UNIVERSITY OF MINNESOTA

GEOLOGICAL SURVEY

THE DULUTH COMPLEX IN THE PERENT LAKE AND KAWISHIWI LAKE QUADRANGLES, LAKE AND COOK COUNTIES, MINNESOTA

D. M. Davidson, Jr.

A Discussion To Accompany
Miscellaneous Map Series
Maps M-7 & M-8

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MINNESOTA GEOLOGICAL SURVEY

P. K. Sims, Director

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ABSTRACT

The Perent Lake and Kawishiwi Lake quadrangles are in Lake and Cook Counties, Minnesota, about thirty miles north of Little Marais. The quadrangles are located along the eastern contact or upper part of the Keweenawan Duluth Complex.

The eastern part of the Duluth Complex in the map areas consists of mafic rocks, principally gabbroic and troctolitic anorthosite, which contain inclusions of both hornfels and anorthosite and are intruded by younger mafic units. In turn, the younger mafic units are intruded by several types of felsic rocks, the most common of which is granophyre of granitic composition. Field relationships indicate at least two periods of intrusion for the felsic rocks, both apparently at shallow depths.

Except locally, foliations and lineations are inconsistent in trend, but joints form two steeply dipping conjugate sets, one of which is of regional extent.

The presence of a weakly mineralized, medium-grained, gabbroic anorthosite (NE ¼, sec. 22, T. 62 N., R. 6 W.) is of interest because of the current exploration for copper-nickel deposits in the complex. Although only gossan outcrops were located in mapping, detailed investigations seem warranted.

Field data suggest that emplacement (1.1 b.y. ago) of the rocks in this part of the complex occurred under conditions of relatively high oxygen pressure. Possibly, fractional crystallization of mafic magma can account for derivation of the rocks. However, the felsic rocks may be products of anatexis of Keweenawan lavas.

INTRODUCTION

The Perent Lake and Kawishiwi Lake 7 ½-minute quadrangles are in Lake and Cook Counties, in northeastern Minnesota. Inasmuch as they are situated near the eastern or upper contact of the Duluth Complex, the quadrangles contain several types of felsic intrusive rocks in addition to the more common mafic rocks. They were mapped as part of a continuing, broader study of the Duluth Complex and associated rocks of Upper Precambrian (Keweenawan) age by the Minnesota Geological Survey.

