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THE DULUTH COMPLEX IN THE GABBRO LAKE QUADRANGLE, MINNESOTA

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Report of Investigations 9

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THE DULUTH COMPLEX IN THE GABBRO LAKE QUADRANGLE, MINNESOTA

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THE DULUTH COMPLEX IN THE GABBRO LAKE QUADRANGLE, MINNESOTA

W. C. Phinney

ABSTRACT

Mapping of the lower part of the Duluth Complex in the Gabbro Lake 15-minute quadrangle, near Ely, Minnesota, shows a series of mafic intrusions against a basal contact of older Giants Range Granite. Oldest of the intrusive rocks is gabbroic anorthosite, which itself consists of several intrusions that probably formed from a crystal mush. Plagioclase is the only primary material in this rock; all other minerals are interstitial. Abundance and textural relations of the various interstitial minerals can be used as a basis for delineating smaller units within the gabbroic anorthosite. Orientation of planar plagioclase and minor layers in the rock unit indicate structural variations ranging from conformable over several miles to irregular over several miles.

Intrusive into gabbroic anorthosite is the funnel-shaped Bald Eagle Intrusive, which is elliptical in plan, nearly 10 miles long, and 3 miles wide. The intrusion has two concentric units, an outer zone of troctolite and an inner zone of gabbro; it has no contact aureole or chilled margin. The internal structure of the intrusion and systematic changes in the composition of plagioclase and olivine from margin to center, indicative of differentiation, suggest that the mass formed in large part by flowage while differentiation was taking place at depth.

Also intrusive into gabbroic anorthosite is the South Kawishiwi Intrusion, which is essentially a troctolite mass. The mass can be divided into (1) a northeast-trending dike more than half a mile wide and about 4 miles long, and (2) a basin or synformal structure about 6 miles wide and at least 7 miles long that is defined by excellent layering and oriented plagioclase. The dike contains several structural features indicative of flow; and the basin contains shallow dipping layers, some of which have gradational changes from higher olivine to plagioclase ratios at the base to lower ratios at the top, which indicate accumulation by settling. Many lenticular masses of anorthosite occur within the troctolite.

A noritic intrusion and several basalt dikes, all having chilled margins, intrude the gabbroic anorthosite. Granite dike sets at three localities and granophyric joint fillings also occur in anorthositic gabbro. Economically significant deposits of copper and nickel sulfides are marked by gossans near the basal contact of the troctolite basin and in the troctolite dike.

Introduction

The 15-minute geologic map of the Gabbro Lake quadrangle, published as Miscellaneous Map M-2 of the Minnesota Geological Survey (Green, Phinney, and Weiblen, 1966), lies at the base of the Duluth Complex, approximately at the mid-point of the 170-mile-long northwest perimeter (fig. 1). The area is about 10 miles southeast of Ely

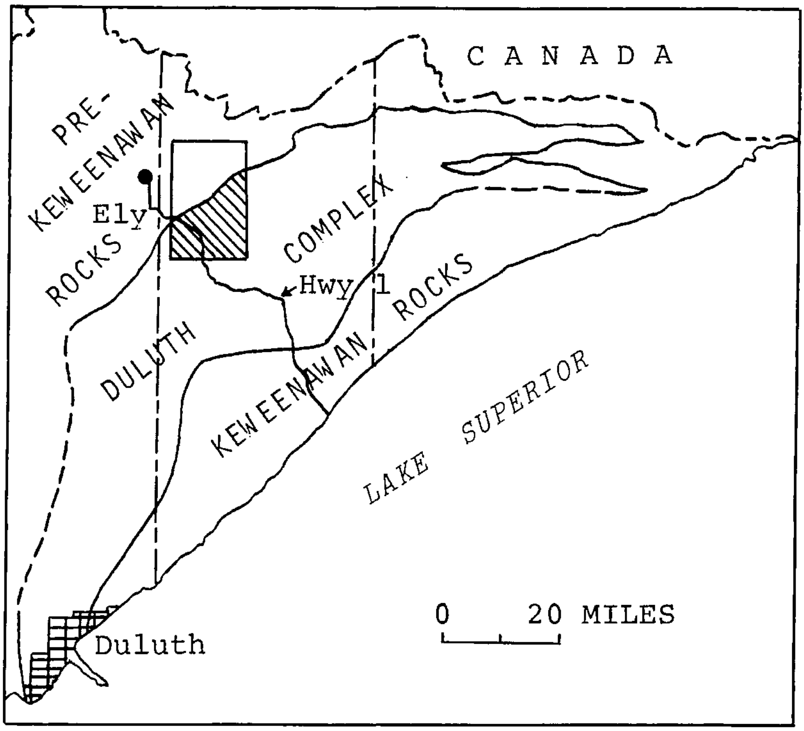

Figure 1--Map of part of northeastern Minnesota showing location of Gabbro Lake quadrangle.

and 80 miles north of Duluth. The Duluth Complex underlies the southeastern half of the quadrangle, and was mapped during a total of about 12 months in the summers of 1961 through 1964 by Phinney and P. W. Weiblen. Weiblen was primarily responsible for the mapping of the intrusion at Bald Eagle Lake. Pre-Keweenawan rocks underlie the northwestern half of the quadrangle, and were mapped during the summers of 1962 through 1965 by J. C. Green. A separate report will be published on the pre-Keweenawan rocks.

