FRONTISPIECE

Dr. Donald M. Davidson
the
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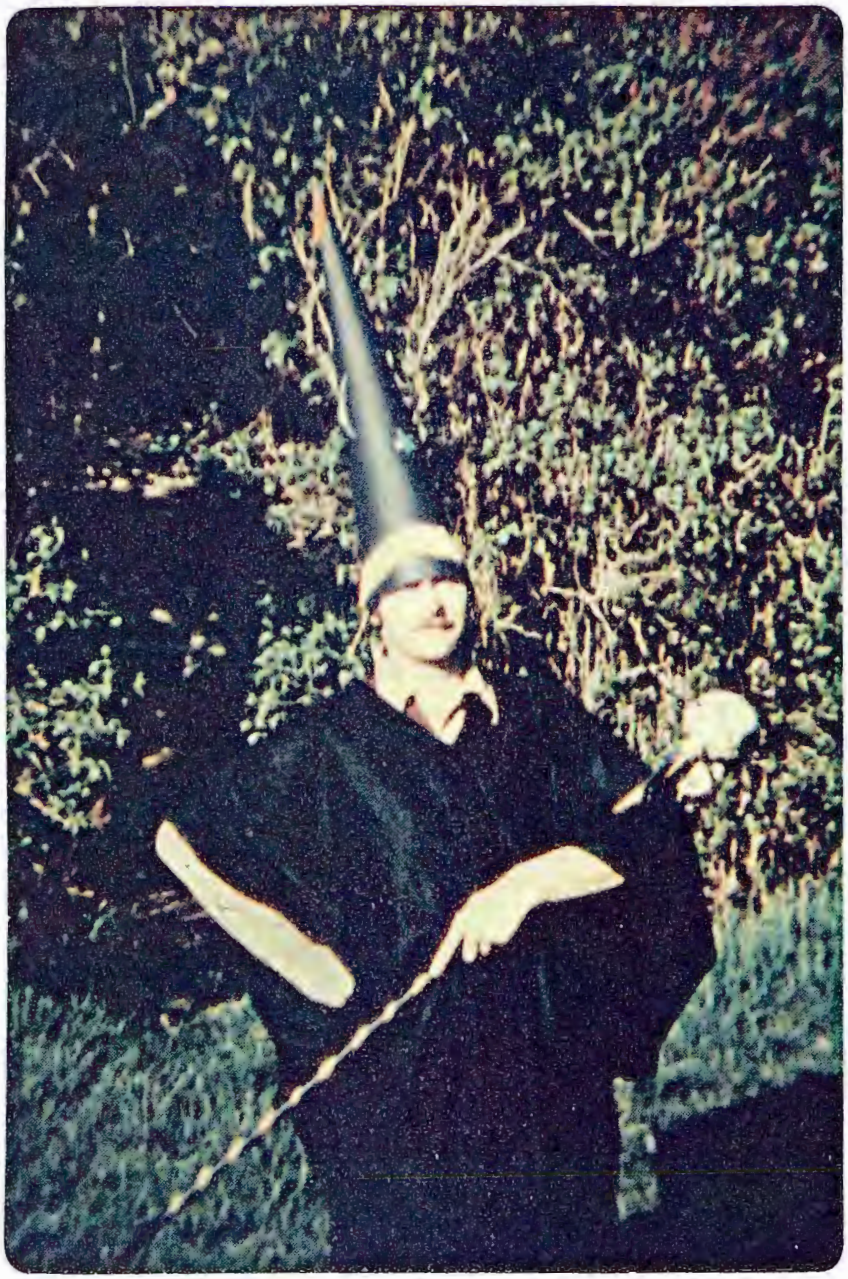

THE BEDROCK GEOLOGY OF A PORTION OF THE CRAMER 15' QUADRANGLE, LAKE COUNTY, MINNESOTA

A THESIS

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL

OF THE UNIVERSITY OF MINNESOTA

BY

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ABSTRACT

The area studied consists of sections 20 - 29 and 32 - 36 of T60N, R6W of the Cramer, Minnesota 15' quadrangle. Units exposed include the anorthositic "series," troctolitic "series," and felsic "series" of the Duluth Complex, volcanic rocks of the North Shore Volcanic Group, melagabbroic-gabbroic intrusive rocks, diabasic rocks, and a hypabysal intrusive. Bedrock units are locally covered by a variety of glacial deposits related to the Rainy Glacial Lobe of the Wisconsin Ice Age.

Troctolites and gabbros of the troctolitic series of the Duluth Complex display cummulate textures and regular cryptic (chemical) variation in the anorthite content of plagioclase (An_{78} to An_{58}), the forsterite content of olivine (FO_{70} to FO_{50}), and in the FeO/FeO+MgO ratio in augite (22 - 40). Orientations of igneous laminations as well as the areal distribution of rock types and cryptic variations strongly suggest the troctolitic series is a sill-like intrusion which differentiated in place as the result of crystal settling.

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INTRODUCTION

Location

The area of study is located in Lake County, northeastern Minnesota, approximately 33km west of Lutsen, 31km north of Finland and 11km north of Cramer (Figure 1). The map area consists of about 40 square km including sections 20 - 29 and 32 - 36 of T60N, R6W. Access is by dirt road from Cramer to the south, Isabella to the west, or from Schroeder to the east.

Regional Geology

During Late Precambrian time, the Lake Superior region was the site of extensive volcanic activity. A thick sequence of tholeiitic lava was unconformably deposited on sedimentary rocks of Middle Precambrian and Late Precambrian age. These flows and related sediments, inclusions and associated intrusive rocks define the "Keweenawan event" (1.10 $\pm$ 0.2 b.y.) of Late Precambrian time (Silver and Green, 1963). In Minnesota, these flows and related intrusives are known as the North Shore Volcanic Group.

After the extrusion of at least the lower portion of the volcanics, large volumes of magmas were intruded along the basal

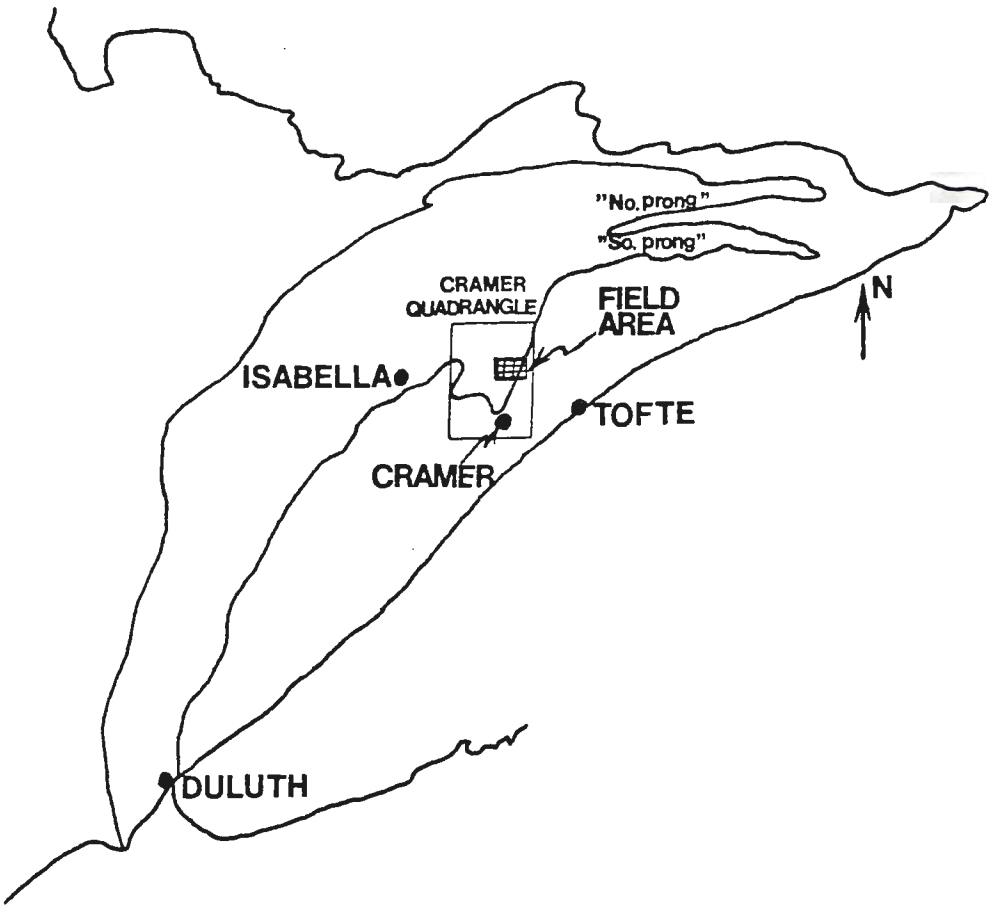


FIGURE 1

Field area location map; showing the Cramer 15' quadrangle and the study area.

contact of the flows. In northern Minnesota these intrusions are collectively termed the Duluth Gabbro Complex (Grout, et al, 1959).

The Duluth Gabbro Complex is generally depicted as a semi-concordant multiple intrusion composed chiefly of gabbroic anorthosite, trotolite, gabbro and felsic rocks. The intrusions define a curvilinear belt which extends northward from Duluth to Babbit, northeastward from Babbit to the Gunflint Trail, and then southeastward terminating near Hovland in the northeastern corner of Minnesota (Figure 2).

Previous workers (Weiblen, 1965; Phinney, 1969; Davidson, 1969; Bonnichsen, 1972; Babcock, 1972) divided the complex into five major series: the early mafic or layered series described by Nathan (1969); the anorthositic series; the felsic series; the troctolitic series; and the late mafic series (Figure 2).

In Minnesota, Late Precambrian rocks crop out along and form the northern portion of the Mid-continent Gravity High, a linear zone of relatively high gravity values, which might represent an episode of continental rifting in Late Precambrian time (Hinz, Roy and Davidson, 1972). This extension of the crust during Keweenawan time may be viewed as providing room for the emplacement of the Duluth Gabbro Complex.

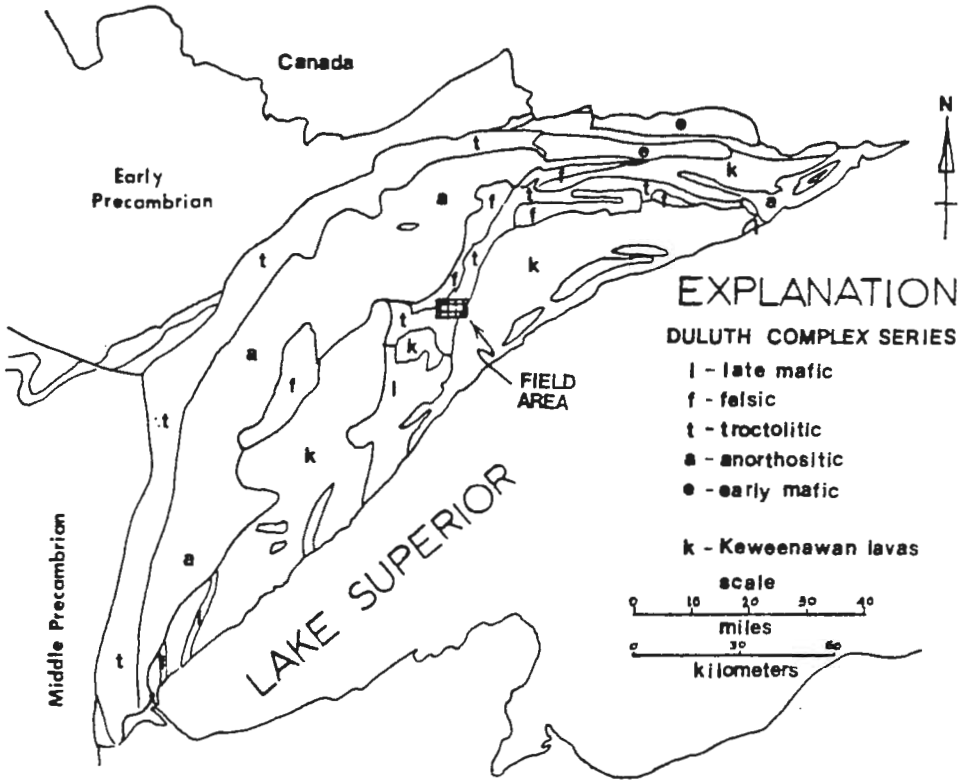


FIGURE 2

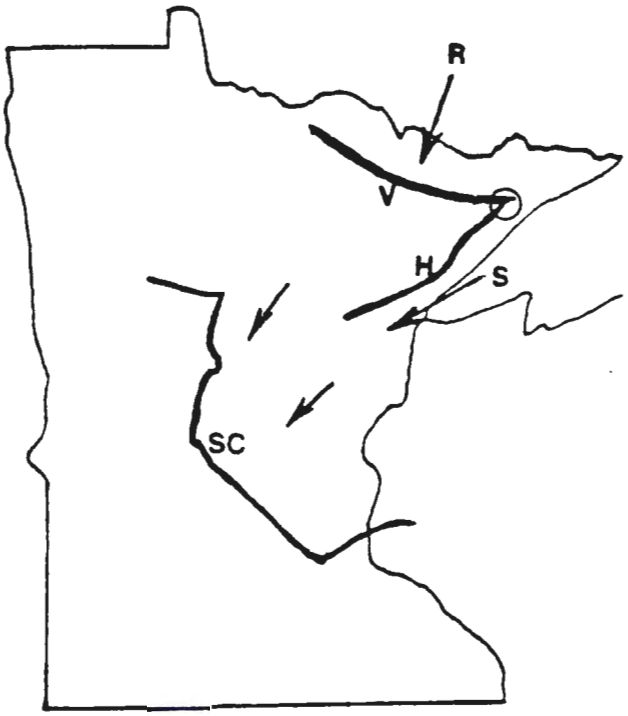
Regional geologic map displaying the study area relative to the major intrusive series of the Duluth Gabbro Complex and the flows of the North Shore Volcanic Group (k) (after Davidson, 1972).

Between Precambrian and Quaternary time, the area underwent minor uplift and erosion; however, several times during the Pleistocene Epoch glaciers of continental proportion covered portions of northeastern Minnesota (H. E. Wright, 1972). In the latest episode of glaciation, the Wisconsinian, two lobes of ice were active. The Rainy lobe occupied an upland position on The Lake Superior Highland and The Superior lobe occupied the Lake Superior Basin to the east (Figure 3).

Several major moraines are attributed to these lobes: (1) the St. Croix Moraine of Minnesota and Wisconsin; (2) the Highland Moraine of northeastern Minnesota; and (3) the Vermilion Moraine is attributed to the Superior lobe and the Moraine of northeastern Minnesota. The Highland Moraine is attributed to the Superior lobe and the Vermilion Moraine is attributed to the Rainy lobe, whereas, the St. Croix lobe is felt to be a product of the action of both lobes. In general, the Superior lobe deposited a red, clay-loam till while the Rainy lobe deposited a brown, sandy till.

Previous Work

Portions of the Cramer Quadrangle were mapped on a reconnaissance basis by Elftman in 1878, Green (1968-69), and Davidson (1970). Elftman noted the existence of a large area of diabase



KEY

ICE LOBES

R - Rainy

S - Superior

MORAINES

V - Vermilion

H - Highland

SC - St. Croix

FIGURE 3

Wisconsin moraines of the Rainy and Superior lobes. Circle indicates the approximate location of the study area. Modified after H. E. Wright, Jr. (1972).

dikes and his observations are noted in volume four of Winchell's 1898 report on the geology of Minnesota. Both Green and Davidson noted anorthositic, troctolitic, gabbroic, granitic and volcanic rocks, while Davidson also recognized areas of granofels (Davidson and Green, personal communication).

Davidson (1972) has mapped areas to the west, north and northeast of the field area and he determined that rocks of the troctolitic series and felsic series constitute the "Southern Prong" (Figure 1) of the eastern Duluth Gabbro Complex. He reported that these rocks form a five to eight mile wide zone extending southwestward into the Cramer Quadrangle (Figure 2) that separates the bulk of the North Shore Volcanics to the southeast from the anorthositic series to the northwest.

Sharp (in Grout, et al, 1959) inspected glacial features in T60N, R5W, including an esker which extends into the northeastern corner of the map area and terminates south of Wilson Lake.

Purpose of Study

It is the purpose of this study to map and evaluate both the surficial and bedrock geology in the thesis area, with particular emphasis on the petrography and chemistry of the

major bedrock units of the Duluth Gabbro Complex, as well as rocks of the North Shore Volcanic Group.

Techniques

Selected areas with distinct topographic features were inspected for outcrop and, where feasible, 1/4 mile spaced traverses were conducted. Representative hand samples were collected at bedrock locations and samples of till and drift were acquired from selected glacial features.

Igneous foliations and layering attitudes were measured in the gabbroic and troctolitic rocks. The orientations of flow tops and columnar jointing surfaces were noted and the strike directions of vertical joints were measured.

A total of 112 thin sections were prepared and modal analyses performed by counting at least 1,000 points per section. Several polished thin sections were prepared for the purpose of opaque mineral study. Sawed surfaces of rock samples and several thin sections were stained to aid in the identification of potassium and calcium rich minerals.

Compositions of plagioclase were determined through use of the Michel Levy method, oil immersion techniques, or by the

method described by Deer, Howie and Zussman (1966, page 330) which utilizes combined albite-Carlsbad twins in a section normal to x (normal to both the [001] and [010] cleavages).

Olivine, pyroxene and iron-titanium oxide compositions were determined through use of an electron micropobe at the University of Wisconin at Madison. Data was reduced by computer employing the Genie 2 program provided by Dr. E. D. Glover of the University of Wisconsin at Madison.

Acknowledgements

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Mr. Peter Juneau, Mr. Drew Strakele, Mr. Bruce Ekland and Dr. Donald M. Davidson visited the field area and aided in a portion of the mapping.

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GENERAL GEOLOGY

Introduction

Mappable bedrock units exposed in the field area include intrusions of the Duluth Gabbro Complex, an intrusive melagabbro which may be part of the Duluth Gabbro Complex, volcanics of the North Shore Volcanic Group, small areas of diabase and a hypabyssal intrusive. Intrusions of the Duluth Complex include olivine-bearing rocks of the troctolitic series, gabbroic anorthosites and anorthositic gabbros of the anorthositic series and granitic rocks of the felsic series. Surficial units exposed in the field area include glacial deposits which are the result of Wisconsin-age glaciation.

Anorthositic Series

Rocks which are part of the anorthositic series of the Duluth Gabbro Complex outcrop on the tops and flanks of hills in Sections 21 and 29 of T60N, R6W. Particularly good exposures are present along the northwestern base of the large hill that dominates Section 29.

