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Lower Precambrian Rocks of the Gabbro Lake Quadrangle, Northeastern Minnesota

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LOWER PRECAMBRIAN ROCKS OF THE GABBRO LAKE QUADRANGLE, NORTHEASTERN MINNESOTA

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ABSTRACT

In an approximately 100-square-mile area east of Ely in the center of the Vermilion district, three major stratigraphic units are mapped. The oldest unit, the Ely Greenstone, contains at least 12,000 feet of dominantly metabasaltic rocks, and the base is not exposed. Thin chert-siderite and chert-magnetite iron-formations are interbedded with the lavas. Overlying this unit essentially conformably (though with a basal conglomerate composed of Ely Greenstone clasts) are at least 5,000 feet of graywackes, argillites, slates, and felsic to intermediate pyroclastic rocks and their clastic debris, which constitute the Knife Lake Group. Apparently stratigraphically above the Knife Lake Group, as here defined, is a thick sequence of felsic and intermediate volcanic rocks, mostly pyroclastic, that interfingers to the west with metabasalts; this sequence has been named the Newton Lake Formation. This unit, which may be continuous with rocks to the east included by Gruner (1941) in the Knife Lake Group, consists of at least 8,000 feet of strata, including a thick sequence of mafic clastic rocks and a 500-foot thick lens of recrystallized calcareous chert. Along the North Kawishiwi River another thick group of metaconglomerates and metagraywackes, now gneisses and schists, is faulted against the lower part of the Ely Greenstone. These rocks are tentatively assigned to the Knife Lake Group.

The stratified rocks are intruded by a variety of porphyries, including a regionally widespread porphyritic dacite-rhyodacite that was extruded onto the surface in Late Ely Greenstone time. The Ely Greenstone and the Knife Lake metasedimentary rocks along the North Kawishiwi River were metamorphosed and intruded by the granitic rocks of the Giants Range batholith, which is dominated in this area by two facies, a non-porphyritic (Clear Lake) and a porphyritic (Farm Lake) type. Both facies are composed predominantly of hornblende-biotite adamellite, monzonite, and granodiorite, and contain many local variations including mafic types. Most of the contacts within the batholith are unchilled, and many suggest physical mixing of viscous magmas. Fine-grained biotite adamellite is the youngest mappable phase, and aplite and pegmatite dikes are common. A variety of dioritic and gabbroic dikes cut the batholith but they are metamorphosed by it.

At the northwestern margin of the quadrangle are several small outlying plutons of the Vermilion batholith, which has metamorphosed the adjacent rocks. Southeast of Fall Lake, granitic rocks have been faulted upward into the Knife Lake metasedimentary rocks, and southeast of Stub Lake small bodies of pink quartz syenite to granodiorite intrude the Ely Greenstone. Keweenawan

diabase dikes cut all the major stratigraphic units and the Lower Precambrian structures.

The entire structural deformation of the Lower Precambrian rocks in this area is attributable to the Algoman orogeny (2.6-2.5 b.y. ago). The strata are nearly vertical, and depositional structures indicate that tops are generally to the north, away from the North Kawishiwi fault. There is local internal isoclinal folding, however, in all the formations. Faults are of particular significance, and at least some followed intrusion of the batholith. Several eastward- to northeastward-trending faults of regional importance cross the area, and lesser north-northeastward- and northeastward-trending faults with apparent displacements of as much as two miles cut the Ely Greenstone into many blocks. Strong, steeply-plunging lineations are widespread in the northern edge of the area and along the North Kawishiwi River. Kink-folds with gently-plunging or vertical axes, which represent minor displacements and a higher level of deformation, are superimposed on the earlier structures, especially in a zone centered in the Knife Lake belt. Their age is unknown but probably is late Algoman.

Metamorphism of the stratified rocks is generally of very low grade (greenschist facies), and a lack of equilibrium is widespread. Near the Vermilion and Giants Range batholiths, epidote-amphibolite and amphibolite facies are attained, and next to the Duluth Complex is a narrow zone of pyroxene hornfels.

Although much effort has been spent in the past in prospecting the iron-formations, no economically viable deposits have been found in this area. Sulfides, as disseminations and small veins, are scattered through the greenstones and rarely in other rocks, and exploration for sulfide deposits currently is in progress.