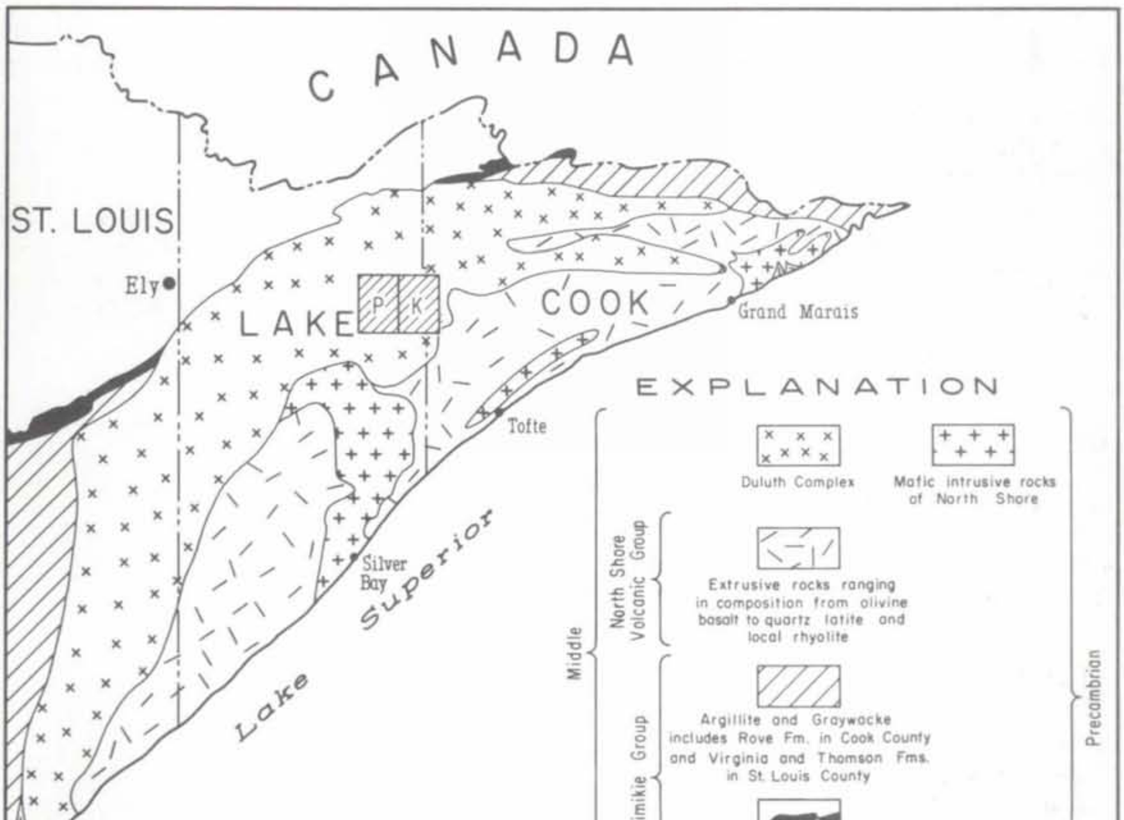

Figure 1 -Map of northeastern Minnesota showing location of the Perent Lake and Kawishiwi Lake quadrangles.

PREVIOUS WORK

Taylor (1964) has presented an excellent summary of the earlier geologic studies carried out on the Duluth Complex. More recent work has been done by H.D. Nathan (1969) in the Gunflint Lake, South Lake, and Hungry Jack Lake quadrangles, Cook County; by Bill Bonnichsen (1968) in the Babbitt N.E. quadrangle, St. Louis and Lake Counties; and by Green and others (1966) in the Gabbro Lake quadrangle, Lake County. The easternmost part of the Kawishiwi Lake quadrangle was mapped earlier by Grout and others(1959). The results of the present investigation differ somewhat from those reported by Grout and others (1959), but such differences are to be expected because of the greater detail of the present mapping and the more ready access at the present time.
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The quadrangles were mapped in somewhat more than five months during the summers of 1966, 1967, and 1968, and mapping was done on topographic base maps at a scale of 1:24,000. Although the area is situated along the southern edge of the Boundary Waters Canoe area, it is moderately accessible by means of graded dirt roads and to a lesser extent by temporary logging roads. Much of the region is covered by extensive glacial till and by swamps, making mapping difficult.

Thanks are due Mr. L. Lustik, Mr. W. Mann, and particularly Mr. Norman Gladen for their cooperation in providing materials, maps, and logistic support. The assistance of P.W. Weiblen with electron microprobe analyses and Richard B. Darling in the preparation of the illustrations is appreciated.

GEOLOGY OF THE DULUTH COMPLEX

The Perent Lake and Kawishiwi Lake quadrangles contain gabbroic and troctolitic anorthosite which have been intruded by mafic rocks, such as gabbro, troctolite, and basalt, as well as by felsic rocks, such as granite and granodiorite.

Rock Classification Used In This Report

The scheme for classifying the gabbroic rocks of the Duluth Complex that is used in this report is illustrated in Figure 2. This scheme is useful in classifying gabbroic, troctolitic, and anorthositic rock types. Although somewhat impractical for field work in that petrographic examination often is required, considerable clarity and consistency can be achieved by use of the scheme.

MAFIC ROCKS

Anorthosite

The oldest gabbroic rock in this part of the complex is anorthosite. The rock generally occurs as massive inclusions, some more than a mile in diameter, within gabbroic or troctolitic anorthosite. These masses form distinct small hills, particularly in the Perent Lake quadrangle. The anorthosite of the area probably is not related genetically to that in the Beaver Bay area as it is not as pure mineralogically as the latter.

The anorthosite is intruded by gabbroic and troctolitic anorthosite bodies that appear to have chilled contacts against it. It appears to occur as inclusions within the younger gabbroic and troctolitic anorthosite for it has foliation directions that differ radically from those in the younger rocks.

It is perhaps noteworthy that within the Perent Lake quadrangle, outcrops of anorthosite appear to be related spatially to a lineament of uncertain origin that can be traced as a topographic low northeastward from sections 3 and 9, T. 61 N., R. 7W. through sections 25 and 35, T. 62 N., R. 7 W. The structural implications of this lineament are discussed below. Though specific age relationships were not determined for the large anorthosite body in the northwest corner of the Perent Lake quadrangle (sections 7 and 8, T. 62 N., R. 7 W.), it is grouped with the anorthosite unit.