Mapping of the Duluth Complex in this area was undertaken for two principal reasons: 1) to determine whether multiple intrusions similar to those reported by Taylor (1964) at Duluth were present further to the north, and 2) to aid in determining the relationships of the economically important copper-nickel deposits to the remainder of the Complex. Mapping was done on two different sets of aerial photos, one flown in 1956 and the other in 1961. Data were then transferred to the 15-minute topographic sheet which was enlarged to twice the scale of the published topographic map. Because much of the quadrangle lies within a wilderness area (Boundary Waters Canoe Area of the Superior National Forest), many traverses could be accomplished only by canoe.

More than 500 thin sections were studied, and modal analyses were made on about 450 of these. The modes were estimated by making at least 1500 point counts on each section. About 100 polished-thin sections were made for chemical studies of individual phases by microprobe analysis; results of these studies are averaged in tables 1 and 2. Studies of the sulfide minerals near the base of the complex are presently being undertaken by P. W. Weiblen. Detailed mapping of adjacent quadrangles and other quadrangles further eastward is presently underway.

Previous Investigations

Although there are a few publications describing some parts of the Duluth Complex, very little data other than unpublished exploration work are available for that part near the basal contact in the Gabbro Lake quadrangle. Anderson (1956) described some of the sulfide occurrences near the base of the Complex but did not undertake any detailed mapping.

In his early work on the Duluth Complex, Grout (1918a, b, c) primarily discussed the relationships in the vicinity of Duluth. He reported at least two gabbroic intrusions: an older "feldspathic gabbro was intruded and cooled before the main mass of more basic gabbro was intruded" (Grout, 1918a, p. 627). He referred to the mass in its entirety as the Duluth Gabbro.

In a report on the geology of Cook County, Grout, Sharp, and Schwartz (1959) include a summary of the "Duluth gabbro complex", which appears to be the first use of the word "complex" in the title of these rock units. In their description they pointed out that many varieties of gabbro are known to exist, but no detailed study of the petrographic and structural relations of the various units was undertaken.

In a discussion of the geochronology of northern Minnesota, Goldich (Goldich and others, 1961, p. 82) was the first to use the term "Duluth complex"; he emphasized the multiple intrusive nature of the rocks in the vicinity of the city of Duluth. In a restudy of the area near Duluth, Taylor (1964) maintained the term "Duluth Gabbro Complex", and he emphasized the multiple intrusive nature of the rocks; he distinguished peridotite, anorthositic gabbro, troctolite, olivine gabbro, ferrogranodiorite, syenodiorite, granophyre, and other units. His mapping of the various rock units of the Complex in the vicinity of Duluth resulted in the first detailed map of the Complex to be published.

Phinney (1968) has pointed out that probably more than half of the area commonly referred to as the "Duluth gabbro" consists of rocks having more than 80 percent modal plagioclase. Such a rock is commonly referred to as gabbroic anorthosite. Because the older terminology emphasizes the gabbroic rather than anorthositic affinities of this well-known complex, continued use of the term gabbro seems misleading, especially to geologists not familiar with the rocks involved. Therefore, the term Duluth Complex, as first used by Goldich and others (1961), is now preferred by the Minnesota Geological Survey.

General Geologic Relations

General mapping of the geology in northeastern Minnesota over the past few years has shown that the Duluth Complex consists of a series of anorthositic, gabbroic, troctolitic, granodioritic, and granitic intrusive bodies. In the aggregate, these intrusives crop out in an arcuate pattern extending for a distance of about 150 miles northeastward from Duluth towards the northeastern tip of Minnesota. As one goes from Duluth northward along the basal contact, the rocks underlying the Complex are successively: North Shore Volcanic Group of Keweenawan age and the Animikie Thomson Formation, west of Duluth; Virginia Formation and Biwabik Iron-formation of Middle Precambrian age, in the East Mesabi area; Giants Range and Snowbank Granites, Knife Lake Group, and Ely Greenstone of Lower Precambrian age, in the Vermilion district; Gunflint Iron-formation and Rove Formation of Middle Precambrian age, near Gunflint Lake and eastward; and flows of Keweenawan age near Hovland. Keweenawan flows form the upper contact along the southeastern contact of the Complex. Radiometric dating of zircons from rhyolitic flows of the North Shore Volcanic Group and granitic fractions of the Duluth Complex (Silver and Green, 1963; personal comm.) indicates that the intrusive rocks and the flows are essentially contemporaneous to within experimental errors at 1,120 $\pm$ 15 million years.

In the Gabbro Lake quadrangle, the base of the Duluth Complex is in contact with the Giants Range Granite over most of its length; an exception is the easternmost margin of the map area, where the Knife Lake Group may be in contact with the Complex, but relations are obscured in this area by the Kawishiwi River. The strike of the contact is somewhat irregular, but in general is northeastward. Although it is not possible to determine the dip of the contact accurately from surface exposures, exploration drilling in the southwestern part of the quadrangle and in adjacent quadrangles further southwest indicates that the dip ranges from 15° to 60° SE. Dips of layers and planar orientations of plagioclase crystals in the gabbroic rocks near the contact are generally in the range 15° - 25°. Near the contact, along the eastern and western parts of the map, the dips are generally to the southeast, but they are to the northwest in the area east and north of Gabbro Lake. The relationship between these internal structural features and the basal contact of the Complex is not known.