INTRODUCTION

Present Study

The mapping was begun in 1962 as the first step in a large-scale re-study by the Minnesota Geological Survey of the major geologic elements of the Precambrian rocks of northeastern Minnesota. The Gabbro Lake 15-minute quadrangle was chosen because it included, according to the earlier work, parts of the Ely Greenstone, Knife Lake Group, Giants Range batholith, and the Duluth Complex, all highly interesting from economic as well as petrologic viewpoints. The fairly detailed mapping in this area should be valuable in interpreting relationships within and between these units to the east and west. The study already has brought out some major relationships — further elucidated in subsequent mapping to the west (*e.g.*, Sims and others, 1968) — that had only been dimly anticipated if at all in most of the earlier work. In particular, the importance of faulting in the regional and local structure, the rejection of the old idea of a single volcanic unit ("Ely Greenstone") versus a single metasedimentary unit ("Knife Lake Group"), the contemporaneity of at least some of the dacite porphyry with Ely Greenstone, the nonexistence of a major continuous iron-formation at the top of the Ely Greenstone, and the lack of an important angular discordance between Ely Greenstone and overlying metasedimentary rocks, are of regional significance.

Field work was carried out principally during the summers of 1962, 1963, and 1964; a short visit to the area was made in 1965. Aerial photographs at a scale of 1:23,600 were used as a base. Daily traverses were made from base camps at the east and west sides of the area and also from eight temporary tent camps, in areas accessible only by canoe.

The geologic map was compiled in 1965-66 and published in 1966 as Minnesota Geological Survey Miscellaneous Map 2 (Green, Phinney and Weiblen, 1966). All references in this report to "the geologic map" refer to this map. Since that time minor field checks and considerable petrographic study have been made, resulting in minor changes in interpretation; these are mentioned in the body of this report, which was written primarily during 1969. The report has also benefited from reconnaissance by the writer to the east, north, and west in adjacent quadrangles since mapping was completed in the Gabbro Lake quadrangle.

In this report, certain conventions are followed in describing the rocks. Grain size is classified as follows: fine-grained = <1 mm; medium-grained = 1-5 mm; coarse-grained = >5 mm; dense = aphanitic. In metamorphic rock descriptions the term "gneiss" is used for phaneritic, foliated or lineated rocks that do not split readily along the foliation or lineation. These rocks merge into granofelses with loss of foliation or lineation, and into schists with greater tendency to break along their structural elements. For igneous rock descriptions the following classification was used (table 1). Major minerals present but not implied by the rock name are prefixed (*e.g.*, "hornblende-biotite adamellite"; "quartz andesite").

Previous Work

Early reconnaissance in this part of the Vermilion district was carried out by several geologists, particularly R. D. Irving and C. R. Van Hise of the U. S. Geological Survey, and Alexander Winchell, H. V. Winchell, and N. H. Winchell, U. S. Grant II, and A. H. Elftman of the Minnesota Geological and Natural History Survey; their work has been well summarized by Clements (1903, pp. 70-127). In these studies of the 1880's and 90's, many of the major geologic relationships and units were described, but the monumental work of J. Morgan Clements on "The Vermilion Iron-Bearing District of Minnesota", (U. S. Geological Survey Monograph 45, 1903) appeared to settle many of the controversies that had arisen and established for a considerable period of time the stratigraphic and structural understanding of the area. Clements' map, at a scale of two miles to the inch, covered all the stratified rocks included in the Gabbro Lake quadrangle; however, Clements did not concern himself with the intrusive rocks to the north or south, except for their contact relationships with the supracrustal rocks. A comparison of Clements' map with the new work shows that his major contacts generally were accurately placed, but a major difference was his placing of fragmental (and some pillowed) andesites in the Ogishke Con-

Table 1 — Field classification of igneous rocks

Feldspar	Potassic feldspar predominant (>67%)		2 Feldspars about equal		Plagioclase predominant (67%-95%)		Plagioclase >95%			
							Generally <50% An		Generally >50% An	
Mafics	Generally increasing mafics → mostly biotite and/or hornblende								40-95%, mostly pyroxene & olivine	
Quartz	+ Qtz.	No Qtz.	+ Qtz.	No Qtz.	+ Qtz.	No Qtz.	+ Qtz.	No Qtz.	+ Qtz.	No Qtz.
Phaneritic	Granite	Syenite	Adamellite	Monzonite	Granodiorite	Syenodiorite (and Syenogabbro)	Tonalite	Diorite	Quartz gabbro	Gabbro
Aphanitic	Rhyolite	Trachyte	Quartz latite	Latite	Rhyodacite	Trachyandesite (and Trachybasalt)	Dacite	Andesite	Quartz basalt	Basalt
	Felsite								Basalt	

glomerate; these rocks now are assigned to the Newton Lake Formation and the Knife Lake Group. Another major change is the reassignment of the volcanic rocks northwest of the Knife Lake belt from the Ely Greenstone (Clements) to the Newton Lake Formation (Morey and others, see below). Clements' (1903) stratigraphic interpretation and nomenclature are shown below:

Gunflint Formation, Rove slates	Upper Huronian
	Unconformity
Granites (Giants Range), various dikes	
Knife Lake slates	Lower Huronian
Agawa Formation (iron-bearing)	
Ogishke Conglomerate	
	Unconformity
Granites (Basswood, Burntside Lake) and porphyries	
Soudan Formation (iron-bearing)	Archean
Ely Greenstone	

Several aspects of this standard section have come under doubt or have been discredited as more modern work has been done in the district.