The anorthosite bodies are rather uniform in composition, as might be expected of rocks with such unique mineralogy (see tables 1 and 2). Euhedral to subhedral plagioclase is surrounded by subophitic augite, which is partially altered to uralite.

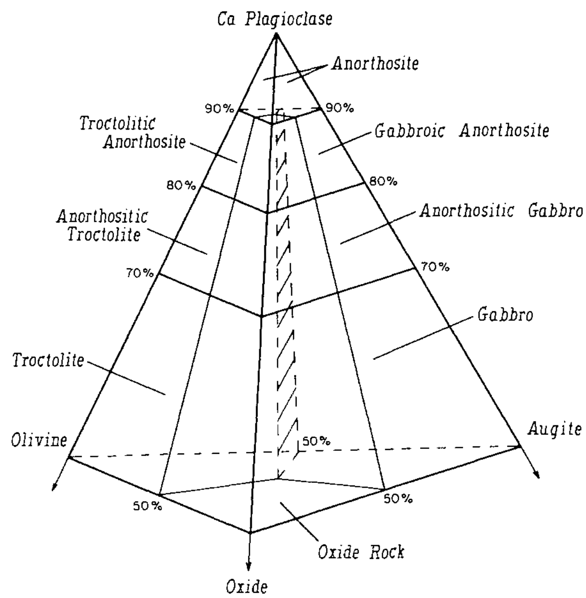

Figure 2 -Classification of selected mafic rocks (after W. C. Phinney, 1966, personal communication).

Olivine is interstitial, and is commonly altered to serpentine and chlorite or partly replaced by biotite. Biotite and leucoxene appear as alteration products of anhedral magnetite. In one sample, quartz was noted to form a myrmekitic intergrowth with magnetite and plagioclase, indicating the possibility of secondary solution activity.

Gabbroic Anorthosite and Troctolitic Anorthosite

More than sixty percent of the bedrock in the Perent Lake quadrangle and the northwest quarter of the Kawishiwi Lake quadrangle consists of gabbroic anorthosite and troctolitic anorthosite. Apparently the weathering of these rocks accounts for the low relief of the area, much of which is covered by muskeg swamplands; excellent exposures occur in the northern part of the area, however.

Table 1. Modal analyses (volume percent) of mafic and intermediate units of the Duluth Complex, Perent Lake and Kawishiwi Lake quadrangles.

	Anorthosite (2)	Gabbroic anorthosite (5)	Troctolitic anorthosite (5)	Anorthositic gabbro (2)	Anorthositic troctolite (2)	Gabbro (ophitic) (2)	Troctolite (2)	Micronorite (1)	Microgabbro (3)	Quartz diorite (1)
Plagioclase	93.2	85.2	87.7	76.0	77.7	59.1	57.4	38.4	58.7	39.7
Augite	4.1	8.4	1.0	18.2	3.2	31.8	1.0	17.3	19.2	--
Orthopyroxene	--	P	1.1	--	P	--	3.6	24.3	0.7	--
Olivine	P	1.4	7.7	2.2	15.7	2.3	23.8	7.8	--	--
Opaque oxides	1.0	3.4	1.2	2.4	2.1	5.9	10.8	12.2	8.3	8.3
Hornblende	--	0.5	--	--	--	--	--	--	--	25.2
Uralite	0.7	P	--	1.2	P	--	--	--	1.9	--
Biotite	P	1.1	1.3	--	1.3	0.4	2.2	--	5.2	9.0
Leucoxene	P	P	--	--	--	0.5	2.1	--	--	--
Chlorite	P	P	P	--	--	--	--	--	--	--
Quartz	1.0	--	--	P	P	--	--	--	--	15.0
Orthoclase	--	--	--	--	--	--	--	--	--	2.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*includes Sericite
(1500 counts per thin section; numbers after each rock type indicate total number of modes used to calculate average.)

Contacts between the two rock types appear to be gradational in the field. Distinction between them was difficult because of a paucity of olivine or pyroxene at a given outcrop; however, differences in foliation trends of the two types in the Kawishiwi Lake quadrangle were helpful in delineating one type from the other. As may be noted on the map of the Kawishiwi Lake quadrangle, foliation in the gabbroic anorthosite trends northeastward, whereas it trends northwestward in the troctolitic anorthosite. Unfortunately, this difference in foliation trend does not prevail uniformly throughout the Perent Lake quadrangle. The units are considered time equivalents.