Rock Units

The oldest intrusive unit of the Duluth Complex in the quadrangle is termed Anorthositic gabbroic rocks on the published map (Green, Phinney, and Weiblen, 1966). Intrusive into this are two major units of troctolitic and gabbroic rocks, one south of Bald Eagle Lake and the other south of the South Kawishiwi River. Several smaller dikes and apophyses associated with these intrusions are found around the southern part of Gabbro Lake and south of August Lake. Another intrusion of more noritic composition occurs around the northwestern perimeter of Gabbro Lake. Because these younger intrusions show crosscutting relationships with respect to the anorthositic unit only, it is not possible at present to determine a definitive time sequence for all of the units.

Anorthositic Rocks

Units on the map (Green, Phinney, and Weiblen, 1966) under the term

Anorthositic gabbroic rocks vary in composition from anorthositic gabbros through gabbroic anorthosites, with the latter being more prevalent (i.e., contain more than 80 percent plagioclase). Northeast and southwest of Gabbro Lake, where exposures and access are good, these rocks were sub-divided into mappable units. Throughout the remainder of the area mapped as undifferentiated anorthositic rocks, it would be possible to subdivide the unit with more detailed mapping.

Although the basal contact of the anorthositic unit is not exposed, it is possible to determine its location within a distance of about 10 feet near dam no. 2 at the northwest outlet of Little Gabbro Lake. In the vicinity of this dam, there are outcrops of hornblende-bearing rocks which appear to be inclusions of granite in the gabbro. There are also rheomorphic dikes of brown-weathering, granular, fine-grained granitic material, one- to four-inches thick, in the gabbro south of the dam. At several localities in this area, in the stream bed to the north, and along the shore to the south, there are clots of cream colored interstitial material, 2- to 3-inches in diameter, in the gabbro; in some cases the interstitial material is coarser grained than the adjacent gabbro. These clots are generally enriched in biotite, hornblende, and quartz.

Many small inclusions of anorthositic material, which are particularly apparent in the contact zone and in the large dike that extends southwest from Gabbro Lake, occur within the South Kawishiwi Intrusion. Also, there are a few larger masses of anorthositic material in the augite troctolite unit. The larger masses may be large inclusions or they may be remnants of mounds, ridges, or pendants that protrude into the troctolite from anorthositic units. Further detailed mapping in the vicinity of these masses might solve the problem of their structural relations. The inferred contact east of Filson Creek, in sec. 19, T.62 N., R.10 W., between troctolite and anorthositic gabbro is based on the presence of inclusions of anorthosite in troctolites that are exposed on a logging road on the west side of the creek, just south of the center of section 19.

On the basis of 299 modal analyses of anorthositic rocks from the quadrangle (tbl. 1), the average plagioclase content is about 86 percent. The range in modal composition is from 70 to 99 percent, with the majority of the modes being between 82 and 93 percent. This compares closely with Taylor's (1964, p. 8-11) estimate of 80 percent plagioclase in the "anorthositic gabbro" unit at Duluth; the unit has a range of 75 to 90 percent plagioclase. The remainder

TABLE 1

Average modes, in volume percent, of units in the Duluth Complex, Gabbro Lake quadrangle

	Anorthositic Gabbro (35) ago	Noritic Anorthosite (37) agh	Gabbroic Anorthosite (215) agu	Basal Contact Zone of Gabbroic Anorthosite (24) agu	Contact Zone of Gabbroic Anorthosite with Troctolite (12) agu	Norite (6) n	South Kawishiwi Augite Troctolite (13) sat	South Kawishiwi Poikilitic Troctolite (33) spt	Dike of South Kawishiwi Intrusion (48) st	Anorthosites in South Kawishiwi Intrusion (9) sa	Margin of Bald Eagle Intrusion (12) bt	Central Zone of Bald Eagle Intrusion (7) bg
Plagioclase	78.87	87.44	87.56	65.51	85.67	67.55	68.57	71.16	63.65	95.2	57.3	42.2
Augite	8.90	2.63	3.10	6.31	5.00	3.91	9.73	4.52	8.63	0.85	2.1	46.0
Hypersthene	1.12	6.09	1.46	2.63	0.59	23.90	2.02	0.55	1.08	0.60	tr	tr
Olivine	3.24	0.24	4.45	14.23	6.17	tr	14.82	19.34	22.42	1.26	34.0*/	10.00**/
Opaques	2.93	1.34	1.36	3.90	1.94	3.06	1.34	2.02	3.40	1.28	5.3	1.0
Biotite	2.50	1.07	1.33	3.33	.37	1.25	1.97	.63	tr	tr	tr	tr
Symplectite	2.15	0.55	0.19	3.18	tr	tr	1.30	0.15	tr	tr	--	--

Numbers after each rock type indicate number of thin sections used to calculate average mode.