The debate about the existence in Minnesota of the "Coutchiching Series," defined apparently as a major metasedimentary sequence underlying the metabasaltic Keewatin Greenstone (including the Ely Greenstone), has continued since the late 19th century (Lawson, 1888); it is still the subject of intensive study by detailed mapping and radiometric age determinations (*e.g.*, Hart and Davis, 1969). These studies have considerable bearing on the validity of Clements' stratigraphy in that he recognized only one metavolcanic and one metasedimentary sequence. Sutton's (1963) mapping in the pre-Animikie rocks of the Virginia Horn area showed by depositional structures that the slate-graywacke sequence in that area underlies the greenstone there exposed. At Soudan, 18 miles west of Ely, Klinger (1956) also found metasediments stratigraphically underlying greenstone.

A. C. Lawson's extensive work, mainly on the Canadian side of the border, resulted in a revision of the generally accepted names for the major series and orogenies, as shown below (Lawson, 1913):

$$\text{Algonkian}\begin{cases}\text{Keweenawan}\\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\text{unconformity}\\ \text{Animikie}\end{cases}$$

Eparchean interval .... unconformity
Algoman granitic rocks, orogeny

$$\text{Huronian}\begin{cases}\text{Upper}\\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\text{unconformity}\\ \text{Lower}\end{cases}$$

.... unconformity
Laurentian granitic gneisses, orogeny

$$\text{Ontarian}\begin{cases}\text{Keewatin}\\ \text{Coutchiching}\end{cases}$$

The Keewatin, as used by Lawson, included the Ely Greenstone and Soudan Iron-formation.

F. F. Grout (1925) studied the Vermilion batholith north and northwest of Ely, and concluded that it, as well as the Giants Range batholith (Allison, 1925), was intruded after deposition of the Knife Lake slates and is thus associated with Lawson's Algoman orogeny.

In 1941, J. W. Gruner published the results of a major effort of detailed mapping of the 28-mile belt from Moose Lake eastward to Saganaga Lake that had been mapped by Clements as Lower Huronian (principally Knife Lake slates). He found that (1) the "Ogishke conglomerate" of Clements was not worthy of formational status as it is very lensoid and discontinuous and appears at several horizons within the "Lower Huronian" metasediments; (2) Clements' "Agawa Formation" should also be discredited as it is very thin and discontinuous, and in fact many exposures so mapped by Clements proved to be vein deposits containing ferrous carbonate; and (3) major portions of the "Lower Huronian" consist of felsic to intermediate volcanic rocks, principally pyroclastic, and their clastic debris. Some of these are similar to rocks mapped by me as Newton Lake Formation in the northern part of the Gabbro Lake quadrangle, which earlier had been called Ely Greenstone by Clements. Gruner was able to subdivide the entire Knife Lake "Series" into nineteen mappable units, but found that these were so commonly separated by major faults of unknown displacement that several could represent lateral facies equivalents of each other, and that correlation from one fault slice or block to another is hazardous if not impossible. He also abandoned use of the terms "Lower Huronian" and "Upper Huronian" because their use obscures the significance of the major unconformity beneath the Animikie ("Upper Huronian").

No further field work was done in the Archean rocks of the Gabbro Lake quadrangle until the initiation of the present study in 1962.

In a review of the Precambrian stratigraphy of Minnesota in 1951, Grout and others found general agreement with Lawson's column as modified by Gruner.

Goldich and others published in 1961 a further review and revision of the Precambrian of Minnesota, based in large part on recent radiometric age determinations. For the Vermilion district, one of the chief results was the demonstration of the age equivalence, insofar as current techniques could tell, of the Vermilion batholith (Basswood Lake, Burntside Lake) and the Giants Range batholith. However, this work could not distinguish the age of the "Algoman" granitic intrusions from that of the "Laurentian" Saganaga granite, which clearly is unconformably overlain by conglomerate associated with the Knife Lake Group. Combining all the strata of the Vermilion district into the Early Precambrian, Goldich and others (1961) agreed on the following nomenclature and sequence:

Middle Precambrian	Huronian	Animikie Group	
. . . .	Algoman orogeny, granitic rocks		
Early Precambrian	Timiskamian	Knife Lake Group	
	. . . . Laurentian orogeny, granitic rocks		
	Ontarian	Keewatin Gp.	Soudan Iron-formation Ely Greenstone
		Coutchiching (?)	
			Older rocks

It is the purpose of the present study to further elucidate the details of stratigraphy and structure of this part of the Vermilion district and to provide a base for further work on specific aspects of the geology.