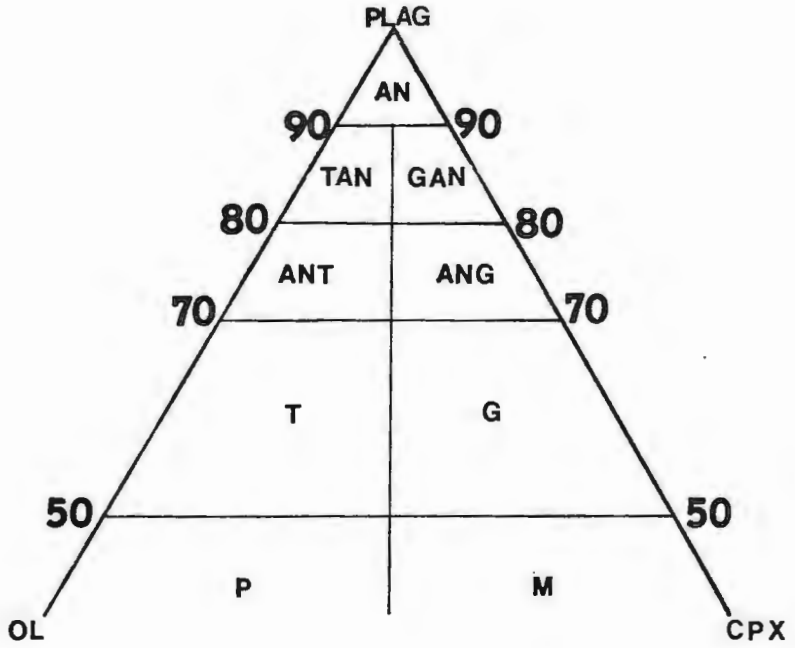
In outcrop the anorthositic series rocks display a rubbly surface which apparently is the result of extensive deuteric

alteration and recent weathering. Fresh areas are rarely seen on exposures and microscopic examination of these fresher samples also showed extensive alteration.

In hand specimen the unit appears gray to dark gray and weathers to a light brownish-gray. Gray plagioclase laths up to 2cm and averaging 6mm in length constitute the most conspicuous phase. The plagioclase occurs with black pyroxenes and iron-titanium oxides which appear interstitial and are generally less than 4mm in extent. Plagioclase makes up about 80 percent of the rock, pyroxene about 15 percent and oxides about 5 percent. According to the classification of Phinney (Figure 4), rocks of this unit observed in the thesis area may be considered as either anorthositic gabbros or gabbroic anorthosites.

A planar preferred orientation of plagioclase was observed in several outcrops. This igneous foliation is highly variable and does not display a consistent orientation between adjacent exposures.

Taylor (1964) observed the anorthositic series outcrops near Duluth and noted the presence of large blocks within the series in which the plagioclase exhibited a preferred orientation. He noted that the orientation of plagioclase laths varied from block to block and the blocks were set in a "groundmass" in which the



KEY

AN - anorthosite

TAN - troctolitic anorthosite

GAN - gabbroic anorthosite

ANT - anorthositic troctolite

ANT - anorthositic gabbro

T - troctolite

G - gabbro

P - picrite

M - melagabbro

plagioclase does not display a consistent orientation. Taylor felt that these features indicated flow of partially crystallized magma. Features similar to those noted by Taylor were not observed in the thesis area.

Contacts of the anorthositic series with flows of the North Shore Volcanic Group were not observed. On the western side of the small hill in the SE1/4, NW1/4, NE1/4 of Section 29 a contact between these units can be approached within 3 meters and at that location the anorthositic rocks appear to be unaltered when observed in hand specimen. A contact of the anorthositic series with felsic series rocks and North Shore Volcanic rocks is inferred to exist on the northern slope of the small hill mentioned above. Other inferred contacts of the anorthositic series are marked by topographic lows filled with glacial and alluvial deposits.

Troctolitic Series

According to the classification of Phinney (Figure 4) the rocks of the troctolitic series in the area of study range in type from gabbro and anorthositic gabbro to anorthositic troctolite and troctolite (Figure 5). These olivine-bearing rocks display consistent characteristic textures probably representing gradational modal values within a single major unit. Troctolitic

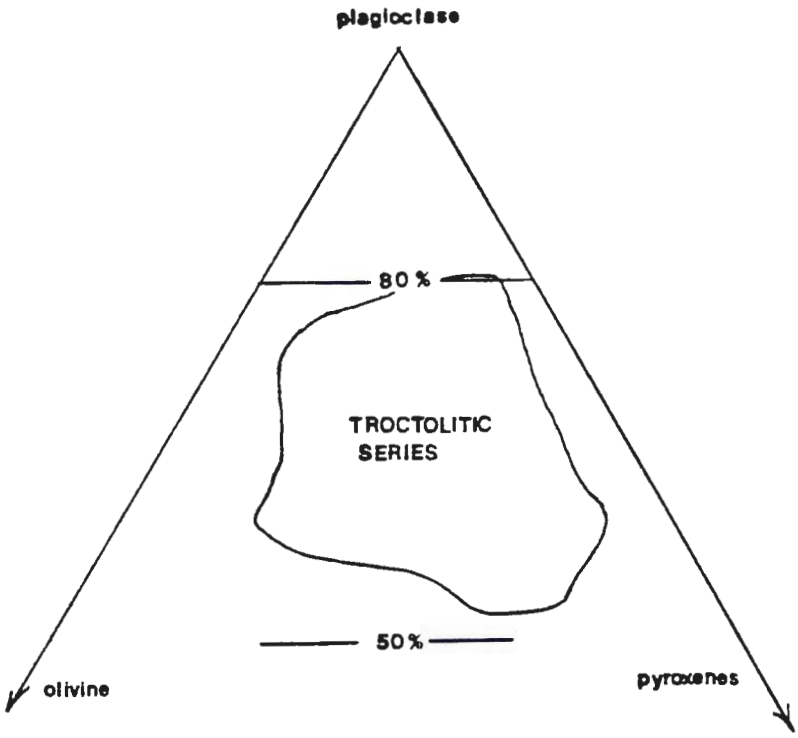


FIGURE 5

Modal (volume percent) abundances of major minerals as measured within the troctolitic series rocks of the thesis area. Contour represents the approximate limit of all values measured.

rocks predominate along the northwestern boundary of the series while olivine-bearing gabbroic rocks dominate to the southeast.

In outcrop these rocks are typically dark green-gray to gray with a 2-3mm light-tan to tan weathering rind. This rind displays 1-4mm brown spots and pits, owing to the weathering of olivine and elevated grains of dark pyroxene which stand with a relief of 1-2mm above the rest of the weathered surface as a result of their relatively resistant nature. Many exposures exhibit a well-developed exfoliation which is contributing to spheroidal weathering.

The unit is best exposed along a northwest trending hill which is the major topographic expression in the SE1/4 of Section 35 and also outcrops on small hills and whalebacks scattered through Sections 24, 26, 27, 33, 34 and 36 of T60N, R6W. These exposures define a northeast-southwest trending outcrop pattern.

In hand specimen 2-6mm lath shaped plagioclase and 1-4mm equant olivines are enclosed by anhedral black pyroxenes. Oxide phases are magnetic.

Two types of primary igneous foliations are present in the troctolitic series: a planar preferred orientation of plagioclase laths and a modal layering owing to variations in the relative

abundances of plagioclase, olivine and pyroxene (Plate 3). The primary foliation of planar feldspar laths is well-developed and regular in nature throughout the troctolitic zone although weakly developed and less regular in nature within the gabbroic zone. Modal layering was observed in a few locations along the base of the troctolitic zone. When these foliations are both present in an outcrop they are concordant.

The average strike of the igneous foliations is about N57E and is parallel to the trace of the northwestern boundary of the troctolitic series. Foliation dip varies between 2 and 30 degrees and averages 15 degrees towards the southeast (Figure 6). The average orientation of the foliation is about the same as the general orientation of the bedding of volcanic flow units of the North Shore Volcanic group which Green (personal communication) has measured in the Tofte Southwest 7.5 minute quadrangle, 5-10 miles to the southwest.

Measurements of the strikes of nearly vertical joints were plotted on a rose diagram (Figure 7). This plot displays a structural "grain" in the troctolitic series, the strike of which is approximately parallel to the strike of both of the igneous foliations mentioned previously and the trace of the northwestern contact of the troctolitic series.

PLATE 3

Modal layering in the troctolitic series; light bands are plagioclase-rich and dark bands are olivine and pyroxene rich. SE¼, SE¼, section 23, T60N, R6W. Note coin (quarter) for scale.

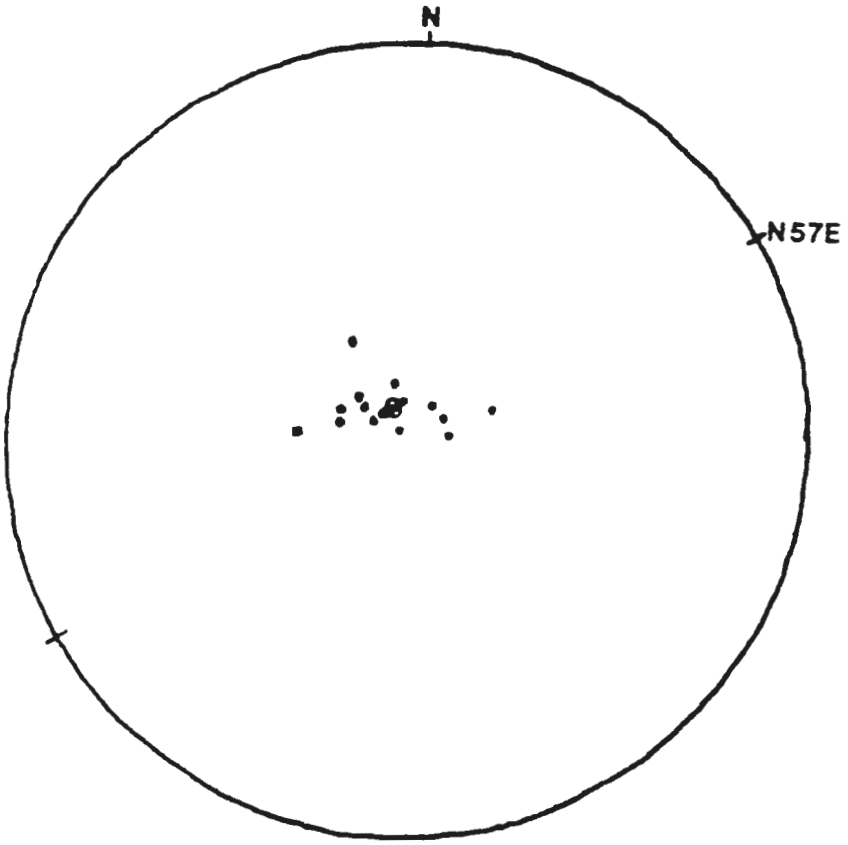


FIGURE 6

Stereographic plot of poles to planes of igneous foliation and modal layering in the troctolitic series. Open circle indicates the average measurement (N57E, 15S). Tic marks display average strike.

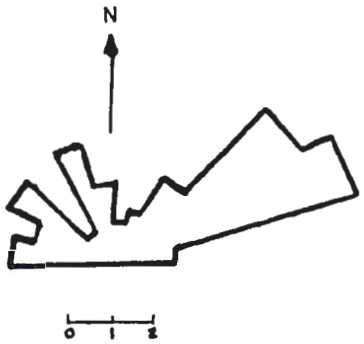


FIGURE 7

Rose (variation) diagram displaying strike directions of near vertical joints in the troctolitic series over an interval of 15 degrees.

The contact of the troctolitic series with the felsic series, anorthositic series and melagabbro is marked by a distinctive lineament which can be seen on aerial photographs and on LANDSAT (ERTS) imagery. In the field the contact is a shallow linear 3 to 9 meter deep swail devoid of outcrop (L_1, Figure 8). The contact of the troctolitic series with the North Shore Volcanic Group in the southeastern portion of the field area is also covered, although a distinctive topographic expression, in the form of a ridge, helps to identify its trace. No chilled margins or intrusive relationships were observed.

Felsic Series

Rocks of the felsic series are exposed on hills and along ridges and ledges in Sections 20, 21, 22, 23, 24 and 29 of T60N, R6W. Outcrops of the felsic series are generally massive and lacking in internal structure.

In hand specimen the rocks are salmon colored, weathering to a light salmon hue which often shows black tarnished areas, presumably a coating of manganese oxide or an alteration to jarosite. Euhedral, medium-grained to fine-grained feldspars are surrounded by a finer grained groundmass of felsic material which contains minor areas of an anhedral, dark green, mafic mineral. In some specimens the groundmass is coarse enough to

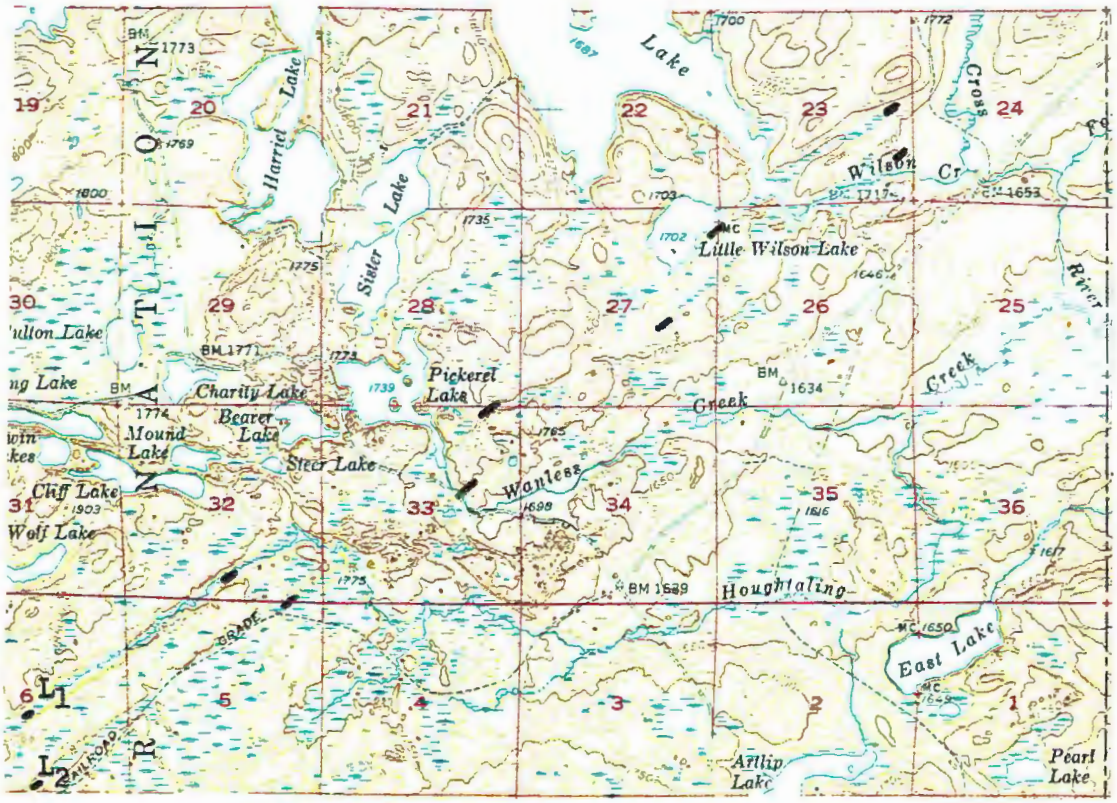


FIGURE 8

Topographic map of a portion of the Cramer quadrangle. L_1 and L_2 are lineaments associated with the Duluth Gabbro Complex. Base map from U. S. Geological Survey. Sections are approximately 1 mile (1.6km) on a side.

allow identification of quartz, which varies in shape from irregular anhedral grains to angular graphic growths. Staining of sawed surfaces for potassium feldspar indicated a fairly uniform granitic composition.

Strongly developed topographic lows characterize the contacts of the felsic series with rocks of the anorthositic series and the North Shore Volcanic Group. An exception is an inferred contact of the felsic series with both of these units on a hill in the SE1/4, NW1/4, NE1/4 of Section 29. On its northern slope, a wedge-like body of felsic series rocks is situated above anorthositic series rocks and below North Shore Volcanic Group rocks; this is 0.2km to the north and east of a contact between these two units which has no felsic series rocks associated with it.

The contact of the felsic series with rocks of the troctolitic series forms a distinctive linear feature, possibly the result of a fault. This lineament (L1) and a parallel lineament in the troctolitic series (L2) are depicted on Plate 1 and in Figure 8 crossing the thesis area from southwest to northeast.

North Shore Volcanic Group

The North Shore Volcanic Group is exposed along the southwestern edge of Section 36 and on hilltops in Sections 21, 27,

28 and 29 of T60N, R6W. The volcanic rocks in Section 36 are located along the western margin of the main body of the North Shore Volcanic Group (Figure 2) while the exposures in Sections 21, 27, 28 and 29 are outliers, generally preserved as resistant caps on hill tops.

The volcanics are slate-gray to reddish-brown on a fresh surface and mottled light-gray and reddish-brown when weathered. Feldspar phenocrysts and occasionally quartz phenocrysts are set in an aphanitic to fine-grained groundmass. Staining for potassium-bearing feldspars reveals that the flows vary from basaltic to rhyolitic in composition.

The volcanic nature of these rocks is indicated by their porphyritic texture and the presence of columnar jointing, vesicular flow tops and ropy flow tops. The columnar and vesiculated nature of the flows is best displayed in the SE1/4, NW1/4, NE1/4 of Section 29. A ropy flow top crops out in the center of the SE1/4 of Section 21.

Near the basal contact of the flows in Sections 21, 28 and 29 areas of granofels occur. Though displaying volcanic attributes, such as columnar jointing and ropy flow tops, the rocks have a granoblastic texture. These granofels locally contain inclusions of amphibolite and are commonly laced with stringers of leucocratic granophyric material.

Both troctolitic series rocks and melagabbroic rocks crop out near the volcanic rocks of Section 36, although no contacts were observed. Anorthositic and felsic series rocks are exposed very near the basal contact of the flows in the SE1/4, NW1/4, NE1/4 of Section 29. The attitude of the base of the volcanic flows along a northeast-southwest exposure on this large hill is nearly horizontal.

Oxide-Rich Melagabbro and Gabbro

Areas of oxide-bearing melagabbro and gabbro up to 2km across occur adjacent to the contacts of the troctolitic series. The melagabbro is exposed in Sections 21, 22, 23, 28, 33 and 36 of T60N, R6W. These oxide-rich rocks are not conclusively shown to be part of a Duluth Gabbro Complex major series in this report, although their areal distribution (Plate 1, pocket) seems to indicate they are related to the emplacement of the anorthositic series.

The melagabbro generally forms "pavement" type outcrops from which it is difficult to obtain hand specimens. Exfoliation and intense weathering are developed on outcrops which do protrude from the ground surface.