Letters after each rock type indicate unit symbol on geologic map of Gabbro Lake quadrangle (Green, Phinney, and Weiblen, 1966).

Modes total less than 100 percent because a few alteration and accessory minerals are excluded from the tabulation.

*/about 20 percent of olivine is serpentinized. **/about 2 percent of olivine is serpentinized.

of the minerals consists of various proportions of olivine, augite, hypersthene, biotite, and opaque oxides. In a large majority of the rocks examined these minerals are poikilitic, enclosing plagioclase laths. Symplectic intergrowths of hypersthene and plagioclase also are common. Specific textural relations and modal abundance of the ferromagnesian phases generally are persistent over a moderate areal extent, and may be used as a basis for distinguishing units within the anorthositic rocks. For example, in the vicinity of Gabbro Lake, where outcrops and access are good, it is possible to distinguish one unit in which the predominant ferromagnesian phase is poikilitic hypersthene (5 to 12 modal percent). Another unit contains poikilitic augite and olivine and is characterized by a brown-spotted weathering surface. In the undifferentiated unit, there are some rocks in which olivine may comprise 10 to 12 percent of the rock, whereas in about half of the total of 299 thin sections of the undifferentiated anorthositic rocks there was less than 1 percent olivine. The major similarity for all of these rocks is that plagioclase is the only primary precipitate; other minerals are interstitial. Compositions of the major phases are compiled in table 2.

Pegmatitic segregations, primarily composed of plagioclase and augite, occur in a few places in the gabbroic anorthosite. They are local in occurrence, and range in observable outcrop width from about one-foot to 100 feet. One of the most notable such occurrences is on a small island in Gabbro Lake, in SW1/4 SE1/4, sec. 15, where crystals of pyroxene and plagioclase attain lengths of several inches. In segregations having well-exposed contacts it is common to find parts of the perimeter in sharp intrusive-like contact with gabbroic anorthosite but other parts gradational with gabbroic anorthosite.

Within about half a mile of the basal contact of the anorthositic unit there is a significant increase in the olivine content and a consistent decrease in the plagioclase content (table 1). Such a mineralogic change has not been observed in the anorthositic unit near the contacts with younger intrusive units, and it is not certain whether this change results from fractionation within the anorthositic unit or from a younger troctolite intrusion between the anorthositic unit and the underlying country rock. The latter interpretation is suggested by the similarity of modes of this basal unit with those of the augite troctolite of the South Kawishiwi Intrusion as well as by the occurrence of small dikes of similar material on the north shores of Pietro and Turtle Lakes.

TABLE 2

Compositions of minerals in the Duluth Complex, Gabbro Lake quadrangle

	*/Plagioclase	Olivine	***/Augite	Hypersthene
Anorthositic gabbro, ago	An_{54-70}	**/Fo_{35-48}	**/$En_{40}Fs_{21}Wo_{39}$	**/$En_{45}Fs_{52}Wo_{3}$
Noritic anorthosite, agh	An_{58-70}	—	—	**/$En_{51}Fs_{43}Wo_{6}$
Gabbroic anorthosite, agu	An_{55-85}	**/Fo_{54-60}	**/$En_{44}Fs_{16}Wo_{41}$	**/$En_{46}Fs_{52}Wo_{2}$
Gabbroic anorthosite contact zone	An_{53-67}	Fo_{59-65}	**/$En_{45}Fs_{16}Wo_{39}$	—
Bald Eagle troctolite, bt	An_{62-81}	Fo_{71-74}	**/$En_{39}Fs_{21}Wo_{41}$	—
Bald Eagle intermediate rock	An_{67}	Fo_{69-70}	$En_{53}Fs_{12}Wo_{34}$	**/$En_{74}Fs_{24}Wo_{2}$
Bald Eagle gabbro, bg	An_{57-63}	Fo_{61-62}	$En_{45}Fs_{14}Wo_{41}$	—
South Kawishiwi contact zone, scz	An_{55-65}	Fo_{50}	**/$En_{38}Fs_{21}Wo_{42}$	**/$En_{39}Fs_{59}Wo_{2}$
South Kawishiwi troctolite, sat	An_{57-70}	Fo_{50-55}	—	—
South Kawishiwi troctolite, spt	An_{57-67}	Fo_{59-62}	**/$En_{43}Fs_{16}Wo_{41}$	**/$En_{64}Fs_{34}Wo_{2}$
South Kawishiwi troctolite, st	An_{58-72}	Fo_{55-63}	—	—
anorthosite, sa	An_{60-68}	**/Fo_{60-62}	—	—
norite at Gabbro Lake, n	An_{35-46}	**/Fo_{51}	—	$En_{60}Fs_{36}Wo_{4}$

All analyses are based on several replicate microproble analyses on several points on each of several grains from between 2 and 10 samples from each unit.

* Range of compositions is for most calcium-rich parts of grains

** Mineral compositions are of interstitial phases; all others are primary

*** Augite analyses show much variation within individual grains depending upon degree of exsolution and proximity to exsolved lamellae. Only averages are listed.

