Keweenawan is represented in this area by a coarse quartz pebble conglomerate. Outcrops of this unit are rare in Wisconsin, but Aldrich (p. 110) has shown that they are numerous enough so that one can say with some confidence that it is continuous from Mellen eastward to the Montreal River.

The Middle Keweenawan, represented by the entire group of volcanics, is found along the north and south shores of Lake Superior. In Wisconsin the volcanics have been intruded along bedding planes or bedding plane faults by both basic and acidic plutonic rocks. Although some of the intrusive rocks may be younger all are considered to be Middle Keweenawan in this paper. The granite that intruded the gabbro in the area west of Mellen has been dated by Goldich et al. (1959) at one billion years. This granite body appears to be the youngest of the intrusive rocks and there is little doubt as to the relationship between it and the complex of gabbroic rocks.

Between the uppermost volcanic unit and the south shore of Lake Superior there occurs a very thick sequence of coarse to fine clastics that is assigned to the Upper Keweenawan. The total thickness of this series is probably on the order of 20,000 feet, but it is poorly exposed and little is known of the structures. The dip of the Upper Keweenawan steadily decreases as one traverses from south to north, until it is

essentially flat lying near the axis of the syncline near the city of Ashland and the Bayfield Peninsula (Van Hise and Leith (1911, p. 376).

Structure of the Area

Basically, the structure of the area is simple although numerous complexities may be seen locally. Aldrich notes that the northeasterly striking units have been tilted toward the northwest so that in the map area the structure is a homocline but is really the south limb of the larger Lake Superior synclinorium. As may be expected, the degree of tilting that has taken place has not been uniform and has resulted in the production of local torsional stresses. The release of these stresses resulted in structures of two types; cross faults that are of the nature of hinge faults and cross folds whose axes strike at an oblique angle to the major structures.

Aldrich (1929, p. 130) concluded that many of these transcurrent structures cut across both the Keweenaw and Animikian rock units, hence, those stresses which have affected the younger rocks likewise were operative in the tilting of the underlying Animikian rocks. It is apparent to the present writer that such evidence is inconclusive for, regardless of the events that have affected the Animikian series prior to Keweenaw time, it is to be expected that the later event also may have affected these rocks.

Several lines of evidence indicate that the sinking of the Lake Superior basin and resultant tilting in the area continued over a rather long period. Deformation appears to have commenced soon after the beginning of the Middle Keweenawan volcanic activity and probably continued until near the end of Keweenawan time. The gradual decrease of dip of both volcanics and overlying sedimentary units as one traverses northward seems to support this idea. Sandberg (1938, p. 820) indicated that the fanning of dips of the flows in the Duluth area points to simultaneous volcanism and tilting.

If the reasoning here is correct and deformation continued over the period of time indicated, then it follows that this deformation influenced the emplacement of the intrusive rocks of the area. Aldrich (1929) proposed a hypothesis involving the differential tilting that, as mentioned above, produced both the cross faults and folds. He advocates that the folds produced at an oblique angle to the major structure would inhibit the release of stresses in the usual manner of parallel folding, and that the release would take place in one "integral," movement rather than several. Such release along one thrust plane, in this case near the base of the Keweenawan unit although at a slight angle to it, provided a locus for the intrusion of the large masses of gabbro that are now found in this position. The proposed fault plane is actually some distance from the base of the gabbro near the Michigan-Wisconsin boundary, but gradually

cuts deeper into the flows further west and eventually intersects and cuts the Animikian series. The subsequent intrusion of gabbro along this plane bevels the Animikian series in the area south of Mineral Lake in the map area, whereas further east, it is seen to be well up in the extrusives.

Aldrich (1929, p. 117) further concluded that the final foundering of the Keweenawan syncline resulted in the formation of several cross faults that extend across the Keweenawan-Huronian contact. From the present field work the writer can only conclude that there are several north-northwesterly striking lineaments along which no specific evidence of differential movement can be determined. One of these prominent lineaments may be found slightly east of the eastern edge of the Mineral Lake Intrusion. The lineament is a stream that has cut a gorge that is perfectly straight for over a half a mile. The bedrock in this area is a heterogeneous mixture of metabasalt, gabbro and granite so that at best one can only say that some differential movement may have caused a weakening which has resulted in the straight gorge. Katzman (personal communication, 1965) has indicated that a similar lineament exists about two miles east of this feature. Aldrich drew cross faults on both of these lineaments, but neither of them shows noticable displacement of geologic boundaries which cross them.

Mineral Lake Intrusion

The Mineral Lake Intrusion represents a thickening of the intrusive sequence of the area on the order of two to three times of that found either to the east or west. The entire section of intrusive rocks in this area is made up of two and possibly three separate sheet-like bodies, but the lowermost has by far the greatest thickness and appears to be the most complex. As previously stated, the Mineral Lake Intrusion is on the order of 12,000 to 14,000 feet thick and a length along the strike of about ten miles. The western half of the intrusive has not been mapped due to the lack of exposures, but according to maps published by Aldrich and after a reconnaissance of the area by the writer there is little doubt as to its westerly extent. The approximate strike of the long axis of the intrusion is about N. 50 E., and the average dip of the structure is on the order of 55 degrees to the northwest.

The details of the intrusion itself will not be dealt with at this point, but a few of the general facts concerning its petrologic description seem appropriate. As one traverses the Intrusion, it is apparent that it is mineralogically zoned. This is represented by both cryptic zoning and "Phase Layering" as defined by Hess (1960, p. 131). The former is defined as changes in composition of various phases as cooling proceeded while the latter indicates the appearance or disappearance of a phase. The lower part of the body has the

composition of olivine gabbro grading upward into anorthositic gabbro with decrease of mafic content and ultimately into anorthosite. Above the anorthosite, an iron rich rock that is best described as ferrodiorite appears rather abruptly and then grades into a rock of granitic composition as mafic content decreases and quartz and orthoclase become dominant constituents. The uppermost rock of the intrusive has some of the appearance of the granophyre found farther to the west, but the typical myrmikitic and graphic texture of the granophyre or, "redrock," is lacking. Rhythmic layering typically observed in parts of the Duluth and Stillwater and other large basic intrusions is almost totally lacking in the Mineral Lake Intrusion. The absence of this feature may have significance in the flowage mechanism proposed above and will be discussed at a later point.

Previous Investigations

The only previous detailed petrologic investigation dealing with the intrusive rocks of this area has been reported by M. W. Leighton (1954). This study dealt with the petrologic and geochemical problems surrounding the gabbro-granophyre association that occurs immediately west and north of the present map area.

Van Hise and Leith (1911) described the Keweenaw gabbros of the area as having many similarities to the Duluth gabbro. Their description indicates that the gabbro intrusion has an extent along strike of some sixty miles

from the Black River in Michigan to R. 7 W. in Wisconsin. They cited the reasoning of Irving (1892) indicating the intrusive nature of the gabbro, but no more detailed descriptions were presented.

Aldrich (1929, p. 2) noted that the field investigations accomplished between 1922 and 1929 by the Wisconsin Geological and Historical Survey included the areas underlain by Keweenaw rocks. Indeed, much of the reasoning involved in his hypotheses of the structure of the Huronian series involves structures observed in Keweenaw rocks. He further indicated that a companion volume was to be published dealing specifically with the Keweenaw series. This publication has never materialized although field notes and rock specimens are on file with the Wisconsin Geological and Historical Survey.

Numerous other authors, two of whom are Daly (1913) and Grout (1918), have noted the presence of these gabbroic sheets and the striking symmetry of the Lake Superior syncline. Both of these authors advanced the idea that the Keweenaw gabbros of Wisconsin are the southern equivalent of the Duluth Gabbro. Van Hise and Leith also suggested this possibility in their earlier paper.

The most recent geological investigations that have been conducted in the area were by the Bear Creek Mining Company between the years 1952 and 1956. An intensive mapping, geophysical and drilling program was carried out for the purpose of investigating the numerous occurrences of copper

mineralization. The writer was able to obtain outcrop maps and a compilation map for the area as prepared by Bear Creek as well as samples from some of the exploratory drill cores which are presently housed at the United States Bureau of Mines offices at Minneapolis, Minnesota. No additional information from this project has been made available to the writer at this time.

CHAPTER II

FIELD RELATIONS

General

Although the entire area had been mapped in previous investigations it appeared advisable to re-map the area of the study. Mapping was carried out on a scale of 1:12000 directly on aerial photographs obtained from the United States Geological Survey and the United States Forest Service. The field studies were accomplished during the summers of 1963 and 1964. Mapping data was plotted directly on the aerial photographs and control was maintained with the aid of topographic and cultural features and by pace and compass methods. Table 2 indicates the sections that were mapped and the extent of mapping that was accomplished in each section.

Shape and Attitude of the Intrusion

The Mineral Lake Intrusion is a tabular body with a thickness on the order of 15,000 feet. The strike of the basal contact is about N. 50 E. The average strike of the fluxion structure, (Fig. 2), is about N. 40 E., indicating that flow of the magma during intrusion was nearly parallel

TABLE 2.--Sections and parts of sections mapped.

Township and Section	Mapping Detail
T. 44 N., R. 3 W.	
5	West third
6	Entire section
7	Southwest quarter
T. 45 N., R. 3 W.	
19	West half, outcrops rare
29	Southwest quarter
30, 31	Entire section
32	West half
T. 44 N., R. 4 W.	
1	Area east and south of river
2	West half
3	Entire section
10	North half, outcrops rare
11	All but small area in SW corner
12	Entire section
13	Area north of Co. Hwy. GG
14	Area around Mineral Lake
T. 45 N., R. 4 W.	
24	All but NW quarter
25	Entire section
26	South half
34, 35, 36	All but small area SW of river in 36 and SE 1/4 of 35

to the basal contact. The intrusive appears to have been tilted to the northwest so that the fluxion structures are now dipping in that direction at about 60 degrees. On the basis of drilling data obtained by the Bear Creek Mining Company (W. F. Read, personal communication, 1963) the basal contact of the intrusion is nearly vertical. A weathering phenomenon in the rocks above the upper contact that gives the outcrop the appearance of a masonry wall and is probably controlled by a compositional variation may provide a clue to the orientation of these overlying rocks. The attitude of these structures is N. 50 E. dipping NW. 30.

If all of these values are representative of the present attitude of the various parts of the intrusive and the enclosing units we can draw some tentative conclusions concerning the orientation of the intrusion and the relationships between different rock units. From the base upwards there is a decrease or fanning of the dips, which may indicate that tilting was under way during the intrusion of the gabbro. Leighton (1954, p. 411) noted that in the gabbro belt to the west of this area the dip of the fluxion structure decreased in the higher levels of the intrusive, suggesting simultaneous intrusion and tilting. The dip measurements made in this study do not show such a systematic decrease toward the top of the intrusive but the other data presented here combined with Leighton's all agree that the present attitude of the intrusive was achieved during emplacement.

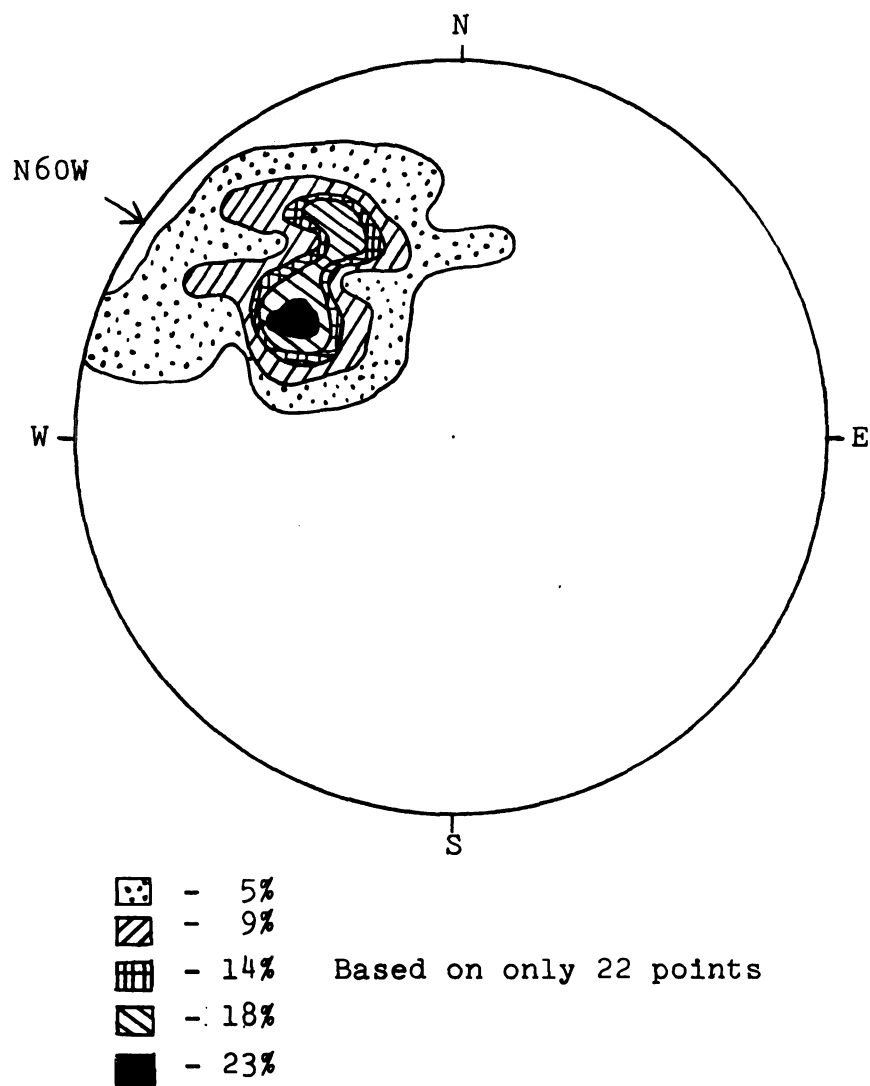


Fig. 2.--Pole diagram of fluxion structure in anorthosite of the Mineral Lake Intrusion.

Rock Unit Descriptions

On the basis of the above information, one may conclude that the intrusive has been tilted to a high angle and from the regional structure it is obvious that as one traverses toward the northwest he is crossing rock units that are higher and higher in the intrusive. As stated earlier the intrusive was divided in the field into four mappable units of distinct rock types (Plate I). The boundaries of these as shown on the map are somewhat arbitrary due to their gradational nature. For the most part the units are divided on the basis of rock type but in some cases textural and gross structural features are used. An example of division based on structure is the lower boundary of the gabbroic anorthosite which is marked by the appearance of the pronounced fluxion structure. The four units described here are, from the base upward: anorthositic olivine gabbro, gabbroic anorthosite to anorthosite, ferrodiorite and rocks approaching granitic and granitic rocks. These four general rock types form units which are northeasterly striking belts that are parallel to the base of the intrusive. Their general characteristics only are described here while the more detailed descriptions are found in the following chapter. It should be noted that the fine grained gabbro of the basal chill zone possesses a texture that is sufficiently distinct for subdivision in the field. However, its limited exposure

and extent in the field made such a distinction both unnecessary and impractical.

Anorthositic Olivine Gabbro

The anorthositic olivine gabbro composes the lower 3,000 feet of the intrusive. It is a rather heterogeneous unit containing very minor amounts of more basic rocks in small pods and layers. There are two types of ultrabasic rocks, eucrites and pyroxenites, which are found in small pods near the base of this layer and these are considered in detail in the section on petrography. Near the top of this layer there are several occurrences of "basic" pegmatite which probably have a similar composition to the anorthositic gabbro but are much more coarse.

At the base of the intrusive the rocks of the chill zone grade into the anorthositic gabbros over a distance of about 200 feet. The transition involves a slight increase in grain size and decrease of mafic content. The rock is medium to dark grey on a fresh surface, weathering to a dark brownish grey. Grain size is variable, even over a single outcrop, but in general 1 cm. is the upper limit for this unit. The texture is typically ophitic to subophitic or diabasic with the mafic content decreasing gradually toward the top of the unit where there is a gradual transition into gabbroic anorthosite.

Gabbroic Anorthosite and Anorthosite

The boundary between the anorthositic gabbro and gabbroic anorthosite is shown on the map as a gradational boundary, however, the actual boundary was picked at the point where the fluxion structure becomes strong enough to be a characteristic texture of the rock. At the time that the field work was under way the exact significance of the change from an ophitic texture in which the plagioclase is randomly oriented to one in which the plagioclase is well oriented in one plane was not understood. It was noted, however, that the rocks in all of the outcrops which possess the well developed fluxion structure contained considerably lower amounts of mafics than those in which the fluxion structure was not developed. The petrographic work has confirmed the distinct differences in mineralogical composition associated with the two types of textures supporting the basis used in the field work for differentiating the two types. The fact that this textural change is coincident with the reduction in mafic content is not entirely understood by the writer. Since rocks which are considerably more mafic often possess a pronounced fluxion structure,* the answer does not appear to lie in the composition of the rock. A change in physical conditions within the magma chamber occurring at this point of the intrusive history is probably

*The ferrodiorite contains an average of about 60 per cent plagioclase and yet possesses a very well developed fluxion structure.

a more accurate answer. This topic is discussed in more detail in the section concerned with the origin of the fluxion structure later in this chapter.

The anorthosites and gabbroic anorthosites are light grey to greenish grey in color and they weather to a whitish grey. There is a gradual increase in size upwards from about 1 cm. near the base of the layer to about 5 cm. in the upper levels. Although it is difficult to recognize in the field, olivine is common in small amounts in the lower parts of this layer. Olivine ceases to occur as an important constituent at about the five thousand foot level of the intrusion which is about two thousand feet above the base of the anorthosite zone. The total thickness of the anorthosite layer is on the order of 8,000 feet.

Many outcrops of the anorthositic rocks, notably those in the eastern half of the map area, show evidence of some crushing and strong alteration. This is particularly evident along the straight section of the Brunsweiler River north of Beaverdam Lake. There are also numerous occurrences of calcite and epidote along a line projected southeasterly from Beaverdam Lake. These exposures also show evidence of shearing indicating that some postmagmatic stresses have effected the intrusion along this line. East of this line there is also some evidence of shearing and distortion of plagioclase grains indicating that the zone that has been effected by these stresses is rather wide. The deformation that resulted

in the tilting of the intrusion to its present attitude is probably related to this late tectonic activity.

Ferrodiorite

The contact between the anorthosite and the overlying ferrodiorite is abrupt with the transition taking place over a few feet. The actual contact was not observed in the field, but in one group of exposures it was located to within a few feet. In every case where the anorthosite near this contact was observed it appears to have undergone considerable alteration, suggesting deuteric alteration of the anorthosite during the crystallization of the ferrodiorite.

The ferrodiorite layer is less than 2,000 feet thick and forms a relatively narrow belt across the upper part of the intrusive. The color of the rock is dark grey to black and is usually heavily stained with iron oxides on weathered surfaces. The average grain size is 3 to 5 mm. with plagioclase laths as large as one centimeter. The lower parts of the ferrodiorite layer show a pronounced fluxion structure indicating that the physical conditions during crystallization were similar to that of the underlying anorthosite layer. Higher in the ferrodiorite where the gradation to a more acidic composition begins to take place the fluxion structure is less noticeable. Two factors are probably responsible for this change, the gradual replacement of plagioclase by the more equidimensional potash feldspar and the less tabular habit of the more sodic plagioclase.

The high iron content of the ferrodiorite is reflected in the high specific gravity (3.2) of the rock. Modal analyses are given in Table 6 showing the presence of fayalitic olivine and ferroaugite. Most of the samples examined in thin section show considerable alteration of the mafic minerals to hornblende indicating that some late magmatic activity was operative.

Transition and Granitic Rocks

As shown on Plate I the granitic part of the intrusive is represented by two wedge shaped bodies near the top of the intrusion. There is a slight increase in grain size from the ferrodiorite toward the more acidic rocks but the most notable feature in the field is the appearance and gradual increase in potash feldspar content. The end product of this transition is a rock of granitic composition and coarse (5 mm.) granular texture. The granite is of a light brick red color similar to that of "redrock" but without the graphic or myrmikitic texture. The weathered surface of the rock often contains what appear to be miarolitic cavities although they are not obvious on a fresh surface, giving the impression that they may be weathering pits. The possible presence of miarolitic cavities indicates the increasing amounts of volatile constituents contained in the crystallizing magma at this point.

Relationships With the Enclosing Rocks

Basal Contact

The lower chill zone and adjacent country rocks are poorly exposed except for the area near the northeast corner of English Lake, and the area south of Mineral Lake where there are several outcrops but no actual contacts. The relationships in these two areas indicate that the basal contact in the west is at a lower stratigraphic horizon than it is further east. This intrusive contact has been described as having been controlled by a thrust fault, Aldrich (1929, p. 120) and by an unconformity, Van Hise and Leith (1911, p. 376) either of which could have equally well caused the present crosscutting relationships.

In the area near English Lake the contact between the gabbro and the underlying rocks is fairly well exposed. Here, there are what are believed to be both metabasalt and metasediments in contact with the intrusive rocks. The basalts, presumably Keweenawan, have been metamorphosed to pyroxene hornfels facies containing mostly orthorhombic pyroxene and plagioclase (An. .30), and have a texture that is best described as mosaic in nature. The extent of the metabasalt is not great and in this area is probably no more than a few feet thick. Within no more than 50 feet of the lowermost gabbros the metasediments, of the Tyler formation are encountered. These are highly variable rocks ranging in composition from nearly pure quartzites to metagreywackes.

The bedding of these rocks is dipping steeply to the northwest indicating approximate conformable relationships between the intrusive and the enclosing rocks.

In the area south of Mineral Lake the intrusive is in contact with the Ironwood and Palms formations. The actual contact was not observed on the surface but the two rock types are seen within a few feet of each other and the contact was found in a drill core taken from the area. The iron formation is composed of magnetite and quartz. Bedding is plainly visible in the iron formation as well as in the quartzite in the underlying upper part of the Palms formation. These quartzites have been strongly recrystallized so that they possess a mosaic texture and often show a strong blue color.

In conclusion, it is readily apparent that the rocks adjacent to and underlying the intrusion have been metamorphosed to a rather high degree. All of the Huronian rocks examined have typical xenoblastic metamorphic textures and those of the proper chemical composition indicate pyroxene hornfels conditions close to the intrusion decreasing to lower grades away from the contact. The crosscutting relationships indicate that emplacement of the intrusion was not exactly along the bedding but may have been controlled either by faulting associated with the tilting of the region during Keweenawan time or by a zone of weakness at the Huronian-Keweenawan contact. Any evidence of faulting in this area cannot be expected to be found as it would have been destroyed by the subsequent intrusion of the gabbro.

However, this does not negate the possibility that the intrusion has been emplaced along a zone of weakness created by thrust faulting.

Eastern Boundary.