Acknowledgments

This report and geologic map are a part of the mapping program of the Minnesota Geological Survey, which supported the field work and provided thin sections, some of the chemical analyses, and much of the time for preparation of the report. The field work was assisted by C. Marshall Payne, Robert E. Bell, William L. Griffin, and Antoni Wodzicki. Wodzicki was solely responsible for mapping several small areas in the quadrangle. Personnel of the U. S. Forest Service, Superior National Forest, Kawishiwi District, kindly gave permission for use of the Fernberg Lookout cabin and provided other assistance and information. A Grant in Aid of Research from the Graduate School of the University of Minnesota paid for many of the chemical analyses of metavolcanic rocks, and is much appreciated. Rapid-method analyses of many specimens for base and precious metals were kindly provided by the U. S. Geological Survey. The United States Steel Corporation, Jones & Laughlin Steel Corporation, and the Garden Lake Iron Company allowed the use of unpublished dip-needle, outcrop mapping, and drilling records. Finally, the writer has benefited from valuable discussions of regional and local geology with many geologists, but particularly with other members of the Minnesota Geological Survey, including W. L. Griffin, Antoni Wodzicki, W. C. Phinney, and especially G. B. Morey, R. W. Ojakangas, and P. K. Sims.

STRATIGRAPHY

Introduction

One of the most vexing problems to a geologist working in unfossiliferous, eugeosynclinal or mobile-belt areas is the difficulty in finding dependable criteria for the correlation of strata. In the Vermilion district this problem is a severe one, and the dependence in earlier work on lithic similarity for correlation probably has slowed progress toward a realistic picture of the geologic history and structure. Several different rock types, grossly uniform from place to place, recur commonly over much of the length of the Vermilion district, and have been used essentially to define major stratigraphic units, and even time intervals. For example, pillowed metabasalt has meant "Ely Greenstone"; conglomerate and metagraywacke and slate (or phyllite) have meant "Knife Lake"; banded, cherty iron-formation has meant "Soudan"; and quartz porphyry has been assumed to be "Laurentian" (post-Ely, pre-Knife Lake). Careful mapping elsewhere in the Canadian Shield and younger orogenic areas (*e.g.*, Pettijohn, 1937) has indicated, however, that such generalizations are unlikely to be valid over such a large area of mobile crust.

In fact, the recent detailed field investigations in the Gabbro Lake quadrangle and in the Vermilion district (*e.g.*, Sutton, 1963; Sims and others, 1968) have clearly demonstrated the impossibility of long-distance correlation on lithic similarity. This in turn implies the necessity, undoubtedly anticipated by Clements and earlier workers, of reorganizing our ideas of the local geologic history and paleogeography according to new evidence coupled with a more sophisticated appreciation of the complexities of orogenic belts. Therefore, an attempt has been made in this report to use stratigraphic names only in a restricted and locally defined sense.

However, several considerations—the continuing "Coutchiching problem," Sutton's work in the Virginia Horn area, the strong discordance of fold structures in the Saganaga Lake area suggesting an earlier and later series of greenstone and clastic rocks, recent mapping by R. W. Ojakangas and G. B. Morey in the Tower-Soudan area (Minn. Geol. Survey, in prep.) and by R. W. Ojakangas in the Rainy Lake-International Falls area (Sims and Westfall, 1969), and the evidence in the Gabbro Lake quadrangle — tend to place in doubt the validity of a major distinction between "Keewatin," "Coutchiching," and "Knife Lake" as regional time-stratigraphic terms. The same doubt would also apply to the distinction between Ontarian and Timiskamian as used by Goldich and others (1961). In view of the difficulty of long-distance correlation of these rocks, it is beginning to seem more realistic to group all these clastic and volcanic series together, although in local areas certain time relations between units can be inferred.

As an example, the terms "Ely Greenstone" and "Keewatin Greenstone" (Ontarian) have been considered essentially equivalent in northern Minnesota, but in the Gabbro Lake quadrangle what was formerly called Ely Greenstone is now known to consist of two major and distinct units, one older and one younger than metasedimentary rocks that are clearly equivalent to Gruner's "type" Knife Lake (Timiskamian). The term "Keewatin" was originally applied by Lawson (1885) to greenstones near Lake of the Woods in Ontario, 150 miles to the northwest. He traced these rocks to the east into mafic metavolcanic rocks at Rainy Lake, which he thus also considered to be Keewatin; and Van Hise and Clements in 1901 correlated greenstones in the Ely area with the Keewatin series by gross lithologic similarity. Pettijohn (1937), however, suggested that there might be more than one greenstone sequence in this part of Ontario; furthermore, the Vermilion batholith separates the Rainy Lake exposures from those at Ely.