As Phinney (1969) has noted, these rock types constitute a significant volume of the Duluth Complex where it has been investigated. For example, anorthositic rocks are abundant in the Gabbro Lake quadrangle (Green and others, 1966), in Duluth proper (Taylor, 1964), and to the north of the area described herein (Lake Polly, Alice Lake, and Long Island Lake quadrangles).

Field evidence suggests that these anorthositic rock types were emplaced as a unit, and subsequently were intruded by younger rocks of the complex. In the Perent Lake quadrangle (secs. 10-15, T. 62 N., R. 7 W.), granite and micronorite bodies and mafic pegmatite dikes cut both the gabbroic anorthosite and the troctolitic anorthosite units.

Both rock types have moderately uniform mineralogic compositions. The gabbroic anorthosite contains

Table 2. Compositions of selected minerals in mafic and intermediate rocks of the Duluth Complex, Perent Lake and Kawishiwi Lake quadrangles, Minnesota.

(Analyses marked by * designate electron microprobe analyses; all other determinations were by optical petrographic methods.)

Rock type	Map symbol	Plagioclase	Olivine	Augite
Anorthosite	(an)	An_{49-62}*		$En_{35}Fs_{22}Wo_{43}$*
Gabbroic anorthosite	(ga)	An_{52-65}*		$En_{35}Fs_{22}Wo_{43}$*
Troctolitic anorthosite	(tan)	An_{48-69}*	Fo_{56-57}*	$En_{41}Fs_{15}Wo_{44}$*
Anorthositic gabbro	(ang)	An_{57-67}*	Fo_{55-57}*	
Anorthositic troctolite	(ant)	An_{52-67}*		
Gabbro (ophitic)	(og)	An_{55-65}		
Troctolite	(t)	An_{55-65}	Fo_{55}	
Micronorite	(mn)	An_{52}		
Microgabbro	(mg)	An_{53-58}		
Quartz diorite	(qd)	An_{36-48}		

(An-Anorthite, Fo-Foresterite, En-Enstatite, Fs-Ferrosilite, Wo-Wollastonite) anhedral to subhedral, zoned plagioclase which commonly is partly altered to sericite. Anhedral augite generally shows excellent development of cleavage, and occurs in subophitic texture with plagioclase. Anhedral olivine occurs in subpoikilitic, interstitial texture with plagioclase; it is altered commonly to chlorite, and rarely is rimmed by hypersthene. Leucoxene (?) or biotite are common alteration products of anhedral magnetite, whereas uralite is a common alteration product of augite or occurs as thin kelephitic rims about olivine and hypersthene.

Troctolitic anorthosite generally contains euhedral to subhedral, zoned plagioclase. Olivine generally occurs in subpoikilitic, anhedral grains with plagioclase, although poikilitic and interstitial textures are also present. Hypersthene commonly occurs as rims on anhedral olivine crystals. Augite generally forms anhedral, interstitial masses; locally it has a subophitic texture or is enclosed within larger olivine crystals. Magnetite is commonly anhedral and interstitial; it is commonly partly altered to biotite. Olivine is altered to magnetite and serpentine (?), whereas uralite occurs both as an alteration product of pyroxene and as kelephitic rims about olivine and hypersthene.

Anorthositic Gabbro and Anorthositic Troctolite

Anorthositic gabbro and anorthositic troctolite are rather uncommon rock types in the area. Both form topographic highs in the respective quadrangles, and both have somewhat distinctive foliation trends. The ages of these rocks relative to the older anorthosites and younger gabbros and troctolites are uncertain, as exposed contacts between these rock types were not observed.

Anorthositic gabbro commonly contains zoned, euhedral to subhedral plagioclase, which may be partly altered to sericite. Augite has an ophitic, or more commonly subophitic texture, and is somewhat altered to uralite. The edges of subpoikilitic or poikilitic olivine commonly are altered to magnetite; magnetite also occurs in subpoikilitic interstitial grains with plagioclase. Uralite and sericite are common secondary alteration products, and myrmekitic intergrowths of quartz and K-feldspar were noted in one specimen.

Anorthositic troctolite contains euhedral to subhedral plagioclase that is surrounded by poikilitic olivine; olivine also occurs in anhedral, interstitial crystals. Anhedral augite may occur in interstitial masses or in ophitic intergrowths with plagioclase. Hypersthene

Table 3. Modal analyses (volume percent) of the intermediate and felsic units of the Duluth Complex, Perent Lake and Kawishiwi Lake quadrangles, Minnesota.