Because of the later granite intrusion the original contact relationships of the gabbro with the enclosing rocks on the northeast side are obscure. There is reason to believe that the original boundary of the gabbro may have approximated the present location of the gabbro granite contact. Several observations have been made in this area which seem to support this location of the original gabbro boundary as well as provide valuable evidence concerning the mode of intrusion of the gabbro.

1. In Secs. 13 and 24, T. 45 N., R. 4 W. there is a prominent northwest striking ridge which faces east. Outcrops are lacking east of this ridge, but are common along the ridge and farther west. In Sec. 24, west of the ridge, granitic rocks of the upper part of the Mineral Lake Intrusion are exposed. Further north in Sec. 13, gabbros and basalts which overlie the Mineral Lake Intrusion in other areas are found in their expected locations. East of the ridge, none of these rocks are exposed but, based on magnetic studies, Aldrich (1929, p. 128) located flows offset to the south from their normal positions to the west of the ridge. This

magnetic data combined with the presence of the sharp linear topographic feature suggest the presence of a strike slip fault of dextral nature.

2. The arching of all the flows which overlies the Mineral Lake Intrusion suggests an upward bulging in this area. Figure 1 indicates that this bulging is sharply terminated on the east along the above mentioned ridge.
3. A most noticeable observation made when mapping along the granite-gabbro contact is the very great abundance of basaltic inclusions found in the granite and lack of such inclusions within the gabbro.
4. In the anorthositic part of the Mineral Lake Intrusion, one of the most prominent features of the rock is the very well developed fluxion structure. Furthermore, throughout the entire intrusion there is a notable lack of any chilling or intrusive relationships. Along the eastern boundary several features are distinctly well developed within the intrusion which suggest that this was the original boundary of the magma chamber.
 - a. In this region there is a disruption of the fluxion structure, often to the point of total obliteration.

- b. There is evidence of intrusive contacts, often between two rather similar anorthositic gabbros or anorthosites suggesting the presence of cognate inclusions.
- c. Some banding has been noted, but its orientation is random and apparently not related to the main intrusion.

All of these features suggest that the present eastern boundary may have been the boundary of the intrusion at the time of emplacement. It is to be expected that any laminar flow which existed well within the chamber during emplacement would be disrupted near the boundaries.

- 5. Near the base of the gabbro in Sec. 5, T. 44 N., R. 3 W. and to the east of this area we find a gabbro belt overlying the Tyler formation which extends almost to the Village of Mellen. This belt of gabbro which is on the order of a mile in width separates the Mellen granite and the Tyler formation. There is no reason to believe that this is a separate body from the Mineral Lake Intrusion, but its finer texture and gabbroic composition indicates that in this area cooling of the gabbro preceeded more rapidly than in the main part of the intrusion restricting the differentiation process. Also it should be noted that the gabbroic inclusions found within the granite are considerably finer than most of the gabbros of

the Mineral Lake Intrusion implying that they may have been derived from sills or thick flows that predate the Mineral Lake Intrusion.

On the basis of the information cited here the following hypothesis has been constructed. With the exception of the thinner belt of gabbro which overlies the Tyler formation east of the map area, the present eastern boundary approximates the original eastern boundary of the Mineral Lake Intrusion. The point at which the width of the gabbro increases to form the Mineral Lake Intrusion is the point where the original thickening took place. Plate I shows that this point is in line with the presumed fault noted above which is an important factor in the mode of intrusion of the gabbro.

As for the actual mechanism of emplacement of the Mineral Lake Intrusion, the following is proposed. The bulging of the overlying flows indicates that they were simply uplifted by the magma as it was emplaced. This bulge has about the same east-west extent as the Mineral Lake Intrusion. The steep ridge noted in Sections 13 and 24 marks the eastern extent of this bulging and as seen on Plate I is in line with the present eastern boundary of the Mineral Lake Intrusion. The offsetting of the flows as noted by Aldrich and apparent dextral fault along this line seems to support the above idea. The faulting along this line took place simultaneously with and was an integral part of the mechanism of emplacement of the Mineral Lake Intrusion. The writer envisions the rocks overlying the Mineral Lake

Intrusion being wedged upward as though hinged on the west, but faulted on the east as indicated in Figure 3. This accounts for the abundance of basalt inclusions in the later granite, for east of the fault the flows were uplifted to a lesser extent, and occupied the area east of the Mineral Lake Intrusion until the granite was emplaced.

Upper Contact

Due to the lack of exposures it is not known whether the rocks immediately above are earlier or later than the Mineral Lake Intrusion. As shown on Plate I, the uppermost rocks of the Mineral Lake Intrusion represent the granitic differentiate of the very large mass of gabbroic rocks of the intrusive. The granite is wedged out near the center of the upper contact so that in this area the iron-rich diorites are in contact with the roof rocks. The western wedge of granitic rocks extends about six or seven miles further west forming the top of the intrusion for its entire western extent.

In the map area the rocks which overlie the Mineral Lake Intrusion are olivine gabbros. These rocks are medium grained and often grade into troctolites which in some cases approach an ultrabasic composition. The olivine is strongly altered to serpentine, and bent and broken feldspar grains provide some small evidence that tectonic activity post dates their emplacement. However, there is no conclusive

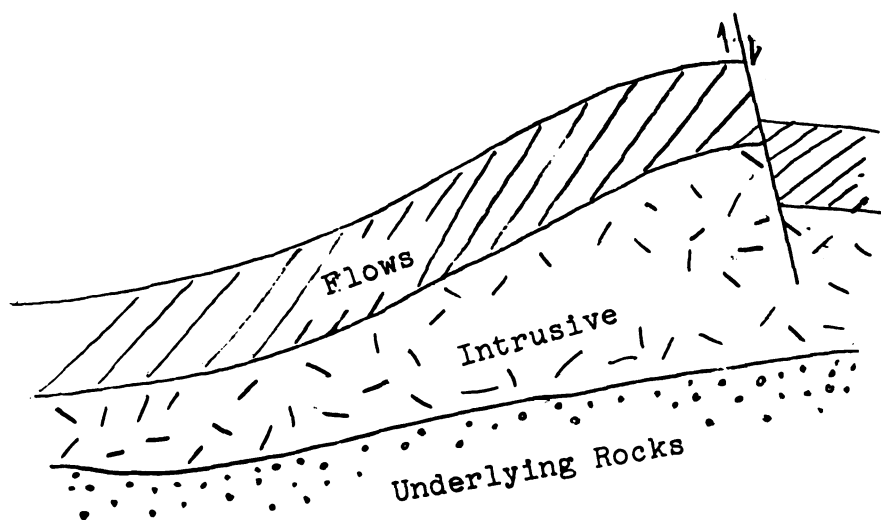


Fig. 3.--Mode of emplacement of Mineral Lake Intrusion showing bulging of overlying flows.

evidence available that would indicate whether these rocks are earlier or later than the Mineral Lake Intrusion.

Origin and Significance of the
Fluxion Structure

Fluxion structure or orientation of the plagioclase crystals in a particular plane has been observed in nearly all large basic intrusives that have been studied. Wager and Deer (1939) use the term "igneous lamination" to describe the orientation of the platy feldspar crystals. Many large intrusions such as the Duluth and the Stillwater complexes display in addition to fluxion structure, a pronounced layering of alternate layers of mafic rich and poor rocks. Grout (1918) concluded that the combination of alternate light and dark bands and fluxion structure must be due in some way to the action of convection currents in the magma. Hess (1939) has independently arrived at a similar conclusion.

The hypothesis that convection currents in a cooling magma may often be the cause of both layering and fluxion structure is not disputed. The arguments presented by the above mentioned authors are sound and convincing, but this is not to say that other activity cannot also cause similar structures. Flow or movement of a partially crystalline magma has commonly been invoked as the cause of a strong orientation of platy or rod-shaped crystals (Balk, 1937). Numerous authors have called upon this mechanism for the production of fluxion structures; indeed, it is often seen

in minor dikes and sills where the crystals are oriented parallel to the walls of the intrusive body.

It may be noted that layering such as mentioned above is conspicuously lacking in the Mineral Lake Intrusion. Banding due to layering was noted in only two or three exposures in Sec. 5, T. 44 N., R. 3 W. along the extreme eastern boundary of the intrusion, and in every case very poorly developed and was not oscillatory as described in other large mafic intrusions. It is also of note that the fluxion structure is well developed only in the anorthositic part of the intrusion and the overlying iron-rich dioritic rocks and almost totally lacking in the lower olivine gabbros.

Figure 4 shows some of the features often seen in the field in exposures where fluxion structures were well-developed. The wavy orientation of crystals as shown in Figure 4 seems to attest to the idea that flow was the agency responsible for the structures rather than settling of the crystals from the overlying liquid material. The very perfect orientation as seen in numerous examples (Plate VII) seems almost too perfect to be the result of the settling of crystals from the magma. Plate VII seems to indicate that this orientation is somewhat disrupted by the crystallization of the mafic constituents from the interstitial magma, at least in some cases.

In conclusion, it seems most reasonable that movement of an unidirectional nature is responsible for the fluxion structure rather than convection currents or crystal

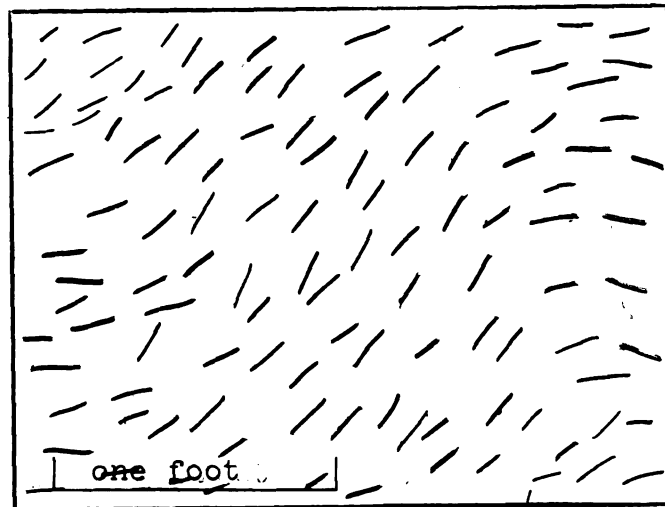


Fig. 4.--Sketch showing distortions of fluxion structure due to flow.

settling. Later, it will be seen that upward movement of the partially crystalline magma may have played a role in the differentiation of the entire body that resulted in the large amount of anorthosite in the central part of the intrusion.

CHAPTER III

PETROGRAPHY

Introduction

In the field the Mineral Lake Intrusion can be divided into four rock types that constitute mappable units. These subdivisions are based upon gross texture and general composition. The petrographic examination has allowed further more definitive subdivision on the basis of mineral percentages and composition as well as textures.

There are seven major rock types recognized as important to the descriptive aspects of differentiation of the magma. They are as follows:

Fine-grained gabbro--medium to dark grey or black weathering to brownish-black. Intergranular to ophitic texture; pyroxene abundant with minor olivine.

Pyroxenite--dark grey to black, coarse-grained, composed almost entirely of orthorhombic pyroxene with minor plagioclase, sulfides, and magnetite-eilmenite. Found only in very minor patches near the base of the intrusive.

Anorthositic olivine gabbro*--medium to light grey with ophitic to subophitic texture. Generally medium grained.

*Buddington's (1939) classification is used to differentiate the feldspar rich gabbros. Greater than 90 per cent

Contains over 65 per cent plagioclase with varying amounts of olivine and pyroxene. Magnetite and Ilmenite are minor.

Gabbroic anorthosite and anorthosite--medium to light grey, coarse to very coarse-grained with plagioclase laths usually showing fluxion structure. Composed chiefly of labradorite and augite with minor hypersthene, olivine, and opaques.

Ferrodiorite--dark grey to black, often heavily iron stained. Medium grained, commonly showing fluxion structure. Composition is plagioclase (andesine) about 55 per cent, olivine and pyroxene 40 per cent, and significant apatite and magnetite and very minor quartz. Mafics are often altered to hornblende and biotite.

Transition (quartz monzonite)--Usually light grey to pink. Often spotted with brick red orthoclase phenocrysts. Contains about equal amounts of plagioclase and orthoclase and with small amounts of quartz. Significant amounts of hornblende and biotite with minor zircon and apatite.

Granite--pink to brick red, medium to coarse grained sometimes porphyritic. Composed mainly of orthoclase and quartz with minor plagioclase and hornblende. Some myrmekitic intergrowths are seen in interstitial material, but individual grains are more common.

plagioclase - anorthosite; between 90 per cent and 77.5 per cent - gabbroic anorthosite; between 77.5 per cent and 65 per cent - anorthositic gabbro; less than 65 per cent - gabbro.

Although gross textural features often vary because of changes of relative mineral percentages, there are particular textures which may be associated with certain cooling conditions. An excellent example of this may be seen when studying the basal, chilled, fine-grained gabbros which increase in grain size away from the contact. In addition to this, textural changes take place with the appearance or disappearance of certain mineral phases.

Many authors have studied ophitic textures and their variants and many systems of classification have been adopted. Walker (1957) and Oppenheim (1965) have reviewed the literature and conducted intensive studies of rocks displaying ophitic textures and have adopted classifications which seem to be in some agreement. Relative amounts of pyroxene and plagioclase play an important role in the textural type that is evolved, however, Oppenheim (1965, p. 555) has noted that rate of cooling also has a considerable influence.

It is apparent to the writer that Oppenheim's classification for ophitic textures in basalts is applicable to the chill zone of this intrusive, while Walker's classification based upon relative amounts of pyroxene and plagioclase is more useful where studying the coarse anorthositic rocks.

The following classification is presented for use in this paper. The author to which the particular definition is attributed is noted.

Ophitic--(Walker) "Pyroxene in optically continuous areas completely enclosing plagioclase laths, with average lengths less than that of pyroxene areas."

Subophitic--(Walker) "Pyroxene in optically continuous areas partly enclosing plagioclase laths, with average length greater than that of pyroxene areas."

Nesophitic--(Walker) This is a sub-variety of the above in which plagioclase greatly predominates. Walker notes, "Pyroxene interstitial to plagioclase and in isolated but optically continuous areas--though connected in three dimensions."

Isogranular--(Oppenheim) "A texture due to the presence of hypidiomorphic to idiomorphic pyroxene grains in the interstices between, and having the same order of size as the plagioclase prisms."

Intergranular--(Oppenheim) "A texture due to the aggregation of pyroxene grains lying in the interstices between, and having a much smaller size than the plagioclase prisms . . ."

To some degree these terms are based upon relative percentages of minerals and to some degree on relative grain sizes. Such a classification may be subject to criticism on the point that one is not always evaluating the same parameter. This is true, however it should be noted that in this intrusive the major variation within the body is relative mineral abundances, whereas, within the chill zone the major variation is in relative grain size, not

composition. Here then, is a classification which admittedly is not perfect, but is capable of measuring the parameter which is most pertinent at that point in the intrusive with the greatest genetic significance.

Petrologic Discussion

Fine Grained Gabbro

All of the rocks which fall within the class of fine grained gabbro are relatively chilled rocks that were collected from exposures and drill cores which were known to be located within a few feet of the basal contact. The best exposures of these rocks are found in Secs. 6 and 7, T. 44 N., R. 3 W., near the northwest corner of English Lake and in Sec. 13, T. 44 N., R. 4 W., southeast of Mineral Lake. A similar sample was taken from a drill core (DDH-16) which is located just north of Potter Lake on Plate I.

The texture of the fine grained, chilled gabbro varies from intergranular to subophitic. The average grain size of these samples ranges from 0.2 mm. to 0.5 mm. with the length of the plagioclase laths ranging up to about 2.0 mm.. The two textural types arise from variations in grain size of the pyroxene as indicated in the foregoing descriptions of textures. The difference in habit of the pyroxene presumably results from differing rates of cooling and the resulting different degrees of supersaturation which that particular phase has undergone at the time of crystallization Oppenheim (1965), Wager (1961). It follows from this that

those samples taken closest to the contact with country rocks should possess the intergranular texture, grading into the subophitic with distance from the contact. This relationship is seen to hold in most cases and is accompanied with a general increase in grain size of all of the mineral constituents.

Modes of two chilled gabbro specimens are presented in Table 3 and their compositions may be compared with those of the overlying rocks in Figure 6. A chemical analysis and the normative composition are given in Tables 15 and 16 for comparison. Sample 6-5-65 was collected from outcrop at a point about two feet from the contact of the intrusion with the underlying metabasalt and sample 16-822 is from the exploratory drill core located in Sec. 12, T. 44 N., R. 4 W. The former sample displays the subophitic texture while the latter is intergranular.

TABLE 3.--Modal compositions of two chill zone gabbros.

Minerals	Specimen Number	
	6-5-65*	16-822
Plagioclase	51.2	47.9
Clinopyroxene	20.2	{39.1
Orthopyroxene	10.8	
Olivine	3.6	Tr.
Biotite	4.5	3.7
Magnetite	5.4	4.3
Uralitic Hornblende	3.8	4.9

*Average of four mode counts taken on different thin sections cut from the same slab.

Plagioclase of the chill zone rocks is found as sub-hedral laths which are often tapered on the ends. Strong normal zoning is common with compositions ranging from An. .68 in the cores to An. .35 in the rim. On the basis of the chemical analysis of the plagioclase separated from sample 6-5-65, the composition is An. .42. (Table 8) This value is in good agreement with the plagioclase calculated in the norm from the chemical composition of the same rock sample.

A notable characteristic of the plagioclase in the chilled gabbro is the presence of minute dusty inclusions in the core of the crystals while the rims are relatively free of inclusions (Plate II-A and B). Optically the inner cloudy zone is considerably more calcic than the outer inclusion free zone and it is not known whether the compositional zoning and the zoning due the inclusions is coincidental or whether the optical zoning is due to strain caused by the inclusions. This problem will be discussed in more detail in the section on mineralogy.

Both orthorhombic and monoclinic pyroxene are present in the chilled gabbros. Both types occur as discrete grains in the intergranular textured rocks and molded around the ends of plagioclase laths in the rocks of subophitic texture. Hypersthene (En. .48, Fs. .52) is pleochroic from pale bluish green to pink and is usually relatively free of inclusions. Augite (Wo. .38, En. .34, Fs. .28) is pink in thin section and usually heavily inclusion filled. The augite often displays a peculiar pattern resulting from the inclusions being

oriented in a concentric manner about the ends of the plagioclase (Plate II-D). In close connection with this pattern it has been noted that the extinction position seems to sweep through the crystal in a radial manner at right angles to the direction of orientation of the inclusions. It appears as though these crystals have been bent about the plagioclase while they were in a plastic state. No further explanation of this feature will be attempted at this time.

Olivine (Fo. .39, Fa. .61) is rare in these rocks occurring only as remnants in larger grains of pyroxene. It may be noted that olivine is considerably more abundant in the normative composition than in the modal composition. This is believed to be due to the fact that the composition of the magma had been strongly enriched in iron relative to magnesium by the time the solid phases of the chill zone began to crystallize at this level. It is difficult to predict the phase relationships in such cases as are encountered in the chilled rocks as equilibrium conditions are not met with. In any case it appears that under these conditions olivine was either eliminated as a phase through reaction or its position in the sequence of crystallization was replaced by pyroxene.

Although the rock of the chill zone is usually quite fresh in appearance, such alteration products as biotite, chlorite and uraltic hornblende are occasionally seen. They are usually present along the boundaries of earlier minerals where interstitial or later fluids have the best opportunity to react.

As stated earlier the textural variations of these rocks are probably due to the cooling rates and to the degree of supersaturation to which the various phases have been subjected. It would be useful to have some measure of undercooling that a magma has undergone to result in the production of two textural types found here. An estimate of the undercooling may be gained from a brief investigation of the zoning found in the plagioclase. The samples of which the modes are given in Table 3 provide a particularly good example of the two textures mentioned above with related intensity of zoning. Specimen 6-5-65 is subophitic and contains plagioclase that is zoned from An. .68 to An. .35, while 16-822 is intergranular and contains plagioclase that is zoned from An. .60 to An. .40. These values are plotted on a plagioclase equilibrium diagram in Figure 5 to show the relatively different temperatures at which the cores of the compositions given would be stable. On this basis alone it appears that 16-822 was undercooled some 35 degrees more than the other sample. This difference may well be more than sufficient to cause the pyroxene to crystallize from the middle labile stage on many nucleation centers giving rise to the intergranular texture.*

Finally, the chemical composition of sample 6-5-65, (Table 15) is considerably different than that of a typical basaltic rock. The peculiarity of this composition is

*See Wager (1961) for a thorough discussion of the relationships between chilling and resulting mineralogical habits and textures.

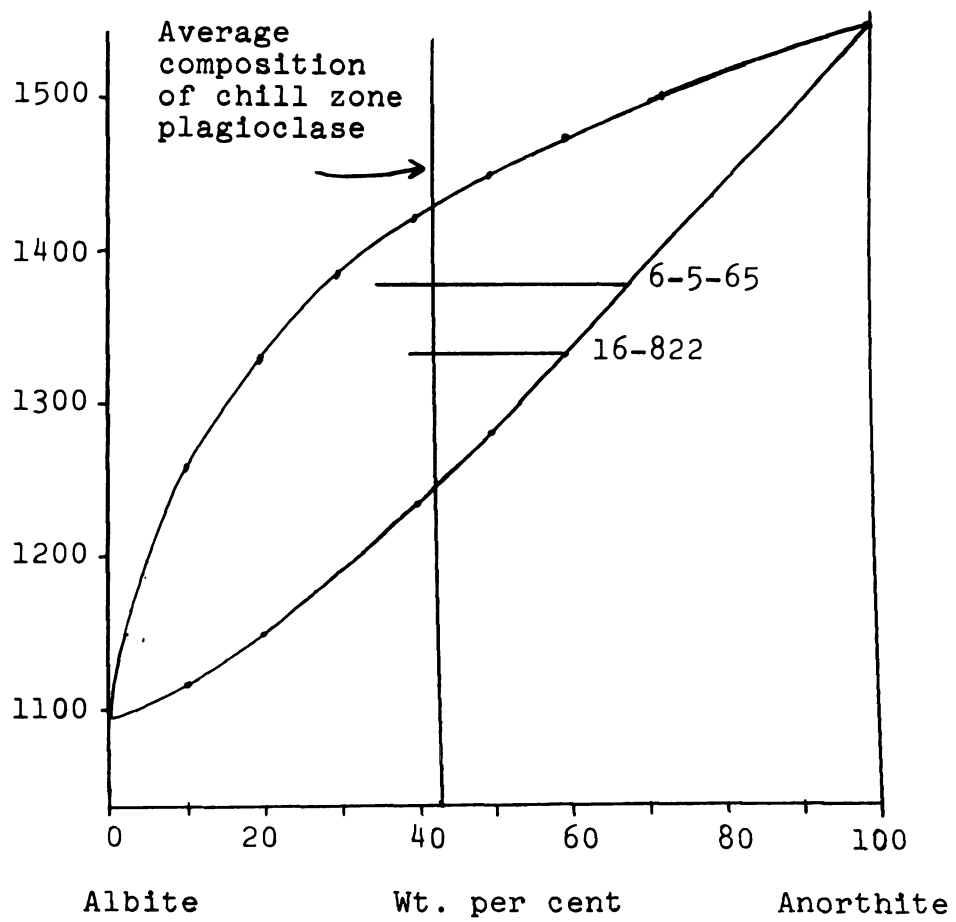


Fig. 5.--Plagioclase equilibrium diagram showing range of zoning of two chill zone feldspars.

sufficiently so to demand an explanation. This fact combined with the compositions of the constituent minerals gives strong indication that the chilled rocks have crystallized from a magma which has undergone strong fractionation. This matter will be given a considerable amount of attention in the sections concerning mineralogy and the petrology of the intrusion as well as in the later parts of this chapter.