The formation name "Ely Greenstone" has been used since it was proposed by Van Hise and Clements (1901) to include all metavolcanic strata (which are principally mafic in this district) except the intermediate and felsic pyroclastic rocks described by Gruner (1941) in the Knife Lake area, immediately to the east of the Gabbro Lake quadrangle. Although Gruner found pillowed greenstone surrounded by rocks that he had mapped as part of the Knife Lake Series, he concluded that the metabasalt belonged to the Ely, and that "no ellipsoidal greenstone flows formed during Knife Lake time" (p. 1640). The present study, and subsequent reconnaissance to the north, northwest, and west, have shown, however, that: (1) rare metabasalts, some of which are pillowed, are interbedded with metasediments that are continuous with Gruner's Knife Lake Group; (2) felsic and intermediate pyroclastic rocks, identical to those mapped by Gruner as part of the Knife Lake Group (across some faults) about five miles to the northeast, intertongue with metabasalts in the northwest corner of the Gabbro Lake quadrangle; and (3) the contact between these metavolcanic rocks and the Knife Lake metasediments, though faulted at the western border of the quadrangle, is at least nearly conformable, with no sign of the intensive shearing that characterizes most faults in this area, for the rest of the distance across the quadrangle to the east. The Knife Lake metasediments, on the other hand, overlie the belt of greenstones to the south that continues directly westward to the town of Ely. These observations, plus lithic differences, imply that the metavolcanic rocks that lie north of the Knife Lake metasedimentary belt, are not equivalent to the Ely Greenstone belt *sensu stricto* south of it, even though Clements had mapped them all as Ely Greenstone. For this reason the northern belt was distinguished on the geologic map as an "un-named formation," awaiting further regional investigations. In this report the name "Newton Lake Formation" is used for these rocks (Morey and others, 1970; see regional map, pl. 1).

The distribution of metasedimentary rocks among the various stratigraphic units also calls for comment. It should here be noted that the distinction in the field, and even in thin section, between some volcanic graywackes and tuffs, and even between them and some metabasalts, is often difficult in this area. Clastic metasedimentary rocks (graywackes, conglomerates, some argillites), as well as iron-formation stringers, were found in both major mafic metavolcanic units (Ely Greenstone and Newton Lake Formation), and volcanic rocks, including flows as well as pyroclastic deposits, were found in the predominantly metasedimentary Knife Lake unit. In the Ely Greenstone, for instance, a rather persistent stratum of metagraywacke and conglomerate several tens of feet thick is found roughly 1,000 feet below the top of the formation, overlain by more pillowed flows. Other, smaller metasedimentary stringers and strata were seen widely scattered throughout it. In the Newton Lake Formation, at least one rather thick sequence (possibly a few thousand feet) of clastic metasedimentary rocks was found, but its structural relationship to the nearby metavolcanic rocks is unclear. In view of these observations, further regional use of the stratigraphic names "Ely Greenstone" and "Knife Lake" must be done only with great caution unless these terms are to be redefined. This caution is more especially necessary because of the major faults that separate the district into slices and blocks (Sims and others, 1968).

Another regional generalization commonly held since Clements' work has been the existence of a major iron-formation unit, the Soudan Iron-formation, at the top of the Ely Greenstone and directly beneath the Knife Lake Group. In the Gabbro Lake quadrangle no such unit is present; the apparently conformable top contact of the Ely Greenstone lies on metabasalt, and the stratigraphically highest mappable stratum of iron-formation, itself only 20-50 feet thick, is some 2,000-4,000 feet below the top. Similar, and thinner iron-formation beds and stringers are found at many horizons throughout the Ely Greenstone, but no iron-rich stratum of formational or member status exists in this quadrangle. Furthermore, recent mapping to the west (Sims and others, 1968) indicates that the major ore zone at Ely (in the "Ely trough") may not be the same horizon as that at Tower-Soudan.

Dikes and other small intrusive bodies of dacite porphyry, very similar to those in the present area, are common throughout much of the Vermilion district. Previous workers have found pebbles of this rock in Knife Lake conglomerates, and have found "the" dacite porphyry to cut Ely Greenstone but not rocks of the Knife Lake Group. These observations have led geologists to assign a "Laurentian" age to these intrusions, analogous to the post-"Ely Greenstone" pre-"Knife Lake" relationships of the Saganaga Granite, 24 miles to the northeast (Goldich and others, 1961). In the Gabbro Lake quadrangle many dikes and small bodies of this rock cut the Ely Greenstone, but a large, partly concordant mass of identical rock in and east of Jasper Lake appears to have vented to the surface during Ely Greenstone time; unmistakable clasts of it are found in grit and conglomerate pockets and lenses on its upper flank and farther away, overlain by more pillowed greenstone, and it shows pyroclastic structure itself on certain weathered surfaces in the area one mile east of Jasper Lake. Elsewhere (¼ mile east of Camp 20 Lake, NW¼ sec. 7, T. 63 N., R. 9 W.) this rock, containing inclusions of greenstone, can be seen to intrude a conglomerate lens (within the Ely Greenstone) that itself contains pebbles of the same dacite porphyry (see figs. 1 and 2). Clearly, this rock is at least in part contemporaneous with Ely Greenstone volcanism, and became exposed, by eruption and erosion, at the surface during that time. In accord with previous investigations,