	Granodiorite (1)	Quartz Monzonite (1)	Granophyre (3)	Hornblende Granite (2)
Quartz	11.5	22.1	33.0	21.2
Orthoclase	13.1	24.2	43.3	53.8
Plagioclase	46.3	21.0	18.1	1.8
Hornblende	4.1	27.0	--	16.7
Biotite	7.6	--	--	1.0
Magnetite	4.0	5.7	5.2	1.2
Augite	1.4	--	--	0.2
Uralite	12.0	--	--	--
Sericite	--	--	0.4	4.1
Total	100.0	100.0	100.0	100.0

(600 counts per thin section; numbers under each rock type indicate total number of modes used to calculate average.)

commonly rims olivine, which in turn is surrounded by kelephitic uralite. Biotite is commonly poikilitic and contains pyroxene. Intergrowths of quartz and K-feldspar were noted in certain specimens.

Gabbro and Troctolite

Relatively coarse-grained, foliated troctolite and gabbro are restricted in areal distribution, but can be observed in a number of outcrops to intrude the older anorthositic rocks. The age relationships between the gabbro and troctolite are not known.

Olivine-bearing gabbro is a relatively coarse-grained rock consisting of cumulus, euhedral to subhedral, zoned plagioclase, large poikilitic interstitial augite with Schiller structure, and cumulus anhedral olivine. The rocks contain splotches or patch-like concentrations of mafic minerals, and also contain graphic intergrowths of anhedral magnetite and limonite. This rock occurs in a single, rather isolated outcrop (secs. 17 and 20, T. 62 N., R. 7 W.) in the Perent Lake quadrangle.

Ophitic gabbro is medium- to coarse-grained and contains subhedral to euhedral zoned plagioclase that is intergrown with subhedral, interstitial clinopyroxene and orthopyroxene to form an ophitic to subophitic texture. Small portions of the rock outcrops have sufficient orthopyroxene to classify them as a norite. Ophitic gabbro occurs adjacent to granophyre that intrudes the anorthositic rocks along the eastern edge of the Kawishiwi Lake quadrangle as well as in sec. 9, T. 62 N., R. 7 W. in the Perent Lake quadrangle.

Troctolite is generally medium-grained and contains cumulus, zoned, subhedral to euhedral plagioclase and anhedral olivine. Minor poikilitic clinopyroxene showing Schiller structure and orthopyroxene that rims olivine in kelephitic growths also are present. The rock type occurs as numerous small intrusions, some of which are too small to be mapped. Foliation is exceedingly well developed, and it, together with the brown-stained, weathered olivine crystals, gives the rock a distinctive appearance in the field.

Microgabbro and Micronorite

Microgabbro and micronorite generally occur in rather small, semi-concordant intrusive units within the anorthositic rocks. The rocks are fine-grained, and clearly are not settled fractions of the coarser anorthositic rocks. Both the microgabbro and micronorite appear spatially related to felsic intrusives, and in the Perent Lake quadrangle, west of Nuthatch Lake, the two units are gradational along strike.

The microgabbro which was called diabase in the field, contains randomly-oriented, subhedral, sutured and zoned plagioclase, which occurs as: (1) a cumulus groundmass, (2) larger cumulus crystals on the order of .05-1 mm long, or (3) larger (3mm) poikiloblastic or granoblastic crystals. Augite is subhedral to anhedral, subpoikilitic, and interstitial, and some crystals show well-developed Schiller structure whereas others exhibit zoning. Olivine occurs as anhedral cumulate grains, whereas orthopyroxene is anhedral, commonly rimming olivine as a reaction (?) product. Magnetite forms ubiquitous, distinctive anhedral blebs, which are partly altered to biotite. Perhaps the most distinctive feature of the rock is the granoblastic texture of the rock, which is particularly well shown by the sutured feldspar grains and anhedral magnetite blebs.

Micronorite is a fine-grained, augite-bearing rock with partially altered, subhedral to anhedral, zoned plagioclase. Orthopyroxene occurs in large, anhedral oikocrysts intergrown with clinopyroxene and having abundant Schiller structure. In this rock, augite occurs as cumulus anhedral crystals, as does olivine, although it is finer grained than the latter. Most fresh hand specimens of this rock type do not have a visibly granoblastic structure.