Pyroxenite

Although occurrences of pyroxenites are limited, their presence is considered of importance to the trend and mechanism of differentiation. Their location very near the base of the intrusion in Sec. 14, T. 44 N, R. 4 W. is strongly suggestive of crystal settling as a mechanism for the accumulation of the pyroxene. In other areas near the base, (Sec. 7, T. 44 N., R. 3 W.) small pods of olivine rich rock (picrite) appear to have a similar origin.

The pyroxenite is nearly monomineralic, being composed of orthorhombic pyroxene (En. .63, Fs. .37) which is usually of anhedral habit. The grains of pyroxene are often interlocking in such a manner so as to impart an allotriomorphic texture to the rock. When plagioclase is present it is found interstitially to the pyroxene and often in optical continuity over a large area. The average grain size of the pyroxenites is 2.0 mm. to 3.0 mm., so that they are usually more coarse than the rocks that surround them.

The paragenesis of these rocks is the reverse of most of the gabbros in that the plagioclase crystallized late. The only mechanism that can provide such a sequence is crystal settling with the plagioclase crystallizing from the inter-precipitate liquid. Other minerals include opaques and secondary biotite which occurs as an alteration product along plagioclase pyroxene boundaries.

The composition of the pyroxene and plagioclase (An. .65) in the pyroxenites is noteworthy. On the basis of their compositions it is apparent that these minerals have crystallized from a liquid that is considerably more magnesian and calcic and hence more primitive than that from which the chill zone rocks have crystallized. The fact that these rocks overlie the chill zone and are apparently crystal accumulates but have a more primitive composition indicates that their constituent minerals crystallized from a more primitive liquid than the chill zone minerals. It follows then, that these rocks accumulated at an earlier point in the history of the intrusion before the magma evolved to the composition shown in the rocks of the chilled basal margin.

Anorthositic Olivine Gabbro

There is a very rapid transition from the fine-grained rocks of normal gabbroic composition at the base of the intrusion to rocks in which the plagioclase content is above 65 per cent. This usually takes place over a distance of less than 300 feet. The belt in which the composition falls

within the range of anorthositic gabbro is about 2,000 feet in width. Olivine is an important constituent here although it continues as a minor phase to a somewhat higher level of the intrusive. An important textural feature of the rocks of this belt is that plagioclase is randomly oriented, whereas the more anorthositic rocks above possess a distinct fluxion structure. This difference may be due to the different amounts of mafics in the two rock types as well as to differences in processes or conditions that may have been operative. The interface between the two types on Plate I is chosen as the level where the fluxion structure becomes prominent.* Figure 6 shows the relative amounts of the mineral phases in relationship to distance from the base of the intrusion. It may be noted that olivine content falls very rapidly across the rocks of this layer above the 1,000 foot level.

The grain size at the lower boundary of the layer is on the order of 2 mm., gradually increasing to about 4 mm. at the top. At the base of the anorthositic gabbro, the average composition of the rock is 65 per cent plagioclase, (An. .60 average), 22 per cent pyroxene (total) (Clino. Wo. .42 En. .38 Fs. .20) (Ortho. En. .66 Fs. .34) and 14 per cent olivine (Fo. .53 Fa. .47). Proceeding upward in the intrusion

*There is a gradual decrease of mafics from the base upward until the rock is a true anorthosite. Olivine continues as a phase to about the 5,000 foot level. Hence there is no compositional boundary but a gradual change.

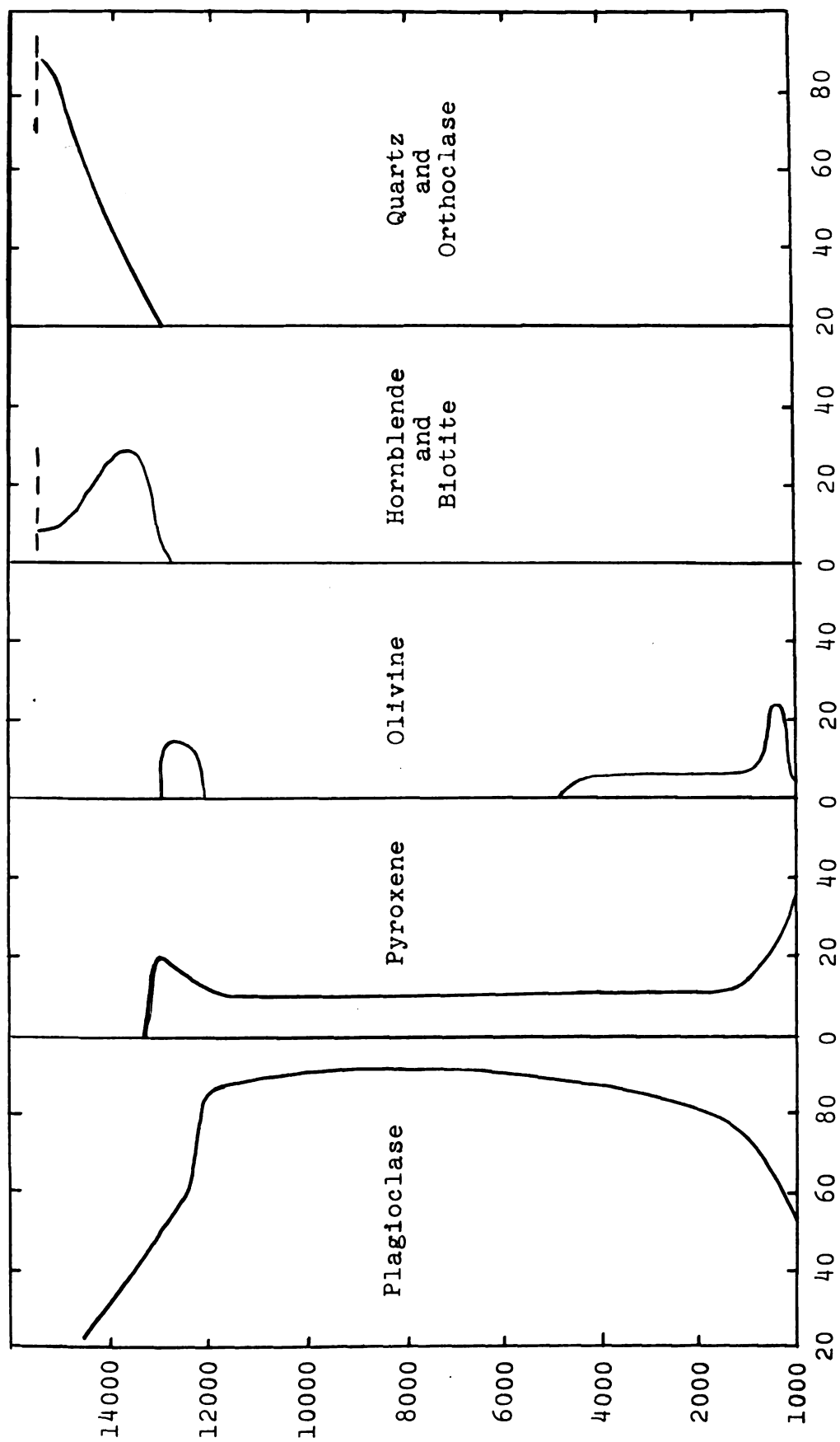


Fig. 6.--Modal rock compositions in relationship to distance above base of the intrusion.

the quantity of plagioclase gradually increases to 75 per cent at the top of the zone with the average composition remaining at about An. .60. At this point the olivine and pyroxene have been reduced respectively to 8 per cent and 10 per cent, but with little change in composition. Opaques make up about 2 per cent to 5 per cent and there are very minor amounts of apatite and secondary biotite.

TABLE 4.--Modal compositions of five anorthositic gabbros.

Minerals	Specimen Number				
	6-5C	6-16	13-2	14-15A	14-18
Plagioclase An. .60	63.9	72.2	72.64	70.6	76.6
Orthopyroxene	12.8	3.8	5.28	1.7	4.5
Clinopyroxene	3.0	0.5	3.50	12.2	6.1
Olivine	9.4	20.0	15.85	14.3	9.8
Opaques	5.3	2.4	2.36	0.4	2.5
Biotite	4.2	-	0.36	-	0.5
Alterations	1.4	0.9	-	-	-
Serpentine	-	-	tr.	-	-

The mineral compositions will be dealt with in more detail later, but one observation seems to be pertinent at this point. Even though mineral percentages are changing somewhat rapidly over this part of the intrusion the constancy of their compositions is quite striking. It is

apparent that some crystal settling had taken place so as to give rise to the anorthositic rocks above. However, in view of the composition of the chill zone which is much richer in iron than even the lower part of this layer, significant differentiation of some manner must have taken place before the magma reached the level that we now observe. Further, the gradual upward reduction in mafics that we now see implies that crystal settling was active probably during upward transport and possibly after the time that the magma had reached its present level.

The texture of the rock in general grades from ophitic near the base of the layer to nesophitic near the top (See Plates III-F and IV-A). It is to be emphasized that this change is due mainly to the decrease in content of the mafic minerals and not to a decrease in grain size of individual crystals of pyroxene. It is also noteworthy that exceptions exist mainly in cases where olivine content is much greater than pyroxene content. In this case the olivine does not occupy the typical interstitial position, but rather occurs as large, rounded enveloping grains or clumps of grains resulting in a texture that approaches the hypidiomorphic granular texture so common to granites. In some cases the clumps or grains of olivine are of great enough size that they give the rock a porphyritic appearance. Rocks of this composition (picrite) are found in small pods as mentioned earlier and undoubtedly result from accumulation of olivine through crystal settling.

Plagioclase occurs as elongate laths that are well-twinned and commonly, slightly zoned. The laths are anhedral toward one another, but usually are euhedral toward the mafics. An exception to this is seen in the olivine rich rocks where the plagioclase is commonly anhedral toward the olivine. This no doubt, is the result of the fact that the olivine is a cumulate and the plagioclase for the most part has crystallized from an interstitial liquid. Plagioclase is always euhedral towards pyroxene which is molded around the laths of the former resulting in the typical ophitic or subophitic texture.

It may be noted that from about fifteen hundred feet upward that the change in composition is due primarily to the substitution of plagioclase for olivine, while the content of the pyroxene remains relatively constant. Another change that may be noted is that clinopyroxene gradually replaces orthopyroxene with height in the intrusion. Near the top of the anorthositic gabbro, orthopyroxene is rarely found in amounts greater than 2 per cent, although, it is not uncommonly found in these amounts all the way to the top of the anorthosite.

Pyroxene is almost always found to occupy the interstitial position in large continuous network crystals. It often gives the rock a spotted appearance on a weathered surface where weathering of the mafic mineral has been more rapid. Augite is commonly inclusion-filled containing in some cases small opaque rods that are oriented along a

crystallographic directions (Plate VIb) while in other cases the inclusions are very fine, dusty particles. In contrast to this, the orthorhombic variety is usually quite inclusion free or contains a few large, opaque grains. Augite is a yellowish-pink color and nonpleochoric whereas the orthopyroxene is pleochroic from a pale pink to pale greyish-green.

Olivine is found as small rounded grains often mantled by orthopyroxene. The olivine is remarkably fresh but with some alteration to iddingsite along fractures and at the edges. It is normally lacking in color, but in thick sections takes on a pale pinkish color. Some grains contain opaque inclusions clustered along curving surfaces, but in general the olivine is relatively clear and free of foreign material.

The order of beginning crystallization in this zone of the intrusive, based wholly on textural relationships is as follows: Plagioclase appears to be early in all of the specimens except those in which olivine is greatly enriched due to crystal settling. Olivine certainly predates pyroxene which is interstitial and is, thus, later than plagioclase. Opaques are probably later than plagioclase but are often surrounded, or partially so, by olivine. Biotite occurs as the result of reactions between olivine and plagioclase or opaques and plagioclase. The sequence then is: Plagioclase, opaques, olivine, pyroxene, and finally deuteritic biotite. The very minor amounts of apatite must be fairly early as many of them are surrounded by olivine. Rates of nucleation

appear to be slowing as the crystallization proceeded since the later minerals, namely, pyroxene are found as much larger crystals than the earlier plagioclase or olivine.

Near the top of the layer a zone of very coarse "pegmatitic" textured rock of gabbroic composition often separates this zone from the overlying gabbroic anorthosite. This zone is not dealt with in detail as it is not considered to be of importance to the course of differentiation. The pegmatite zone was mapped in several locations along the boundary, but its extent does not seem to be great.

Gabbroic Anorthosite and Anorthosite

Rocks of these compositions are grouped together here because their petrographic and mineralogical similarities far outweigh their differences. This zone makes up the largest single unit of the intrusion and might well be divided into olivine bearing and olivine free zones, but they are described as a single unit to avoid duplication.

As indicated earlier, this rock type represents a mappable unit distinguishable in the field from that which is beneath by the excellent fluxion structure that it displays (Plate VII-B and C). Compositionally there is a significant change at about the 6,000 foot level where olivine ceases to be an important phase. The total thickness of the unit is on the order of 10,000 feet. The top is marked by an abrupt change to ferrodiorite where there are notable alteration

effects on the mafics of the anorthosite, apparently caused by the presence of the overlying more iron-rich magma.

TABLE 5.--Modal compositions of anorthosite and gabbroic anorthosite.

Minerals	Specimen Number				
	11-9	2-3	3-10	3-12	11-18
Plagioclase An. .60	79.5	93.4	78.0	92.0	89.1
Olivine	9.3	-	-	1.7	-
Orthopyroxene	5.1	1.9	12.7	3.9	0.4
Clinopyroxene	2.9	3.3			9.9
Sec. Hornblende	1.7	-	-	-	-
Biotite	1.7	-	0.4	-	-
Opaques	1.4	0.1	0.7	0.7	0.3
Alterations	-	1.3	9.2	1.5	0.3

The range in the composition of the plagioclase of this unit is remarkably small. Near the base of the unit the plagioclase is about An. .60 and at the top it averages about An. .57. However, compositions ranging from An. .55 to An. .65 have been determined. Some zoning of the plagioclase is observed, but usually the range of composition within a single crystal is not greater than ten per cent and as far as can be determined by optical methods, usually much less. The zoning is usually restricted to the rims of the crystals indicating some adcumulus growth of the plagioclase from the

interstitial liquid (Wager, Brown and Wadsworth, 1960). Some evidence of cataclasis is seen in the plagioclase such as the bending of twins and fracturing of grains indicating that there was some movement of the magma after a considerable amount had crystallized (Plate IV-E). The plagioclase laths are usually well oriented with their largest dimensions lying in one plane giving rise to the fluxion structure described earlier. In hand specimen the plagioclase varies in color from a dark green to grey, rarely showing a play of color.

Pyroxene occurs as large network crystals which are seen as many separate wedge-shaped interstitial grains in optical continuity. Clinopyroxene is dominant with a composition of about (Wo. .37, En. .30, Fs. .33) with minor orthopyroxene (En. .45, Fs. .55). In Figure 7 one may note that pyroxene content is nearly constant across the anorthosite layer and that the major mineralogical variation involves olivine and feldspar. Both pyroxenes show some color in thin sections with the orthorhombic type being pleochroic from pink to bluish-green while the clinopyroxene is a faint greyish-pink color.

Although olivine is a minor constituent it is found in some samples in small, rounded grains usually mantled by orthopyroxene. The olivine is usually remarkably fresh, the exceptions being where it was apparently out of equilibrium near the top of the layer in which case it is partially or completely altered to serpentine.

The grain size of the anorthosite is variable but feldspar laths are always in excess of one centimeter in length and commonly about three times that long. The large pyroxene network crystals are typically several inches across, resulting in the nesophitic texture.

Ferrodiorite

The appearance of the ferrodiorite is considerably different from the gabbroic rocks seen in the lower levels of the intrusive. In hand specimen the most obvious features are the dark grey to black color and the ever present iron stain. It has a density of about 3.2 g/cc.. In contrast to the anorthosite immediately below the ferrodiorite is fine-grained with an average grain size of about one millimeter. The well defined fluxion structure seen in the anorthosite is also well-developed in these rocks.

The average composition of the plagioclase in the diorite is An. .45, but zoning is common with a range from about An. .50 to An. .40. The average length to width ratio of the plagioclase is somewhat less than in the gabbros resulting in a more blocky appearance. Textural relationships between mineral grains are somewhat varied. Plagioclase ranges from anhedral to euhedral with somewhat varied relationships toward the mafic minerals.

One of the notable features of the ferrodiorite is the reappearance of olivine as a major constituent. The composition of the olivine (Fo. .25, Fa. .75 Ave.) is reflected

TABLE 6.--Modal compositions of four ferrodiorites.

Minerals	Specimen Number			
	25-60	26-5	35-11	35-20
Plagioclase Ave. An. .45	61.5	53.9	64.0	66.0
Pyroxene	11.9	10.4	14.5	13.2
Olivine	14.3	10.9	14.5	12.1
Apatite	2.9	3.3	0.9	0.5
Magnetite	6.2			
Biotite	1.8	1.0	0.4	
Alteration	1.3		1.4 hlbd.	
Alteration after Olivine		7.1		
Alteration after Pyroxene		6.8		
Opakes		6.6	3.6	4.8
Zircon (?)			0.4	
Quartz		tr.	tr.	tr.

in its light yellowish color, however, there is no noticeable pleochroism. The habit of the olivine is typically anhedral often filling interstitial spaces, sometimes molding itself around the ends of plagioclase laths although its average grain size is less than that of the feldspar. It is also commonly seen as small clumps of rounded to subhedral grains

although this occurrence is much less common than that of larger single grains. The olivine is always fresh and free of inclusions.

The composition of these rocks and of the constituent minerals is typical of the "intermediate" rocks found in many large basic intrusives. Rocks approaching these in composition have been reported in the Duluth area (Taylor, 1964) and are seen to make up a substantial part of the Skaergaard Intrusion (Wager and Deer, 1939).

Transition Rocks and Granite

In a strict sense these rocks belong to the granodiorite-adamellite rock type. Actually there is a continual gradation from diorites to granites. In the absence of chemical analyses of these rocks and lack of detailed data on the mafics, the exact chemical nature is not known. However, some aspects of the textures lead one to the conclusion that they are truly mixed species reflecting certain aspects of both the ferrodiorites and the more granitic rocks. A more complete chemical and petrological study of these rocks would be most useful in determining the exact relationship between the granitic residuum and the earlier and more basic parts of the intrusive.

Leighton (1954) has discussed the intermediate zone found between the gabbro and granophyre immediately west and north of the map area. He presents several observations both from the field and from petrographic studies which he

believes lead to the conclusion that the intermediate rocks are to a large degree metasomatic. This may be true to some degree, but it should be noted that with diminishing volumes of the liquid, more rapid transition should be expected in this part of the intrusion than in the lower parts. Near the top of the ferrodiorite layer, hornblende and biotite

TABLE 7.--Modal compositions of six transition rocks and granitic rocks.

Minerals	Specimen Number					
	25-36	25-35	25-45	25-12	24-7	24-3
Plagioclase	48.3	41.7	30.0	35.5	13.0	
Orthoclase	5.9		23.9	12.4	49.2	58.9
Quartz	15.4	15.6	27.7	13.7	27.9	33.6
Hornblende	20.8	18.6	14.5	25.2		6.0
Biotite	7.1	11.0	3.4	9.4	8.5	0.3
Opaque	2.2	1.3	0.4	2.9	0.2	0.8
Chlorite	tr.	0.3				0.3
Zircon	tr.	tr.		tr.		0.1
Apatite	tr.		0.1	0.7		tr.
Feldspar		10.8				
Muscovite		0.7				
Epidote			0.1	0.1		
Amphibole					1.2	
Fluorite						tr.

replace pyroxene and olivine as the major mafic minerals. Along with this change quartz becomes a significant constituent and the composition of the feldspar changes from calcic to sodic andesine and minor amounts of orthoclase are present as intergrowths with the quartz (Plate V-F).

The overall texture of the lowermost transition rocks is subophitic with large plates of hornblende occupying the interstitial areas between plagioclase crystals. However, in addition to large hornblende plates, some of the interstitial areas are occupied by aggregates of small crystals of both hornblende and biotite. Such occurrences as this seem to be typical of replacement and are believed to be due to the late alteration of either ferroaugite or of fayalitic olivine. Many such occurrences are accompanied by grains of magnetite also indicating secondary origin.

Although the texture near the base of the transition rock is subophitic, there is a gradual change to the more typical hypidomorphic textures of granites, the plagioclase being euhedral while orthoclase is subhedral and quartz anhedral. Leighton has implied that this change is due to metasomatic effects of a granitic liquid in proximity to the earlier gabbro and that the ophitic character of the lower part of the transition is "pseudomorphous." In the area under investigation here, the writer concludes that the subophitic nature of the lower transition rocks is simply due to the presence of early euhedral plagioclase with the

later mafics occupying the interstitial spaces. Other evidence bearing on this problem will be discussed in a later section.

In the field the transition zone is recognized by the presence of pink orthoclase which produces a mottled appearance and is readily distinguished from the ferrodiorite. However the actual change as revealed by the petrographic studies takes place before orthoclase is recognizable in hand specimen. As noted above the change can be recognized by the change in mafic minerals and the presence of interstitial micrographic quartz and orthoclase in relatively significant amounts.

The plagioclase of the transition zone is more characteristic of the intermediate rocks of the intrusive. The composition of the plagioclase ranges from An. .40 to An. .20 with rather strong zoning (Plate V-E) in most examples. The cores of the plagioclase have a composition on the order of An. .40 and are usually euhedral and somewhat altered to secondary mica. The transition to the more salic rim is abrupt showing the euhedral outline of the core (Plate VI-C). Composition of the rims are on the order of An. .20.