Figure 1. Dacite porphyry that contains greenstone xenoliths intrudes conglomerate that has dacite porphyry pebbles, M-7382, sec. 7, 63 N/9 W. In Ely Greenstone.

this study found the dacite porphyry generally restricted to the Ely Greenstone; two significant exceptions were noted, however, where it apparently cuts the lower parts of the Knife Lake metasedimentary rocks: SW¼ sec. 35, T. 64 N., R. 10 W.; and S. shore Moose Lake. This characteristic dacite porphyry has not been found cutting the northern metavolcanic belt (Newton Lake Formation). Thus, the time of dacite magmatism here was mostly coincident with Ely Greenstone extrusion but apparently slightly overlapped the time of transition from predominant mafic volcanism (Ely Greenstone) to predominant clastic sedimentation and felsic volcanism (Knife Lake).

Another problem of regional significance for which evidence has been uncovered in the Gabbro Lake quadrangle is the possible existence of sialic basement beneath the Ely Greenstone. Pebbles and cobbles having a granitoid texture were found at three localities in the quadrangle: (1) in conglomerate and grit interbedded with metabasalt of the Ely Greenstone, just southeast of the center of sec. 8, T. 63 N., R. 10 W.; (2) in metaconglomerate of the Knife Lake Group along the south shore of the North Kawishiwi River, especially in sec. 26, T. 63 N., R. 11 W.; and (3) in conglomerate interbedded with metabasalt of the Newton Lake Formation, NE¼ sec. 28, T. 64 N., R. 11 W. Clasts that appear granitic in outcrop are rather common in the conglomerates in the Ely Greenstone, but closer inspection, and particularly microscopic study, has shown these to be dacite porphyry with aphanitic groundmass. The granitic clasts in the Ely Greenstone mentioned above are small and uncommon, and only one small pebble was obtained for sectioning. This, and associated granules and sand

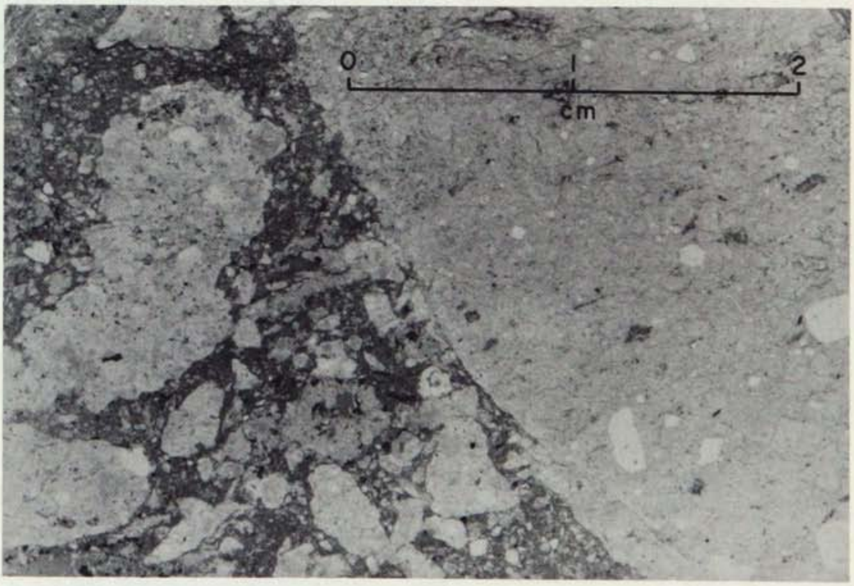

Figure 2. Photomicrograph of breccia in Ely Greenstone that contains clasts of dacite porphyry, M-7346, sec. 12, 63 N/10 W.

grains, contains alkali feldspar and quartz and has some granophyric texture, suggesting a fairly shallow depth of crystallization. It does not resemble, either texturally or compositionally, the dacite porphyry or the Saganaga granite, which might be contemporaneous. There is no evidence for the source of these clasts, but they do imply granitic, plutonic activity coeval with, if not earlier than, deposition of the Ely Greenstone. The pebbles and cobbles in the Knife Lake conglomerate cited above are equigranular, pink, and white and do not resemble the Saganaga Granite. Their age and source are also unknown, but again they must have been intruded well before this particular depositional episode of the Knife Lake. The cobbles in the Newton Lake Formation are also equigranular, and both granitic and syenitic varieties were found. Because this formation is thought to overlie the metasediments here referred to the Knife Lake Group, these granitic rocks may have been intruded and unroofed as late as local Knife Lake time, but their plutonic textures and variety suggest that they also may be considerably older and may well antedate the Ely Greenstone. Again, no source area is known. Because of the uncertainty in the age of the metaclastic rocks along the North Kawishiwi River with respect to the main "Knife Lake" belt through Moose and Wood Lakes, it is even possible that the Giants Range batholith (or this end of it at least) is older than the Knife Lake and Newton Lake, and could thus have been a source of these clasts.