Quartz diorite and diorite

The quartz diorite and diorite unit crops out only in the Kawishiwi Lake quadrangle, and is spatially related to the microgabbro unit. In quadrangles to the northeast this rock type becomes predominant over microgabbro; in the Kawishiwi Lake quadrangle quartz diorite is related to the felsic intrusions and has a definite granoblastic texture. Whether the quartz diorite is a separate intrusive unit or a modified phase of the microgabbro is as yet undetermined.

Cumulus plagioclase (An_{35}) is both sutured and zoned; likewise, quartz is anhedral, interstitial, and often contains associated apatite needles. Anhedral brown biotite forms as an alteration product of green-brown hornblende, which is poikilitic, anhedral, and granoblastic. Hornblende may have formed from augite, as noted in a few thin sections from localities in quadrangles adjacent to those under consideration. Magnetite occurs in anhedral blebs, although in highly variable amounts. Significant amounts of subhedral to anhedral orthoclase have been noted both by optical and staining methods.

FELSIC AND INTERMEDIATE ROCKS

Four distinct felsic rock types and a probable hybrid rock unit -- granogabbro -- have been identified in the Perent Lake and Kawishiwi Lake quadrangles (see table 3). Granophyre is by far the predominant type, and granite, granodiorite, and quartz monzonite occur in decreasing order of abundance. The total volume of felsic and intermediate rocks in this area of the complex is estimated at about 10 percent.

Granodiorite

Granodiorite is medium-grained and moderately abundant in the Phoebe Lake area (secs. 7, 13 and 18, T. 62 N., R. 6 W., Kawishiwi Lake quadrangle); it appears to be gradational with granite and has definite intrusive relationships to the older anorthositic rocks.

Euhedral to subhedral cumulus plagioclase (An_{45}) and orthoclase are surrounded by large, poikilitic, subhedral biotite crystals, possibly of secondary origin. Anhedral crystals of augite and orthopyroxene are much altered and poikilitic; subhedral, green hornblende crystals are the predominant mafic constituent. Magnetite occurs in anhedral blebs and locally is sufficiently abundant to make the rock compositionally equivalent to the ferrogranodiorite in the Duluth area (Taylor, 1964).

Quartz Monzonite

Quartz monzonite occurs only in a small area near Knight Lake (sec. 7, T. 62 N., R. 6 W., Kawishiwi Lake quadrangle), but becomes more abundant to the north in the Lake Polly quadrangle.

Clouded, subhedral to anhedral orthoclase and euhedral to subhedral plagioclase (An_{32}) are considerably altered. Euhedral to subhedral green-brown hornblende shows alteration to chlorite, whereas magnetite and quartz occur in anhedral interstitial blebs.

Granite

There are two principal types of granite, one containing biotite and the other hornblende. Both granites are massive, commonly weathered, have virtually no internal structure, and generally contain small dikes of pegmatitic granite. The relative ages of the two rock types have not been determined. Granite generally forms dikes or small intrusive bodies a few tens of meters wide. Larger intrusive masses -- as much as three miles long -- occur east of Nuthatch Lake (secs. 11-14, T. 62 N., R. 7 W. and secs. 7 and 18, T. 62 N., R. 6 W.) in the Perent Lake quadrangle. Such intrusive bodies, having rather ill-defined contacts and containing many inclusions of older anorthositic rocks, have been noted sporadically throughout the Duluth Complex (W.C. Phinney, personal communication).

The granitic rocks are medium-grained to pegmatitic and most are coarse-grained. Orthoclase and plagioclase (An_{10-15}) are subhedral to euhedral and commonly highly weathered to sericite. Subhedral green hornblende is the predominant mafic mineral, occurring in subhedral to anhedral subpoikilitic grains that commonly are altered to anhedral chlorite and biotite. Biotite also occurs as primary interstitial material, as does quartz and magnetite.

Granophyre

Granophyre is by far the predominant felsic rock type in this part of the complex, forming topographically distinctive ridges and hills along tne eastern margin of the Kawishiwi Lake quadrangle. In a few areas this rock type is cut by basalt and granite dikes, but otherwise appears to be younger than all other rocks. Few good contacts between granophyre and anorthositic rocks were noted within the quadrangles studied, although excellent exposures are available further to the north and east (Lake Polly and Beth Lake quadrangles, respectively,) and to the south (Cramer quadrangle). At a few places the rock type has the extremely fine-grained texture typical of rhyolite, indicating intrusion at shallow depths.