Patchy zoning is common in the plagioclase with square or rectangular patches of more sodic plagioclase enclosed within a more calcic host. Vance (1965) investigated this type of zoning and proposed that it is due to resorption of early calcic plagioclase as it becomes unstable under

conditions of lower pressure when the magma rises to higher levels within the crust. A more sodic plagioclase is then crystallized under the conditions of lower pressure and no doubt lower temperature. Wylie (1963) illustrated that in complex systems the slopes of the liquidus and solidus along a cotectic are much lower than in simple binary (eg. plagioclase) systems. The effect of this is to cause a greater compositional change with temperature than in the simple system or in a complex system when the composition of the liquid has not yet reached a cotectic (Fig. 7). In the system Anorthite-Albite-Diopside, the change of composition of the plagioclase with temperature along the boundary curve is from An. .60 to An. .40 with a drop of only about 25°C, while a temperature drop of nearly 150°C is required for the same change if the composition of the liquid is always on the plagioclase side of the boundary curve while the change takes place. The result of this is that in the final stages of crystallization when the plagioclase is sodic the zoning may be expected to be very rapid as compared with the earlier plagioclases which crystallize when the slope of the liquids is very steep. With these facts in mind, one might expect that with small changes in temperature earlier plagioclase will undergo slight resorption with subsequent mantling by the stable more sodic plagioclase. Since in thin section one sees only a two dimensional picture, the zoning could appear quite irregular and patchy when sections along the

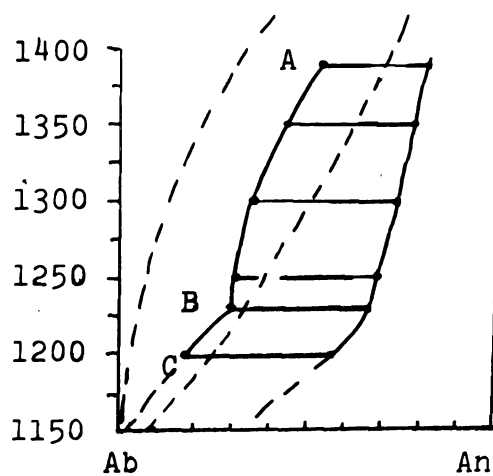
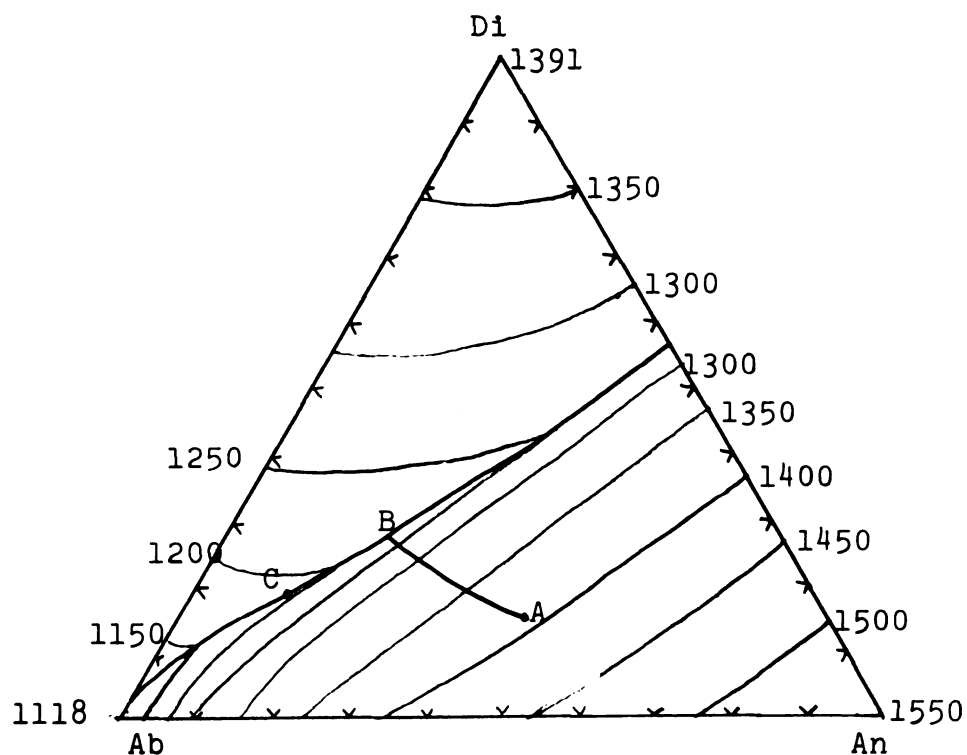


Fig. 7.--Albite-anorthite-diopside diagram showing plagioclase liquidus and solidus slopes as an additional phase is introduced (Wylie, 1963).

edge of a crystal are seen while a section through the center of a crystal would display more regular but rapid zoning.

Shapes of the plagioclase in the transition zone range from lath-like to blocky in outline. A most notable characteristic of the plagioclase of this zone is that as the rock becomes more acid in composition the plagioclase crystals diminish in size. The plagioclase is in turn gradually replaced by orthoclase until the rock is of granitic composition. In the earlier stages of the transition, quartz and orthoclase are very minor, the rock having the composition of a diorite. Orthoclase is found intimately intergrown with quartz as a granophyric residuum in the interstices between plagioclase. As the rock becomes more acidic these two minerals are found as discrete grains with quartz usually occupying the interstitial position.

Orthoclase in the earlier transition rocks does not appear to be perthitic but as it becomes more abundant in the higher rocks it shows a perthitic development although plagioclase continues as a separate phase. Even in the granite that is found in the highest part of the intrusion two feldspars, one an albite and the other perthite exist in apparent equilibrium. The explanation of this will be considered in some detail at a later point.

The orthoclase found throughout the transition zone and the true granites range in color from pale pink to a brick red. Microscopic examination shows the red color to

be the result of the presence of dusty red inclusions of hematite. Orthoclase is typically subhedral with the exception of micrographic or myrmikitic intergrowths with quartz.

As indicated earlier, hornblende occurs in two ways: as large plates and as aggregates of small crystals which are probably secondary. The color of the hornblende is of varying shades of green and is usually moderately pleochroic from light to dark green. Where hornblende is interpreted as being secondary the aggregates are usually ragged and often cut across boundaries of several grains. Otherwise it often takes the form of the areas which it is filling bounded by the edge of the adjoining mineral. Biotite is usually a brownish-red variety which is strongly pleochroic from yellowish-brown to dark reddish-brown or as in a few cases almost a dark greenish-brown. The biotite always has a small 2V, but some separation of the isogyres is always seen. Some distortion of cleavage traces is often seen as though some stress had been applied after crystallization.

Minor minerals include opaques, apatite, zircon which often occurs as unusually large crystals, epidote and in the most acid rocks some fluorite.

It is to be noted here that although the granite is compositionally similar to granophyre or redrock it is texturally much different. While quartz is abundant in redrock it is difficult to see in hand specimen due to its

occurrence as graphic or myrmikitic intergrowths in K-feldspar. Quartz is very apparent in hand specimens of the granite of this area as it as well as feldspar are found as discrete grains and the average grain size may be slightly greater than is found in the redrock.

CHAPTER IV

MINERALOGY

General Statement

Selected minerals and pairs of minerals which best reflect the course and extent of differentiation have been studied in varying degrees of detail. The trends displayed in plagioclase, pyroxene, and olivine are typical of other large basic intrusions. However, some interesting chemical relationships which disclose the character of the differentiation are presented.

Mineral compositions were determined both by optical and by chemical methods. Those studied by optical methods were analyzed both in thin section and grain mounts. Minerals on which indices of refraction were determined were mounted on slides with epoxy cement. By this method orientations on the universal stage could be made without movement of the grains and changes of index oil could be made without using additional crushed material. In this manner, the same grain could be located on the slide after each oil change eliminating the tedious hunting for grains with the proper orientation. In all cases the beta index was measured by means of centering an optic axis figure. All 2V measurements

were made directly and only those in which both optic axes could be centered were used.

Chemical analyses were obtained commercially on mineral separations made by the writer. All of the separations were made on a Frantz separator and purified by use of heavy liquids (methylene iodide). The purified minerals were inspected under the microscope periodically and were determined to be above 98 per cent pure. Purification of the minerals from the chill zone was somewhat difficult due to the presence of minute inclusions, but these have been eliminated from the analysis by computation (see Table 8) and they are considered to be nearly representative of the true composition of the minerals.

Plagioclase

The composition of the plagioclase was determined by the Rittman Zone method, Emmons (1943, p. 115), and by making use of a chart from Deer, Howie and Zussman, Vol. IV (1963, p. 138). Figure 8 shows the variation of plagioclase composition with distance above the base of the intrusion. Precision of the individual determinations is considered to be within three per cent of the average. The use of a large number of analyses as is the case in Figure 8 shows the trends quite accurately.

Near the base of the intrusion the composition of the plagioclase varies widely with little change in level above

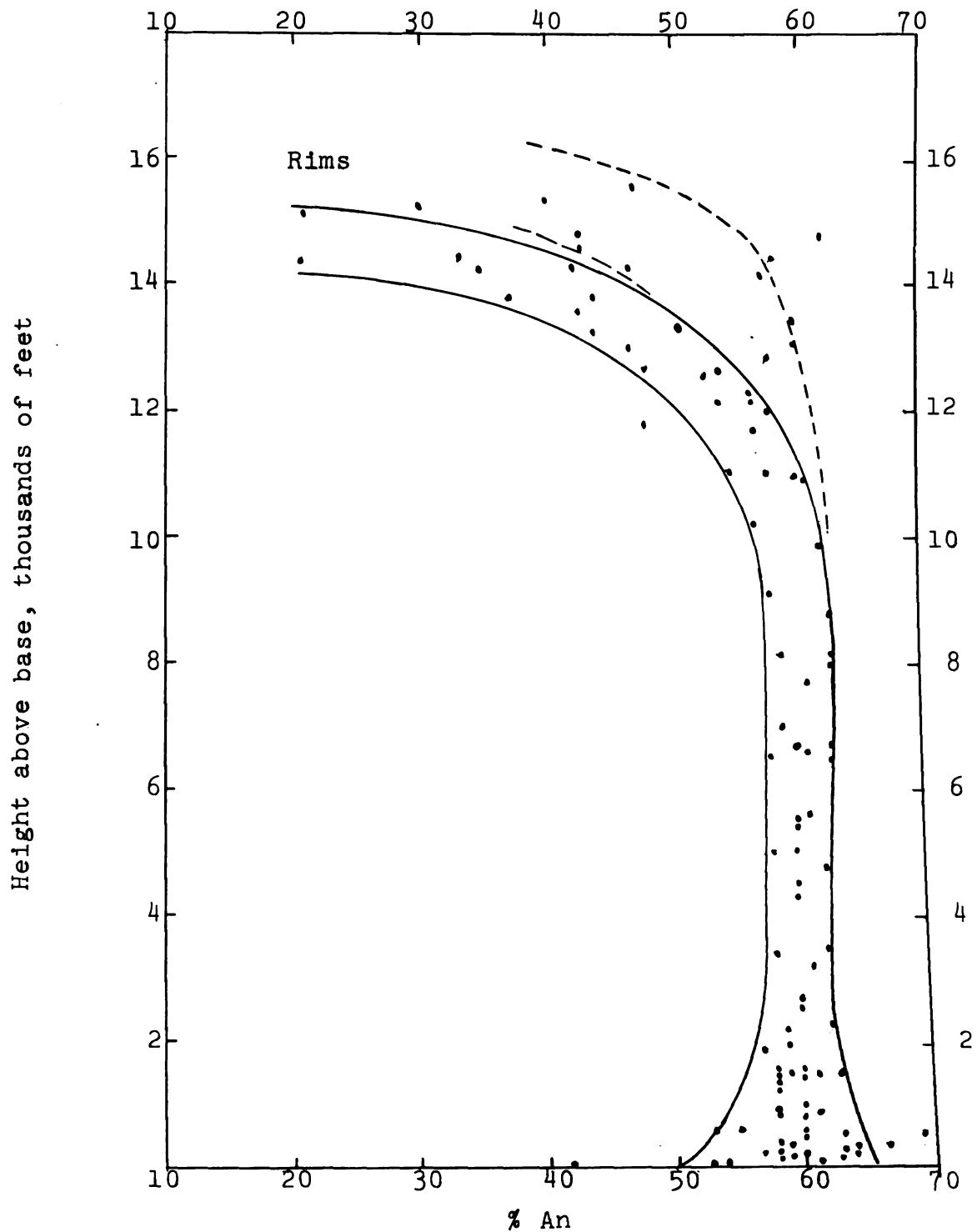


Fig. 8.--Variation of plagioclase composition with height in the intrusion.

the base. There are two factors which are the cause of this fluctuation but it is difficult to estimate the importance of either. The first cause is that of settling of plagioclase which has crystallized from the overlying liquid. If complete equilibrium is not established between the settling crystals and the liquid which surrounds it then some heterogeneity is to be expected in the levels of the intrusion where crystal settling is a factor. The second cause of these fluctuations is that the compositions were plotted with reference to height above the base only, without regard to location along the strike of the intrusive. This effect shows up in Figure 9 in the upper levels of the intrusive where the two traverses from which values were taken (English Lake and Mineral Lake) can be distinguished.

The rather consistent composition of the plagioclase across the intrusion is unusual for intrusives of this type. Turner and Verhoogen (1960, p. 213) and Hess (1960, p. 121) This lack of change is probably due to the large volume of magma involved. The more rapid change near the top of the intrusion is the result of decreasing amounts of liquid hence an accelerated rate of change of composition.

The chill zone plagioclase has a composition of An. .42 and that of most of the overlying rocks is considerably more calcic. Hess (1960, p. 121) noted a similar situation in the Stillwater Complex and reasoned that a sufficient amount of more sodic plagioclase to give an average for the whole

intrusion similar to that of the chill zone would be found in the upper hidden zone. In this case the upper part of the intrusion is available and no such amounts of more sodic plagioclase have been found. On the basis of the chemical composition which was calculated from an average modal composition of the entire intrusive (Table 20) the average plagioclase composition for the intrusive is about 57 per cent anorthite. On the basis of this data alone one is led to a tentative hypothesis that a large part of the intrusion is missing or the composition of the chill zone is not representative of the composition of the original magma. This subject will be considered in detail in later sections of the paper.

The plagioclase of the chill zone has been determined by analysis (An. .42) (Table 8). This value is in contrast with that determined by the Rittman method, (An. .55) but the discrepancy is considered to be due to the strong compositional zoning of the individual crystals, rendering an optical determination of the average value impossible.

Table 8 shows considerable amounts of Fe_2O_3 , FeO and MgO . Some of these ferric oxides can be calculated as magnetite but the high percentage of magnesia requires the presence of some spinel or silicates. The plagioclase cores of the chilled rocks are filled with minute or dusty inclusions that appear to be opaque material. The presence of these tiny inclusions make a pure sample difficult to

TABLE 8.--Chemical analysis of plagioclase from Sample 6-5-65 (basal chill zone).
Calculations involving subtraction of impurities are given.

				<u>Impurities to be Subtracted</u>		
				<u>Ionic Ratios</u>	<u>Titaniferous Magnetite</u>	<u>Pyroxene</u>
						<u>Plagioclase</u>
SiO ₂	56.03	Si	935	--	57	878
TiO ₂	0.10	Ti	1	1	--	--
Al ₂ O ₃	24.73	Al	484	--	--	484
Fe ₂ O ₃	0.61	Fe ⁺³	8	8	--	--
FeO	1.04	Fe ⁺²	15	5	10	--
MgO	0.99	Mg	25	--	25	--
CaO	9.27	Ca	165	--	22	143
Na ₂ O	5.50	Na	177	--	--	177
K ₂ O	0.81	K	17	--	--	17
H ₂ O ⁺	0.24	Total	1827	12 = 0.7%	114 = 6.4%	1699 = 92.9%
H ₂ O ⁻	0.02	Cations				
	<u>99.34</u>					
Plagioclase Composition CaAl ₂ Si ₂ O ₈				(CaNaK)	Al	Si
				143	+ 286	+ 286 = 715
NaAlSi ₃ O ₈				177	+ 177	+ 531 = 885
KAlSi ₃ O ₈				<u>17</u>	+ 17	+ 51 = 85
				337	<u>480</u>	<u>868</u> = 1685

TABLE 8--Continued

Cations per 8 oxygens	CaNaK	Al	Si
	.99	1.41	2.55
Composition of cell	(CaNaK) .99	Al _{1.41} Si _{2.55}	O ₈
Plagioclase composition	An. = 42.5	Ab. = 52.5	Or. = 5.0
Pyroxene compositions	Wo. = 38.5	En. = 44.0	Fs. = 17.5

obtain. On the basis of the data of Table 8, it appears as though a large percentage of these inclusions may be a pyroxene of a composition very similar to that which is found in the immediately overlying coarse-grained gabbros. (Compare pyroxene data of Table 8 with Table 13.)

The implication gained from these data then, is that the magma from which the chill zone plagioclase crystallized must have been carrying tiny crystals of pyroxene in equilibrium which became caught up in the earliest feldspar to crystallize. The disequilibrium of these chilled rocks is demonstrated by comparing the calculated composition of the pyroxene inclusions with the megascopic pyroxene of the same rock sample. (Compare pyroxene data on Table 8 with Table 9.)

The average composition of the plagioclase of the anorthositic gabbro and gabbroic anorthosite may be seen in Figure 9. The composition appears to stabilize at about 60 per cent anorthite throughout most of the anorthositic part of the intrusive and then becomes more sodic in the ferrodiorite, a trend which continues into the transition rocks. The final plagioclase which is found in the uppermost granite is albite which is undoubtedly in equilibrium with the orthoclase of the granite (Fig. 10).

Alkali Feldspar

Considering the entire volume of the intrusion, alkali feldspar is a very minor constituent, but some information

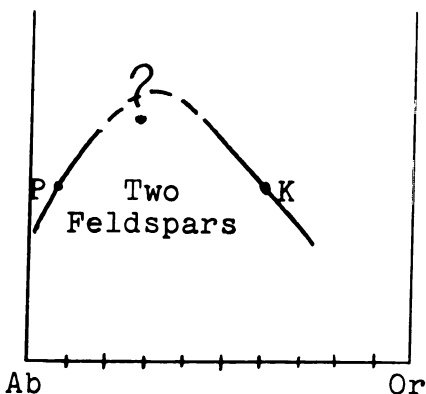
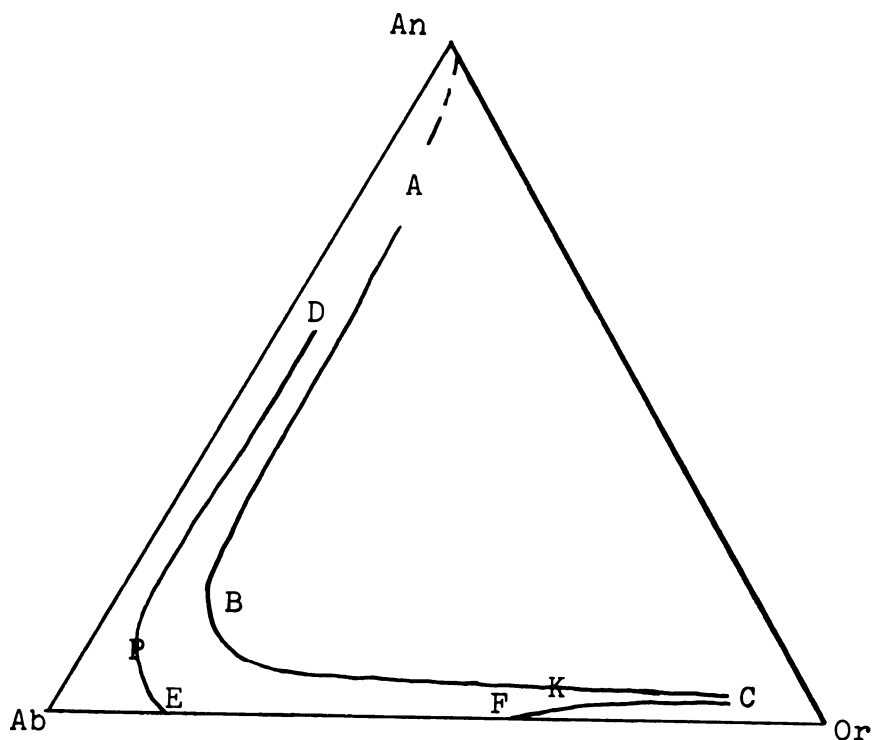


Fig. 9.--Ternary diagram of Ab.-An.-Or system showing approximate location of solvus for high water content conditions (Tuttle and Bowen 1952, p. 135).

The diagram shows what might be the expected location of the solvus when P_{H_2O} is high and anorthite content is low.

Curve ABC for slightly lower water content than DE FC. Points P and K are possible feldspars in equilibrium. The feldspar at point K then exsolves to form perthite as the temperature drops. The lower diagram is a projection of P and K into the Ab-Or sideline showing possible location of the solvus. Slopes of solvus are hypothetical.

of the late stage cooling of the magma may be obtained from this mineral. The presence of albite and perthite coexisting as discrete crystals is indicative that they have crystallized from a melt at a temperature below 660°C, as shown in Figure 9. The fact that the alkali feldspar is perthitic with a considerable amount of exsolved albite indicates that the original feldspar contained sufficient amounts of the albite molecule (720 per cent) to cause the exsolution to take place (Tuttle-Bowen, 1958, p. 19). Tuttle and Bowen (1958, p. 128) have classified these granites containing two feldspars as "subsolvus" types. Although no quantitative determinations have been accomplished, it is reasonably sure that the perthites of the uppermost granite contain more than 30 per cent albite. This places these rocks as "subsolvus" type A (Bowen and Tuttle, p. 129) indicating that they are of magmatic origin.

Olivine

Olivine has not been studied in detail. However, some mention may be made of the trends of composition that are shown in Table 9 and Figure 10. The olivine of the chill zone is relatively rich in fayalite but as will be shown appears in equilibrium with orthopyroxene even though these rocks are the result of strong undercooling. The olivine of the anorthositic gabbro is more magnesian (samples 13-2 and 11-9) and is also in equilibrium with the pyroxenes (Fig. 10) of these rocks.