Finally, the problems of time-correlation must be stressed again. It must be recognized that the type of strata found in the Vermilion district generally are those associated with rapid deposition on an active, shifting crust. Changes in depositional regime (submarine, basaltic volcanism to clastic deposition to felsic, pyroclastic activity, for example) may not have occurred either at the same time or at the same level of accumulation from one place to another along the district. Moreover, conditions producing a certain type of deposit may well have recurred after such a change, giving two or more sequences of very similar characteristics, yet without internal evidence (such as fossils) by which to distinguish them. It is possible, of course, that subsequent, exacting studies of trace elements or isotope ratios may bring the answer to this problem, but such data are not now available. This probable shifting nature of deposition (rapid lateral facies changes) coupled with the major faults along which the district has been sliced and broken, makes time-equivalence statements quite unwise, and correlation of rock-stratigraphic units highly risky over distances of twenty miles or so along strike, much less across the strike. Thus the Ely Greenstone and the Newton Lake Formation, though both predominantly metabasaltic, have been found to constitute quite separate sequences, on the bases of structural evidence and differences in lithic character. Also, whereas at the east end of the Vermilion district there exists a hiatus between times of basaltic and clastic deposition sufficiently long for the intrusion and unroofing of the Saganaga granite, in the Gabbro Lake quadrangle the Ely Greenstone is overlain apparently with no discernible angular discordance by the Knife Lake metasedimentary rocks. It is as yet impossible to be sure the greenstone-metasediment contacts in the two areas are in fact the same contact; even if this could be demonstrated with further detailed mapping, considerable time-transgression could have occurred, and the hiatus at Saganaga Lake could have been filled with either basaltic or clastic deposition to the west.

Stratified Rocks

Ely Greenstone

General Statement. In this report the name Ely Greenstone is applied only to that belt dominated by metabasalts that passes through the town of Ely (see pl. 1), in contrast to the original application of Van Hise and Clements (1901) to all the metavolcanic sequences in the Vermilion district. Eastward from Ely, this belt passes north of White Iron Lake and the North Kawishiwi River and south of Shagawa, Fall, Wood and Moose Lakes. In the Gabbro Lake quadrangle it is faulted off at its south (stratigraphically lower) side, and is overlain on the north by the Knife Lake Group. Where not faulted, the contact with the overlying Knife Lake Group is characterized by a basal conglomerate that consists dominantly of pebbles of the common rock types of the Ely Greenstone: metabasalt, metadiabase, chert, jasper, and dacite porphyry. This implies some erosion of the underlying formation, but no angular discordance was seen, either on an outcrop or on a quadrangle-wide scale, and therefore little deformation could have occurred in this interval. Mapping in 1969 by the writer about one mile east of the eastern quadrangle boundary, southeast of Fernberg Hill, disclosed an interbedded sequence of conglomerate and pillowed basalt at the contact.

From the vertical bedding, consistently north-facing pillows, presence of non-repetitive distinctive units, and the apparent fault pattern, a minimum of approximately 12,000 feet of strata is estimated to be exposed above the faulted base and below the overlying Knife Lake Group.

Well over 90 percent of this formation is estimated to consist of rocks of basaltic composition. The remaining fraction includes felsic volcanic rocks, chert and banded iron-formation, and clastic rocks. The basaltic rocks are predominantly extrusive, but include abundant intrusive bodies as well, the largest and most continuous of which are shown on the geologic map. At many exposures of massive, slightly coarser-than-normal greenstone it could not be determined whether the rock is the interior of a flow or actually intrusive. Some of these rocks could have been intruded beneath a cover of contemporaneous pillows.

As can be seen on the geologic map, a few rock types could be traced as mappable units over distances of a few miles and across faults, and in the central part of the area a rather consistent sequence was found repeated in several fault blocks. However, because of faulting, local scarcity of outcrops, and probable lenticularity of the units, this sequence could not be extended more than a few miles along strike, and would not necessarily be expected in other areas of the Ely Greenstone. Therefore no type section is here described.