Petrographically the granophyre has a rather simple mineralogy. Quartz occurs in myrmekitic intergrowths with orthoclase, which is clouded and commonly has color zoning. Plagioclase (An_{28-34}) is extremely difficult to identify except by staining techniques, but appears to be subhedral and generally is altered. Magnetite occurs in interstitial blebs.

Granogabbro

Granogabbro (orthoclase-bearing quartz-gabbro, Johannsen, 1939, p. 254) crops out locally in small areas at the western edge of the Perent Lake quadrangle (secs. 20 and 29, T. 62 N., R. 7 W.). The rock is considerably weathered, making petrographic analysis difficult. The rock seems to be a hybrid.

YOUNGER ROCKS ASSOCIATED WITH THE COMPLEX

The youngest rock type associated with the complex, basalt, is the smallest volumetrically. Basalt occurs only in lenticular, fine-grained dikes on the order of 1-2 meters wide. The petrography on this rock type has not been studied because of its limited volume and extremely fine grain size.

STRUCTURAL GEOLOGY

Lineation

Elongate minerals that give a distinct lineation are rare in the area. A hornblende granite in the Kawishiwi Lake area and a quartz monzonite in the Knight Lake area have a good lineation.

Lineaments

Lineaments marked by long, linear topographic depressions are fairly common in the quadrangles, but the factors responsible for them are poorly known. A particularly conspicuous lineament trends northeastward from sec. 9, T. 61 N., R. 6 W., in the Perent Lake quadrangle. Apparently glacial ice has preferentially eroded fractured zones in the rocks, but the cause and nature of the fracturing is unknown.

Foliation

All mafic rocks in the quadrangle have a foliation that is imparted by tabular crystals of plagioclase. In general, anorthosite, gabbro, and troctolite have more distinct and persistent foliations than do the other mafic rock types, but nowhere is the foliation consistent. Microgabbro has a foliation that is readily noted in thin section but not in the field.

Fractures

Nearly vertical joints are present throughout the area and a frequency diagram of them is given in Figure 3. Two conjugate fracture trends are noted.

A N. 40 E.-N. 30 W. conjugate set appears to be a regional fracture pattern, whereas a N.-N. 70 W. set appears more localized and possibly is controlled somewhat by the foliation in the rocks. Both sets are interpreted as having resulted from regional stresses, possibly related to glacial unloading and uplift together with some tectonic readjustments resulting from erosion, basin formation, and isostatic rebalancing.

Intrusive Relationships

Bonnichsen (1969 a, b) has proposed a model for the emplacement of the Duluth Complex that seems

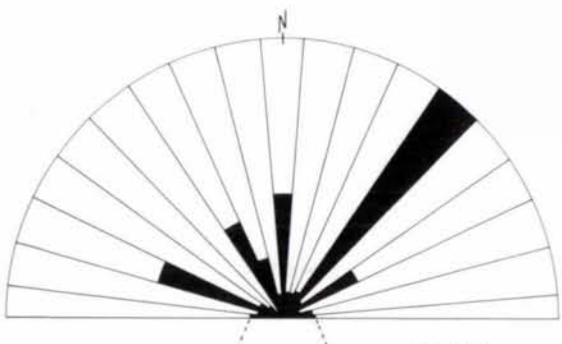

Figure 3 -Vertical-fracture pattern, Perent Lake and Kawishiwi Lake quadrangles, Minnesota. (Fractures averaged over a five degree interval. One hundred six data points are represented.)

applicable to the area of this study. In brief, he proposes that the major gabbroic and anorthositic rocks were intruded into the overlying Keweenawan lavas and that intrusion, particularly near the base of the complex, possibly was structurally controlled by extensive fractures or rift zones. Felsic intrusions followed emplacement of the major gabbroic units, with the granophyre being emplaced in a somewhat more conformable arrangement than the other felsic rock types.

ECONOMIC SIGNIFICANCE OF THE AREA

The sulfide content (generally less than 1 percent by volume) of the rocks of Perent Lake and Kawishiwi Lake quadrangles appears to slightly increase eastward; pyrite is the principal sulfide mineral. The only area of possible potential significance for ore deposits is in sections 21 and 22, T. 62 N., R. 6 W. of the Kawishiwi Lake quadrangle. In section 22, a gossan in medium-grained gabbroic anorthosite contains visible chalcopyrite and pyrrhotite. Analyses of outcrop samples revealed the following elemental concentrations: copper, 300 ppm; nickel, 200 ppm. Additional investigations, including drilling, probably are warranted at this locality.