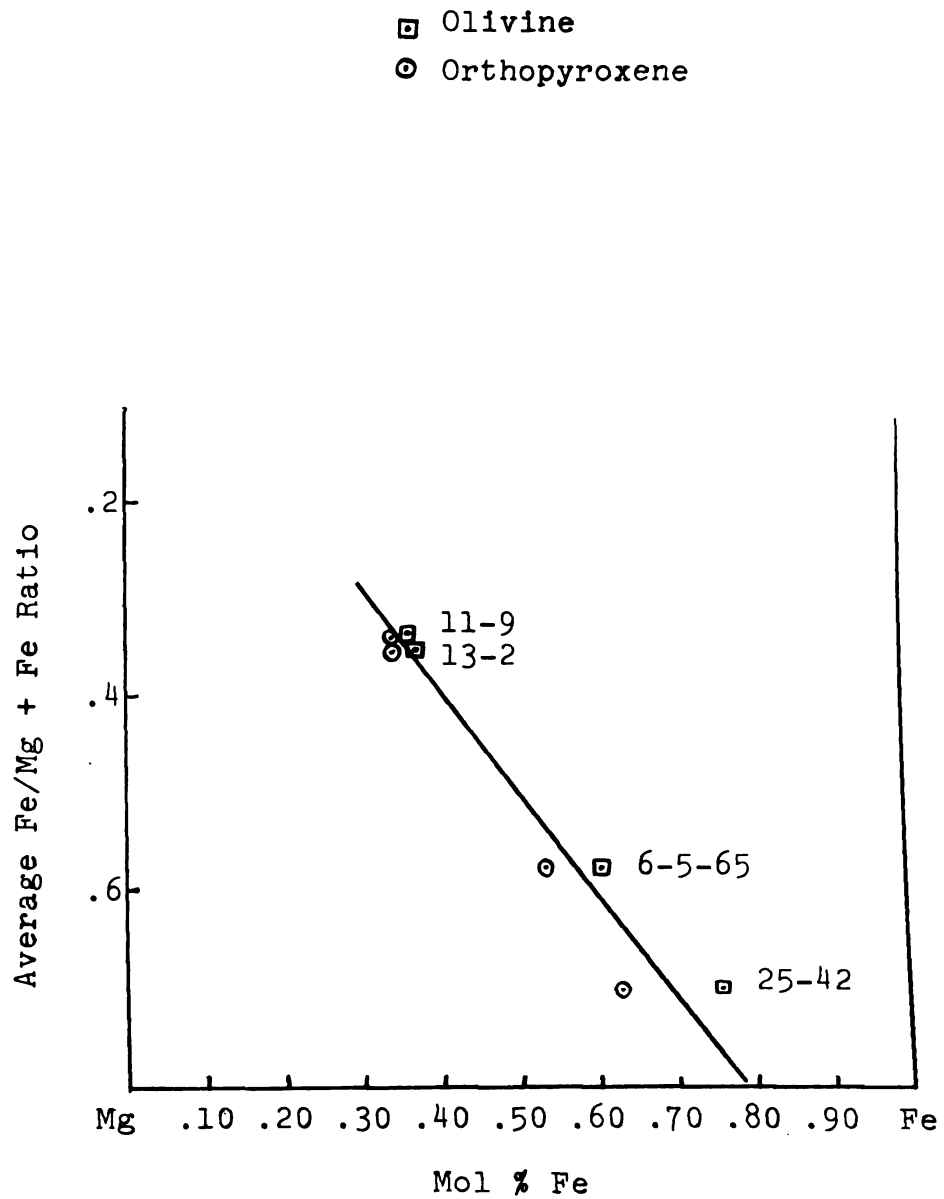


Fig. 10.--Plot of olivine orthopyroxene compositions versus average Fe/Fe + Mg ratio of the coexisting pair.

Olivine disappears as a phase at about 6,000 feet above the base of the intrusive. It is absent throughout that part of the intrusion that is truly anorthosite and reappears as an important constituent in the ferrodiorite. The presence of fayalitic olivine in this rock is indicative not only of the extent to which fractionation has proceeded at this level but also its presence along with pyroxene in place of hornblende is indicative of the very low P_{H_2O} that must have obtained throughout the cooling period.

Since olivine is found co-existing with small amounts of quartz as well as pyroxene in the ferrodiorites, some additional information as to the composition and temperature of the magma is made available. Point F on Figure 11 is the ternary invariant point where pyroxene, olivine and silica co-exist. As temperature drops lower toward the low of 1178°C . olivine continues to crystallize in equilibrium with silica. When studying the ferrodiorites it appears as though the onset of hornblende crystallization interrupts the relationships shown on the diagram. The important fact shown on this diagram is the extreme iron rich composition of the magma at this point.

Pyroxene

Several investigators have studied the pyroxenes of differentiated intrusives, and their chemistry in relationship to fractionation is fairly well known. For

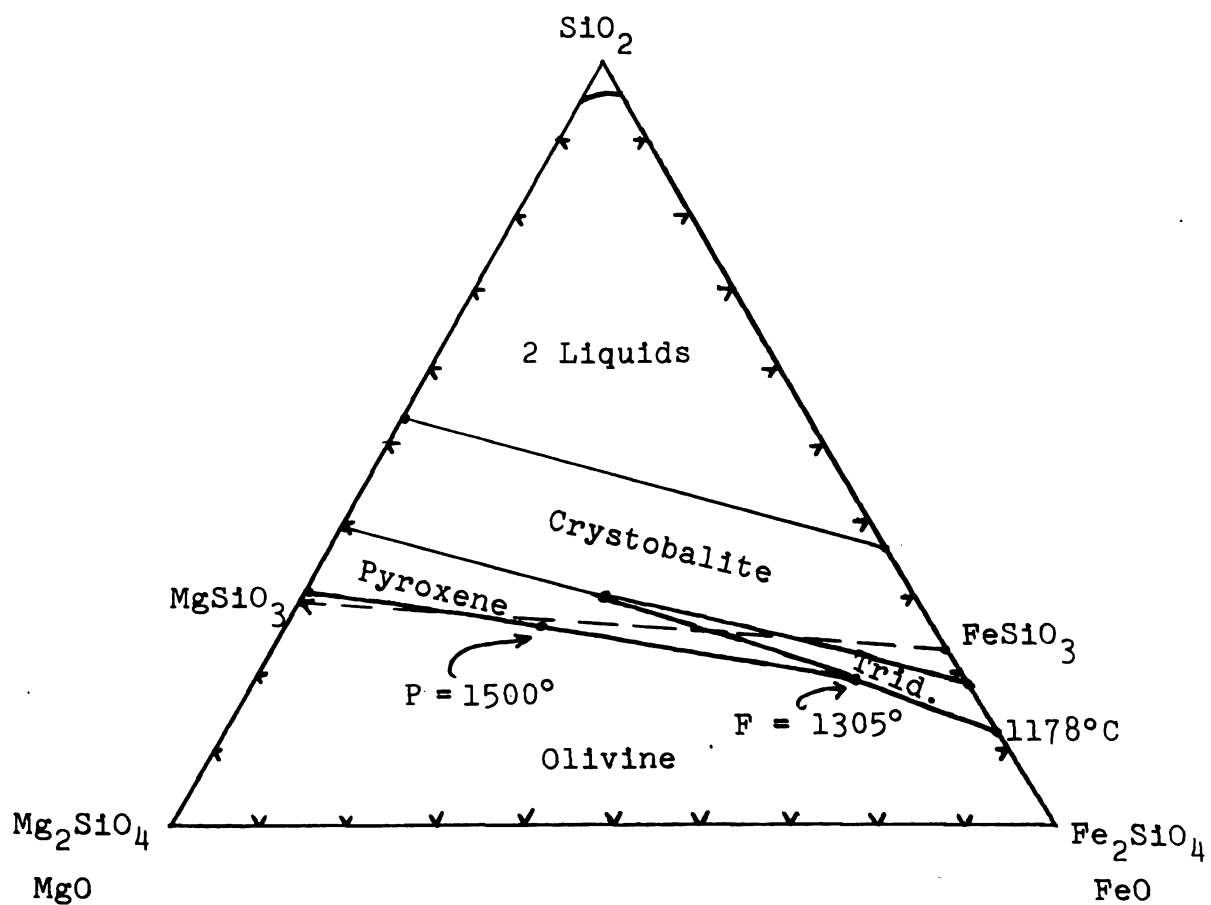


Fig. 11.--Equilibrium diagram of part of the FeO-MgO-SiO₂ system (Bowen and Schairer, 1935).

TABLE 9.--Optical data and compositions of olivine, orthopyroxene and clinopyroxene.

Specimen Number	Olivine			Orthopyroxene			Clinopyroxene				
	β	2V*	%Fa	β	2V*	%Fs	β	2V*	Wo	En	Fs
D15-42	--	--	--	--	55	37	--	--	--	--	--
3-10	--	--	--	--	49	54	1.711	46	37	29	34
6-5-65	--	67	61	1.725	50	53	1.700	49	40	34	26
13-2	--	79	36	--	57	34	1.694	--	38	40	22+
25-42	--	60	76	--	55	63	1.715-8	47	38	24	38
14-4	--	--	--	--	51	48	--	--	--	--	--
11-9	1.722	80	35	1.704	57	34	1.693	49	42	39	19
14-15 ^A	--	--	--	--	56	36	1.697	--	40	35	25+
25-60	--	60	76	--	51	54	1.715	46	35	25	40

*All 2V measurements are direct measurements and only those were used where both optic axes could be centered upon rotation of the OEW axis of the universal stage.

[†]Only the β index has been determined. The composition was then determined by plotting the index on the trend of the variation of the pyroxene composition.

this reason it was evident that a detailed study of the chemistry of the pyroxenes would be useful in determining the extent of differentiation. Further, this data provides a basis for estimating the conditions under which the intrusive solidified.

The compositions of the investigated pyroxenes are shown in Table 9 and Figure 12. Comparisons are made with pyroxene trends from other intrusives of varying sizes and shapes and the trends are similar. As is to be expected the trend is toward iron enrichment in the later rocks of the intrusion. The pyroxenes of the chill zone have a composition that is higher in iron than those from the higher levels of the intrusive. This situation is similar to that already discussed concerning the plagioclase in that the chill zone composition occupies an intermediate position in the trend of the pyroxenes. The fact that the pyroxene in the rocks immediately above the chill zone are more magnesian requires later enrichment in iron, as is shown in the pyroxene of the upper levels of the anorthosite and the ferrodiorite, to give an average value for the whole intrusion that matches the composition of the chill zone pyroxene. Based wholly on the composition of the pyroxene from the different zones of the intrusive it appears as though the chill zone pyroxene represents about an average composition for the pyroxenes. However this is not to say that the bulk composition of the chill zone is representative of the bulk composition of the

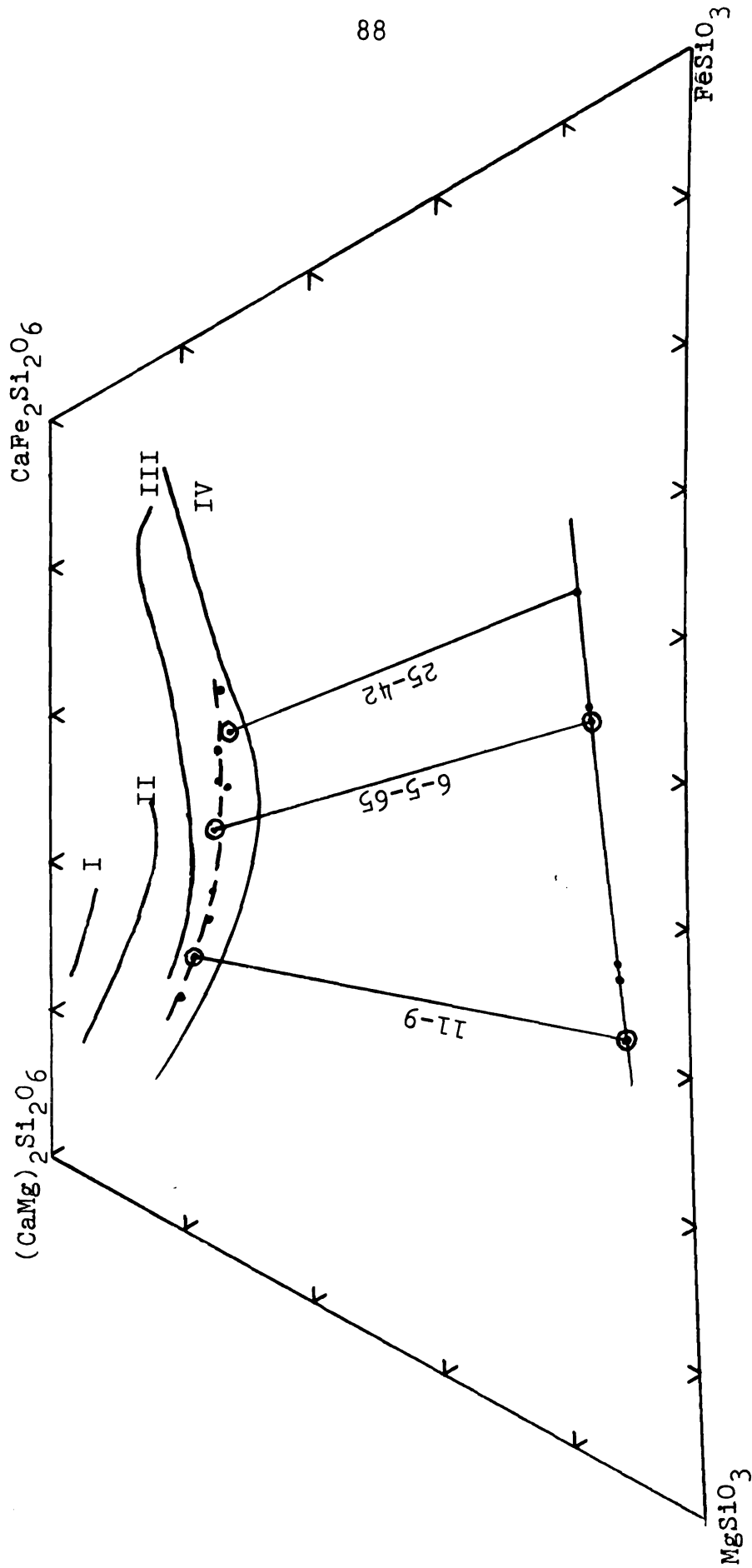


Fig. 12.--Pyroxene composition showing trends of Mineral Lake Intrusion and trends of pyroxenes of other intrusions.

KEY: I - Black Jack Sill, Wilkinson (1957); II - Garbh Eilean Sill, Murray (1954); III - British and Icelandic Tertiary Glasses, Carmichael (1960); IV - Skaergaard Intrusion, Muir (1951), Brown (1957); --- - Trend of pyroxenes of Mineral Lake Intrusion. Tie lines are shown for these pyroxenes determined by chemical analysis. $\circ$ - Determined by chemical analysis; $\bullet$ - Determined by optical methods.

entire intrusive since it will be recalled that the plagioclase of the chill zone is far too sodic in comparison to the rest of the plagioclase of the intrusive. What the chill zone probably represents is the composition of an interprecipitate liquid from which most of the pyroxene now seen in the intrusive crystallized. The plagioclase then, at least in part, crystallized from an earlier liquid and formed the bulk of the solid portion of the crystal mush which contained the liquid from which the pyroxene crystallized. This topic will be considered further in the following chapter in conjunction with the bulk chemistry of the rocks.

Geothermometry from Pyroxene Data

All of the orthopyroxenes of the intrusive show exsolution of a more calcic, monoclinic pyroxene (Plate VI-A) indicating that they have inverted from pigeonite as cooling proceeded. Hess (1960, p. 39) has discussed the usefulness of evidence that this inversion has taken place as a geologic thermometer (Fig. 13). Based on the composition of the orthopyroxene, the crystallization of the original pigeonite must have taken place above 109°C and probably no higher than 1120°C . On the basis of the same diagram, the latest pyroxenes of the ferrodiorite are seen to have crystallized above 1040°C ., as they also show evidence of exsolution of calcic pyroxene due to this inversion of pigeonite to orthopyroxene. On the basis of this

TABLE 10.--Chemical analysis of clinopyroxene 6-5-65.

	Atomic Ratios	Fe ⁺³ Na	Al Na	2Al Ti	Al Al	Z Y W	Cations To Six 0
SiO ₂49.67	Si.....828					Z	
TiO ₂ 0.20				6	10	844	1.962
Al ₂ O ₃ 2.00	Al..... 39		13		10		
Fe ₂ O ₃ 0.59	Fe ⁺³ .. 7	7					
FeO.....16.32	Fe ⁺² ..227						
MgO.....11.44	Mg.....286						
MnO..... 0.53	Mn..... 7						2.074
CaO.....17.89	Ca.....319					892	
Na ₂ O..... 0.49	Na..... 16	3	13				
K ₂ O..... 0.22	K..... 4	2	4				
H ₂ O..... <u>0.50</u>	Ti..... 3			3			
99.85	O = 2279						

Analyst - Norman D. Berlin, Jr. For optical data see Table 9.

TABLE 11.--Chemical analysis of clinopyroxene 25-42.

	Atomic Ratios	Fe ⁺³ Na	Al Na	2Al Ti	Al Fe ⁺³	Al Al	Z Y W	Cations To Six 0
SiO ₂48.81	Si.....814							
TiO ₂ 0.39	Al..... 28			8	3	2.5	827.5	1.963
Al ₂ O ₃ ... 1.41								
Fe ₂ O ₃ ... 0.02	Fe ⁺³ .. 3				3	2.5		
FeO.....21.32	Fe.....296						874.5	
MgO..... 9.70	Mg.....242		12					2.073
MnO..... 0.19	Mn..... 3							
CaO.....16.80	Ca.....300							
Na ₂ O..... 0.28	Na..... 9		12					
K ₂ O..... 0.15	K..... 3							
	Ti..... 4			4				

Analyst - Norman D. Berlin, Jr. For optical data see Table 9.

TABLE 12.--Chemical analysis of clinopyroxene 11-9.

	Atomic Ratios	Fe ⁺³ Na	Al Na	2Al Ti	Al Fe ⁺³	Al	Z Y W	Cations To Six 0
SiO ₂50.81	Si.....847							
TiO ₂ 0.24	Al..... 49			6	3	20	876	1.982
Al ₂ O ₃ 2.52						20		
Fe ₂ O ₃ 1.26	Fe ⁺³ .. 16	13			3		899	
FeO.....10.58	Fe ⁺² ..147							
MgO.....14.45	Mg.....361							
MnO..... 0.24	Mn..... 3							
CaO.....18.66	Cu.....333							2.034
Na ₂ O..... 0.39	Na..... 13	13						
K ₂ O..... 0.13	K..... 3							
	Ti..... 3			3				
	O.....2650							

Analyst - Norman D. Berlin, Jr. For optical data see Table 9.

TABLE 13.--Chemical analysis of orthopyroxene 11-9.

	Atomic Ratios	Fe ⁺³ Na	Al Na	2Al Ti	Al ⁺³ Fe	Al Al	Z Y W	Cations To Six 0
SiO ₂52.12	869			2		7	878	1.947
TiO ₂ 0.10	Al..... 26							
Al ₂ O ₃ 1.32								
Fe ₂ O ₃<0.02	Fe ⁺³ .. 0							
FeO.....19.36	Fe.....269							
MgO.....22.99	Mg.....574							
MnO..... 0.76	Mn..... 11							
CaO..... 2.40	Ca..... 43							
Na ₂ O..... 0.25	Na..... 8							
K ₂ O..... 0.11	K..... 2							
H ₂ O..... 0.53	Ti..... 1			1				
			10					
								2.052

Analyst - Norman D. Berlin, Jr. For optical data see Table 9.

TABLE 14.--Chemical analysis of Orthopyroxene 6-5-65.

	Atomic Ratios	Fe ⁺³ Na	Al Na	2Al Ti	Al Fe ⁺³	Al Al	Z Y W	Cations To Six 0
SiO ₂45.61	Si.....760							
TiO ₂ 0.19				4	24		788	1.939
Al ₂ O ₃ 1.24	Al..... 24							
FeO ⁺³ 5.56	Fe ⁺³ .. 69	12			24*			
FeO.....30.16	Fe ⁺² ..419							
MgO.....12.68	Mg.....317							2.027
MnO..... 0.29	Mn..... 4					833		
CuO..... 3.30	Ca..... 59							
Na ₂ O..... 0.25	Na..... 8	8						
K ₂ O..... 0.19	K..... 4	4						
	Ti..... 2			2				
	O.....2469							

*An excess of Fe⁺³ remained at this point so it is considered to be magnetite impurities which is subtracted as Fe⁺³ + 1/2 Fe⁺².

Analyst - Norman D. Berlin, Jr. For optical data see Table 9.

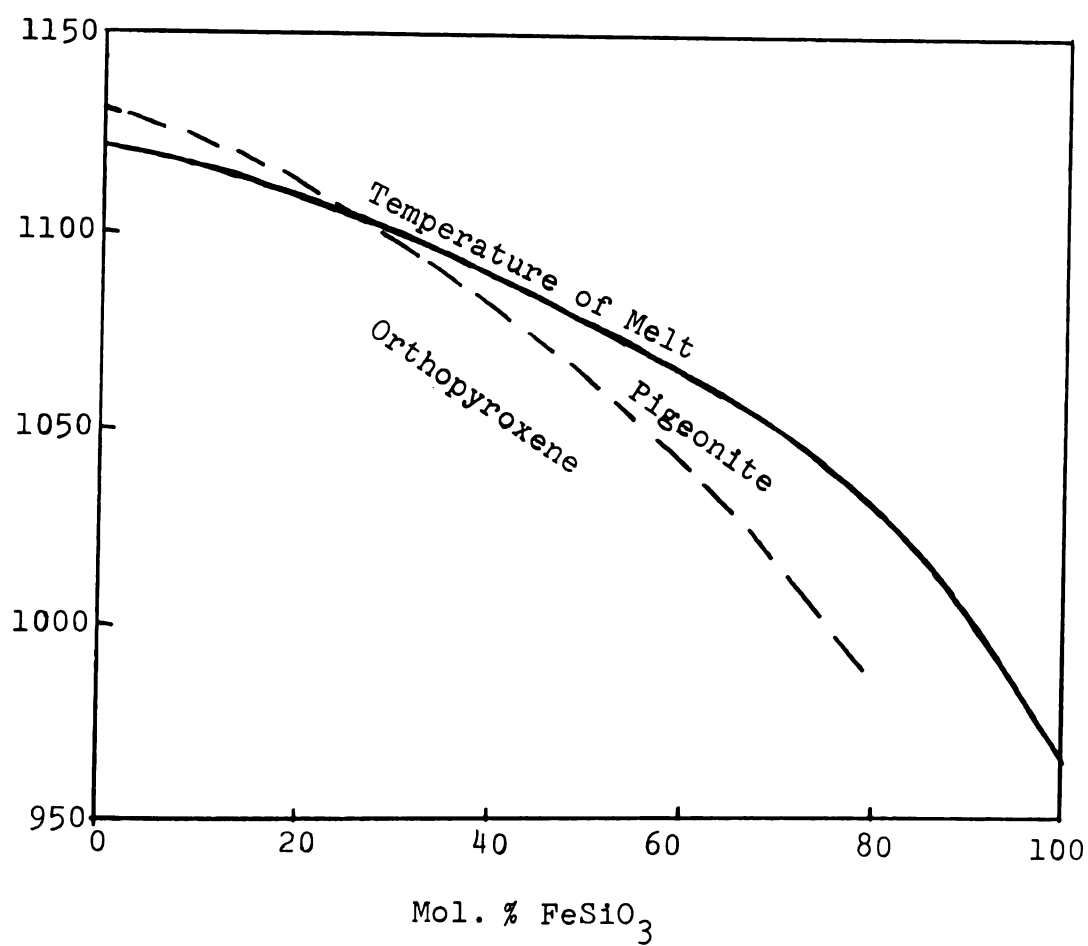


Fig. 13.--Pigeonite orthopyroxene inversion curve (Hess, 1960, p. 40).

information alone it appears that during crystallization of approximately 90 per cent took place with a drop of no more than 100°C.