Planar orientation of plagioclase and minor layering are indicative of extreme structural variations within the anorthositic units. Trending northeastward across Gabbro Lake is an antiformal structure with consistent plagioclase orientation and layering over a distance of several miles. Also in an area having an extent of 4 to 5 square miles northeast of Pagami Lake the rocks dip quite consistently 20° - 30° SE. In contrast, the anorthositic units in the area between Bald Eagle and Clearwater Lakes as well as in areas east and west of the Bald Eagle Intrusion show many irregularities. Along the south shore of Clearwater Lake, near the island in the NW1/4 sec. 7, is an outcrop which shows an intrusion of one gabbroic anorthosite into another. Cross-cutting plagioclase orientations are quite striking in this outcrop.

It is reasonable to conclude from structural observations of these variously oriented plagioclases in which coarse-grained (>2 cm) plagioclase is the only primary precipitate that most of the anorthositic rocks intruded as a crystal mush. A similar conclusion was reached by Taylor (1964) in his study of the Duluth area.

Bald Eagle Intrusion

A funnel-shaped intrusion, elliptical in plan and nearly 10 miles long and 3 miles wide, having two concentric units marked by an outer zone of troctolite and an inner zone of gabbro, is exposed from the northern margin of Bald Eagle Lake southward into the adjacent Greenwood Lake quadrangle. Structural and petrographic relations of this intrusion have been described in detail by Weiblen (1965). A contact aureole or chilled margin of the troctolite body is lacking but its intrusive relations to gabbroic anorthosite are confirmed by cross-cutting contacts. A planar orientation of plagioclase and isomodal layering parallel the steeply-dipping contact in the outer zone, and become horizontal at the center of the intrusive body.

Modes and compositions of the major phases in this intrusion are compiled in tables 1 and 2. The troctolite zone contains tablets of plagioclase and elongate olivine grains on the order of a few mm in length. Throughout this zone are lenses of anorthosite which vary in width from a few centimeters to as much as 10 to 15 centimeters. Contacts between lenses and troctolite are sharp and parallel to the planar plagioclase and the layering. A few outcrops of troctolite contain slightly coarser olivine grains on the order of 5 mm in length. These coarser grained rocks contain less olivine than the finer grained troctolite, and have fewer anorthosite lenses. Coarse-grained pyroxene occurs locally in both pegmatitic aggregations and subophitic aggregates, which stand out on the weathered surfaces, imparting a knotty appearance.

Plagioclase and olivine are the primary phases in the troctolite. Clinopyroxene is the most common interstitial mineral. Magnetite-ilmenite and Fe-rich chromite are minor interstitial phases. Orthopyroxene and clino-pyroxene occur as reaction rims around olivine. Serpentine and iron oxides are alteration products of olivine.

Plagioclase in the troctolite occurs as well-developed euhedral laths having albite twinning. Despite the extensive alteration of olivine, which results in some fracturing of the plagioclase, alteration and sercitization are insignificant in the plagioclase. The plagioclase in the anorthosite segregations is similar in grain size, orientation, and composition to that in the surrounding troctolite. Oscillatory zoning and zone extinction is not common, although some plagioclase is zoned compositionally.

Olivine in the troctolite occurs as subhedral to anhedral elongate grains, randomly oriented in the plane of lamination. Alteration of the olivine ranges from minor to complete. In general, the lower the olivine content in a rock the less extensive the alteration. The olivine contains minor iron-oxide schiller and inclusions. The olivine is not zoned optically or compositionally.

Clinopyroxene occurs as an interstitial phase and as reaction rims around olivine. In one section it was found as a mantle around orthopyroxene. Magnetite-ilmenite schiller is extensive in the interstitial pyroxene, but not in the reaction rims around olivine.

The gabbro zone of the intrusion contains tablets of plagioclase and elongate grains of olivine and pyroxene as primary phases. Mineral grains are on the order of 2 to 3 mm in length. Magnetite-ilmenite occurs as a minor interstitial phase. None of the minerals are altered appreciably. Plagioclase lenses similar to those in the troctolite also occur in the gabbro. In addition to lenses, layers of anorthosite as much as several inches wide can be traced along strike for tens of feet, and at one locality for more than 200 feet. Layers on the order of one-foot thick, caused by variations in proportions of plagioclase and pyroxene, are common and can be traced for distances of 20 to 30 feet. These layers characteristically pinch out along strike.

Commonly plagioclase and pyroxene have a planar orientation as well as a layering of the type mentioned above. Without exception, the layering and planar orientation are parallel. In several outcrops the pyroxene has a well-developed lineation that plunges generally down-dip.

Plagioclase is similar in texture and habit to that in the troctolite. The major difference is the absence of fracturing on the scale found in the troctolite. This difference, of course, reflects the decrease in olivine content and its alteration.

Olivine is much less abundant in the gabbro than in the troctolite, the average content being about 10 percent. Single olivine grains are elongate and have a random orientation in the plane of lamination in most of the gabbro, but locally impart a well developed lineation. Mantling of the olivine is not common, but some reaction rims of orthopyroxene are found.

Clinopyroxene is elongate in the c direction and has abundant magnetite-ilmenite schiller. Blades of biotite are also common in the pyroxene. Orthopyroxene occurs only as reaction rims around clinopyroxene and olivine.