The melagabbro is speckled white, brown and black with euhedral to subhedral plagioclase and pyroxene that vary from

0.5mm to 7mm in size. Oxide phases account for up to 20 percent of the rock and are difficult to identify in hand specimen; their presence is indicated by the magnetic nature of the rock.

An oxide-rich pegmatitic zone was noted in an outcrop at the Wilson Lake public boat launching site, SW1/4 of Section 23, T60N, R6W. The pegmatite contains subhedral crystals of opaque oxide up to 5cm in length. The pegmatite is cut by veinlets of fine-grained felsic material which occurs along joints.

The plagioclase, pyroxene and in some places, the oxide crystals of the melagabbro are arranged in a preferred planar orientation. The nature of the outcrops generally prevented accurate measurements of the orientation of this igneous foliation. Where measurements were obtained the orientation of the foliation was not always constant, although it is probable that a detailed study (in drill core, for example) could reveal that an overall preferred orientation exists at each locality studied.

Contacts of the melagabbro with neighboring extrusive or intrusive rocks were not found and inferred contacts are marked by topographic lows. The melagabbro-troctolitic series contact is topographically expressed as a lineament.

Diabase and Porphyritic Hypabyssal Intrusive

Diabasic intrusives were mapped along the south and southeastern shores of Sister Lake in Section 28. They also form the cliffs along the southern shore of Cliff Lake in Section 32 (Figure 8).

Outcrops are massive and elongate in an east-northeasterly direction. Nearly vertical joints with a north-northwesterly trend are common.

The diabases are dark gray and fine-grained. Lath-shaped plagioclase up to 1.5mm and subhedral pyroxene up to 1mm are the dominant phases visible under a hand lens. The Sister Lake diabases contain a few percent of plagioclase phenocrysts up to 4mm long, while the Cliff Lake diabase is not porphyritic. The latter displays uralized pyroxene.

A hypabyssal porphyry crops out in the center of the SE1/4 of Section 29 (Plate 1). The intrusive contains phenocrysts of feldspar up to 2cm long and aggregates of plagioclase, pyroxene and oxide up to 1cm across. The phenocrysts and aggregates float in a quartzofeldspathic "matrix" which contains quartz, orthoclase, biotite and plagioclase. The "matrix" is evidently the result of alteration produced by hot, volatile-rich fluids.

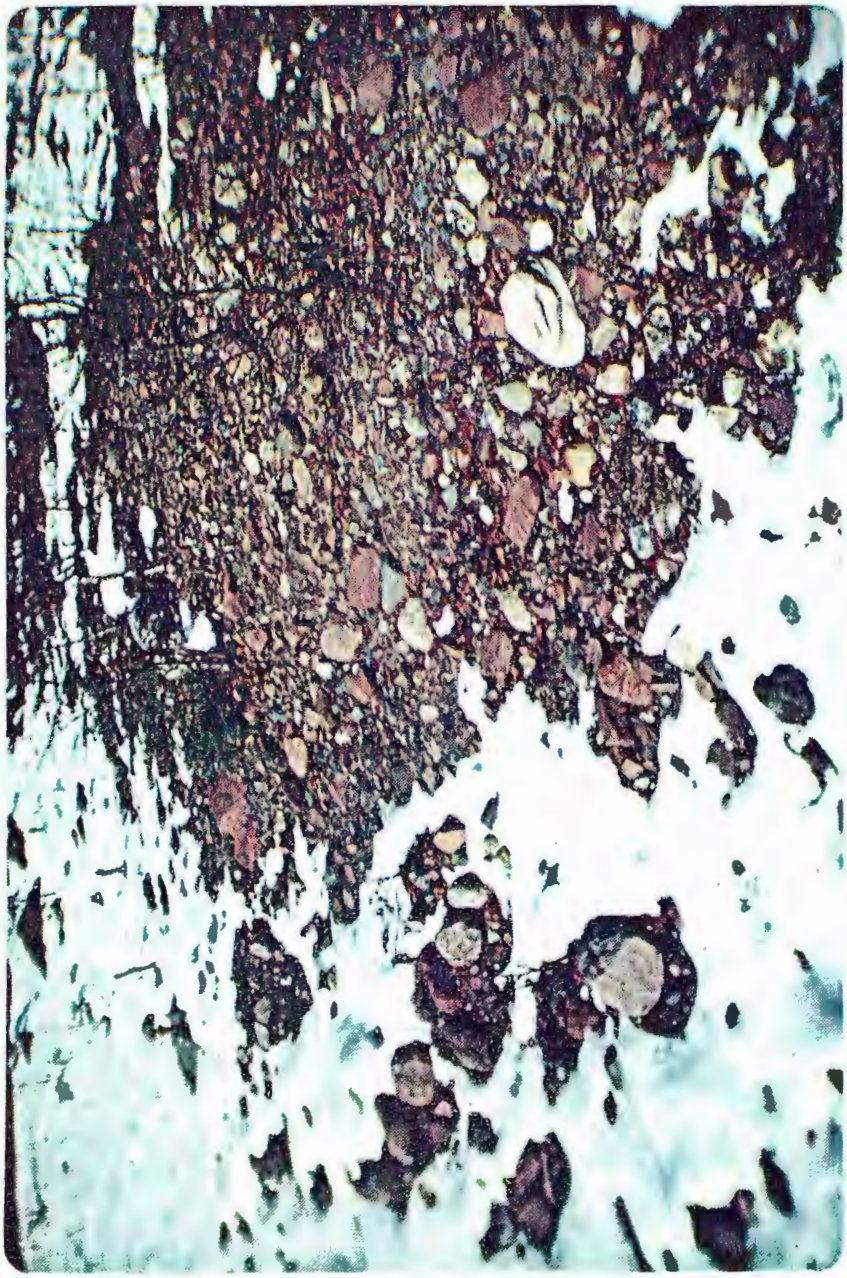
Surficial Geology

The unconsolidated surficial deposits of the field area are dominated by brown sandy Rainy lobe till of Wisconsin age. The till is usually brown, but grades to reddish-brown and gray. Although the till is primarily composed of sand size material, it also contains numerous pebbles, cobbles and boulders of gabbro, troctolite, granophyre, diabase, iron formation, basalt, graywacke, quartzite and argillite (Plate 4). The composition of the boulders in the till typically reflects the nature of the local bedrock, particularly the troctolitic and granophyric boulders which are usually found in abundance in areas of troctolitic or felsic series bedrock.

The Vermilion Moraine (H. E. Wright, 1972), an end moraine of the Rainy Lobe, is one of the most conspicuous glacial features present in the field area (Figures 3 and 8). The moraine, manifested as a swath of numerous steep-sided, sand- and cobble-strewn hills, enters the field area in the NW1/4 of Section 32, extends along the lower 1/2 of Section 33 and terminates in the SW1/4 of Section 34. Wright (1972) stated that the Vermilion and Highland Moraines (Figure 3) meet near Isabella, 23km (14 miles) to the west ot the area of this report. It is apparent on the Isabella and Cramer 15' Quadrangles that the Vermilion Moraine continues east to end in Section 34 and that fact is

PLATE 4

Photograph of till; note the predominance of felsic (reddish) rocks. Hat (white) for scale. NW¼, NW¼, section 26, T60N, R6W.



cited in this report as further evidence that till in the area is of Rainy lobe origin.

Three eskers were identified in the map area: (1) in Sections 20 and 29 on Harriet Lake; (2) crossing Sections 23, 24, 26 and 27 to the south and southeast of Wilson Lake; and (3) a 1/2km long arcuate body in the NE1/4 of Section 34. The esker on Harriet Lake extends in arm-like fashion from the east and southwest shores and is either submerged or washed out for 1/2km in the central portion of the lake (Figure 8 and Plate 5). The esker south and southeast of Wilson Lake extends from the shore of Little Wilson Lake eastward to a point in Cook County where it was inspected by Grout, Schwartz and Sharp in 1959. It is best exposed by a roadcut in the SW1/4, SW1/4, SW1/4 of Section 24 (Figure 8 and Plate 6). The third esker noted in Section 34 is but a short segment the nature of which is not evident upon inspection of the Cramer 15' Quadrangle topographic map, but its steep flanks and long sinuous nature are evident at the site.

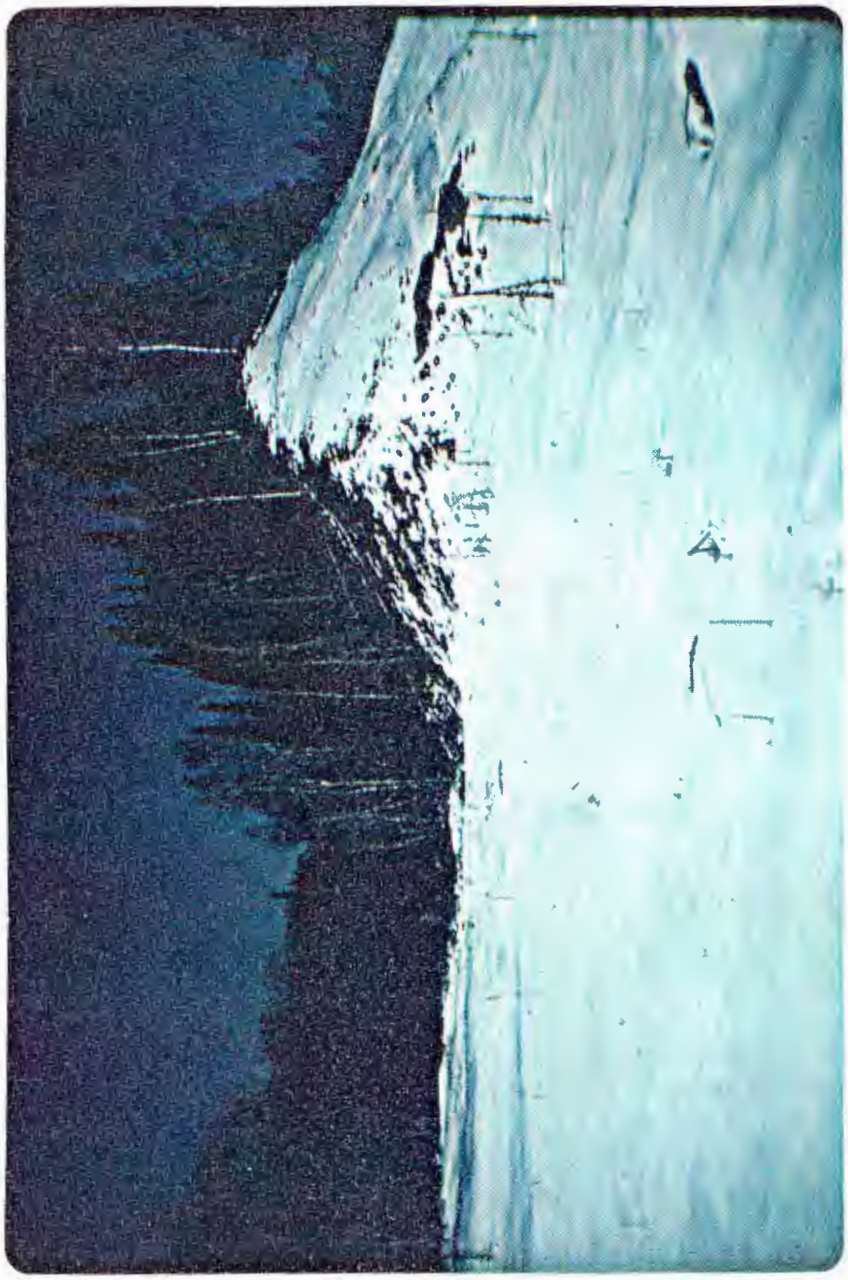
These eskers all are related to areas of outwash. The esker on Harriet Lake feeds an outwash plane of about $1km^2$ (247 acres). A gravel pit along a road in the SW1/4, NW1/4 of Section 35 best displays sediments related to the Section 34 esker.

PLATE 5

Esker crossing Harriet Lake; sections 20 and 29, T60N, R6W.

PLATE 6

roadcut through esker, SW¼, SW¼, section 24, T60N, R6W.



Several conical features are interpreted as being kames: two occur as hills in Section 21, two occur as islands in Pickerel Lake (Dam Five Lake on some maps) and one occurs as an island in Wilson Lake. These features are principally composed of boulders of local bedrock types.

PETROGRAPHY

Anorthositic Series

The majority of anorthositic series rocks plot as gabbroic anorthosite according to the classification scheme of Phinney (Figure 4). Major minerals present in anorthositic series rocks include cummulate plagioclase feldspar (labradorite) together with ilmenite, olivine and poikilitic augite. Minor constituents in the anorthositic series rocks include orthopyroxene, biotite, muscovite, hornblende, apatite and oxide-quartz-orthoclase-albite-biotite symplectite.

The gabbroic anorthosite contains, on the average, 79 percent plagioclase, 11 percent augite, 4 percent opaque oxides and 1 percent olivine. The average of three modal analyses is given in Table 1 and the modal values of major minerals in each thin section is depicted in Figure 9.

A few areas with well-developed primary mineral foliation occur within the anorthositic series. The foliation, which reflects an alignment of plagioclase laths, is inconstant in orientation. Davidson (1972) concluded that this fabric resulted from flow and convection rather than from crystal settling.

TABLE 1

AVERAGE OF MODAL (VOLUME PERCENT) MINERAL ABUNDANCES IN THREE SAMPLES OF ANORTHOSITIC GABBRO FROM THE CRAMER QUADRANGLE, MINNESOTA (Thin Sections 5-7-4, 9-2-1 and 9-2-16)*

MINERAL	PERCENT
Plagioclase	81.23
Augite	10.84
Orthopyroxene	0.48
Symplectite	1.23
Opaque Oxides	4.03
Amphibole	0.57
Biotite	0.64
Chlorite	0.40
Muscovite	tr.
Apatite	0.57
Total	100.0

* An average of 1.08 percent of each rock is estimated to have been olivine which is now altered to, and included in the table above as, biotite, chlorite and opaque oxides.

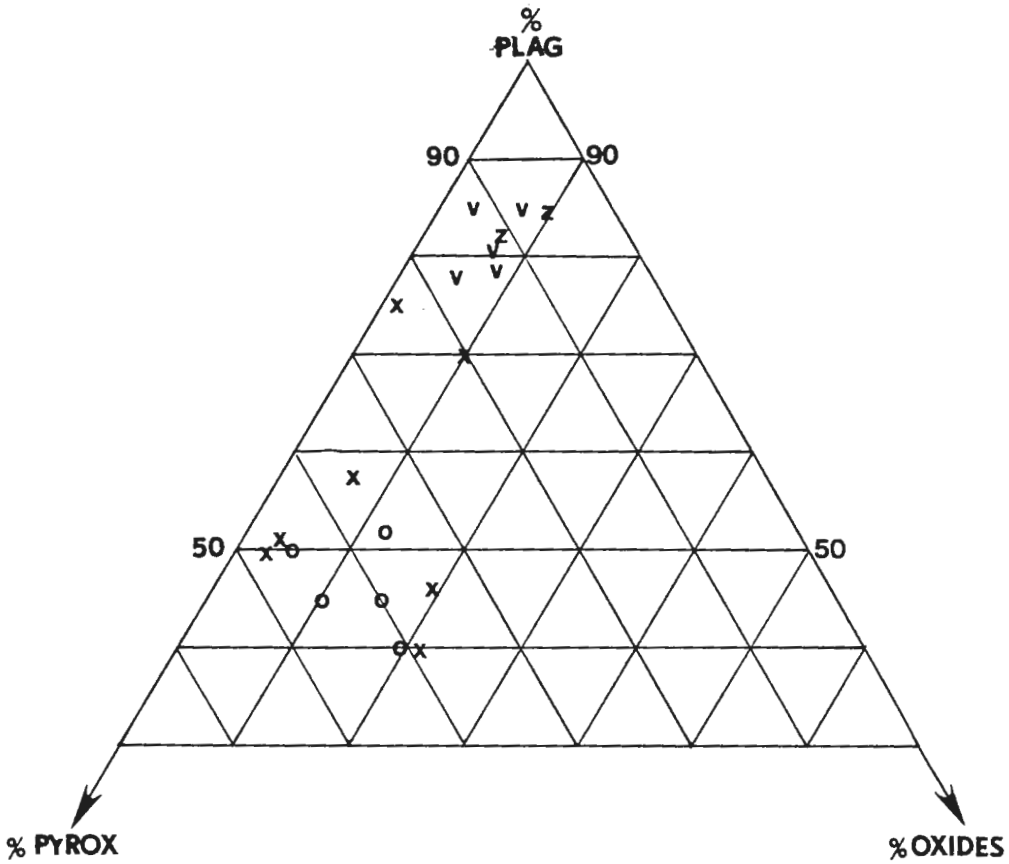


FIGURE 9

Mineral abundances in anorthositic series and melagabbroic-gabbroic rocks.

Z - plot of modal (volume percent) mineral abundances of anorthositic series rocks.

V - plot of estimates of mineral abundances of anorthositic series rocks.

X - plot of modal (volume percent) mineral abundances of melagabbroic-gabbroic rocks.

O - plot of estimates of mineral abundances of melagabbroic-gabbroic rocks.

mode = statistically counted percentage

estimate = percentages estimated by petrographer

As determined by measurements of extinction angles, the labradorite feldspar varies in composition from An_{69} to An_{56}. Lath-shaped to subhedral crystals up to 1.5cm long average 5 to 6mm in length. Laths typically display normal zonation; that is, the grain cores are more calcic than the grain rims. Interstitial post-agglomeration growths of plagioclase are anhedral to subhedral.

Rocks of the anorthositic series contain microscopic 0.2 to 3mm areas composed of fine to medium grained biotite, chlorite and opaques which are altered from original olivine.

Augite is anhedral, interstitial and usually poikilitic in habit (Plate 7). Oikocrysts up to 7mm across envelope plagioclase and apatite. Orthopyroxene is present as exsolution blebs along cleavage traces within the augite.

Interstitial, anhedral ilmenite also encloses plagioclase and augite. Some of the ilmenite is rimmed by very fine biotite and magnetite.

Symplectic intergrowths of quartz, opaque oxides, biotite, orthoclase and albite occur as late interstitial growths. With the exception of sparse euhedral orthoclase, the grains within the symplectite are anhedral.

PLATE 7

Photomicrograph of an anorthositic series gabbroic anorthosite; poikilitic augite, light yellow; lathy plagioclase, grey and white. 1 inch = 2mm. Polarized light.

Anhedral, green, pleochroic amphiboles (0.7mm or smaller) and anhedral biotites (0.02mm and finer) were observed to be present in trace amounts. Amphibole constitutes 1 percent of the rock (sample 9-2-1) in one sample near the contact with the North Shore Volcanic Group.

Myrmekitic intergrowths of feldspars were observed along the crystal boundaries of plagioclase laths.