The distribution of iron and magnesium between the co-existing pyroxenes provided additional data concerning the temperatures at which crystallization took place. Kretz (1961) and Bartholomé (1962) have discussed this distribution and have calculated tentative temperatures corresponding to varying distribution coefficients. Based on the calculations of Bartholomé, the coefficients calculated from the analyses are in the range of magmatic temperatures. Kretz has provided the theoretical calculations and by use of the following equation is able to determine approximately the change of the distribution coefficient with temperature.

$$K_{D2} = K_{D1} e^{\left[\frac{\Delta H}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) \right]}$$

Unfortunately in the absence of adequate thermochemical data, namely ΔH of the reaction involving the equilibrium of Mg and Fe between the phases, precise calculations of temperatures are impossible. The major problem here is that ΔH is variable with temperature as well as the coefficients. However, we are able to see that the determined coefficients for samples 11-9, 6-5-65 and 25-42 show changes in what are considered to be the correct directions which no doubt result from temperature variations.

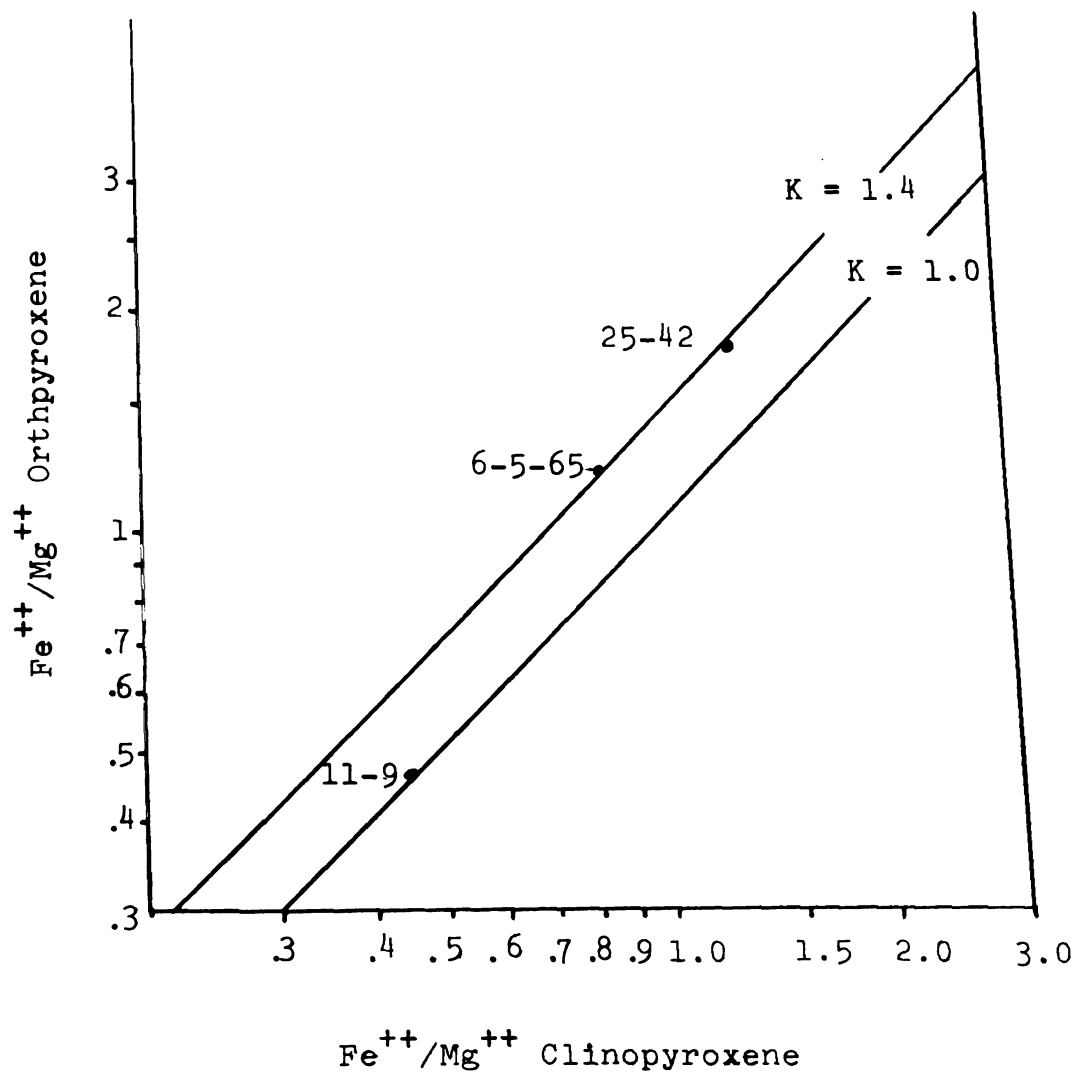


Fig. 14.--Plot of Fe⁺⁺/Mg⁺⁺ ratios from pyroxene pairs showing distribution coefficients.

Although quantitative results cannot yet be determined for temperatures at which mineral pairs were equilibrated, the calculations of Bartholomé and Kretz show that the coefficient K (of the following equation) is

$$K = \frac{Fe_{or}(1 - Fe_{cl})}{(1 - Fe_{or}) Fe_{cl}}$$

inversely proportional to temperature. From this we see that the Sample 11-9 crystallized at a higher temperature than either 6-5-65 or 25-42. A plot of temperature vs. coefficient published by Bartholomé indicates that this change is representative of about 350°C.

If we assign a temperature of 1150°C to Sample 11-9 then by the time the pyroxenes of 25-42 (ferrodiorite) crystallized the temperature was in the range of 800°C. The low coefficient of 6-5-65 (Figure 14) may be partially due to the presence of opaque inclusions in the analyzed material and probably to a lesser degree to some disequilibrium due to chilling effects.

The pyroxenes have provided two means with which some statements concerning the temperatures of crystallization may be made. The first method, making use of exsolution phenomena in orthopyroxenes, results in a temperature range of about 100°C. between the crystallization of the early olivine gabbros and the ferrodiorites. The latter method making use of distribution

coefficients of Fe and Mg between ortho- and clino-pyroxene gives a range of 350° between these rock types. Because of the uncertainty of ΔH of the reactions which involve the distribution of these elements, one must place less emphasis on the latter method at this time.

CHAPTER V

PETROGRAPHIC DISCUSSION

Introduction

Three major questions concerning the nature of the intrusion appear at this point to be of primary importance. Briefly they may be stated as follows:

1. The mechanism of intrusion and the related processes through which the various rock types have evolved.
2. The nature and extent of differentiation.
3. The origin of the anorthosite.

It is difficult to consider any one of these issues without involving the others and for this reason they will all be discussed with one particular point in mind; namely, the origin of the large mass of anorthosite.

Several factors have been discussed in the proceeding sections which point up the fact that this gabbro mass possesses many characteristics that are typical of all large basic intrusions. However, there are several characteristics which apparently set this complex apart from many others, not the least important of which is its highly feldspathic composition. Another most significant aspect

of this intrusion is the fact that it is fairly well exposed in cross section from its base to the uppermost rocks which crystallized from the acid residuum. This has provided an excellent opportunity for study and the collection of a large amount of data which appears to throw some new light on the origin of the large masses of anorthositic rocks that are exposed here, as well as at Duluth. Several of the pertinent facts and inferences that have been described in earlier sections are listed here to set the stage for the following discussion.

1. The present attitude of the intrusion was attained through regional tilting which began prior to intrusion so that during its ascent the magma was moving upwards along an inclined surface. Tilting probably continued after solidification was completed.
2. A large proportion of the magma must have crystallized before upward movement ceased, resulting in the strong fluxion structure seen in the anorthosite.
3. The gradual upward decrease of mafic minerals throughout the anorthositic gabbro and into the anorthosite would indicate that relative downward movement of mafics was taking place during ascent of the magma.

4. The presence of ultramafic concentrations at the base of the intrusion indicates that the heavier minerals were settling downward relative to the lighter plagioclase crystals.
5. The rarity of phenocrysts in the basal chill zone suggests that the magma was in motion so that large crystals were swept away from the walls of the intrusive toward areas of higher velocity.
6. The unusual composition (Table 15) of the chill zone indicates that the liquid from which these rocks crystallized was already partially differentiated at the time of intrusion.
7. The fact that even the earliest orthopyroxene contains more than 30 per cent orthoferrosilite indicates that the magma at this level of the intrusion had undergone some differentiation.
8. The very gradual cryptic layering of the constituent minerals and phase layering caused by the appearance or disappearance of a mineral throughout the entire intrusion combined with the lack of any chilling within the body strongly supports the hypothesis of a single intrusion.
9. The coarse grain size, slight zoning and nearly constant composition of most of the plagioclase of the anorthositic gabbros and anorthosite

points to a slow cooling rate and the maintenance of equilibrium during the period of crystallization.

10. The presence of the ferrodiorite in considerable amounts across the top of the intrusive provides evidence as to the character of the environment and the resulting trend of differentiation that was followed during the cooling period.
11. Almost complete lack of compositional or rhythmic banding as typically seen in many large gabbroic intrusives indicates that the physical processes that were active during the cooling period were different from those which display such features.

All of these factors appear to be related to one or two aspects of the intrusion. They are: the composition of the original magma and the changes that it suffered during its ascent to the present ground level and the physical process by which the final rock type was formed. There is much evidence to direct our judgment as to the latter aspect, but much discussion of this is within the realm of speculation. The original composition of the magma may be considered directly. It is to this chemical aspect of the intrusion that attention is now directed.

Composition of the Intrusion

The composition of the chilled marginal facies found at the base of the intrusion is presented in Table 15 along with some compositions of other basaltic rocks for comparison. Inspection of Table 15 makes clear the fact that the chilled rocks of this body are not of ordinary composition and are either the product of differentiation or contamination of a pre-existing magma.

Bowen (1929, p. 75) has demonstrated a method of determining if a rock is the product of contamination or differentiation. The method makes use of a Harker variation diagram (Fig. 15) and the assumption that the change in all oxide percentages will be linear with the change of silica. Since an analysis of what might safely be considered an unaffected rock from this area was not available, a composite analysis from the Keweenawan Greenstone flow in Michigan, after Cornwall (1951, p. 155) has been used to represent the original magma composition. This analysis is very similar to others that have been considered to be typical of the Keweenawan lavas (Lane, 1911, p. 100).

The plots of the two analyses are shown in Figure 15, with M representing the oxides of the chill zone of this intrusive and A, Cornwall's average analysis. The composition of the material that must be subtracted from A to give M must be plotted at the right of A. The

TABLE 15.--Comparison of analyses of chilled rocks from Mineral Lake Intrusion with other chilled rocks.

	6-5-65 Chill Zone ¹ Mineral Lake	Cornwall's ² #1 Liquid	Skaergaard ³	Stillwater ⁴
SiO ₂	47.01	47.84	47.97	50.68
TiO ₂	1.15	1.53	1.32	0.45
Al ₂ O ₃	13.26	16.98	18.32	17.64
Fe ₂ O ₃	2.19	3.18	1.23	0.26
FeO	15.08	7.92	8.58	9.88
MnO	0.09	0.17	0.12	0.15
MgO	6.99	6.73	8.09	7.67
CaO	9.03	10.01	10.77	10.47
Na ₂ O	2.75	2.63	2.42	1.87
K ₂ O	0.80	0.48	0.21	0.24
P ₂ O ₅	0.31	0.18	0.08	0.09
H ₂ O+	0.74	2.23	0.61	0.42
H ₂ O-	0.11	--	0.09	0.06

¹Analyst - Norman D. Berlin, Jr.

²Average of two analyses of basalts from Greenstone flow (Cornwall, 1951, p. 155).

³Average of three chill phase analyses (Wager, 1960, p. 375).

⁴Hess (1960, p. 162).

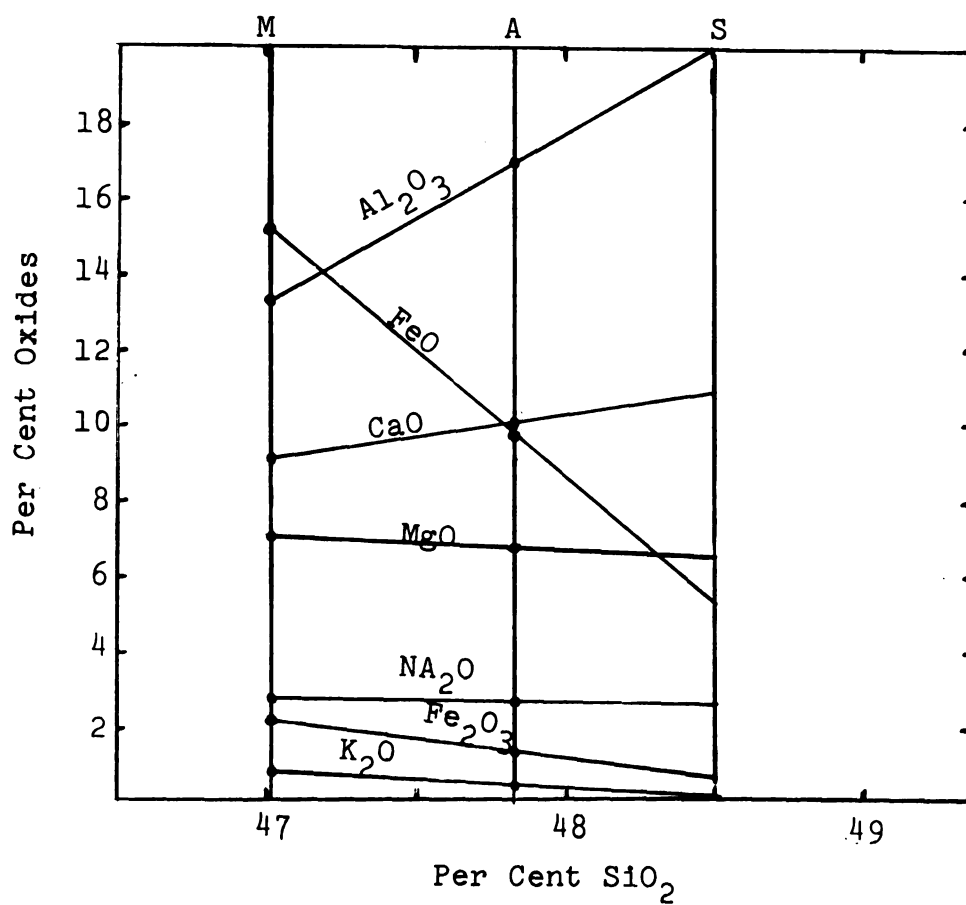


Fig. 15.--Subtraction diagram using composition of Mineral Lake Intrusion in comparison with an average basalt.

composition shown as S will serve as an example of subtraction of material from A. The actual composition of S might be varied somewhat but as the silica content is increased its composition becomes more extreme (anorthositic). The most extreme possibility would appear to be at about 49.3 per cent SiO_2 which is the point where FeO , Fe_2O_3 and K_2O all fall to zero. The composition chosen at point S gives reasonable values for the compositions of the resulting normative mafic minerals. The norms of A and M are shown in Table 16 along with the norm of the material to be subtracted from A to give M. It would be necessary for 52 per cent of A to crystallize to give a solid of composition S and a liquid of composition M. It is noteworthy that the composition of the solid material actually approaches what might best be called an anorthositic norite. Attention should be called to the fact that the early differentiates of large mafic intrusions are often noritic.

To be completely objective, consideration should be given the alternative hypothesis of contamination. Critical examination of Figure 15 will reveal that if the graph were continued far enough to the right and if the content of MgO , Na_2O , and K_2O were slightly higher in A, all of the oxides but FeO and Fe_2O_3 would fall to zero as the silica content is reduced. If this is the case and a poor example of the average magma (A) has been chosen then the possibility of contamination by iron formation remains.

TABLE 16.--Normative compositions of chilled rock from Mineral Lake Intrusion and Cornwall's #1 liquid. Column 3 is the material to be subtracted from Column 2 to give Column 1.

	1	2	3
	6-5-65 Mineral Lake Intrusion	Cornwall's* #1 Liquid	Material to be Subtracted from Column 2 to Give 1
	Per Cent	Per Cent	
Apatite	0.5	0.4	---
Ilmenite	1.6	2.2	
Orthoclase	5.0	3.0	1.5
Albite	25.5	24.5	23.0
Anorthite	22.0	33.8	44.3
Magnetite	2.4	1.5	0.9
Pyroxene			
Wo. 9.0			4.8
En. 6.8	21.4	22.6	14.8
Fs. 5.6			5.6
Olivine			
Fo. 10.05	21.60	11.7	3.0
Fa. 11.55			1.2
Plagioclase Composition	An. .42	An. .55	An. .64

*The $\text{Fe}_2\text{O}_3/\text{FeO} + \text{Fe}_2\text{O}_3$ ratio was much too high for the purpose of these calculations so it was changed to match that ratio of the Mineral Lake Intrusion specimen.

However, it should be noted that considerable amounts of material would have to be assimilated to modify a magma of the composition of A to produce one of the composition of M. Further, although this may be within reason, the fact that at the point where Sample 6-5-65 was collected the nearest iron formation is over a mile to the south. Although the dips of the iron formation and the base of the intrusion are such that they may intersect at depth, the hypothesis now begins to require a number of fortuitous circumstances.

Considering the probabilities involved for the hypothesis of contamination, it appears that the alternative of modification of an original magma by crystal fractionation is the most likely. Furthermore, as Bowen (1928, p. 77) pointed out, the material that must settle out is of a composition that it is expected to be, while the other alternative requires assimilation of large amounts of material of a specific composition.

The foregoing discussion then, assumes that the composition of the chill zone rocks is the result of differentiation of some pre-existing more normal magma, namely one of a composition similar to that of the Greenstone flow. Three factors are important to this line of reasoning:

1. Mineralogical data of the chill zone and the overlying rocks,

2. The trend of differentiation of the intrusive,
3. The actual composition of the exposed section of the intrusive.

If the above hypothesis is workable and the rocks of the chill zone are indeed the product of differentiation (fractionation), then these three factors must show data that is in agreement and in turn suggest a mechanism by which the various rock types have evolved. The mineralogical data has already been presented but a brief review is useful at this point.

Mineralogy

Figure 16 provides some impression of the average composition by volume of the major minerals of the intrusion. It was noted in the discussion concerning the plagioclase that on the basis of modal composition the average composition of the plagioclase for the entire intrusion (An. .56) was far more calcic than that of the chill zone (An. .42). There are two possibilities that will explain this discrepancy, a large, more acidic portion of the intrusive is missing or the chill zone is not representative of the bulk composition of the original magma. If the former suggestion is true then similar compositional discrepancies should be found for all of the minerals. The pyroxenes of the chill zone have a composition that is far more rich in iron than those immediately above, however, it may be noted in Figure 16

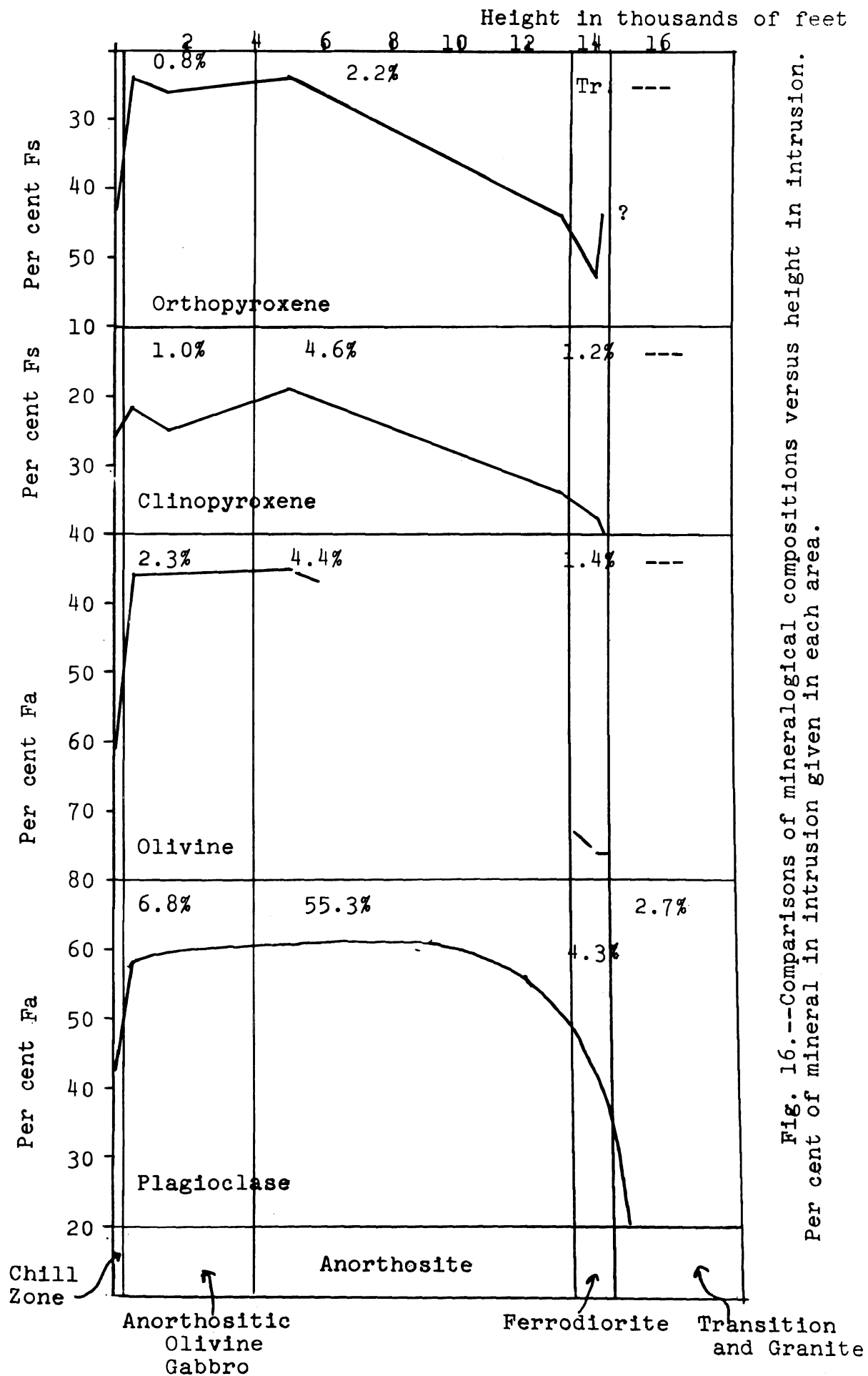


Fig. 16.--Comparisons of mineralogical compositions versus height in intrusion.
Per cent of mineral in intrusion given in each area.

that the pyroxene compositions over the whole intrusive probably average out to about that of the chill zone pyroxene. The olivine like the plagioclase appears in Figure 16 to be too magnesian where it occurs to average out over the whole intrusive the same as the chill zone olivine composition.