The troctolite zone and the gabbro zone are transitional across a distance of a few hundred feet. The change from one rock type to the other is not gradual; instead, at one locality the transition is marked by alternating layers of the two rock types, and at another is marked by a rock composed predominantly of plagioclase. At yet another locality it consists of thin-layered troctolite that has more interstitial pyroxene than is commonly present in typical troctolite.

Although obvious inclusions are not common in the Bald Eagle Intrusion, a distinction must be made between clear-cut anorthositic inclusions and the anorthosite lenses referred to earlier. The definite inclusions have textures typical of anorthositic gabbro, with interstitial olivine and pyroxene, but the anorthosite lenses contain olivine that appears to be primary.

The variation from steeply-dipping layers at the margin to horizontal layers in the central part, combined with the differentiation indicated by changes in mineralogy and changes in compositions of plagioclase and olivine from margin to center, make it difficult to interpret the mode of emplacement of the Bald Eagle Intrusion. Steep layers around the entire margin, lensing of these layers, down-dip lineation of pyroxene, and absence of typical interstitial textures formed by gravity settling suggest that these rocks formed primarily by flowage. Horizontal layers and mineral orientation at the center would indicate that flow was practically negligible at the time this portion of the mass formed. To reconcile the observed differentiation and the flow structure, it is presumed that the differentiation probably took place at depth; whether it occurred in a deeper magma chamber or at the magma source is not known at the present time.

South Kawishiwi Intrusion

The South Kawishiwi Intrusion consists essentially of troctolite, and can be subdivided on the basis of textural variations into several units. Structurally there are two major features in the intrusion: (1) a northeast-trending dike between Omaday and Gabbro Lakes, and (2) a basin or synformal structure which straddles Minnesota Highway #1 east of Heart and Bogberry Lakes.

The dike consists primarily of plagioclase and olivine and has significant amounts of augite and opaque minerals. Generally the grains are 1 to 2 mm in size, although they are as much as 6 mm in length in a few of the mafic zones. In many places the plagioclase laths and elongate olivine grains are alined, presumably as a result of flowage. Pyroxene is interstitial, generally occurring as oikocrysts, but it also locally mantles olivine grains.

Plagioclase generally shows normal zoning that has a magnitude of 5 to 10 percent An. A few sections show bent albite twins. Alteration in this unit is minor and occurs only along a few small fractures in unzoned olivine. Augite contains extensive exsolution of hypersthene lamellae, especially in the central parts of grains. Associated with the exsolution are well-developed shiller of titaniferous magnetite and plates of pseudobrookite. Plates of biotite are common at the margins of augite grains.

A planar orientation of grains and a layering resulting largely from variations in olivine content are prevalent throughout the dike. The layers range in thickness from less than one inch to several feet. In the area southeast of Nickel Lake, there are some layers that contain more than 50 percent olivine. Because of the extreme variations in dip and strike of these planar features and of the presence of highly contorted and truncated layers, it is assumed that most of the dike was emplaced as a flowing mass.

The dike grades southwestward into the troctolite units near Omaday Lake. In the gradational zone, the grain size and plagioclase content gradually increase southwestward, and the elongate olivine grains give way to more equidimensional grains. In contrast, the contact of the dike with the anorthositic rocks is sharp. This contact is particularly well shown in a recently burned area in the northwest corner of section 28.

Within the dike there are numerous inclusions of various rock types as well as intrusions of pegmatitic gabbro. Inclusions of anorthositic rocks range in size from a few inches across to large blocks such as the one mapped in the northeast quarter of Section 29. Gabbroic anorthosite inclusions several feet across occur on both the east and west shores of Gabbro Lake. Other small inclusions, rounded and shaped more or less like tear-drops, are found along the steeply-dipping layers in NW1/2 sec. 28. In SE1/4 sec. 30, north of Omaday Lake, there is a 1,500-foot long inclusion of banded iron-formation in which coarse quartzite and magnetite layers are interlayered with iron-silicate layers. Many fine-grained inclusions may be hornfels derived from the Virginia Formation; others may be fine-grained margins of the dike, which have been broken off and carried along in the flowing magma. In the burned area of NW1/4 sec. 28 there are several of these fine-grained inclusions concentrated near the southeast margin of the dike. These inclusions contain clots of fine-grained plagioclase one-inch in maximum dimension.

An intrusive gabbroic pegmatite rich in magnetite-ilmenite occurs along the central part of the dike. The same pegmatitic material also occurs in several small dikes throughout the main mass of the troctolite dike. Some elongate hornblende grains are present in the pegmatitic dikes.

At Gabbro Lake, the dike appears to break up into several small dikes, and concomitantly the general trend of the dikes changes from northeast to southeast. Whether these dikes are related to the troctolite of the Bald Eagle Intrusion is not known, for no outcrops of the dikes were discovered in direct contact with the Bald Eagle Intrusion.