Textures indicate the crystallization sequence of the gabbroic anorthosite to be: (1) plagioclase and olivine; (2) augite and orthopyroxene; (3) ilmenite; and (4) symplectite. Strong deuteric alteration of plagioclase to sericite, pyroxene to chlorite and olivine to biotite and chlorite is evident. This alteration is presumably the result of the deuteric effects of the volatile-rich fluid from which the symplectite crystallized.

Troctolitic Series

Rocks of the troctolitic series are principally composed of plagioclase, olivine, augite, orthopyroxene and ilmenite. Accessory minerals include apatite, biotite, muscovite and magnetite.

Figure 10 is a plot of modal abundances of plagioclase, olivine and pyroxene (both clinopyroxene and orthopyroxene) of rocks from the troctolitic series. These minerals account for 95 to 99 percent of the troctolitic series rocks.

Rock names which can be properly applied to rocks of the study area assigned to the troctolitic series include: (1) olivine gabbro; (2) anorthositic gabbro; (3) augite troctolite; and (4) anorthositic troctolite. It is evident from Figure 10 that the majority of troctolitic series rocks studied are olivine-bearing gabbros; however, all of the rocks portrayed in Figure 10 are considered to belong to the troctolitic series because of textural, chemical and spacial relationships which are described below.

From Figure 10 it can also be noted that, in general, olivine is more abundant in the northwestern portion of the unit (base), whereas pyroxene predominates to the southeast (top).

Figure 11 is a plot of a moving average of modal (volume percent) olvine/pyroxene plotted against each averages "percent height" in the inferred "column". Each mode is averaged with its closest neighbors on the basis of their relative distance to the two troctolitic series contacts. The modes are taken from samples from scattered outcrops within the troctolitic series (Plate 1,

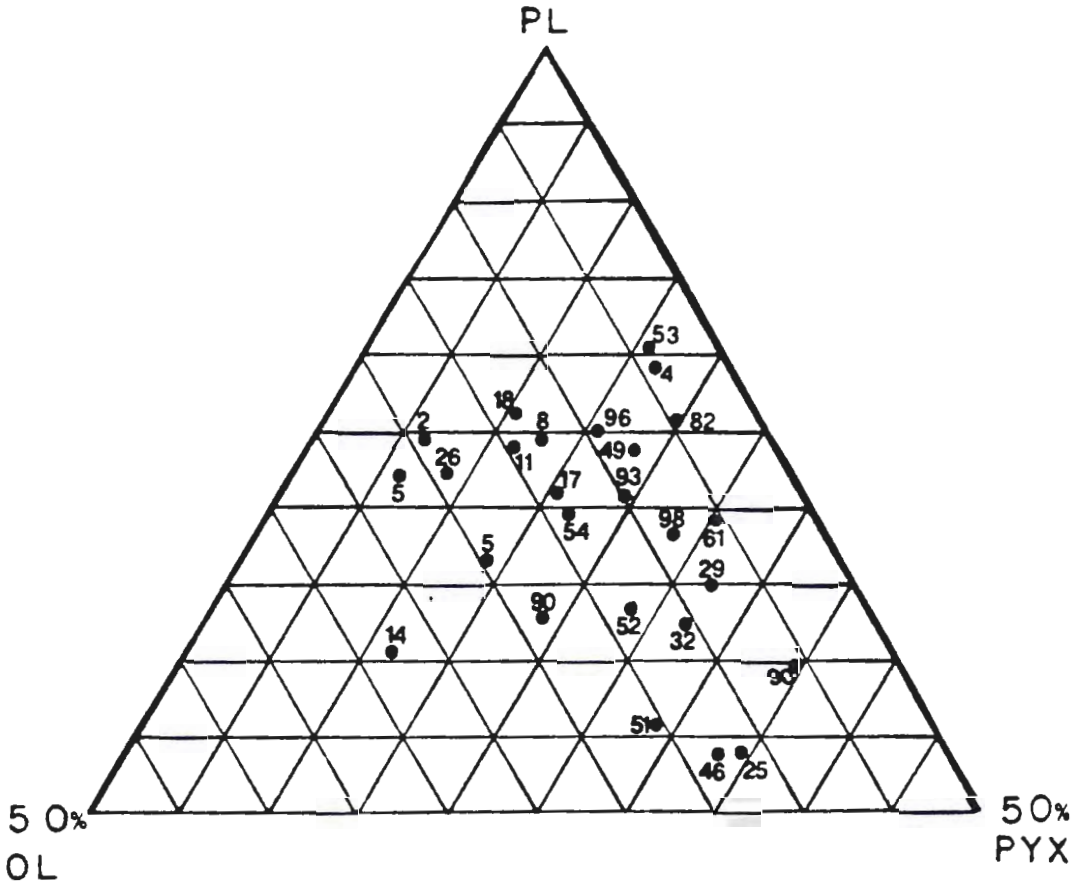


FIGURE 10

Modal (volume percent) mineral abundances of olivine, pyroxene and plagioclase in the troctolitic series rocks of the study area. Small numbers next to each measurement represent percent height in stratigraphic column, i.e., a value of 0 = base of column and 100 = top of column. Height in column obtained using formula $H = \frac{d_1}{d_1 + d_2}$ where:

H = Height in column
d_1 = Samples distance from the series' NW contact (base)
d_2 = Samples distance from the series' SE contact (top)

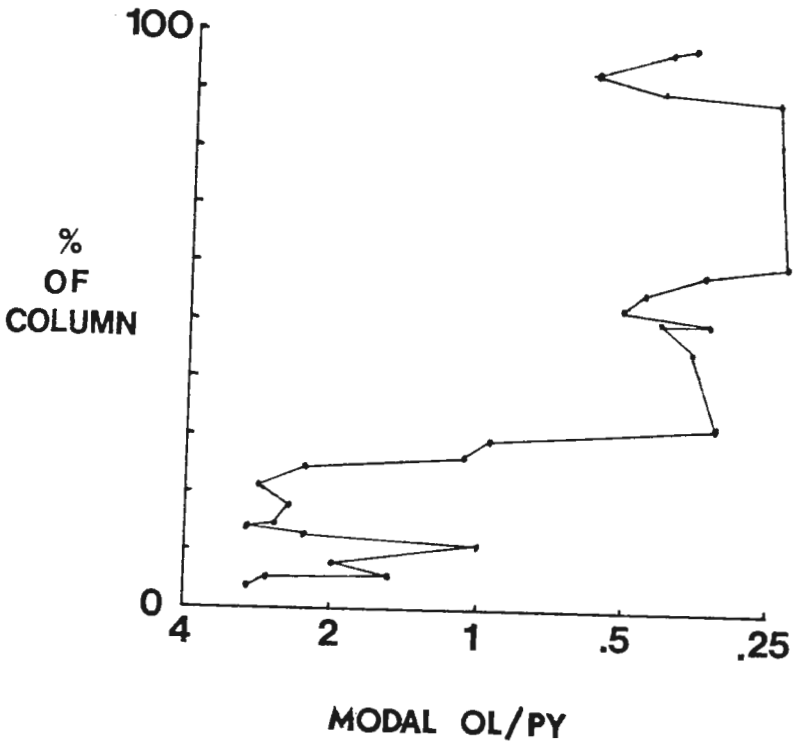


FIGURE 11

Moving average of modal (volume percent) olivine/pyroxene in the troctolitic series. Height in column calculated in the same manner as for Figure 10.

pocket). Figure 11 clearly shows a modal variation with height, with a break between olivine dominant rocks and pyroxene dominant rocks at about 30 percent of height in the column. It should be recognized that the method of averaging modal mineral values used to construct Figure 11 tends to smooth out the overall trend from olivine-rich to pyroxene-rich rocks.

On the basis of this modal mineral distribution the troctolitic series of the thesis area is here divided into a lower troctolitic zone and an upper gabbroic zone. However, it should be recognized that troctolitic rocks do occur in the gabbroic zone and vice versa.

Data for average modal mineral values in the troctolitic and gabbroic zones of the troctolitic series are presented in Table 2. Individual model analyses have been weighted by the amount of the rock column they represent to arrive at the average figures presented in Table 2.

Plagioclase is lath-like and euhedral to subhedral when it occurs as a cummulate phase. The cummulate laths vary from .2mm to 10mm in length and average about 3mm long. Post-cummulate plagioclase occurs interstitially and as adcummulate rims on cummulate grains of plagioclase.

TABLE 2

MODAL ANALYSES (VOLUME PERCENT) OF TROCTOLITIC SERIES ROCKS FROM THE CRAMER QUADRANGLE LISTED AS AVERAGES OVER PORTIONS OF A CONSTRUCTED COLUMN

	LOWER 40% (7)	MIDDLE 34% (9)	UPPER 26% (7)	TOTAL COLUMN (23)
Plagioclase	71.19	64.35	67.91	68.01
Clinopyroxene	9.35	23.07	22.18	17.35
Orthopyroxene	2.30	0.96	0.58	1.40
Olivine	15.84	9.73	7.93	11.71
Opaques	1.19	1.41	1.40	1.32
Apatite	tr.	0.47	tr.	0.16
Biotite	0.13	tr.	tr.	0.04
Chlorite	tr.	tr.	tr.	tr.
Iddingsite	tr.	tr.	tr.	tr.
Symplectite	tr.	tr.	tr.	tr.
Total	100.0	100.0	100.0	100.0

Individual modal counts used to construct these averages have been weighted to reflect the proportion of column they represent. Numbers in parenthesis indicate total number of modes used to calculate average.

Both the cummulus core and adcummulate rims of grains are normally zoned. Cores vary in anorthite content between An_{58} and An_{75}. Zoning is particularly well developed in the rims which are six to eight percent more sodic (An_{52} to An_{63}) than the cores.

The plagioclase laths sandwich equant anhedral to subhedral and rarely euhedral, cummulate olivine grains which range from 0.5 to 9mm across and average about 3mm across (Plates 8 and 9). Post-cummulate olivine growths occur interstitially in optical continuity with the cummulate grinsa. Olivine ranges in composition from Fo_{70} to Fo_{50}; the post cummulate interstitial olivine grains are more fayalitic than the cummulate grains.

Interstitial to poikilitic augite typically occupies wedge-shaped intercummulate areas (Plates 8 and 9). The poikilitic augite forms oikocrysts up to 3cm across which enclose the cummulate phases. Some sections show calcium-poor pyroxene partially exsolved along cleavages in an augite host (Plate 9). Rarely augite is present as euhedral, cummulate crystals with post-cummulate interstitial overgrowths.

Orthopyroxene occurs as interstitial, occasionally poikilitic grains up to 1cm across. The orthopyroxene exsolves calcium-rich pyroxene as irregular blebs along cleavage planes. The blebs are often in optical continuity with adjacent augite grains.

PLATE 8

Photomicrograph of a olivine gabbro from the troctolitic series. Cummulate olivine, blue and mottled blue and purple; poikilitic augite, reddish brown; and lathy plagioclase, grey and black. Sample 8-31-5. 1 inch = 1mm. Polarized light.

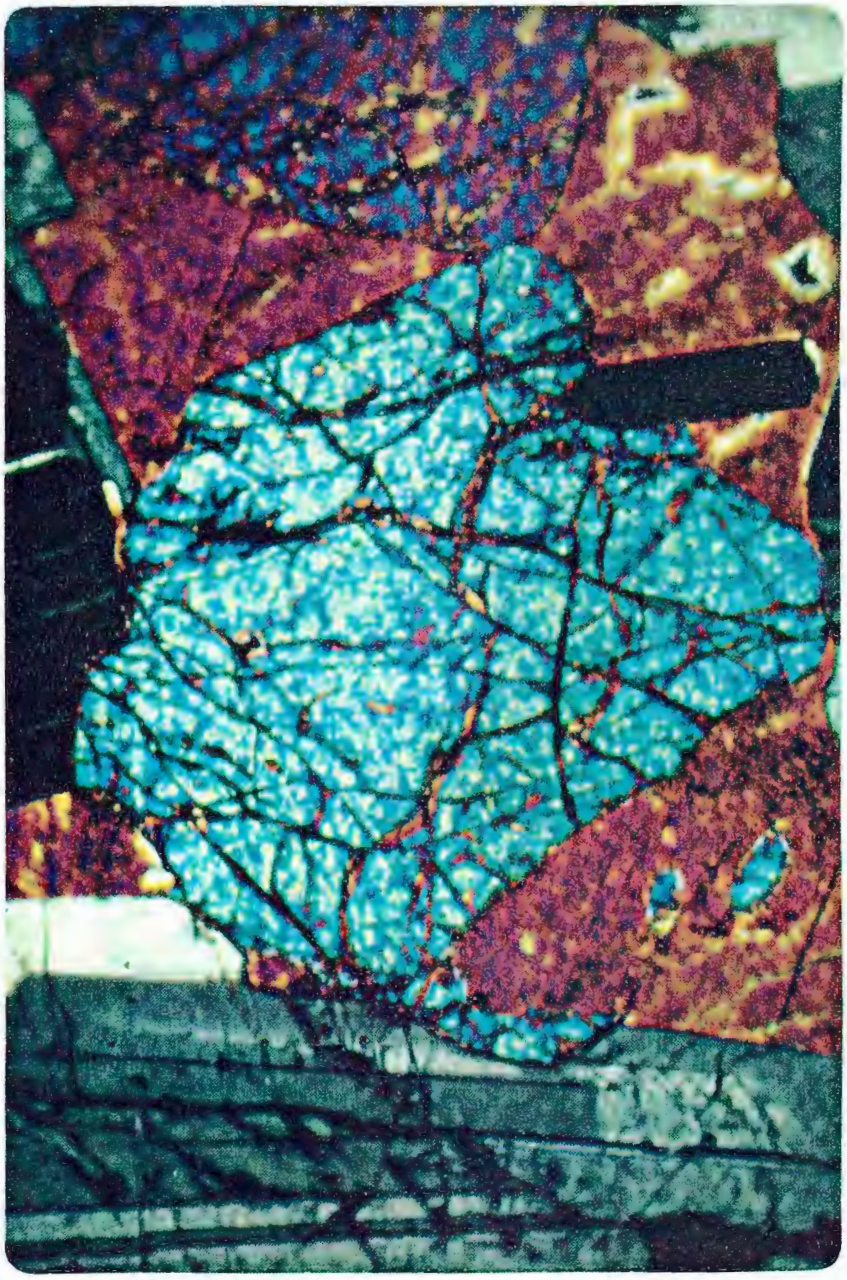
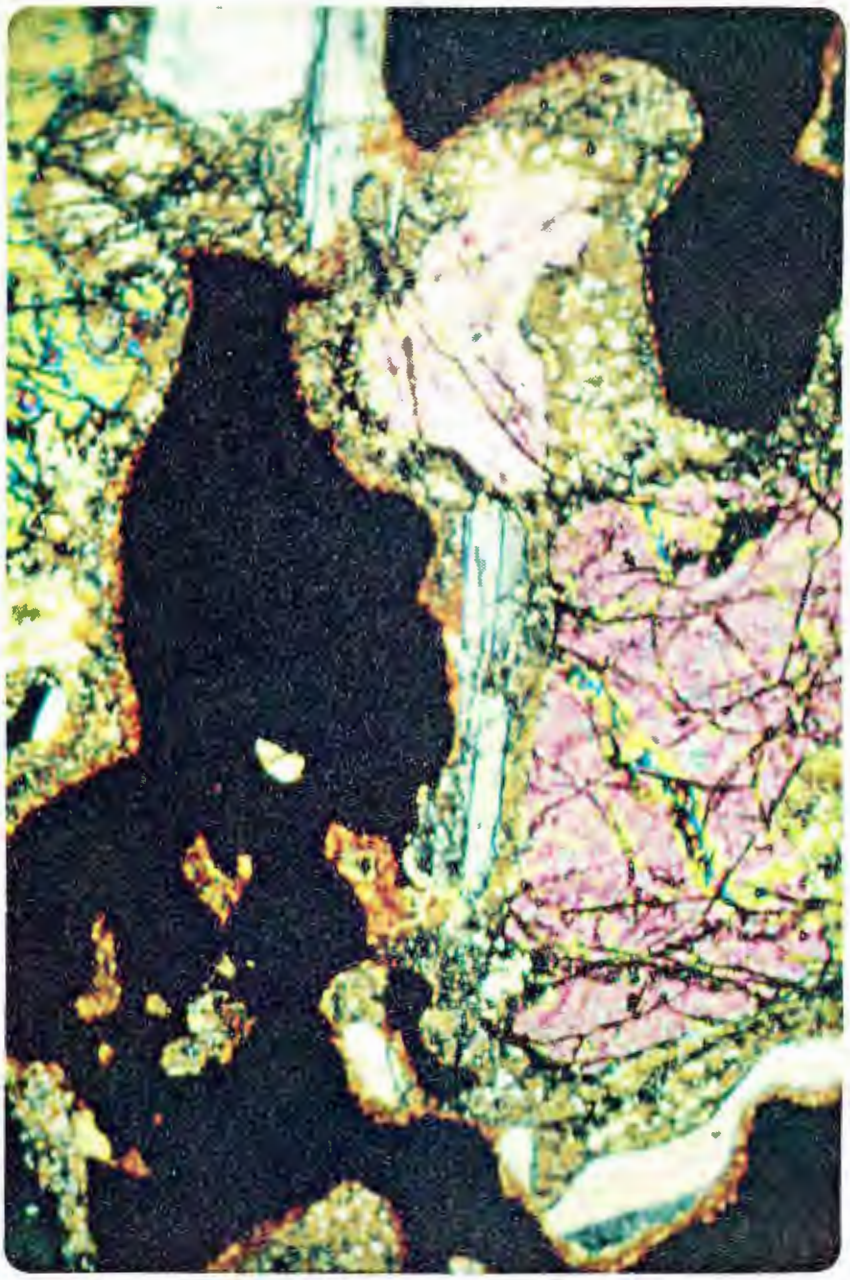


PLATE 9

Photomicrograph of an olivine gabbro of the troctolitic series. Cummulate olivine, pink; interstitial clinopyroxene, pea green, with exsolution blebs of orthopyroxene, white; opaque oxide, black; and plagioclase, gray and white. Sample 5-15-3. 1 inch = 2mm. Polarized light.



Ilmenite is interstitial, euhedral and may occur as poikilitic grains which enclose cummulate minerals (Plate 8). The irregular-shaped areas of ilmenite average 0.8mm across, but may exceed 6mm across.

Accessory minerals include magnetite, apatite, muscovite and biotite. Magnetite occurs as very fine, subhedral to euhedral grains generally enclosed within the rims of cummulate minerals. Very fine euhedral apatite is enclosed by olivine, pyroxene and plagioclase while muscovite and biotite occur interstitially as anhedral grains which are often related to ilmenite. Biotite (?) also is seen rimming interstitial oxides.

Minor alterations noted include plagioclase going to sericite, olivine going to iddingsite and pyroxene being replaced by fine micaceous and chloritic minerals.

The order of crystallization of major minerals can be inferred from textural relations to be: plagioclase and olivine, and then augite and calcium-poor pyroxene followed by ilmenite.