On the basis of this data, it appears that the pyroxene composition found in the chill zone is roughly representative of the average value for the whole intrusion while the compositions of the chill zone olivine and plagioclase are respectively too iron rich and too sodic. The only possible answer to this situation is that the olivine and plagioclase in the middle levels of the intrusion, at least in part, have crystallized from a magma which had a composition relatively richer in magnesium and calcium than the liquid from which the chill zone rocks crystallized. These minerals then represent the solid portion subtracted from the average liquid in Figure 15 while the pyroxene has crystallized, for the most part from the remaining liquid, which has been called the interprecipitate (Wager, et al., 1960). The later, more iron rich mafics and more sodic plagioclase of the ferrodiorite are also products of the interprecipitate liquid some of which may have migrated upward through filter pressing. It appears that the plagioclase of the anorthositic rocks has to a large degree crystallized before the magma reached the level of the intrusion which is now observed

at ground level and was carried up to this level in suspension in the magma. At the same time the olivine also crystallized at a lower level and was carried upward, but due to the greater density settled more rapidly and is now found in the lower third of the intrusion. A more precise analysis of settling velocities will be made later in this chapter.

Trend of Differentiation

The hypothesis which has been introduced in the preceding paragraphs proposes that parts of the intrusive are products of the fractionation of a liquid which is more primitive than that from which the lower marginal rocks crystallized while later parts of the intrusion and the interprecipitate are direct descendants of the "chill zone magma." It follows then that the "chill zone magma" must be on the line of descent from the earlier magma.

Table 17 presents the oxide data from several rock analyses in tabular form which is plotted graphically in Figure 17. The plotted data suggests that the ultramafics and the anorthosite have been subtracted from the original magma (Cornwall's #1 liquid) to give the composition of the chill zone rocks. The line of descent then continues in the direction of iron enrichment toward the composition of the ferrodiorite. In the later rocks the trend of iron enrichment is reversed toward the

TABLE 17.--Partial chemical analyses of four rocks of the intrusive, showing the trend of differentiation. Cornwall's #1 liquid is also given for comparison.

Sample Number	Rock Type	Height Above Base (feet)	Per Cent Oxides		
			FeO & Fe ₂ O ₃	MgO	Na ₂ O & K ₂ O
6-5-65	Chilled Gabbro	2	17.27	6.99	3.55
11-9	Gabbroic Anorthosite	5500	7.93	5.48	3.55
25-44	Ferrodiorite	12000	22.91	4.03	3.23
24-3	Granite	16000	1.87	0.84	8.32
Cornwalls #1 Liquid	Basalt	--	11.10	6.73	3.11

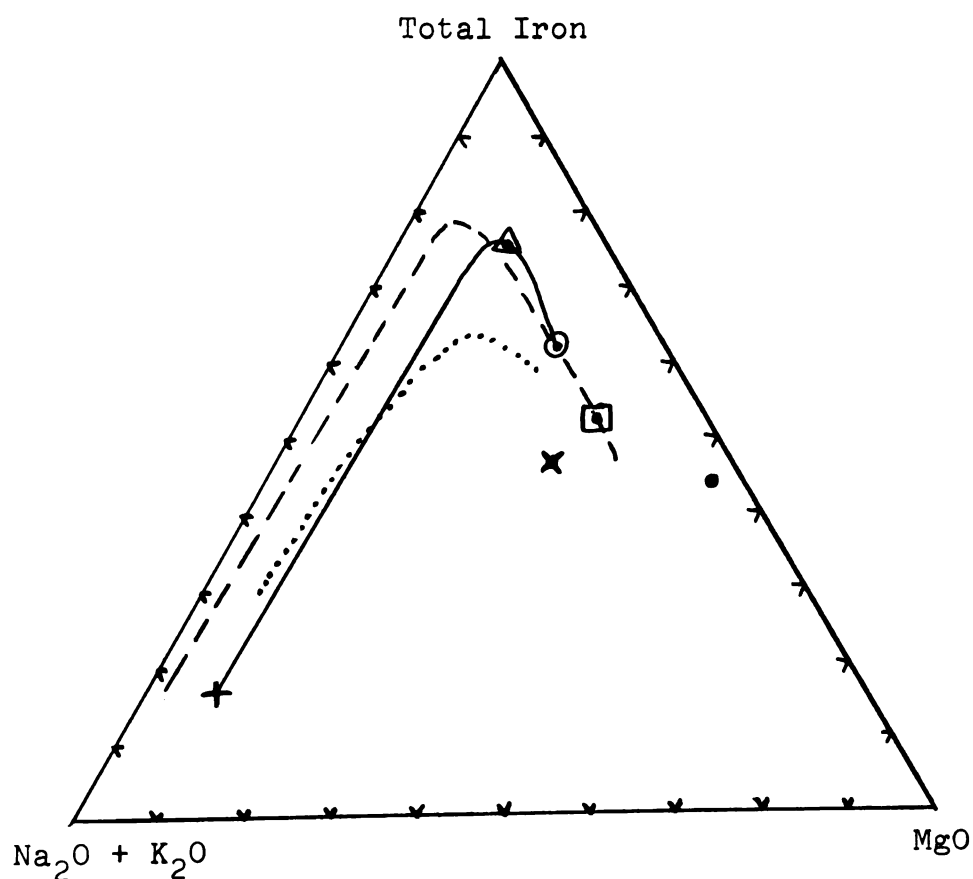


Fig. 17.--Differentiation trends of the Mineral Lake Intrusion compared with the Skaergaard and Duluth trends.

LEGEND:

Trend

- Skaergaard Liquid
- Duluth Rocks (From Taylor, 1964, p. 48)
- Mineral Lake Intrusion

Rock Types

- Cornwall's #1 Liquid
- ⊙ Basal Chill Rocks
- x Gabbroic Anorthosite
- △ Ferrodiorite
- + Granite
- Approximate composition of ultra mafics

composition of the granite. This trend, as is shown in the diagram, is similar to that shown by the Skaergaard and Duluth complexes.

Numerous writers, Wager and Deer (1939), Kennedy (1955), and Osborn (1959) to mention a few, have discussed the trends of differentiation observed in mafic rocks. Kennedy (1955, p. 500) reviewed the problem of alkali versus iron enrichment as argued by Bowen and Fenner respectively and on the basis of his melting experiments concluded that either trend was possible depending upon P_{H_2O} on the system at the time of crystallization.

Through studies of the system $MgO-FeO-Fe_2O_3-SiO_2$, Osborn (1959) has defined the paths of liquid descent under conditions of: (1) constant oxygen pressure, (which requires that oxygen content varies during crystallization) and, (2) constant total composition, (which requires that oxygen pressure change during crystallization). If Figure 11 is compared with Figure 18 it is apparent that these represent essentially the same systems under different conditions. The latter diagram contains Fe_2O_3 as a result of the higher oxygen pressure which requires that some of the iron be in the ferric state allowing the formation of magnetite as an early phase coexisting with olivine. The earlier diagram (Figure 11) does not contain iron oxides as a phase in the area of basaltic rock compositions and hence allows iron to be enriched in the liquid as the early silicate phases are rich in

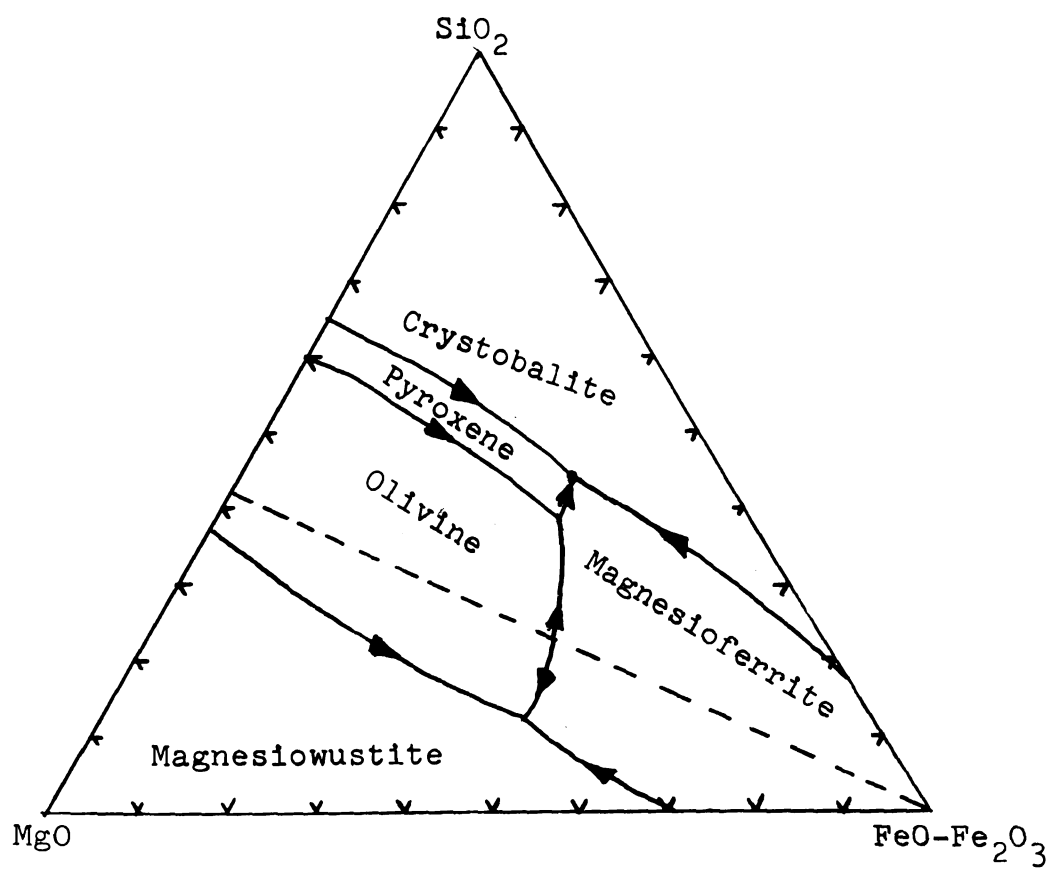


Fig. 18.--Section from the tetrahedron $\text{FeO-Fe}_2\text{O}_3\text{-MgO-SiO}_2$ at $P_{\text{O}_2} = 0.21$ atm. (Osborn, 1959).

magnesium. Furthermore, the thermal low in Figure 18 is at point D which prevents the liquid from becoming enriched in iron while the thermal low in Figure 11 is along the $\text{FeO} - \text{SiO}_2$ sideline so that liquids may proceed in the direction of extreme iron enrichment under conditions of low P_{O_2} where early iron oxides cannot form.

The situation then is as follows. If the P_{O_2} is high resulting in a high $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio in the magma then magnetite may form during the early stages of crystallization using large amounts of iron and allowing later enrichment in alkalis. If the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio is low then theoretically magnetite cannot form (although in reality it does in small quantities) and a magnesian olivine is the early mafic precipitate. In the first case no silica is used as a result of precipitation of magnetite so that silica enrichment results under these conditions. However, in the second case considerable amounts of both silica and magnesia are used in the early precipitates so that a decrease of both elements may accompany crystallization. The Skaergaard Intrusion shows this trend particularly well.

The trend of iron enrichment holds for the Mineral Lake Intrusion and Figure 19 indicates that the trend of differentiation is similar to that of the Skaergaard Intrusion and the Duluth gabbros. Very little data concerning the trend of silica has been collected for the Mineral Lake Intrusion but data from the chill zone

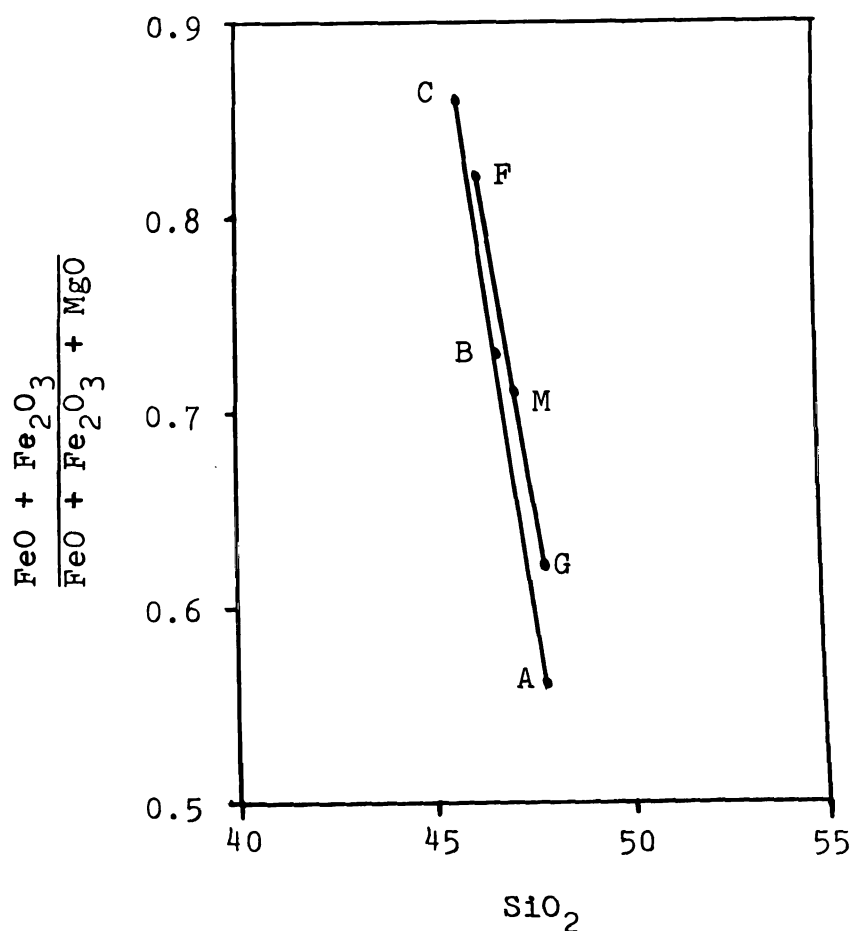


Fig. 19.--Comparison of magma compositions of the Skaergaard Intrusion and the chill zone rocks of the Mineral Lake Intrusion.

KEY:

- A = First liquid of Skaergaard* All Liquid
- B = Second Liquid of Skaergaard* 60% Solid
- C = Third Liquid of Skaergaard* 82% Solid
- M = Chill Zone of Mineral Lake Intrusion 6-5-65
- G = Cornwall's #1 Liquid Greenstone Flow
- F = Calculated from average modal compositions of the four ferrodiorites in Table 6.

* After Wager and Deer (1939).

analysis, a modal analysis of four ferrodiorites and the Greenstone flow are compared with the Skaergaard trend in Figure 19 and a remarkable parallelism is shown.

Finally, an investigation of the $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios was accomplished to determine if the oxygen pressure was as it should have been to produce the trends shown in Figures 17 and 19. These ratios are presented in tabular form in Table 18 and again a striking similarity to the Skaregaard Intrusion is shown. Kennedy (1955, p. 501) notes that these ratios from the Skaergaard are among the lowest found in any rocks in the world and considering the unusual suite of rocks that appears to be a cause and effect relationship. Osborn's work appears to confirm this relationship.

One further comparison between the Mineral Lake and Skaergaard Intrusions is of interest. Wager (1960, p. 398) has estimated the composition of the "hidden zone" of the Skaergaard Intrusion and has determined that when the magma was about 70 per cent solidified the solid portion was about 80 per cent plagioclase. This would suggest that under the conditions outlined above and where crystal settling is a strong factor that the early precipitate would normally be anorthositic in composition. So far as the writer has been able to determine, this possibility has not been widely recognized in the literature. The only additional factor necessary to produce anorthositic rocks under these conditions in a mechanism by which the

TABLE 18.-- $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios of the Mineral Lake Intrusion and the Skaergaard Intrusion.

Mineral Lake Intrusion			Skaergaard		
Specimen Number	Rock Type	$\text{Fe}_2\text{O}_3/\text{FeO}$	Specimen Number	Rock Type	$\text{Fe}_2\text{O}_3/\text{FeO}$
6-5-65	Gabbro Basal Chill	.145	1825	Chilled Marginal Gabbro	.142
13-2	Olivine Gabbro	.114	1851	Gabbro Marginal Border Gp.	.096
11-9	Gabbroic Anorthosite	.003	4077	Gabbro from Layered Series	.145
1-15	Anorthosite	.660	4136	Quartz Gabbro	.292
25-44	Ferrodiorite	.198	3047	Trangressive Ferrogabbro	.615
25-47	Ferro- granodiorite	.134			
24-3	Granite	.011			

early precipitate is separated from the remainder of the magma. With this in mind, we shall now consider the average composition of the intrusion based on modal analyses in an effort to compare the actual composition with what would be expected from the fractional crystallization of a basaltic magma.

Average Composition of the Exposed Section
of the Mineral Lake Intrusion

With the full realization of possible inaccuracies, the writer has attempted to provide some indication of the average composition of the exposed section of the intrusion that was mapped. Two methods have been used both of which are subject to errors. The simplest method was to pick modal analyses every thousand feet across the intrusion and calculate from these an average composition giving each sample equal weight in the calculations. This was done for two traverses using a total of 31 modal analyses from which an average rock composition was determined.

The second method was considerably more sophisticated although possibly no more reliable. The relative areas of the four major rock types as shown on Plate I were determined with the use of a compensating polar planimeter. The relative sizes of these areas are given in Table 19 along with the weighted amounts of each of the minerals determined for each area. The calculated chemical compositions from both methods are presented in Table 20.

TABLE 19.--Modal analyses (converted to weight per cent) of the average composition of the four major rock types, multiplied by the per cent area over which that rock type is exposed. Percentages are of the entire area.

Rock Type & Relative Area	Gabbroic Anorthosite 73.2%	Olivine Gabbro 11.5%	Ferro- Diorite 7.7%	Granite and Transition 7.7%	Totals 100.1%
Mineral*					
Plagioclase	55.32	6.87	4.27	2.67	69.13
Clinopyroxene	4.57	1.01	1.18	--	6.76
Orthopyroxene	2.22	0.83	--	--	3.05
Olivine	4.41	2.30	1.36	--	8.07
Biotite	1.13	0.29	0.07	0.67	2.16
Magnetite	0.87	0.55	0.82	0.19	2.43
Quartz	--	--	--	1.29	1.29
K-feldspar	--	--	--	1.20	1.20
Apatite	0.01	--	0.20	0.02	0.23
Hornblende	<u>3.73</u>	<u>0.22</u>	<u>0.35</u>	<u>1.36</u>	<u>5.66</u>
Totals = Relative Weight %	72.26	12.07	8.25	7.40	99.98

*Minerals are given in weight per cent.

TABLE 20.--Calculated analyses from the two methods described in the text.

	1000 Feet From 31 Modal Analyses	Area Method From 62 Modal Analyses
SiO_2	53.50	50.36
Al_2O_3	21.30	21.32
Fe_2O_3	1.47	2.62
FeO	5.23	7.02
MgO	3.64	4.63
CaO	10.49	9.73
Na_2O	3.72	3.42
K_2O	0.61	0.39
P_2O_5	ND	0.10

Some interesting comparisons may now be made. If we compare the average modal compositions of the intrusive as shown in the right hand column of Table 19 with normative composition of the solid (Table 16, Column 3) that must be subtracted from Cornwall's average liquid to give the composition of the chill zone a striking similarity may be noted. However, this comparison is not entirely valid, as column 3 of Table 16 represents only about one-half of the original magma, the other half having the composition of the chill zone. Again the evidence suggests a discontinuity between the chill zone composition and that of the overlying rocks.

If the above data is anywhere near valid it is apparent that a considerable amount of the mafic minerals has been removed from the bulk composition of the intrusion. There are at least three mechanisms that may be active during the cooling period which would tend to cause contrasting rock types to be produced. Crystal settling in combination with a convecting magma has been proposed by several workers, Hess (1938) and Wager and Deer (1939), to produce cryptic zoning combined with igneous banding. Such a mechanism would also explain fluxion structures found in many of the large mafic intrusions. A second mechanism that has been proposed to explain contrasting rock types in a single intrusive is filter pressing. Finally, flow in one direction combined with crystal settling could produce contrasting rock types if the proper conditions are achieved.

Form of the Intrusion and the Mechanics of Differentiation

The roughly tabular shape and northwesterly dipping attitude appears to be reasonably well established. The timing of the tilting also is well enough established to indicate that the intrusion was emplaced along a tilted surface. The exact dip of the plane along which the intrusion was emplaced cannot be known for sure but when all of the factors discussed in Chapter II are taken into account the dip appears to be between 30 and 60 degrees.

The studies of the composition of the intrusive and of the chill zone indicate that a large portion of the original magma had crystallized by the time the intrusive reached the present ground level. The chemical calculations indicate that about half of the original magma must have crystallized to produce a liquid of the chill zone composition, so that one might envision the magma at this point as a crystal mush of which a high percentage is solid material. The fabric of the anorthositic rocks is so strikingly well oriented that flowage of a crystal mush seems the obvious conclusion. Another distinct possibility is that a crystal mush as pictured here would be a natural situation under which filter pressing could take place. However, filter pressing alone does not seem adequate to account for the removal of a large amount of early mafic material. The fact must be kept in mind that the high iron content of the chill zone rocks requires the early removal of considerable amounts of magnesian mafics. The early plagioclase is available to see in the anorthosite but the mafics are not.

The former alternative that flowage played some role in the production of these rock types deserves some further consideration. If an igneous body of the proportions of the Mineral Lake Intrusion is to rise to the level in the crust at which it is now found, the magma probably moved a vertical distance of at least 20 miles. The mechanisms that are currently popular for the production of such

magmas, Turner and Verhoogen (1960, p. 442), would not allow a large amount of superheat and we can probably assume that crystallization begins soon after the ascent of the liquid. We cannot expect that very much crystal settling could take place if the magma were one-half crystalline material but at the lower levels the magma was less than half crystalline by considerably amounts and under these conditions crystal settling could take place. The next step then is to determine if and how crystal settling might affect the composition of an intrusive.

Hess (1960, p. 139) has discussed settling velocities of crystals in a magma in reference to the origin of layering in the Stillwater Complex. He makes use of Stoke's law which he notes is fairly accurate even for large grains under conditions of high viscosities and low settling rates. Hess has calculated values for settling velocities for several grain sizes and viscosities. Table 21 is from Hess' data and shows the very great difference in settling velocities between the two minerals of similar size.

Several factors about Hess' data should be noted. The effectiveness of differential settling is highly dependent upon the rate of flow of the magma itself (see Fig. 20). Bhattacharji and Smith (1964, p. 151) have used magma velocity values in the range of 3 to 15 meters per hour for the Muskox feeder dike. If these values are applicable to the Mineral Lake Intrusion, a great lateral distance would be required for differential settling to

TABLE 21.--Settling velocities of crystals in meters per year. Slightly modified from a table and graph by Hess (1960, pp. 141-142). Magma density 2.58.