The major mass of troctolite in the South Kawishiwi Intrusion consists of three units: the contact zone, augite troctolite, and poikilitic augite troctolite. The contact zone is characterized by very irregular textures and mineral assemblages, and contains numerous fine-grained inclusions. Some of the inclusions are fine-grained gabbro and may represent fragments of a chilled margin, whereas others are definitely fragments of the Virginia Formation. Also, many inclusions of anorthositic rock types occur in the contact zone, and patches of gabbroic pegmatite are present sporadically. Plagioclase is the predominant mineral; the mafic minerals are mostly olivine and pyroxenes with a few percent of iron-titanium oxides. All of these appear to be in part primary, whereas in the other troctolite units of the South Kawishiwi Intrusion pyroxenes and oxides appear to be entirely interstitial. The olivine in the contact zone appears to contain slightly more iron (Fa_{50}) than that in the other troctolite units of this intrusion (Fa_{40}). Gossans are common throughout the contact zone, and contain primarily the sulfides chalcopyrite, pyrrhotite, and pentlandite as well as some cubanite. Mapping of surface outcrops failed to disclose any significant structural trends in the contact zone, for plagioclase is poorly oriented and layering is rare and irregular.

The troctolite contains plagioclase laths about one centimeter long and subhedral olivine grains about 5 mm across as primary cumulate minerals. Augite, magnetite, biotite, and some hypersthene occur as interstitial material. Augite normally occurs as medium-sized grains, but also as large grains several inches across. Augite and oxides generally occur in clusters of grains throughout the augite troctolite.

Many plagioclase grains have normal zoning over a range of 5 to 10 percent An. Within most plagioclase grains there is a well-developed shiller consisting of fine brown needles that are probably ilmenite. Alteration is rare except along some fractures in olivine. Some of the interstitial hypersthene mantles olivine. Augite contains extensive exsolution lamellae of hypersthene, especially in the central parts of the grains. Associated with the exsolution are shiller of titaniferous magnetite and plates of pseudobrookite. Biotite plates are common at the margins of augite grains. Biotite occurs as both rims that mantle ilmenite or as sympletic intergrowths with ilmenite.

A few iron-formation and hornfels inclusions occur in the unit. Several large anorthositic bodies, some being elongate and nearly two miles long, occur in the augite troctolite. These bodies may be large inclusions, plagioclase-rich segregations within the troctolite, or mounds, ridges, or pendants protruding from underlying or overlying anorthositic rocks into the younger troctolite. Textures in these outcrops are very similar to those in the main mass of anorthositic rocks. Some smaller units of anorthosite (sa) also occur within this unit, but are more predominant in the poikilitic augite troctolite and will be discussed under that rock type.

Although the strikes and dips of oriented plagioclase laths and of layers resulting from variations in mineral proportions are quite irregular throughout the augite troctolite, the dip seems to be about 10° to 20° SE. This attitude is conformable with the overlying poikilitic troctolite.

The augite troctolite grades into the poikilitic augite troctolite across a distance of 300 to 400 yards. Clusters of augite and oxides gradually give way to poikilitic grains a few inches in diameter, and also biotite and augite gradually decrease in amount. In the poikilitic augite troctolite, the grain size, textural relations, and composition of the plagioclase and olivine, as well as exsolution, shiller and pseudobrookite plates in augite, are virtually identical to those of the augite troctolite. Along the eastern margin of this unit, at the contact with anorthositic rocks, the olivine content within the lowest few hundred feet significantly increases and comprises as much as 30-40 percent of the rock. Numerous examples of gradational layering occur throughout the poikilitic troctolite.

At all localities where both mineralogic layering and plagioclase orientation are observed they are conformable. With few exceptions, the plagioclase has a well-defined planar orientation. Northwest of Heart Lake there are dozens of repeated cycles of gradational layers containing higher olivine to plagioclase ratios at the base than at the top. These layers are generally one and one-half to two feet thick. The layering and plagioclase orientation throughout this unit appear to define a synformal, or possibly an elongate basin-like structure, that has an axis trending south-southwest across Minnesota Highway #1. In the vicinity of Harris Lake the structural relations become more complex and are not entirely understood. Perhaps this may be a zone of slumping towards the central part of the basin. There seems little doubt that, in general, the structures in the augite and poikilitic troctolite formed through accumulation of settling grains.

Many lenticular anorthosite masses ranging in diameter from a few inches to about one-quarter of a mile occur throughout both the poikilitic troctolite and the augite troctolite. The largest of the lenses in the outcrops examined in this area has a diameter of about 400 meters. Similar anorthosite masses occur along the continuation of this troctolite unit to the southwest, in the Babbitt Northeast quadrangle, which is presently being mapped. The anorthosite masses contain 95 to 98 percent plagioclase, which is well foliated, and sparse poikilitic olivine, which is aggregated into "spots" between 1 and 2 cm in diameter. Planar plagioclase grains produce a foliation in both the anorthosite and the surrounding troctolite that is parallel to the compositional layering in the troctolite; contacts between the two rock types, however, are sharp, and in a few exposures can be seen to crosscut the plagioclase foliation. About 100 meters from the contact of one of the larger anorthosite masses, the troctolite contains a few 1/2-to one-meter diameter inclusions of the anorthosite that have the same grain size and poikilitic olivine as the larger nearby mass. In contrast to the conformable plagioclase orientation mentioned above, these small inclusions contain plagioclase that is oriented differently than in the surrounding troctolite; and the plagioclase laths in the troctolite at the margins of the inclusions are deflected into positions which parallel the perimeter of the inclusions. These inclusions suggest that the troctolite consolidated later than the anorthosite. The composition of plagioclases in the lens-like masses of anorthosite is in the range An_{60}-An_{68}, and in the troctolite An_{57}-An_{67}. The composition of olivine in the oikocrysts of the anorthosite is Fo_{60} - Fo_{62}, and in the troctolite Fo_{59}-Fo_{62}. Whether these masses are large segregations of plagioclase within the troctolite or inclusions from some unknown unit remains an unsolved question. The concordancy of the plagioclase orientation, some interfingering at contacts, and similarity of mineral compositions seem to indicate that the masses are large segregations of plagioclase within the troctolite.