Textural variation is related to spacial distribution (height in column) within the troctolitic series. When olivine is more abundant than pyroxene (near the base) then adcummulate olivine is abundant. Near the top of the column where pyroxene predominates

pyroxene oikocrysts become smaller and some pyroxene grains become subhedral and possibly cummulate in nature.

Felsic Series

The felsic series is made up of granitic rocks which are fairly uniform in composition. Major minerals include orthoclase, albite, perthite, antiperthite and quartz while biotite, hematite, apatite, magnetite, hornblende, augite, olivine, epidote and chlorite are all accessory.

A modal analysis of sample CQ-20 appears in Table 3. While the mode presented is representative with respect to major mineralogy of the unit, it is not representative of minor mineralogy. In fact, the abundances of accessory minerals varies greatly. Potassic feldspar and plagioclase feldspar types were not identified separately during the analyses because of their fine, perthitic nature and their characteristic dusty hematitic and kaolinitic alteration. A rough estimate of the ratio of orthoclase and perthite to albite in the rock was obtained through use of staining techniques; the ratio of potassic feldspar to plagioclase is on the order of 5:1 to 10:1.

TABLE 3
MODAL ANALYSIS OF SAMPLE CQ-20
(Volume Percent)
NW1/4 Sec. 24 T60N, R6W

	Feld.	Qtz.	Chl.	Hem.	Apat.	Biot.	Total
%	69.90	25.79	2.16	1.17	0.54	0.45	100.01

Under the microscope, reddish dusty anhedral feldspar appears intergrown with anhedral quartz. Such intergrowths are characteristic of the unit and several types can be recognized (Plates 10, 11, 12 and 13): (1) cunieform wedge-like quartz intergrowths; (2) granophyric worm-like quartz intergrowths; (3) radial fringe growths in which quartz-feldspar intergrowths radiate outward from the fringe of a subhedral to euhedral feldspar core with which they are in optical continuity; (4) spherulitic growths in which both quartz and feldspar exhibit broad sweeping extinction; and (5) irregular intergrowths which have an allotriomorphic-granular texture. These textures may occur together in a single thin section, with the transition from one to another somewhat gradational.

The same types of intergrowths have been recognized in the felsic series previously by Taylor (1964, p.36) and in similar rocks near Mellon, Wisconsin, by Leighton (1954, p.418). Leighton partially ascribed these textural variations to variations in the albite content of the plagioclase, while Barker (1970, p.339)

PLATE 10

Photomicrograph of a cuneiform intergrowth texture, felsic series. Feldspars, extinct; quartz, white. Sample 5-7-1a. 1 inch = 1mm. Polarized light.

PLATE 11

Photomicrograph of granophyric, texture, felsic series. Quartz, light grey and clear; feldspar, darker grey and slightly cloudy. Sample 9-2-2. 1 inch = 1mm. Polarized light.

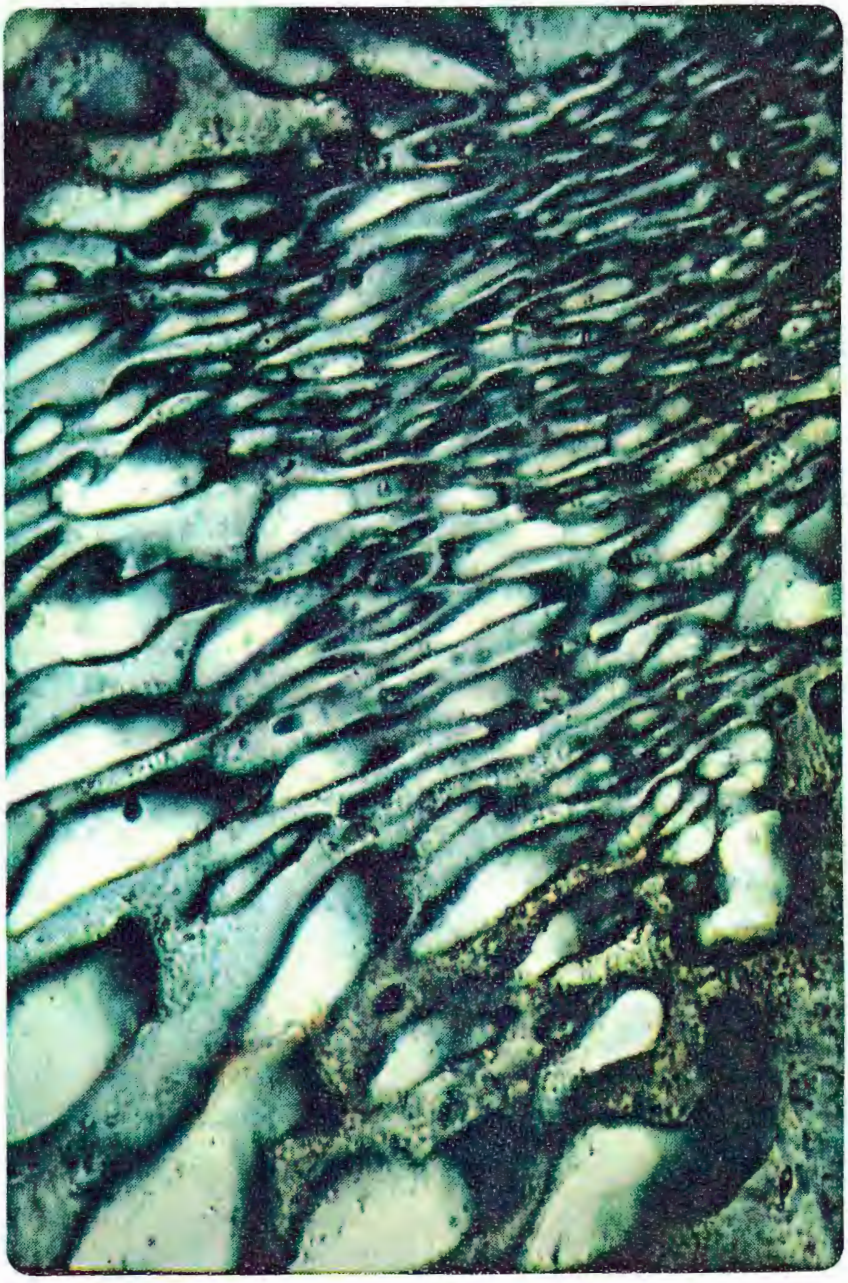


PLATE 12

Photomicrograph of radial fringe growth texture, felsic series. Plagioclase, grey; quartz, white. Sample 9-2-2. 1 inch = 1mm. Polarized light.

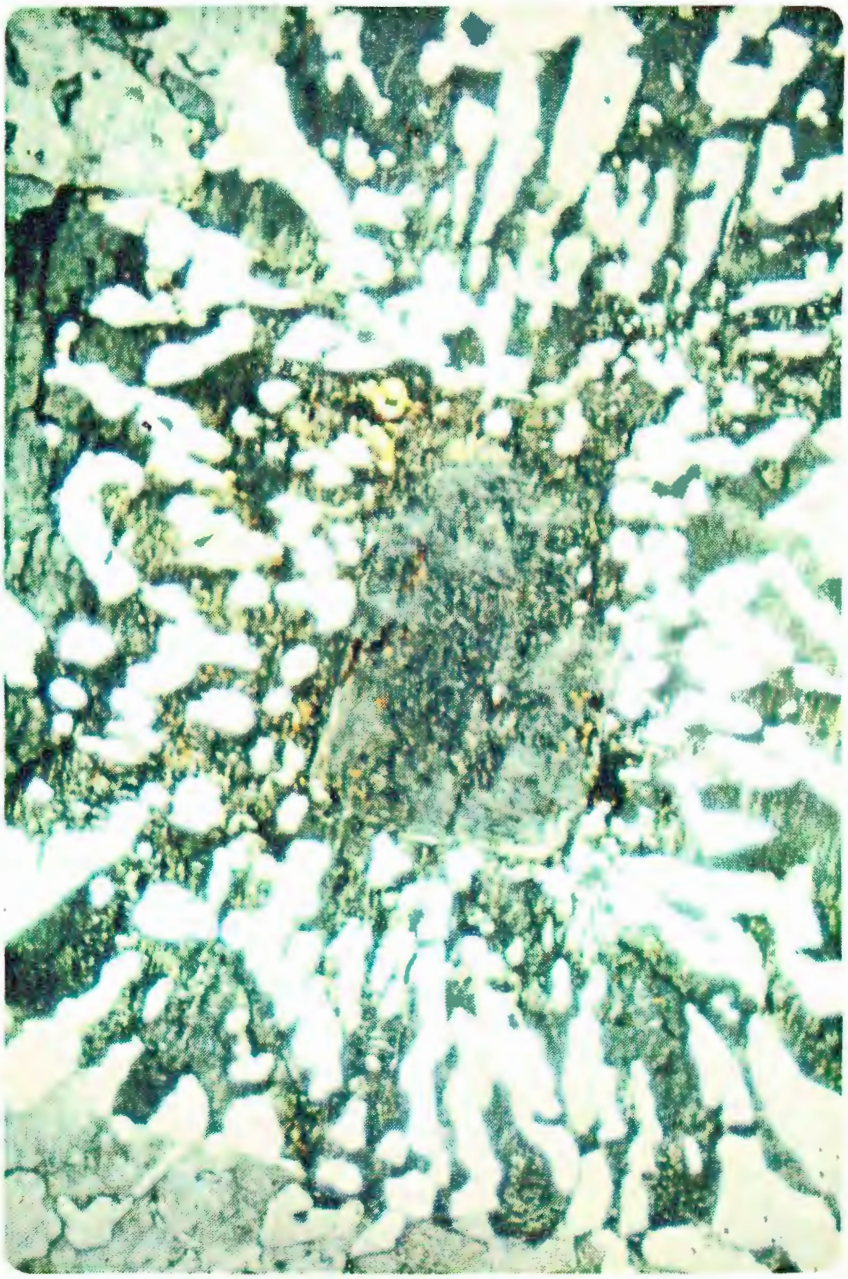


PLATE 13

Photomicrograph of allotriomorphic-granular texture, felsic series. Feldspars, dark; quartz, white. Sample 5-7-1a. 1 inch = 1mm. Polarized light.

felt that textures such as these may be polygenetic and that the origin of such features was not well understood.

Feldspars occur as orthoclase, albite and as perthitic intergrowths with perthite being the most common type. Euhedral to subhedral albite or antiperthite often serve as the cores around which the radiating fringe type of intergrowth occurs. These cores average about 1mm across while the related optically continuous intergrowths are commonly between 2mm and 1cm across.

Euhedral to subhedral accessory minerals are generally fine-grained and include olivine, augite, hornblende, epidote, magnetite and apatite. Anhedral accessories include biotite, chlorite and hornblende. The occurrences of olivine, augite, hornblende and epidote are irregularly distributed and these minerals are usually noted in trace amounts. Biotite, chlorite, magnetite and apatite are ubiquitous and in places make up to four percent of the rock by volume. Areas around magnetite typically are stained red, indicating that oxidation has occurred.

Melagabbro and Gabbro

Intrusions of melagabbro and gabbro up to 2km across were mapped along both the upper and lower contacts of the troctolitic series (Plate 1, pocket). The exact age relationships between

these gabbroic rocks and the major series of the Duluth Gabbro Complex are unknown because the unit contacts are concealed.

Plagioclase, augite, oxides, sympletite and sparse orthopyroxene are the principal modal constituents of these rocks; orthoclase, biotite, apatite, myrmekite and orthopyroxene are generally present in minor quantities.

The values of modal mineral abundances from seven thin sections are presented in Table 4. These abundances are plotted in Figure 9. The most striking aspect of these modes is the high pyroxene content, which ranges between 38.5 and 47.6 volume percent. Plagioclase accounts for 38.5 to 67.2 percent of the rock while opaque oxides make up 0.9 to 21.5 percent and symplectite makes up between 1.0 and 4.3 percent.

The melagabbro-gabbro unit shows well-developed foliation which results from the alignment of plagioclase laths, elongate pyroxenes and in some cases, subhedral elongate oxides (Plate 14). It is not apparent from microscopic analysis whether this preferred orientation is the result of flow or of crystal settling or floating.

Plagioclase occurs as euhedral to subhedral, cummulate laths averaging 4mm and generally less than 6mm in length and as

TABLE 4

MODAL MINERAL ANALYSES (VOLUME PERCENT) OF
MELAGABBROIC AND GABBROIC INTRUSIVE ROCKS,
CRAMER QUADRANGLE, MINNESOTA

SAMPLE	1 8-20-2	2 8-20-5	3 5-6-4	4 5-6-3	5 8-18-4	6 8-20-3	7 8-20-6
Mineral				Percent			
Plagioclase	74.06	67.24	57.65	49.18	47.59	38.50	46.9
Clinopyroxene	4.37	19.98	36.05	42.50	42.44	36.68	35.3
Opaques	0.89	11.95	0.93	1.77	2.95	21.46	15.5
Orthopyroxene	20.18	-	1.02	5.12	1.41	tr.	-
Symplectite	-	-	3.98	1.16	5.29	1.17	1.0
Biotite	-	0.15	0.37	0.27	*	0.18	1.3
Apatite	0.50	0.68	tr.	tr.	0.33	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0	100**

* Included in Symplectite
**Only 300 points counted

(1) anorthositic norite;(2) oxide bearing gabbro;(3) gabbro;(4) orthopyroxene bearing melagabbro; (5,6,7) oxide rich melagabbro. 1,000 points or more counted per thin section unless otherwise noted.

PLATE 14

Photograph of a thin-section of a gabbro of the melagabbroic-gabbroic intrusive of Wilson Lake. Pyroxene, light green and equant with high relief;Plaogioclase, light green and elongate; Fe - Ti oxides, black. Note the igneous lamination and cummulate nature of pyroxene and plagioclase. 1 inch = 6mm. Plain light. Plate 15 is a photomicrograph of this thin-section.

anhedral interstitial grains. Strong normal zonation is common with cores ranging from An_{49} to An_{63} in composition and rims ranging from An_{40} to An_{55} as determined by extinction angle measurements.

Pyroxenes are 0.5 to 4mm across, cummulate, euhedral to anhedral and usually equant to slightly elongate. Anhedral crystals are characteristically elongate along the [100] plane and display feathery-edges and well-developed herringbone structure (Plate 15). The most common pyroxene is augite though, locally, inverted pigeonite is predominant. The latter commonly occurs as herringbone twins which have exsolved calcium-rich pyroxene along cleavage traces.

Opaque oxides occur as skeletal growths of ilmenite, cummulate grains of ilmenite and as interstitial, oxide-cemented crystal aggregates of fine-grained euhedral magnetite. The skeletal growths, cumulate grains and crystal aggregates are between 2mm and 8mm long. Areas of interstitial oxides which are not obvious crystal aggregates of magnetite may be interstitial ilmenite.

Symplectic intergrowths of anhedral quartz, biotite and potassium-bearing feldspar are interstitial in nature. Intergrowths are up to 2mm across with individual constituents being .05mm or less in size.

PLATE 15

Photomicrograph of a gabbro of the melagabbroic-gabbroic intrusive of Wilson Lake. Augite, bright yellow and equant; plagioclase, gray and twinned. Note the commulate nature of the augite and plagioclase. 1 inch = 1mm. Polarized light.

Prismatic apatite up to 0.02mm long and approximately 0.005mm across the prism face is enclosed by plagioclase and pyroxene.

North Shore Volcanic Group

Rocks of the North Shore Volcanic Group which are exposed in the map area range from basaltic to rhyolitic in composition. Outcrops are scattered and, in general, are not correlative as units in terms of either rock type or texture.

Sample 9-1-1 (Plate 16), a porphyritic quartz latite, is typical of intermediate volcanic rocks in the field area. Plagioclase (An_{30}) occurs as subophitic 0.5 - 1mm laths together with interstitial augite and orthopyroxene. Palagonite encloses partially resorbed, medium-grained phenocrysts of quartz. Anhedral orthoclase and perthite up to 0.3mm occur interstitially. Euhedral 0.1mm magnetites and .03mm apatites occur enclosed by palagonite, pyroxene and the feldspars. A modal analysis of sample 9-1-1 appears in Table 5.

Rhyolitic flow rocks were observed as porphyritic units with phenocrysts of orthclase, quartz and plagioclase. Phenocrysts account for about 25 percent of the rock and orthoclase generally

PLATE 16

Photomicrograph of a porphyritic quartz latite of the North Shore Volcanic Group. Note the equant, subhedral partially resorbed quartz phenocryst which is enclosed in palagonite. Sample 9-1-1. 1 inch = 2mm. Polarized light.

accounts for 95 percent and quartz about 5 percent of the phenocrysts. Plagioclase generally occurs in trace amounts, but locally makes up to one-third of the phenocrysts.

Orthoclase phenocrysts are up to 5mm across, euhedral to subhedral and occasionally include euhedral to subhedral quartz crystals. Phencrysts of quartz are generally subhedral and range up to 4mm across. Phenocrysts of plagioclase up to 5mm long show extensive alteration to sericite.

The groundmass of the rhyolitic rocks consists of fine grained anhedral quartz and feldspar, 0.2mm cubic magnetite, 0.01mm euhedral apatite, 0.1mm anhedral hornblende and very fine-grained anhedral hematite.

Features noted in other North Shore Volcanics Group exposures include: porphyritic and glomeroporphyritic orthoclase and albite in a porphyritic rhyolite (sample 8-11-1a; Plate 17); spherulitic otthoclase in a porphyritic quartz latite (sample 8-11-1b); and a bimodal size distribution, approximately 0.6mm and 3mm size, of normally zoned labradorite in a porphyritic, hornblende-bearing basalt (samples 9-2-10a and b; Plate 18).

Locally, near the contact with the anorthositic series, the volcanics are recrystallized and display a granoblastic texture.

PLATE 17

Photomicrograph of a porphyritic rhyolite of the North Shore Volcanic Group. Note the porphyritic and glomeroporphyritic texture of the orthoclase and albite phenocrysts. Sample 8-11-1a. 1 inch = 5mm. Polarized light.