PETROGENESIS

Although detailed petrogenetic conclusions related to the Duluth Complex are premature, sufficient data have been accumulated to make some broad generalizations regarding certain genetic aspects of the complex.

From the chemical data available from the earlier work of Taylor (1964) and Ernst (1960) in the Duluth area, and Babcock (1960) in the northeastern part of the complex, it appears that the felsic rocks of the complex generally are differentiates derived by fractional crystallization of mafic source rocks, but that local units, such as the Endion Sill, may have been derived by other mechanisms such as gravity settling or filter pressing.

There is little petrologic evidence to alter this picture in the area of the Kawishiwi Lake and Perent Lake quadrangles. The modal analyses now available indicate a rather uniform crystallization trend for the felsic rocks of the area (see figure 4). Care should be used in interpreting such data, however, as chemical analyses are not yet available. Although data on oxygen partial pressures also are not yet available, mineralogic relationships such as the apparent early precipitation of abundant iron oxides, the extensive development of hydrous silicates (biotite and hornblende), and the increase in free silica in late differentiates, indicate that the felsic rocks of the complex may well have been derived through fractional crystallization of basaltic

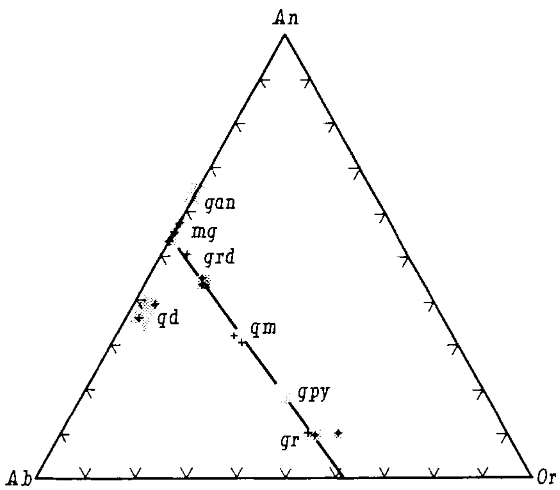

Figure 4 -Plot of Ab-An composition with orthoclase content, selected Modes, Perent Lake and Kawishiwi Lake quadrangles, Minnesota. (gan--gabbroic anorthosite, mg--microgabbro, qd--quartz diorite, qm--quartz monzonite, gpy--granophyre, gr--granite).

(tholeiitic?) magma having a high oxygen content (Osborn, 1959). On the other hand, tentative estimates of the volume of felsic rocks relative to mafic rocks in the complex exceed the 10 percent volume limitation indicated by experimental work for such a mechanism (Bowen, 1928).

SUMMARY AND CONCLUSIONS

In summary, the sequence of geologic events for this part of the complex is interpreted as follows:

1. Outpouring of Keweenawan Lavas (1.1 b.y. ago).
2. Differentiation of remaining (?) magma, segregation of the layered gabbroic rocks and emplacement (about 1.1 b.y. ago), perhaps diapirically, of the anorthositic rocks. Marginal rifting along the northern boundary may account for the abundance of layered gabbroic rocks having rather steep contacts in the south Kawishiwi River area.
3. The intrusion of additional gabbroic, troctolitic, and other mafic rocks followed closely in time. Apparently the emplacement of these rock bodies was in part structurally controlled, as may be inferred from the ethmolythic shape of the Bald Eagle intrusion (Phinney, 1969; Weiblen, 1965).
4. The remaining felsic and intermediate rock types were then emplaced either diapirically or by filter pressing. Clearly more than a single period of felsic rock intrusion is indicated by field relationships.
5. Additional basin subsidence is postulated to have followed the emplacement of felsic rocks, thus enhancing the Lake Superior syncline.
6. Subsequent erosion and glacial activity sculptured the area extensively, giving rise to present topography and drainage.

Time-space relationships between intrusive units of the complex are uncertain. The rather high temperature apparently necessary for formation of anorthosite contrasts sharply with that required for the formation of the relatively low-temperature granitic rocks, yet the two rock types are in close spatial association. Considerable attention in future studies should be given to not only this problem but also to several other problems, among them being:

1. The relationship of titaniferous magnetite concentrations to gabbro-granophyre relationships of the complex.
2. The possibility of an intrusive event 950 b.y. ago.
3. The petrogenesis of the gabbro-granophyre association.
4. The tectonic and petrologic relationships between the Logan Intrusives and the Duluth Complex.

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