Southwest of August Lake and about one mile west of the southern tip of Gabbro Lake, troctolitic and anorthositic rocks are intermixed rather irregularly. The northernmost of the mixed zones shows very irregular banding and textural relations, and the southernmost one has troctolite that contains a flow structure similar to that in the troctolite of the Bald Eagle Intrusion, and which occurs in elongate zones surrounded by typical anorthositic rocks. Possibly these troctolites are dikes and sill-like extensions of the Bald Eagle troctolite into the anorthositic rocks.

Smaller Intrusives

Several outcrops of norite are present along the northwest shore of Gabbro Lake. Laths of plagioclase one centimeter or more long and hypersthene 5 - 10 mm across make up the primary minerals of the norite. Interstitial augite, oxides, and biotite make up most of the remainder of the rock. The norite shows crosscutting relations to the country rock, and is much finer grained within a few inches of the contact. The finer-grained margin can be seen along the shoreline on the point west of the center of section 16. It is possible that this intrusion may be the cause of the domical structure in this area.

Several isolated outcrops of basaltic dikes a few inches to a few feet wide have been observed, primarily in the anorthositic rocks. The chilled margins of the dikes suggest that they intruded after the anorthositic material had cooled. Because these dikes are isolated and could not be traced from outcrop to outcrop, they are not shown on the map.

Three zones of granite dikes, all in anorthositic rocks, have been noted. One of these, at the western end of Gabbro Lake at the end of the inlet that extends into SE1/4 SW1/4 sec. 16, is a 6-inch wide granite dike that trends N. 15° E. and dips 50° W. The granite is red and has a micrographic texture interstitial to quartz and feldspar. A set of four parallel dikes ranging from five inches to a foot thick occurs in the southeastern part of Gabbro Lake, on the south shore of the island that straddles the line between sections 22 and 23. These dikes are red and coarse-grained but have no micrographic texture. They trend N. 60° E. and dip 79° NW. Two parallel granite dikes, one-inch and one-foot wide respectively, occur on the north shore of Pietro Lake in NE1/4 NE1/4 sec. 18. These dikes are white, have coarse-grained margins, trend N. 25° E., and dip vertically. They have much micrographic texture, and contain 61 percent potassium feldspar and 33 percent quartz.

In many places the anorthositic rocks contain joint fillings of a pink or red granophyric material, which is accompanied by sausseritization and sericitization of the adjacent few inches of gabbro. Green chloritic and, rarely, zeolitic joint fillings, which are accompanied by the same type of alteration are found locally in the same areas. Although similar joint fillings and alteration were not found in the troctolite, a few zones of alteration were found. In contrast to the anorthosite, alteration was not limited to joint fillings, but instead consisted of sericitization of plagioclase and formation of green amphibole from the mafic minerals over rather broad irregularly shaped areas. One such area occurs on the southwest side of State Highway #1, extending from the northwest corner of section 11 for a distance of about 1,500 feet into the section.

Economic Geology

Various assemblages of copper, iron, and nickel sulfides occur near the basal contact of the troctolite intrusion southeast of the Kawishiwi River. The surface expression of the sulfide concentrations are typical brown oxidized gossans. As shown on the geologic map (Green, Phinney, and Weiblen, 1966), these occur discontinuously along a roughly linear zone parallel to the base of the gabbro; generally the gossans are a few hundred feet east of the basal contact. Gossans do not seem to be present in the anorthositic rocks, but rather are confined to the troctolite, including its dike-like appendage that extends northeastward from Omaday Lake.

The troctolite in the vicinity of the sulfide concentrations commonly contains many inclusions, some of which appear to be fine-grained gabbro; others are hornfels which may represent the Virginia Formation or the Biwabik Iron-formation, and still others are gabbroic anorthosites. The sulfide-bearing gabbroic and troctolitic rocks are characteristically inhomogeneous, and the sulfides occur with various combinations of types and sizes of silicate minerals. In some places the host is very plagioclase-rich and in others olivine-rich; also, the host may be very coarse-grained or quite fine-grained. In nearly all cases, however, the sulfides appear to fill the interstices between plagioclase and olivine grains.

Abandoned quarries from which dimension stone was taken a few decades ago are present at two localities in the poikilitic augite troctolite along State Highway #1. One of these is located 400 feet north of the highway, about 300 feet east of the line between sections 13 and 18. The other is located 1,500 feet south of the highway, along a trail from it towards the center of section 11 (at a horizontal layering symbol on the map).

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