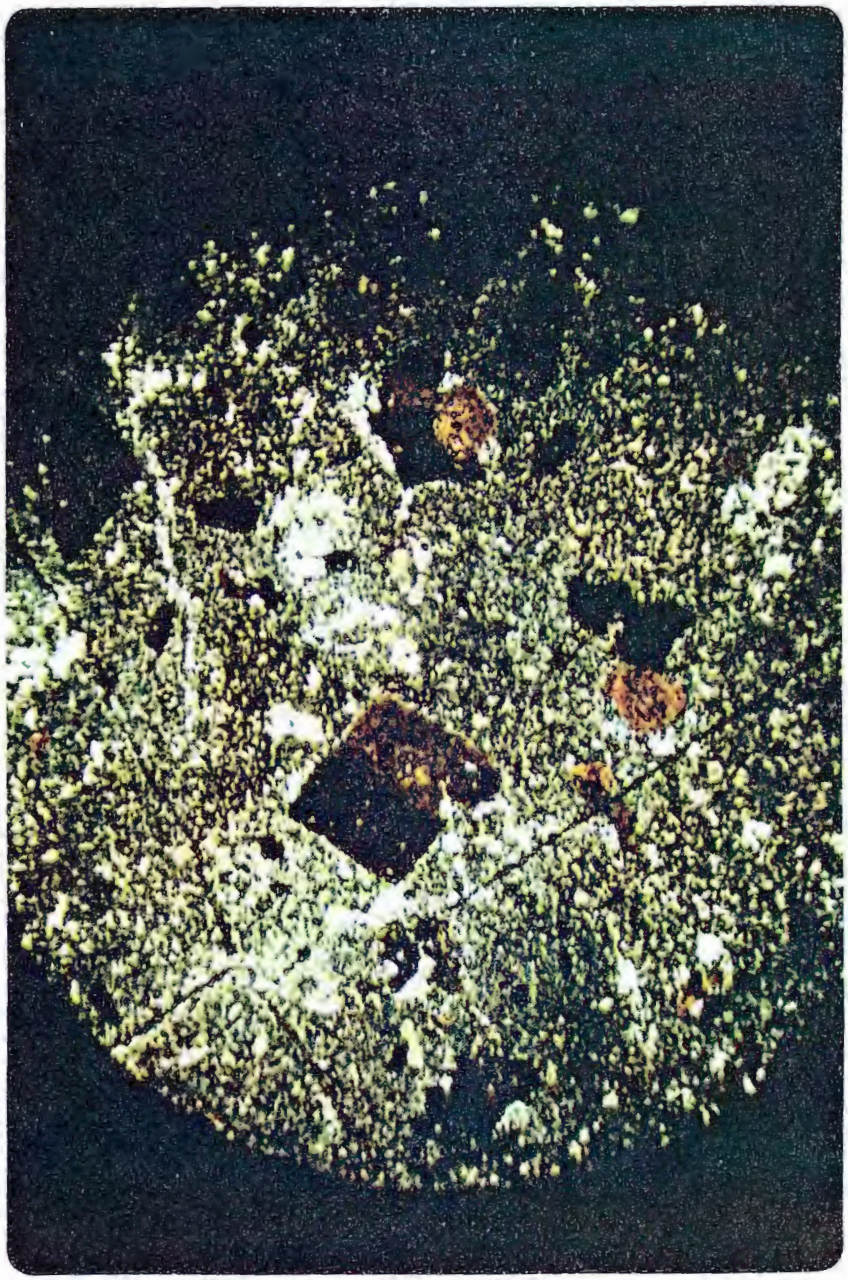


PLATE 18

Photomicrograph of a porphyritic hornblende-bearing basalt of the North Shore Volcanic Group. Note the bimodal size distribution of labradorite (approximately 0.6mm and 3mm in length). Sample 9-2-10a. 1 inch = 2mm. Polarized light.

The resulting granofels displays partially resorbed plagioclase phenocrysts, remnant 2 - 3cm areas of felty groundmass plagioclase and numerous veinlets of quartzo-feldspathic material which locally exhibits a granophyric texture.

Diabasic Rocks

Diabasic rocks which occur in the field area are composed of plagioclase, augite, pigeonite, uralite, quartz, biotite, opaque oxides, symplectite and chlorite. A modal analysis of sample 9-6-7, a diabase from the eastern shore of Sister Lake, appears in Table 5.

Diabases are exposed in two areas (Plate 1, pocket) along the southern shore of Cliff Lake and along the shores of Sister Lake. The diabase of Cliff Lake displays fairly uniform size, 1.5mm plagioclase laths while the Sister Lake diabase's palgioclase laths range in length from 0.2mm to 5mm. The laths are andesine to labradorite in composition and display both normal and occillatory zonation.

Augite, pigeonite and uralite average 0.4 to 0.5mm and are euhedral to anhedral and subophitic. Twinning and alteration to chlorite are common.

TABLE 5

MODAL ANALYSES (VOLUME PERCENT) OF
SAMPLES 9-1-1 and 9-6-7 FROM
THE CRAMER QUADRANGLE, MINNESOTA

	SAMPLE	
	9-1-1*	9-6-7**
MINERAL	PERCENT	
Quartz	4.08	1.34
Palagonite	3.85	-
Plagioclase	38.42	50.25
Orthoclase	17.00	-
Perthite	7.97	-
Clinopyroxene	14.16	29.32
Orthopyroxene	1.41	-
Pigeonite	-	1.01
Biotite	-	0.67
Opaque	7.09	6.20
Symplectite	4.42	10.22
Myrmykite	1.60	1.01
Total	100.0	100.0

* Porphyritic quartz latite of the North Shore Volcanic Group.
**Diabase.

Opaque oxides occur as 1mm or smaller angular interstitial growths. Ilmenite is seen as rod-like growths along cleavages in plagioclase.

Quartz and biotite occur interstitially as symplectic intergrowths and also as .5mm anhedral grains. The ratio of quartz to biotite in symplectite is about 2 to 1.

Sample 9-2-8 (Plate 2, pocket) contains trace amounts of a clear rod-like 1mm by .01mm size mineral which has parallel extinction and is length fast. This mineral may be the magnesium tourmaline, dravite.

PETROLOGY OF THE FELSIC SERIES

Table 6 contains an analysis and CIPW normative mineral composition of sample CQ-20, a granophyric granite of the felsic series (NW1/4, sec. 25; Plate 2, pocket). The sample and analyses were provided by Donald M. Davidson. CQ-20 is a granite in terms of normative quartz, orthoclase and albite, although it is slightly enriched in quartz and orthoclase and slightly depleted in albite relative to the majority of granites in the world, a condition which is typical of granites found in Precambrian Shield areas (Carmichael, Turner and Verhoogen; 1974). A modal mineral analysis of Sample CQ-20 appears in Table 3.

Taylor (1964) recognized four rock types in the felsic series at Duluth. These include ferrogranodiorite, adamellite, syenodiorite and granite. At Duluth these rocks occur as irregular masses within the anorthositic series and along the contact between the anorthositic and troctolitic series. The felsic series rocks display both gradational and sharp contacts (in terms of composition and texture) with rocks of the anorthositic series (Taylor, 1964). Taylor suggested that the felsic series rocks were either a differentiate from the anorthositic series magma or

TABLE 6

WET CHEMICAL ANALYSIS AND
CIPW NORMATIVE MINERAL COMPOSITION OF
SAMPLE CQ-20, A GRANITE OF THE FELSIC SERIES

OXIDE	PERCENT
SiO_2	72.80
Al_2O_3	11.87
Fe_2O	1.80
FeO	1.64
MgO	0.32
CaO	0.87
Na_2O	2.56
K_2O	5.67
H_2O+	0.92
H_2O-	-
CO_2	0.81
TiO_2	0.27
P_2O_5	0.10
MnO	0.03
Total	99.66

CIPW NORM	
Apatite	0.24
Magnetite	2.62
Ilmenite	0.52
Orthoclase	33.53
Albite	21.64
Anorthite	3.70
Corundum	0.12
Hypersthene	1.98
Quartz	33.73
$H_2O + CO_2$	1.73
Total	99.75

represented a younger intrusive phase which had reacted with older anorthositic and troctolitic series rocks.

Davidson (1972) suggests that the felsic rocks could be differentiates of either the anorthositic series or troctolitic series or could represent a remobilized felsic rock that predated the Duluth Gabbro Complex.

Davidson (1969), Nathan (1969) and Morey and others (1969) reported the possible introduction of interstitial symplectite and granophyre into the anorthositic series where it occurs adjacent to felsic rocks. Intense hydrothermal alteration is reported to accompany the symplectite and granophyre. Interstitial symplectite and granophyre as well as intense hydrothermal alteration are present in all anorthositic rocks studied from the thesis area.

Grout (1918) and Weiblen and Morey (1975) suggest that latestage liquid immiscibility in the Duluth Gabbro Complex mafic rocks must be considered in interpreting the genesis of the felsic series rocks. The alteration and interstitial felsic material present in the anorthositic rocks of the study area suggest that late stage felsic fluids were present.

Thus, while the origin of the felsic series magma is unknown, the series has been hypothesized to be the result of differentiation of, or immiscibility in, other Duluth Gabbro Complex series, a reaction with a younger granitic intrusive or the remobilization of pre-Keweenawan rocks. Weiblen and Morey (1975) suggest the felsic series was derived from a low-alumina magma which they believe could also be the parent magma of the anorthositic series and Logan Intrusions.

THE PETROLOGIC SIGNIFICANCE OF MINERAL COMPOSITIONS FROM THE ANORTHOSITIC SERIES AND A MELAGABBROIC-GABBROIC INTRUSIVE

Electron microprobe analyses of clinopyroxenes from an anorthositic gabbro (sample 9-2-1b) of the anorthositic series from the thesis area and an anorthositic gabbro (sample 8-20-5) from the large melagabbroic-gabbroic intrusion of the Wilson Lake area are presented in Table 7. The analyses appear on Figure 12, a pyroxene quadrilateral plot. From Figure 12, it is apparent that the anorthositic series sample is enriched in iron and poor in calcium as compared with the melagabbroic-gabbroic intrusive sample.

The plagioclase compositions co-existing with the pyroxenes analyzed from the anorthositic series and melagabbroic-gabbroic intrusive are An_{62} and An_{61}, respectively. The anorthite content of the plagioclase of the anorthositic series rocks in the thesis area was found to vary between An_{69} and An_{56} while the plagioclase of the melagabbroic-gabbroic intrusive of Wilson Lake ranged from An_{63} to An_{49}.

The pyroxene from the anorthositic series displays significant iron enrichment relative to that from the melagabbroic-gabbroic intrusive. If the anorthositic series and the intrusive of Wilson Lake are genetically related as evidenced by a similar

TABLE 7

ELECTRON MICROPROBE ANALYSES OF CLINOPYROXENES OF THE ANORTHOSITIC SERIES AND A MELAGABBROIC-GABBROIC INTRUSIVE
9-2-1b and 8-20-5, respectively

	9-2-1b	8-20-5
SiO_2	50.92	51.40
Al_2O_3	1.29	2.55
TiO_2	1.16	1.21
FeO	16.13	10.91
MgO	12.70	14.33
MnO	0.25	0.16
CaO	17.05	19.63
Total	99.50	100.20

Atomic proportions on the basis of 6 oxygens

SiO_2	1.918	1.949
Al_2O_3	0.112	0.058
TiO_2	0.034	0.330
FeO	0.341	0.516
MgO	0.797	0.725
MnO	0.005	0.008
CaO	0.785	0.699

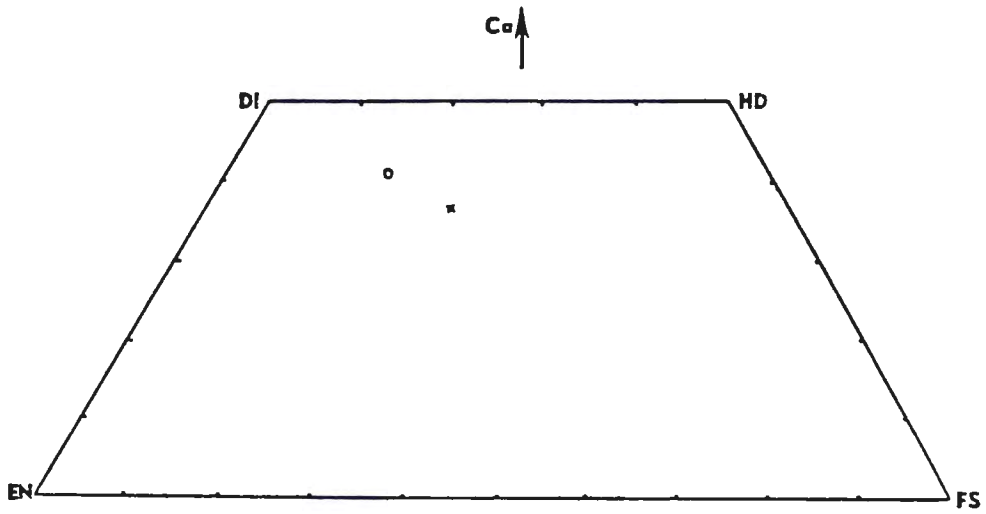


FIGURE 12

Pyroxene quadrilateral plot, anorthositic series and melagabbroic-gabbroic intrusive pyroxenes.

O = melagabbroic-gabbroic intrusive (Sample 8-20-5)
X = anorthositic series (Sample 9-2-1b)

liquid line of descent one would expect similar plagioclase compositions (An content) to co-exist with somewhat similar pyroxene compositions (FeO/FeO + MgO). The compositional data presented here do not support the hypothesis that the melagabbroic-gabbroic intrusive magma was related to the anorthositic series' parent magma.

PETROLOGY OF THE TROCTOLITIC SERIES

Mineral Chemistry of the Troctolitic Series

Scattered outcrops of troctolitic series rocks occur along a southwest-northeast trend across the study area separating the anorthositic and felsic series on the northwest from the North Shore Volcanic Group to the southeast. Melagabbroic intrusives occur along both contacts of the troctolitic series. This section reports results on gross changes noted in mineral chemistry from rocks collected along a traverse perpendicular to the contacts of the troctolitic series.

Plagioclase

The anorthrite (An) content of plagioclase from 13 locations within the troctolitic series was determined by index of refraction (oil immersion) measurements checked by the Michele-Levey and A-normal extinction angle methods. Anorthite values of the samples appear in Table 8 and the samples' locations are plotted on Plate 2 (pocket). As plagioclase in the troctolitic series displays normal zonation, the measurements shown are maximum values obtained from the cores of cummulate crystals. It can be seen in Table 8 that the Anorthite content of plagioclase in the series varies from $An_{77.5}$ to $An_{58.5}$.

TABLE 8

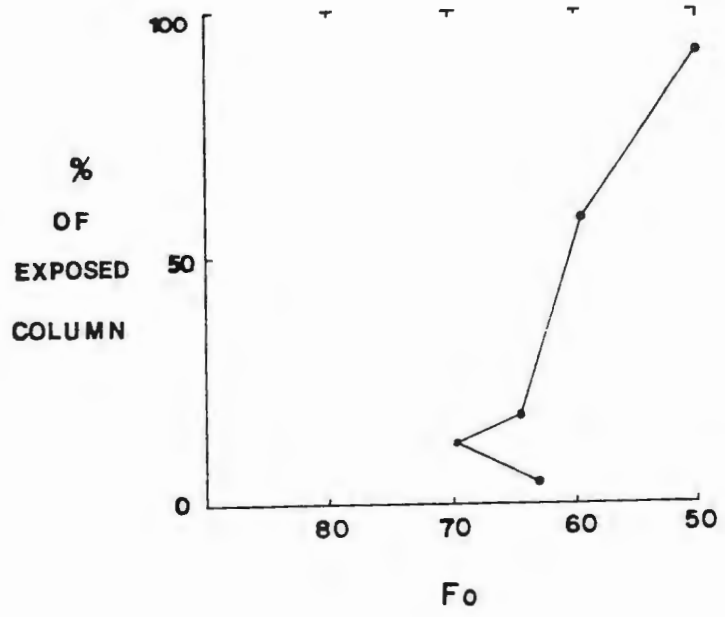
COMPOSITIONAL (An) VALUES OF PLAGIOCLASE FROM TROCTOLITIC SERIES ROCKS OF THE CRAMER QUADRANGLE, MINNESOTA

Sample	Percent Height in Column	PLAGIOCLASE COMPOSITION (An)	
		Derived From Index of Refraction Measurements	Derived From Extinction Angle Measurements
10-22-2	14%	77.5	75.0
8-12-4	4%	70.0	69.5
10-22-7	5%	66.0	-
8-12-3	11%	66.0	67.0
8-18-4	21%	66.0	-
8-21-1	26%	66.0	-
5-6-2	18%	64.5	65.0
4-30-4	45%	64.0	65.0
4-29-4	52%	62.5	64.0
4-29-1	55%	63.0	-
4-29-2	58%	60.5	64.0
5-15-5	90%	58.5	59.5
5-15-1	92%	58.5	59.5

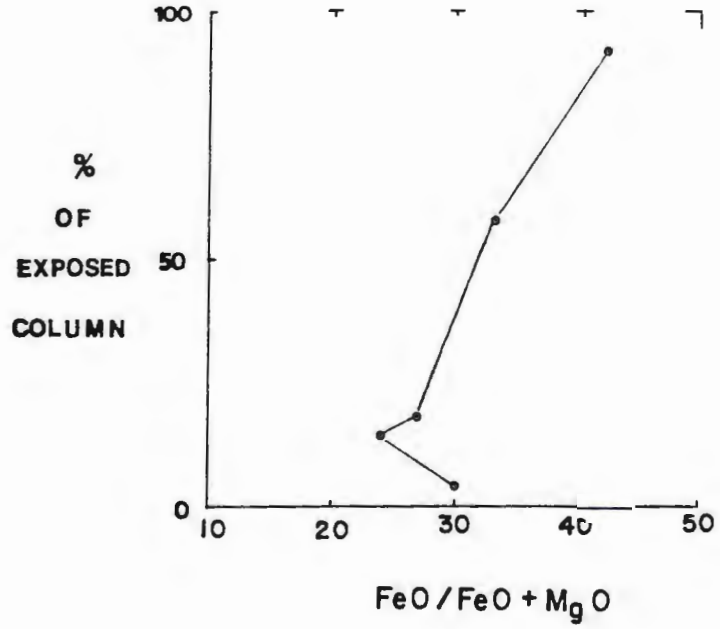
Figure 13 contains a plot of plagioclase content (An) versus "percent height in geologic column" within the troctolitic series. Each sample's height within an artifically constructed column is obtained by measuring the sample location's distance from the series' northwestern and southeastern contacts and dividing the distance to the northwestern contact by the sum of the distances to both contacts. Thus the northwestern contact is here considered to be the base of the column and the southeastern contact is considered the top of the column.

From Figure 13, it is evident that the plagioclase in the troctolitic series displays a fairly regular cryptic variation in composition with high An values occurring near the northwestern contact and lower An values occurring near the southeastern contact.

A reversal in trend occurs at approximately 15 percent height in column. This reversal is associated with a distinctive lineament (L2 in Figure 8) which parallels the northwestern contact. The possible significance of this reversal is discussed in the section on structural geology.


100
%
OF
EXPOSED
COLUMN
50
0
80
70
60
50
Fo

13b


100
%
OF
EXPOSED
COLUMN
50
0
10
20
30
40
50
FeO / FeO + Mg O

13c

Olivine, Pyroxene and Oxides

Electron microprobe analyses were performed on olivines, pyroxenes and opaque oxides from five locations within the troctolitic series. The analysis results are presented in Tables 9, 10 and 11, while the sample locations appear on Plate 2 (pocket).