	Plagioclase			Pyroxene			Density Differences Between Solid And Liquid
Viscosity In Paises	0.1			0.7			Radius mm.
	1.0	2.0	5.0	10	2.0	5.0	
300	229	916	---	1602	6408	---	Settling Velocities In Meters Per Year
1000	69	274		481	1922	---	
3000	23	92	580	160	641	4200	
10000	6.9	27	---	48	192	---	
30000	2.3	9.2	---	16	64	---	

take place with the settling velocities calculated by Hess. However, with grain sizes on the order of 2.0 mm. and velocities of flow of the mass of the same magnitude of the settling velocities this could be a very efficient mechanism over a short distance. An even more efficient mechanism might be one in which velocities of flow were variable. Under conditions such as this during periods of low magma velocity showers of mafics would descend toward the floor while plagioclase remained behind in relative suspension.* With the increase of flow again the plagioclase would be removed to higher levels gradually changing the composition of the remaining solid toward a more anorthositic character.

It should be noted that the ultramafic pods found near the base all seem to be more coarse than the surrounding rocks and always have boundaries which grade toward more normal rocks. The pyroxenites are particularly coarse often containing crystals larger than 5 mm. Also, the textures of the picrites in particular are sometimes glomeroporphyritic which would further enhance differential settling.

Another point which enhances the settling of mafics is density difference. In Table 21 pyroxene has a density of 3.3 while olivine somewhat heavier, settles at greater

*One might expect that with changes of magma velocity, banding could result, but if the surges were infrequent only large zones of relatively mafic content would result, not the "inch scale" layering that is seen in the Stillwater and other large intrusives.

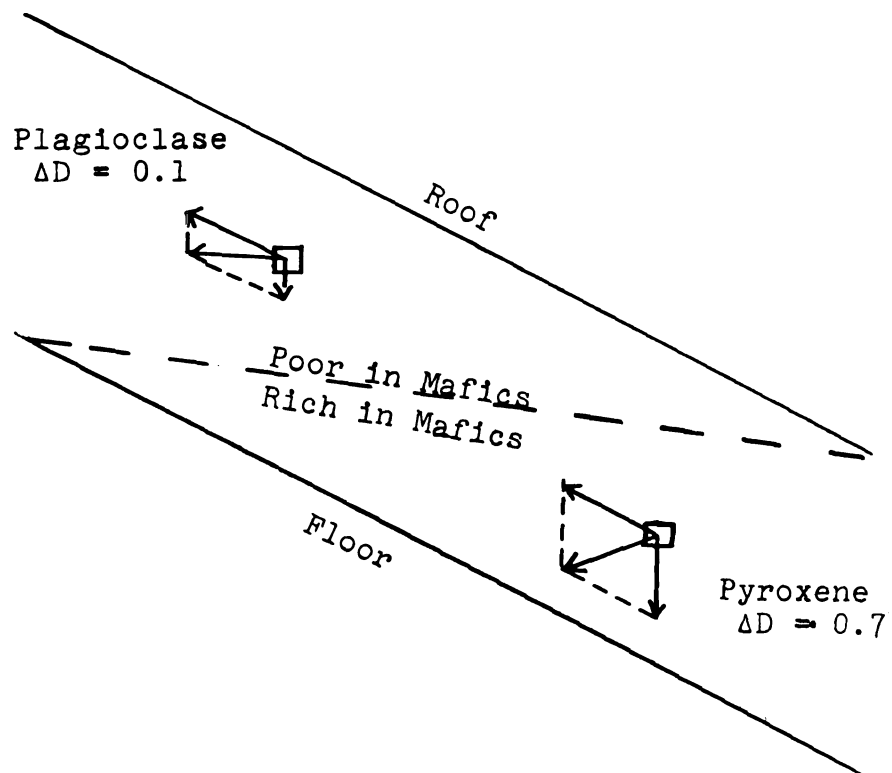


Fig. 20.--Hypothetical cross section of Mineral Lake Intrusion showing possible mechanism for the production of anorthosite.

velocity. A final point of great importance is that the values in Table 21 assume a liquid density of 2.58. The average density of a completely liquid basaltic magma is about 2.65 (Hess, 1960, p. 85). This has been reduced slightly by Hess in the calculations of Table 21 because of the early removal of the mafics which for purposes of the calculations is now solid and cannot be considered in determining the liquid density. Under the trends of differentiation that are displayed in this intrusion, the enrichment of iron should hold the liquid density more nearly constant and it is even possible that plagioclase (density 2.7) could rise.

The crystallization process then is as follows: With the rise of the magma along its inclined floor early mafics settle more rapidly than the plagioclase. As ascent continues the solid portion becomes more feldspar rich as a result of differential settling and the liquid more iron rich. Flow of the magma must have been great enough to hold a large proportion of the feldspar in suspension. The nonporphyritic chill zone probably resulted because the liquid magma preceeded the crystal charged portion or some filter pressing forced the completely liquid material from which the chilled rocks crystallized on ahead of the crystal mush. Figure 17 pictures the probable mechanism.

Taking all of the factors into consideration the hypothesis proposed here seems to be a workable one. However, it is not without difficulties, and several factors

should be evaluated. It is not known for what distance the surface along which the intrusive was emplaced was inclined at the angle suggested earlier. It is to be expected that the dip decreases with depth particularly if the locus of intrusion was a thrust fault plane. Changes of dip would most certainly alter the effectiveness of the mechanism as well as changes of fluid velocity and density.

Upon making comparisons with other similar intrusions in the Lake Superior region one notable difference comes to light. Taylor (1964), and Grout and Schwartz (1939) have noted conspicuous block structures of large cognate inclusions of anorthosite within anorthosite in Minnesota. Such features are notably absent in the Mineral Lake Intrusion. It might be expected that the suggested pulsing mechanism might cause the formation of such blocks by tearing them off from areas where they solidified during low velocity periods and carrying them to higher levels during high velocity periods. The absence of such blocks here seems to require that most of the feldspar remained in suspension during the upward movement of at least the part of the intrusion that is now exposed. Further, the excellent fluxion structure also seems to support this proposal.

It is noteworthy that the solid material subtracted from the normal liquid to give the composition of the chill zone is already anorthositic containing almost 70 per cent plagioclase. Further, the average composition of the exposed intrusion is only 80 per cent plagioclase requiring

that only a moderate amount of mafics settle out by the time the magma body reached this level.

The hypothesis that has been proposed should be treated as tentative. However, when reviewing the literature concerning the origin of anorthosite layers in other similar intrusions such as the Stillwater and Duluth Complexes, it appears that some progress toward a workable solution of the problem may have been made by this study. Concerning the anorthosites at Duluth, Taylor (1964, p. 54) has written:

Some type of differential movement was necessary to separate the feldspar from the liquid; this may have been by crystal floating, but more likely it was accomplished by frictional drag on the crystals during movements of the magma. The expected basic complimentary rocks have been cut out by the intrusion of three miles of gabbro of the layered series but no evidence of their existence is available.

A major difference displayed by the Mineral Lake Intrusion is that at least some of the "basic complimentary rocks" are in evidence and no doubt the remainder would be found down dip. Also the presence of the basal chill zone which is not available in the Duluth gabbro provides a valuable clue as to the nature of the liquid as the intrusion reached the present ground level.

CHAPTER VI

CONCLUSIONS

General

One of the objectives of this study was to show whether the Mineral Lake Intrusion originated by one or more than one intrusive episode. The lack of intrusive contacts is not conclusive as it is negative evidence. Several factors support singular complex intrusion as well as provide evidence for the origin of the various rock types, particularly the anorthosite which has been noted as a major problem in this and many other intrusions. Several observations are listed here.

1. Lack of any chilling within the intrusion suggests only one intrusive event.
2. Cryptic layering resulting from gradual change of mineral compositions with height supports the concept of a single intrusion.
3. Phase layering as well as the cryptic layering provides valuable evidence as to the nature of the changing composition of the magma.
4. The chemical trend which the liquid followed during cooling suggests the environmental

conditions as well as processes of fractionation under which the magma crystallized.

5. The almost perfect fluxion structure in the anorthosite suggests that movement of the partially crystalline mass was an important part of the emplacement process.
6. The almost total lack of banding indicates that some conditions involving this intrusive were different from many large mafic intrusives in which banding is common.
7. The composition of the chill zone is such that it must have evolved from a more primitive basaltic magma.
8. The very low ferric to ferrous iron ratio reflects the strong iron enrichment found near the top of the intrusion and hence supports singular intrusion as well as differentiation by fractional crystallization to form the various rock types now observed.
9. The mineralogical compositions at different levels of the intrusion suggest that plagioclase and olivine crystallized from an earlier liquid than the "chill zone liquid" while the pyroxene for the greater part crystallized from a later interprecipitate.

Regional studies indicate that the intrusive was wedged into position by bulging the overlying rock units

toward the north. Some faulting of the overlying units may have taken place as a result of the tension created by the emplacement of the intrusive. These factors combined with the almost perfect fluxion structure within the intrusive attest to the gradual concordant emplacement of the Mineral Lake Intrusion. Anderson (1940) studied the mechanics of emplacement of tabular igneous bodies such as this and his requirements for emplacement at shallow depth are met in this example. Shallow depth may well be an important factor responsible for the low oxygen pressure in evidence in the intrusive.

Flowage or movement of the magma during emplacement has played an important role in the evolution of the entire intrusive. As upward movement of the intrusive took place and solid material crystallized from the magma the liquid portion was gradually changed in composition. The early very magnesian mafics settled more rapidly than the plagioclase resulting in two radically different products. The plagioclase which remained in suspension was carried upward by virtue of the movement of the entire magma mass, which upon complete solidification produced the anorthositic portion of the intrusive. The other product of the combined fractionation and flowage was the interprecipitate liquid which through the trend of fractionation that was followed suffered strong iron enrichment. The interprecipitate is now seen as the basal chill zone of the intrusion. Settling of plagioclase in the middle and upper parts of the

intrusive caused some of the later liquid to be displaced to even higher levels above the settling plagioclase where it has crystallized as intermediate (ferrodiorite) and late (granitic) residual rocks.

These conclusions more or less specify the history of the intrusion, however, none are counter to current petrologic thinking. One restriction is that the intrusive history begins with a basaltic magma which undergoes strong fractionation during its cooling period. This is neither unreasonable nor presumptuous but is what a magma is expected to do given the opportunity.

A second conclusion is that the magma was under motion of an unidirectional nature during much of its cooling period. Again it seems reasonable to the writer that movement of an igneous body of this nature toward the higher levels of the crust are to be expected. Furthermore, field evidence strongly supports this conclusion. Some late filter pressing may have been responsible for upward movement and separation of the late liquid. This mechanism, however, cannot explain the early removal of magnesian mafics from the magma which must be attributed to combined crystal settling and flowage.

Temperature data appears to be somewhat conflicting. Pyroxenes provide the best geothermal data and they show a temperature drop of between 100° and 300° centigrade between their earliest and latest occurrence. The granitic rocks finally crystallized after an additional drop in

temperature of another 150° , if the higher value above is used for the earlier rocks. Further work may provide more accurate geothermal data with which better estimates concerning temperatures may be made.

Suggestions for Further Work

There are several aspects of the Mineral Lake Intrusion which make it ideal for study. The fact that the entire intrusion is reasonably well exposed is important but the simplicity of the regional structure is also an important advantage.

Several aspects of this intrusive may have important bearing on many current petrologic problems. The writer considers that some progress has been made toward the solution of at least part of the anorthosite problem. It is hoped that in the near future additional work in this area will provide new evidence on this problem.

The pyroxenes of the Mineral Lake Intrusion are particularly well suited for detailed study. It is hoped that in the near future more detailed work will be accomplished with the pyroxenes. A study of the minor elements and their distribution among phases has already been initiated in an attempt to provide additional thermochemical data, particularly between pyroxene pairs.

It is hoped that in the near future additional field work can be accomplished for several purposes. Only the eastern half of the intrusion has been mapped in this

study and it would be useful to tie this map in more closely with that published by Leighton (1954). A more thorough study of the basal rocks in the area further west may also prove of value in the study of the intrusive and cooling history. Although the western half of the area is poorly exposed some useful data along the extreme western contact would be of value. Finally, additional mapping of the overlying rocks will be of considerable value in working out the sequence of intrusive events.

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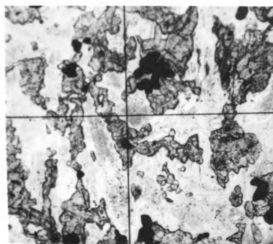
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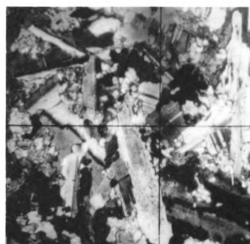
PLATE II

PHOTOMICROGRAPHS OF CHILLED ROCKS

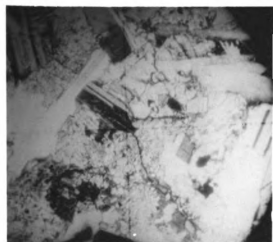
- A. Intergranular texture showing aggregates of granular pyroxene that is interstitial to plagioclase. Note how cores of plagioclase laths are dusted with minute inclusions of what is probably pyroxene. Sample D16-822, x35, ordinary light.
- B. Same as A with analyzer.
- C. Subophitic texture showing large plates of pyroxene partially surrounding plagioclase. Sample 6-5-65, x35, ordinary light.
- D. Same sample as above showing heavily inclusion charged pyroxene (right side of photo). Inclusions are arranged in a concentric pattern and extinction positions are perpendicular to this pattern, suggesting a common origin. Sample 6-5-65, x35, with analyzer.
- E. Very fine porphyritic chilled rock. Sample 7-1, x35, with analyzer.
- F. Same sample as above showing groundmass only. Sample 7-1, x100, with analyzer.



A



B



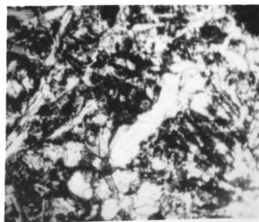
C



D



E

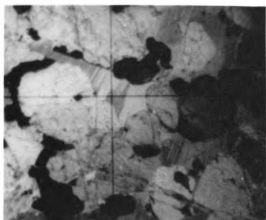


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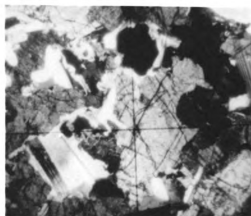
PLATE III

PHOTOMICROGRAPHS OF ULTRABASIC ROCKS
AND OLIVINE GABBROS

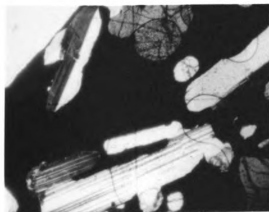
- A. Pyroxenite showing rounded hypersthene grains surrounded by interstitial and somewhat later plagioclase. Sample D15-42, x10, ordinary light.
- B. Olivine rich rock (eucrite). Plagioclase is interstitial to olivine (grey). Sample 7-3, x10, ordinary light.
- C. Olivine gabbro with late crystal of magnetite enclosing olivine and plagioclase. Sample 11-35A, x35, with analyzer.
- D. Large plate of clinopyroxene enclosing plagioclase and olivine (left center). Sample 11-35A, x35, with analyzer.
- E. Paragenetic relationships in olivine gabbro sequence: olivine, plagioclase, pyroxene, opaque. Sample 11-35A, x35, with analyzer.
- F. Ophitic texture with large pyroxene plate enclosing plagioclase and olivine. Sample 14-15A, x10, with analyzer.



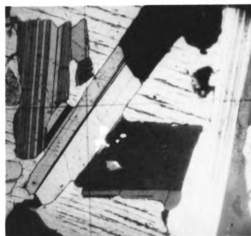
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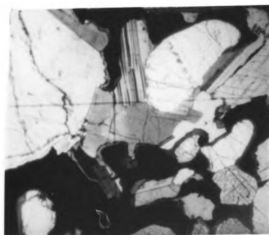
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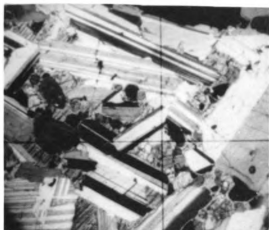


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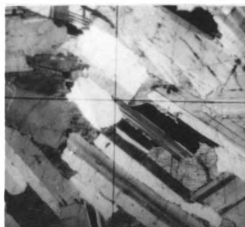
PLATE IV

PHOTOMICROGRAPHS OF ANORTHOSITE

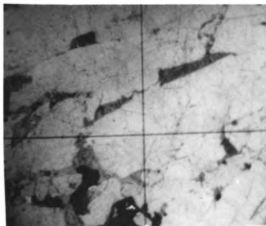
- A. Olivine Gabbroic Anorthosite from lower levels of anorthosite. Sample 11-9, x10, with analyzer.
- B. Well oriented anorthosite. Sample 11-18, x10, with analyzer.
- C. Well oriented nesophitic texture. Dark areas are pyroxene. Sample 1-4, x10, ordinary light.
- D. Same as C with analyzer.
- E. Well oriented plagioclase with many bent and broken crystals. Sample 31-101, x10, with analyzer.



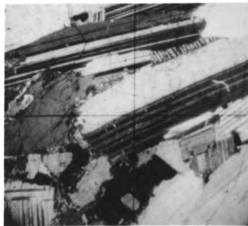
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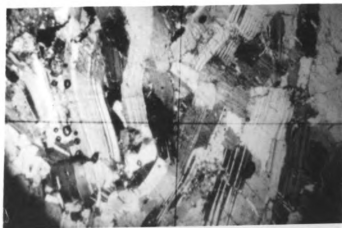
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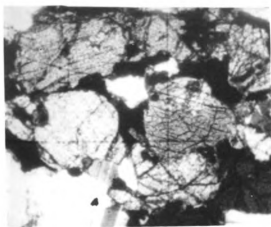


E

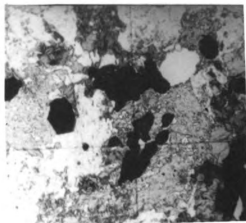
PLATE V

PHOTOMICROGRAPHS OF FERRODIORITE, TRANSITION
AND GRANITIC ROCKS

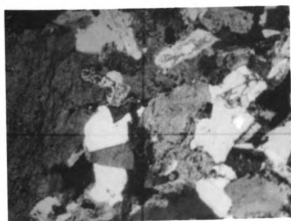
- A. Ferrodiorite. Pyroxene light grey, olivine dark grey, plagioclase white. Sample 25-42, x35, ordinary light.
- B. Altered diorite with abundant hornblende (grey), note euhedral magnetite. Sample 25-12, x35, ordinary light.
- C. Porphyritic quartz monzonite, large K-feldspar phenocryst on left, quartz is white. Sample 24-7, x35, ordinary light.
- D. Quartz diorite showing quartz replacing plagioclase. Plagioclase strongly altered to sericite. Sample 25-38, x10, with analyzer.
- E. Granite - mostly orthoclase (grey) and quartz (white) with minor euhedral plagioclase. Sample 24-3, x10, with analyzer.
- F. Graphic intergrowth between quartz and orthoclase in interstitial areas between plagioclase laths. Sample 25-38, x10, with analyzer.



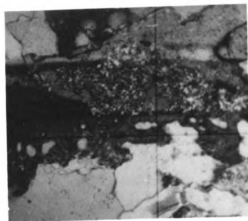
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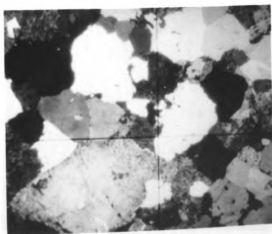
B



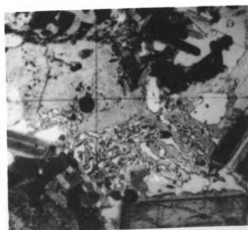
C



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E



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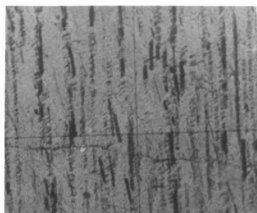
PLATE VI

PHOTOMICROGRAPHS OF MINERALS

- A. Orthorhombic pyroxene showing exsolution along (001) of original pigeonite and along (100) of inverted orthopyroxene. Sample 3-10, x100, with analyzer.
- B. Opaque inclusions in clinopyroxene. Sample 14-15A, x100, ordinary light.
- C. Euhedral zoning in plagioclase from transition to granite zone. Sample 25-37, x100, with analyzer.
- D. Perthite from granite. Sample 24-3, x100, with analyzer.
- E. Graphic intergrowth between K-feldspar and quartz. This always occurs as an interstitial filling in the transition rocks but rarely in the true granite. Sample 25-38, x100, with analyzer.
- F. Intergrowth between plagioclase and orthopyroxene, from chill zone. Sample 6-5-65, x100, with analyzer.



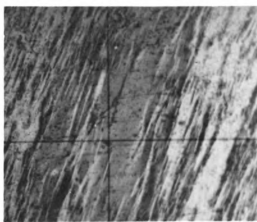
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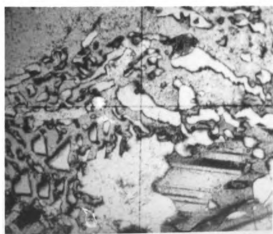
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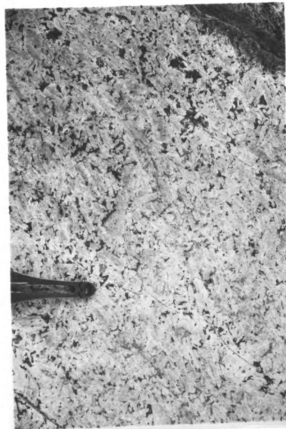


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PLATE VII

MEGASCOPIC PHOTOGRAPHS OF ANORTHOSITE
AND RELATED ROCKS

- A. Poorly oriented nesophitic anorthosite from sample 3-10. Note compass sight for scale.
- B. Well oriented anorthosite with pyroxene phenocrysts resulting in a spotted appearance. Pencil provides scale. Sample 11-7.
- C. Very well oriented anorthosite with some large plagioclase phenocrysts. Sample 11-12.
- D. Very coarse grained gabbro usually found near base of anorthosite zone. Marking pen is five inches long. Sample 11-11.



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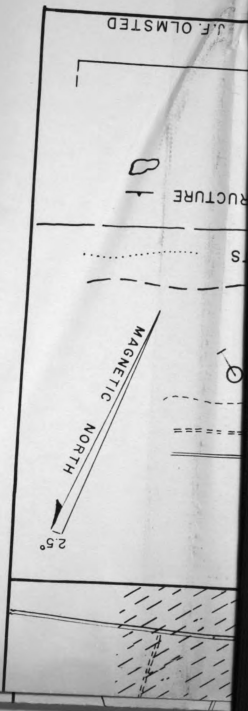
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