The olivines analyzed varied in Fo content from $Fo_{69.8}$ to $Fo_{49.8}$. Figure 13 contains a plot of Fo content versus "percent height in geologic column" which shows that the Fo content of olivine also displays a cryptic variation within the troctolitic series with high Fo values occurring near the northwestern boundary of the unit and lower Fo values occurring near the southeastern boundary.

Figure 14 is a plot of anorthite content in plagioclase versus the forsterite content in olivine for the troctolitic series, the Skaergaard Intrusion and the Sonju Lake Intrusion. The Sonju Lake Intrusion, a layered, differentiated intrusive, is exposed approximately 10km southwest of the study area. As expected, for all three plots the slope is positive. The trend of the troctolitic series on this diagram is characteristic of other Keweenawan intrusive rocks of northeastern Minnesota in that in general, for a given anorthite content the corresponding olivine

TABLE 9

ELECTRON MICROPROBE ANALYSES OF OLIVINES, FROM THE TROCTOLITIC SERIES, CRAMER QUADRANGLE, MINNESOTA

	1 10-22-2	2 8-12-4	3 5-6-2	4 4-29-2	5 5-15-1
SiO_2	38.52	37.65	37.70	36.76	35.79
Al_2O_3	0.14	0.17	0.14	0.07	0.08
TiO_2	-	-	-	-	-
FeO	27.25	32.15	31.37	35.29	42.17
MgO	35.24	29.93	32.03	28.90	23.49
MnO	0.26	0.04	0.34	0.39	0.38
CaO	-	-	-	-	-
Total	101.41	99.95	101.59	101.41	101.92
	Atomic proportions based on 4 oxygens				
Si	1.008	1.024	1.006	1.003	1.006
Al	0.004	0.005	0.004	0.002	0.003
Fe	0.596	0.731	0.700	0.805	0.991
Mg	1.375	1.213	1.274	1.176	0.984
Mn	0.006	0.001	0.008	0.009	0.009
Fo content	69.8	62.4	64.5	59.4	49.8

TABLE 10

ELECTRON MICROPROBE ANALYSES OF
PYROXENES FROM THE TROCTOLITIC SERIES,
CRAMER QUADRANGLE, MINNESOTA

	1 10-22-2	2 8-12-4	3 8-12-4	4 5-6-2	5 4-29-2	6 5-15-1
SiO_2	52.44	52.15	52.39	52.56	51.37	52.35
Al_2O_3	2.53	2.08	0.95	2.43	1.78	1.24
TiO_2	1.14	1.18	0.54	0.88	3.53	0.44
FeO	8.50	10.71	18.87	9.53	12.54	15.81
MgO	15.56	14.77	22.25	15.03	13.62	12.52
MnO	0.14	0.18	0.31	0.13	0.28	0.38
CaO	19.81	19.32	1.54	18.96	19.12	18.32
Total	100.12	100.39	95.86*	99.52	102.23	101.05
Atomic proportions based on 6 oxygens						
Si	1.934	1.937	1.975	1.952	1.895	1.971
Al	0.110	0.091	0.043	0.106	0.077	0.055
Ti	0.032	0.033	0.016	0.025	0.098	0.013
Fe	0.262	0.333	0.606	0.296	0.387	0.498
Mg	0.855	0.818	1.274	0.832	0.749	0.702
Mn	0.004	0.006	0.010	0.004	0.009	0.012
Ca	0.782	0.769	0.063	0.734	0.755	0.739
Wo	41	39	3	40	40	38
En	45	43	66	44	40	36
Fs	14	18	31	16	20	26
FeO/ FeO + MgO	24	30	32	27	33	42

* Error principally due to the use of Wollastonite as a CaO standard. Wollastonite is markedly different from orthopyroxene in composition and structure.

TABLE 11

ELECTRON MICROPROBE ANALYSES OF OPAQUE OXIDES FROM THE TROCTOLITIC SERIES, CRAMER QUADRANGLE, MINNESOTA

	1 8-12-4	2 5-6-2	3 4-29-2	4 5-15-1
SiO_2	2.41	0.07	0.04	0.06
Al_2O_3	-	-	-	-
TiO_2	51.85	48.49	50.54	51.28
FeO	43.36	48.54	47.70	46.86
MgO	1.23	1.42	0.11	1.85
MnO	-	-	-	-
CaO	0.07	0.09	0.04	0.05
Total	98.93	98.61	98.46	100.10
	Atomic proportions based on 6 oxygens			
Si	0.120	0.004	0.002	0.003
Ti	1.934	1.888	1.962	1.940
Fe	1.798	2.102	2.060	1.972
Mg	0.091	0.110	0.009	0.139
Ca	0.004	0.005	0.002	0.003

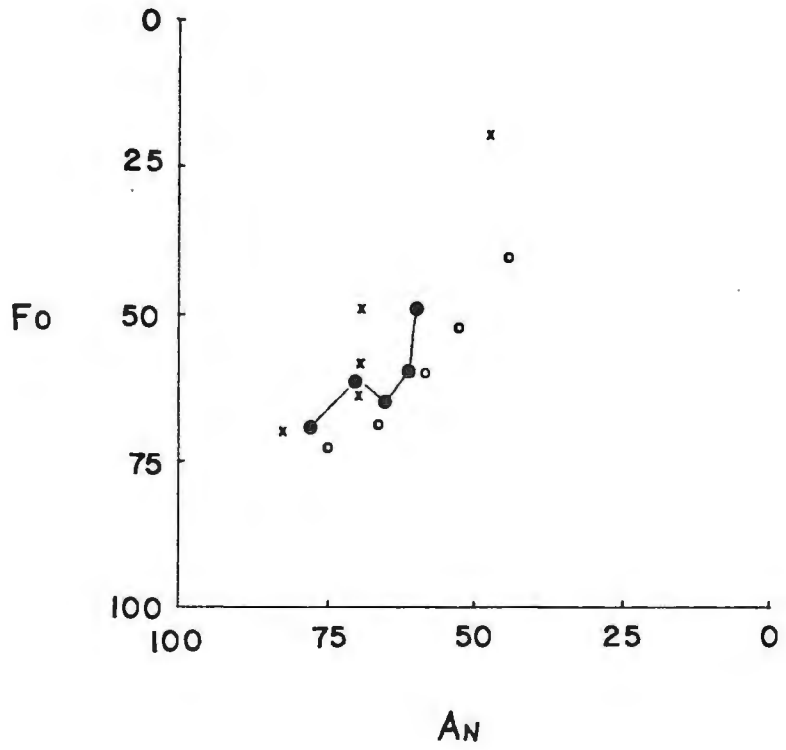


FIGURE 14

Forsterite-anorthite plot of co-existing olivine-plagioclase pairs in the troctolitic series (●) the Sonju Lake Intrusive (X) and the Skaergaard Intrusive (O).

of the troctolitic series is more iron-rich than for the Skaergaard (Bonnichsen, 1972, fig. V-53). Mudrey (1973) suggests that this difference may be related to a lower silica activity in the Keweenawan intrusions compared to the Skaergaard.

Pyroxenes analyzed also show an iron enrichment trend with magnesium enriched augites occurring near the northwestern contact and iron enriched augites occurring near the southeastern contact. Figure 13 displays a plot of FeO/FeO + MgO in pyroxenes versus "inferred height in geologic column". Figure 13 clearly shows the iron enrichment trend mentioned above.

Figure 15 is a pyroxene quadrilateral (enstatite-diopside-hedenburgite-ferrosilite) plot displaying the augite and ortho-pyroxene analyses from the troctolitic series of the thesis area compared to the general trend of the pyroxene from the Skaergaard Intrusive. It is apparent from Figure 15 that the trend indicated for the troctolitic series is similar to that of a portion of the Skaergaard trend and that the tie line between an OPX and CPX pair for the troctolitic series parallels corresponding tie lines for the Skaergard. The OPX analysis in Table 10 (#3) totals less than 100 percent owing to the use of Wollastonite as a CaO standard which resulted in a low CaO value.

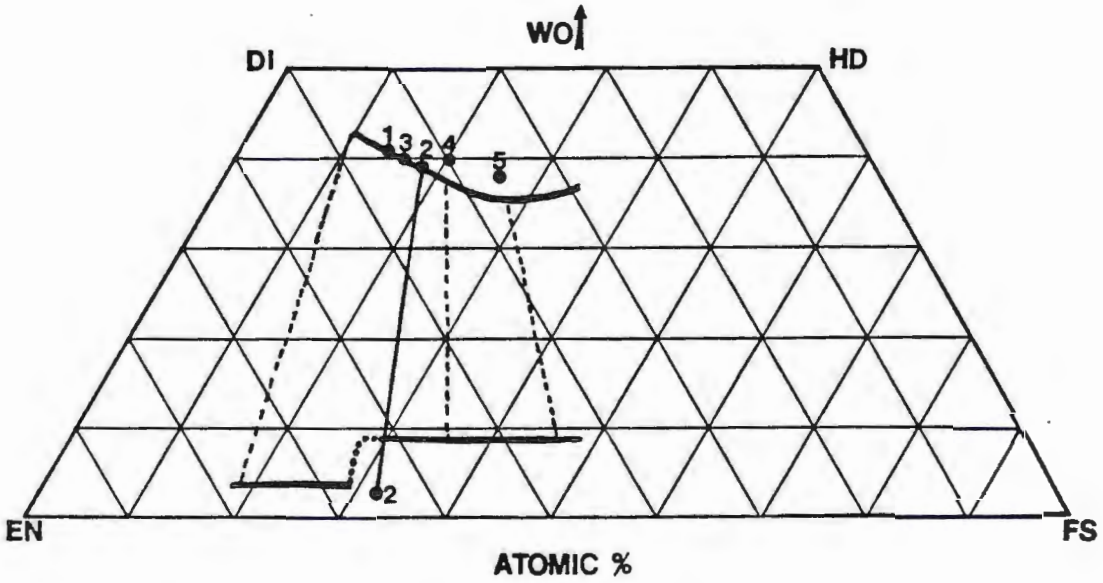


FIGURE 15

Plot of pyroxene compositions on a pyroxene quadrilateral for the troctolitic series. Heavy lines represent the trend of the Skaergaard Intrusions' pyroxene (Wager and Brown, 1967). Dotted lines represent tie lines between co-existing CPX-OPX pairs of the Skaergaard Intrusion. Light lines represent a tie line between a co-existing OPX-CPX pair in the trocolitic series. Mineral compositions in mole percent.

NUMBER	SAMPLE # ON TABLE
1	10-22-2
2	8-12-4
3	5-6-2
4	4-29-2
5	5-15-1

Four analyses of iron-titanium oxides from the troctolitic series appear in Table 11. These oxides are ilmenites which do not show a well-defined cryptic variation as do the other phases analyzed. The ratio of FeO/TiO_2 is approximately 1 in all of the Fe-Ti oxides analyzed.

Crystallization Sequence

The crystallization sequence of the troctolitic series (olivine-plagioclase-pyroxene-ilmenite) as determined from textural evidence is supported by the compositional data presented above and by the stratigraphic relationships which are implied by the areal distribution of mineral compositions. This crystallization sequence is identical to that found in the Bald Eagle intrusion and troctolitic series rocks along the northern portion of the Duluth Gabbro Complex by Weiblen (1972) and similar to that found in the Sonju Lake intrusion by Stevenson (1974) (spinel-olivine-plagioclase-augite-pigeonite-ilmenite-magnetite-apatite). The above crystallization sequences list only cummulate phases, except that forwarded in this study in which the pyroxene of the troctolitic series is intercummulate to subcummulate and the ilmenite is intercummulate.

Bulk Composition

A possible composition of the original liquid of the troctolitic series appears in Table 12 together with a calculated mineral composition (CIPW norm). It is assumed that the bulk composition of the troctolitic series intrusion (as exposed) approximates the composition of the original magma which generated it. This composition is calculated from the chemical analysis of individual minerals presented above and the average mineral abundances presented in Table 2. The calculation assumes that the minerals analyzed were representative of the units in which they were found and that a sufficient number of modal analyses were made to accurately determine the mineral abundances within the unit. For ease of discussion and calculation the troctolitic series has been divided into three portions: the troctolitic zone, the lower gabbroic zone and the upper gabbroic zone. The troctolitic zone and gabbroic zone are defined on the basis of average modal (volume percent) mineral abundances in the chapter on petrography.

The following formula was used in carrying out the calculation of the weight percent of each oxide comprising the original liquid:

TABLE 12

CALCULATED BULK CHEMISTRY
(IN WEIGHT PERCENT) OF THE
TROCTOLITIC SERIES AND ITS
CIPW NORMATIVE MINERAL COMPOSITION

	Lower 40% of Column	Middle 34% of Column	Upper 26% of Column	Calculated Bulk Composition of Series	CIPW Norm	
SiO_2	48.5	49.1	48.8	48.8	il	1.7
Al_2O_3	19.6	18.2	19.1	19.0	or	1.2
FeO	9.8	9.4	9.6	9.6	ab	19.4
MgO	8.7	7.5	5.9	7.6	an	40.9
CaO	10.5	12.2	12.2	11.5	di	13.4
Na_2O	2.2	2.3	2.6	2.3	hy	9.1
K_2O	0.1	0.2	0.2	0.2	ol	14.3
TiO_2	0.9	0.9	1.1	0.9		
			TOTALS	99.9		100.0

$Z_1 + Z_2 + Z_3$ = Weight percent of a particular oxide in the original liquid where,

$(x_1)\ (y_1) = z_1$

x_1 = weight percent of a particular oxide, MgO for instance, in rock unit 1.

y_1 = proportion by weight of the percent of column represented by rock unit 1.

z_1 = amount of a particular oxide in the original liquid attributed to unit 1.

The volume percent (an average value from modal counts) of each mineral in each unit was recalculated to weight percent by weighting each mineral modal abundance (volume percent) by its specific gravity. Each mineral within a petrologic unit was broken down into individual oxide constituents which were then summed to give total oxide weight percents for each rock unit (for example x_1 above).

The specific gravity of each rock unit was calculated by weighing the specific gravity of each mineral by its modal mineral abundance (volume percent). The specific gravity of each rock unit was then used to weight the percent of the rock column represented by that unit to arrive at the percent of the troctolitic series, by weight, that each rock unit represents (for example y_1 above).

Only partial analyses were available for plagioclase; therefore, analyses of troctolitic plagioclase from the series carried

out by Beitsch (Weiblen and Morey, 1975) were used to construct complete plagioclase analyses to represent the total composition of plagioclase. Because neither the top nor the bottom of the series was accurately defined in the field, there may be portions of the series which are not included in the calculated possible original liquid composition presented in Table 12. Thus, the initial composition presented is considered to be a best estimate at this time.

Figure 16 is an AFM plot (weight percent alkali, iron and magnesium oxides) of the calculated compositions of rocks of the troctolitic series along with the trends of the Skaergaard (Wager & Brown, 1967) and Sonju Lake (Stevenson, 1974) Instrusions. It is apparent from Figure 16 that the troctolitic series rocks exhibit a trend which is similar to the early portions of those of the Skaergaard and Sonju Lake Intrusives. This similarily implies that the mechanisms of differentiation of the three intrusive bodies were similar. Whether the troctolitic series continued to differentiate and what direction additional differentiation would have taken are moot points at this time.

Petrologic Significance of the Troctolitic Series Bulk Composition

White (1966) suggested that two periods of tectonism prevailed in the western Lake Superior area. Weiblen and Morey

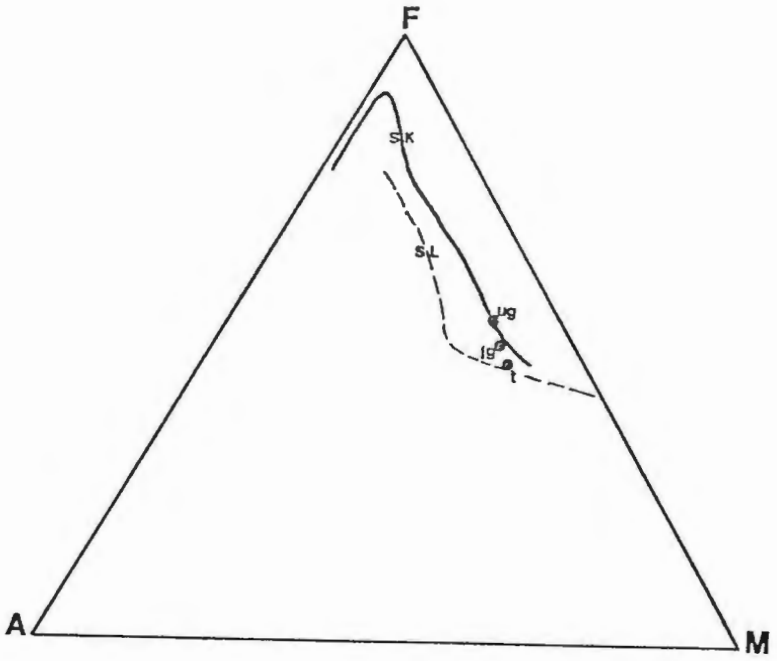


FIGURE 16

Comparison of the Skaergaard and Sonju Lake intrusion rock composition trends with calculated rock compositions for the troctolitic and gabbroic zones of the troctolitic series. Skaergaard rock composition trend is shown as a solid line (Wager and Brown, 1967). Sonju Lake trend is shown as dashed line (Stevenson, 1974). $A = K_2O + Na_2O$; $F = FeO + Fe_2O$; $M = MgO$. Compositions are in weight percent.

gabbroic zone (ug upper 26% of exposed column
(lg middle 34% of exposed column

troctolitic zone (t lower 40% of exposed column

(1972) hypothesized that these periods were related to the intrusion of two distinctive Keweenawan magma types, a low-Al early magma and a high-Al late magma. They also postulated that the low-Al magma and early stage of tectonism were related to anorthositic series rocks, Logan diabases and older magnetically "reversed" North Shore Volcanic Group flows, while the later stage of tectonism and the high-Al magma were related to the troctolitic series units, the Pigeon River intrusions and the younger magnetically "normal" North Shore Volcanic Group flows.

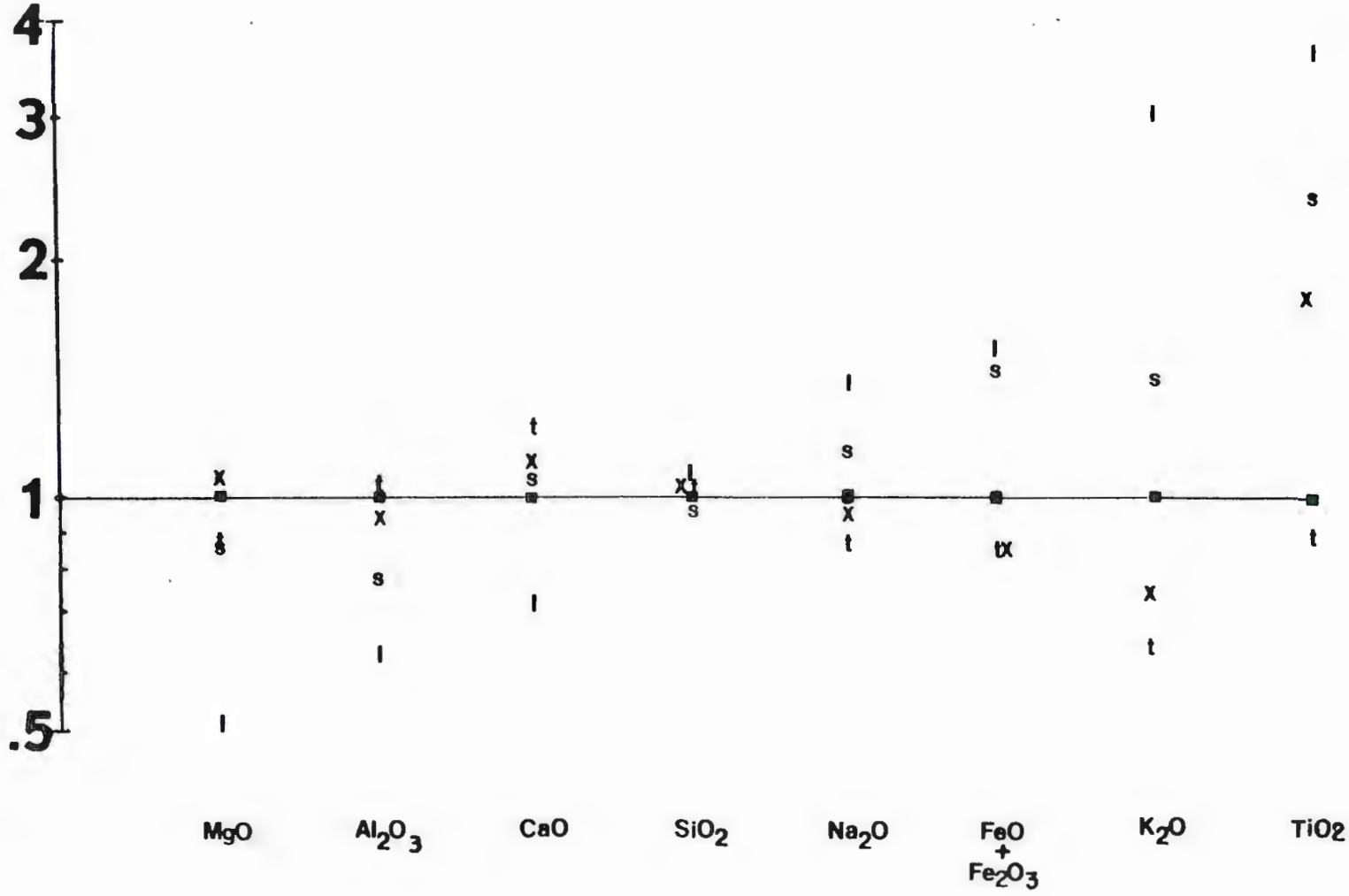
Mudrey (1973) and Stevenson (1974) studied the Pigeon Point Sill and the Sonju Lake Intrusion, respectively. Mudrey published an analysis of a chilled margin of the Pigeon Point Sill which shows the sill to have a high-Al composition similar to that of the Skaergaard Intrusion of Greenland. Stevenson's crystallization sequence for the Sonju Lake Intrusion is similar to the sequence olivine-plagioclase-pyroxene-ilmenite suggested for the troctolitic series in this work. Stevenson calculated a liquid composition compatible with the high-Al magma of the Pigeon Point Sill.

Weiblen and Morey (1975) expanded the work of Weiblen, et al (1972) by showing that the compositions of the Keweenawan rocks which they had attributed to the two magma types outlined above could reasonably be derived from the proposed parent magma

compositions. They also expanded upon the two step tectonic model of White and constructed a series of possible geologic cross-sections across the Duluth Gabbro Complex representing their model for emplacement of the Complex. This model is based upon the rifting-foundered block mechanisms forwarded by Rea (1975).

Figure 17 is a comparison of the proposed Duluth Gabbro Complex parent magma compositions (the Logan and Pigeon Point compositions) with the calculated liquid compositions of the troctolitic series in the thesis area, the Sonju Lake Intrusion and the Skaergaard Intrusion. The compositions are normalized to the proposed high-Al parent magma which has the composition of the chilled margin of the Pigeon Point Sill. The low-Al magma is represented by the composition of the Logan diabase intrusions.

With the exception of K_2O the calculated composition of the troctolitic series is similar to the compositions of the chilled margin of the Pigeon Point Sill and the Skaergaard Intrusion and grossly similar to the composition of the Sonju Lake Intrusion. Figure 17 also points out the marked difference in composition between the troctolitic series and the low-Al Logan Intrusion magma.


4
3
2
1
.5
MgO
Al2O3
CaO
SiO2
Na2O
FeO + Fe2O3
K2O
TiO2

The low K_2O content of the troctolitic series relative to that of the Pigeon Point Sill may be the result of additional fractionation of the series with the corresponding felsic rocks missing from the column observed in the thesis area. These rocks could be absent owing to erosion or could be hidden beneath the North Shore Volcanic Group to the southeast of the thesis area.

Weiblen's petrogenetic model attributes the magnetically normal North Shore Volcanic Group to the high-Al magma which may be the troctolitic series parent. Green (1972) reports that while the more mafic flows of the North Shore Volcanic Group are typical tholeiites, the intermediate and felsic flows are enriched in K_2O relative to MgO. This K_2O enrichment could account for the calculated K_2O deficiency of the troctolitic series.

The data presented here lend support to the idea that the troctolitic series of the Duluth Gabbro Complex is related to a high-Al magma, probably related to the Pigeon Point Sill and possibly related to the parent magma of the Sonju Lake Intrusion. The series is partially differentiated and could reasonably be the source of a portion of the North Shore Volcanic Group flows.

STRUCTURAL GEOLOGY

Since their solidification, the Keweenawan intrusive rocks of the thesis area have undergone tilting, faulting and jointing. The attitudes of igneous laminations and near vertical joints in the troctolitic series and the strike and dip of nearby flows of North Shore Volcanic Group provide information relating to post-intrusive structural events.

The strike and dip of igneous foliation in the troctolitic series (Figure 6) is compatible with the strike and dip of the North Shore Volcanic Group to the southeast (Green, personal communication) and the Sonju Lake intrusion to the east-southeast (Stevenson, 1974). The approximate consistency of the strike and dip both within and between these units suggests that the mineral foliations in the troctolitic series originally had an approximately horizontal attitude and that the beds in the area have subsequently been tilted towards the southeast as a unit after solidification of the Duluth Gabbro Complex intrusives.

Jirsa (1979?) presents evidence of a paleogradient towards the southeast during the extrusion of the North Shore Volcanic Group. It is assumed that this gradient would be reflected in the strike and dip of the volcanics, but not in the igneous laminations of the troctolitic series and the Sonju Lake

Intrusion. The strikes and dips of these three units are roughly equivalent, although it is probable that the strike and the dip of the volcanics reflects an original topographic gradient upon which they were extruded as well as post extrusive regional tilting.

The evidence for the faulting shown on Plate 1 is indirect. The possible fault traces shown are based upon displacement of contacts, repetition of rock units, and/or topographic lineaments. Two very distinctive lineaments cross the map area from southwest to northeast. The northernmost lineament (L1 on Plate 1 and Figure 8) constitutes the contact between the troctolitic series and the various rock units on the series northwestern border. This lineament most likely represents a high angle fault, although it may represent differential erosion of a particularly easily weathered rock type.

A second lineament parallels L1 at a distance of 460 meters (about 1510 ft) to the southeast. This lineament (L2 on Plate 1 and Figure 8) represents the approximate location of several reversals in trends of troctolitic series rocks: a reversal in the ratio of modal (volume percent) olivine to pyroxene, Figure 11; and reversals in trends of Fo in olivine, An in plagioclase and the ratio of percent FeO/MgO + FeO in pyroxene, Figure 13. The spatial coincidence of the lineament and compositional reversals strongly suggest faulting has occurred. Another less likely

explanation for the origin of this lineament is a second injection of magma resulting in a rejuvenation of the melt to a less differentiated state with an easily weathered rock type, such as dunite, being precipitated at a higher point in the column than would be expected. Walker (1969) suggests this mechanism to account for similar reversals in the Palisades Sill in New Jersey.

The displacement along L1, if it is indeed a fault, cannot be inferred from the information available at this time. The displacement along L2 can be hypothesized to be from approximately 70 to 115 meters (230 to 370 ft) of column repeated and 70 to 125 meters (230 to 410 ft) of vertical movement assuming a near vertical fault and that the troctolitic series dips at 15 to 25 degrees towards the southeast.

L1 is of particular interest because it may represent an expression of incipient faulting as a result of Keweenawan rifting (Weiblen, 1975). Thus L1 may be a fault along which major movement occurred after the intrusion of the anorthositic series and before or during the intrusion of the troctolitic series. After the solidification of the troctolitic series, less extensive adjustments along L1 could have resulted in L2.

Numerous near vertical joints are present in troctolitic series outcrops which on the average, have strikes parallel to

L1 and L2 and to the igneous laminations of the series (Figure 7). These joints, as well as less numerous joints perpendicular to them, are perpendicular and parallel, respectively, to the direction of crustal rifting in the Lake Superior area during Keweenawan time (Hinz, Roy and Davidson, 1972). This jointing may represent post crystallization tectonic and isostatic adjustments along structures related to crustal rifting and the structural regimes which resulted from that rifting.

SUMMARY AND CONCLUSIONS

Bedrock Unit Summary

Mappable bedrock units exposed in the field area include intrusions of the Duluth Gabbro Complex, a melagabbroic-gabbroic intrusive which may be part of the Duluth Gabbro Complex, volcanics of the North Shore Volcanic Group, small areas of diabase and a hypabyssal intrusive. Intrusions of the Duluth Complex include olivine-bearing rocks of the troctolitic series, gabbroic anorthosites and anorthositic gabbros of the anorthositic series and granitic rocks of the felsic series.

Anorthositic Series

Rocks of the anorthositic series observed in the field area are anorthositic gabbros or gabbroic anorthosites. Outcrops of the anorthositic series characteristically display a rubbly surface which is the result of extensive alteration and recent weathering. This alteration is apparent under the microscope as interstitial quartz, oxides, biotite, orthoclase, albite and chlorite. A planar preferred orientation of feldspar laths was present in several outcrops.

Troctolitic Series

According to the classification of Phinney (Figure 4), the rocks of the troctolitic series in the area of study range from gabbro and anorthositic gabbro to anorthositic troctolite and troctolite. Troctolitic units are abundant toward the base of the column which is approximated by the northwestern contact of the series. Gabbroic rocks are abundant toward the top of the column which is approximated by the southeastern contact of the series.

Well-developed preferred planar orientation of plagioclase and a mutually concordant modal layering occur locally within the troctolitic series. These igneous laminations indicate a dip of approximately 15 degrees toward the southwest and infer a true thickness of about 3,000 feet for the portion of the intrusion exposed at the surface.

Textures indicate that the series differentiated in place by crystal settling. Major minerals of the troctolitic series display well-developed cryptic variation. Plagioclase becomes enriched in sodium, while olivine and pyroxene become enriched in iron, toward the top of the intrusion.

The calculated bulk chemistry of the troctolitic series in the field area indicates that its magma could be related to the Pigeon Point Sill and the Sonju Lake Intrusion.

Felsic Series

Rocks of the felsic series are of a farily uniform granitic composition in the study area. Outcrops are massive and lacking in internal structure. Rock textures vary from granoblastic to geometrically complex growths. Felsic series rocks are associated with a contact between the anorthositic series and North Shore Volcanic Group flows.

North Shore Volcanic Group

Rocks of the North Shore Volcanic Group in the thesis area vary from basaltic to rhyolitic in composition. These volcanics occasionally display columnar jointing as well as vesicular or ropy flow tops. Near the contacts with anorthositic and felsic series rocks, the flows are metamorphosed to granofels. The granofles are laced with leucocratic, granophyric material.

Melagabbroic-Gabbroic Intrusives

Melagabbroic-gabbroic intrusives of the field area occur adjacent to contacts of the troctolitic series. Outcrops of the

intrusives display exfoliation and intense weathering. Fe-Ti oxides can account for up to 20 percent of the rock locally. Rocks of the intrusives exhibit a well-developed ignenous foliation.

Diabasic and Porphyritic Hypabyssal Intrusive Rocks

Areas of diabasic and hypabyssal intrusives are associated with the anorthositic and felsic series. Both porphyritic and non-porphyritic diabases were observed while the hypabyssal rocks contained altered feldspar phenocrysts up to 2cm long.

Summary of Geologic Events in the Study Area

The extrusion of at least a portion of the lavas of the Keweenawan age North Shore Volcanic Group is the first recorded geologic event in the map area. The volcanics have been metamorphosed along their contact with the anorthositic series and felsic series which are believed to have been emplaced next.

The terrain occupied by the anorthositic series and felsic series and partially capped by the North Shore Volcanic Group also contains diabasic and hypabyssal intrusives. These intrusives were not observed in the troctolitic series terrain and are believed to be post-anorthositic series and pre-troctolitic series in age.

Melagabbroic-gabbroic intrusives occur in the anorthositic and felsic series terrain as well as along the upper, southeastern contact of the troctolitic series. These intrusives may be either pre- or post-troctolitic series, but are most certainly Keweenawan in age.

The next event in the area was the emplacement and differentiation of the troctolitic series. Taylor (1964) working at Duluth mapped inclusions of anorthositic rocks in the troctolitic series and noted a chilled margin in the troctolitic series at a contact with the anorthositic series. Taylor concluded that the troctolitic series was younger than the anorthositic series.

Faulting, jointing and tilting of the rocks of the study area followed the emplacement of the troctolitic series.

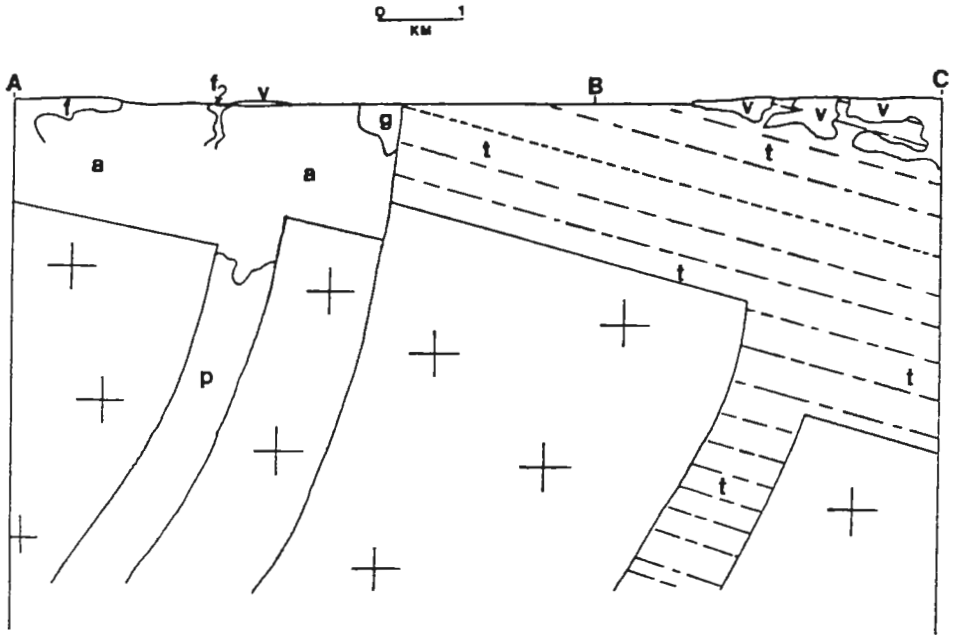
Between Precambrian and Quaternary time, the study area underwent uplift and erosion; however, during the Late Pleistocene Age, the Rainy lobe (H.E. Wright, 1972) flowed over the field area. The lobe was responsible for the deposition of several eskers, kames and outwash deposits, an end moraine and a thin layer of till. A section of the Vermilion moraine, an end moraine of the Rainy lobe, was deposited on the field area and is the most significant remnant of the Wisconsin age glaciation of the thesis area.

Geologic Models of the Study Area

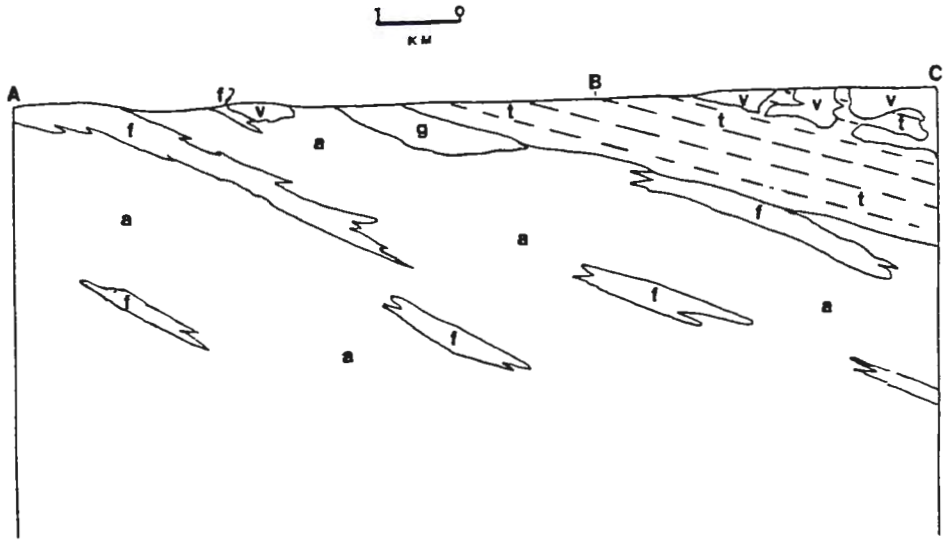
Figure 18a is a hypothetical and generalized cross-section drawn from northwest to southeast across the thesis area. The cross-section is based upon a model presented by Weiblen and Morey (1975) which depicts the troctolitic series as filling voids which resulted from the rifting of an older terrain.

Figure 18b is a second interpretive cross-section of the study area based upon the assumption that the major series of the Duluth Gabbro Complex are semi-concordant and sill-like.

Both cross-sections presented are compatible with the geologic history presented above. Both assume that the mela-gabbroic-gabbroic intrusives are pre-troctolitic series in age. The cross-section based upon the model forwarded by Weiblen and Morey better explains the sharp northwestern contact (L1) of the troctolitic series, which they portray as a major fault. Movement along this fault as the result of Keweenawan rifting is portrayed as providing room for the troctolitic series magma.



18a



18b

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