Extrusive metabasalts. At least half the metabasalts show pillow structures and are thought to have been extruded into water. A large amount of massive greenstone is also thought to be basically extrusive because of its aphanitic to fine-grained texture and its concordant structure. Because vesicularity is weakly developed in such rocks, and no typical flow-surface features were seen, they are not considered to be subaerial, and may in fact have been extruded at depths of thousands of feet; Moore (1965) has shown a clear inverse correlation between depth and vesicularity in pillowed basalts on the submarine flanks of Kilauea, Hawaii. The massive strata commonly alternate with pillowed lavas, in layers a few feet to several tens of feet thick. They are typically slightly coarser-grained (0.1-1.0 mm) than the pillowed types (0.1-0.5 mm). This alternation is particularly well exhibited along the shores of Ojibway (Twin) and Triangle Lakes.

Several different types of pillowed greenstone are present (fig. 3). The most common type has smoothly rounded pillows approximately 1 × 1.5-2 × 2-3 feet, but these are rather variable, and one pillow 10 feet across, and another having dimensions of 8 × 3 feet, were noted. The chilled rinds on these pillows range in thickness from 0.5 to 1 cm normally, and are typically paler in color than the interiors. These pillows rarely show vesicles. Interstitial material is locally muddy (tuffaceous?) material, chert, or pillow-

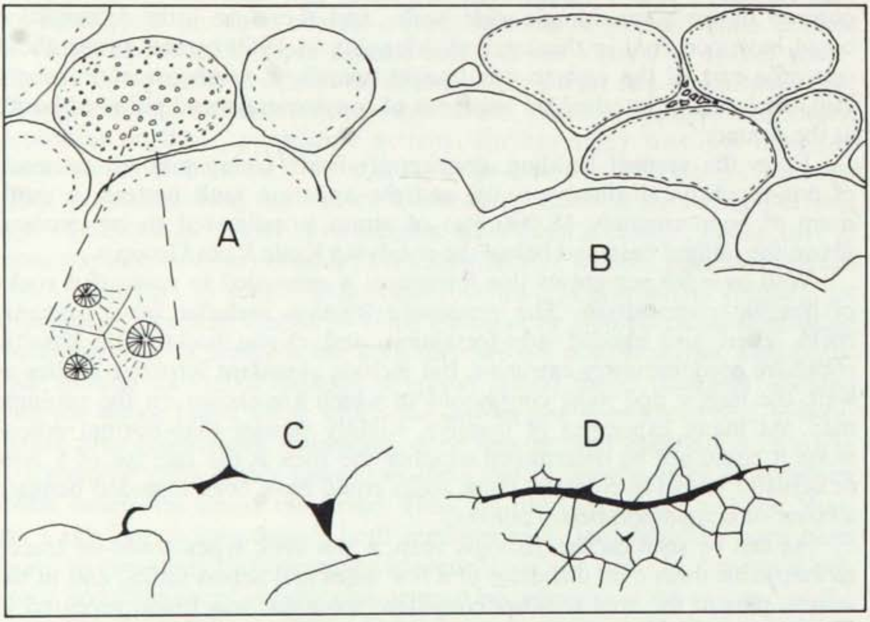

Figure 3. Varieties of metabasalt pillows and variolites in Ely Greenstone. A: variolitic pillows typical of large flow south of Jasper Lake; B: pillow shapes typical of most of the greenstones; C: irregular, thin-rinded pillows, southeastern Triangle Lake (SW¼ SW¼ sec. 13, 63 N/10 W); D: contact between very large pillows or lobes in granular greenstone, eastern Triangle Lake (NE¼, SW¼, sec. 13, 63 N/10 W).

rim breccia. Another fairly common type of pillowed greenstone has dark, chlorite-rich rinds (ex-palagonite?), and a few vesicles in the outer zone. These tend to be slightly flatter than the pillows in flows of the first type. A particularly distinctive type, shown on the geologic map, has variolites (spherulites) ranging from less than 1 to 3 cm, or rarely larger, in diameter (fig. 3a; fig. 4). The variolites are smallest near the edges of the pillows, and become larger toward the center. These variolites typically are mainly composed of radially plumose actinolite, which in many rocks extends beyond the outline of the variolites until it meets and interferes with that growing out from other variolites. These structures are interpreted as evidence for glassy chilling of the entire pillow, rather than of just the rind as is the usual case; this conclusion was reached by Clements (1903, p. 141-2) and still is considered valid. This variolitic greenstone has pillows that are larger than the types described above, and their rims are thicker (1-3 cm). These pillows also commonly show a few round vesicles. Although small variolites are found scattered in occasional outcrops of pillowed greenstone, the major occurrence, containing the largest and best-developed, is a single flow traceable for more than 4.4 miles from south of Gem Lake to north of Madden Lake. Other outcrops and faulted segments of very similar variolitic greenstone are found scattered westward to the north shore of Garden Lake, and may belong to the same flow (see table 2, M-7228). This flow, from 150 to 500 feet thick, is nearly everywhere overlain by a band of cherty iron-formation. In a few outcrops of non-variolitic, non-vesicular greenstone, es-

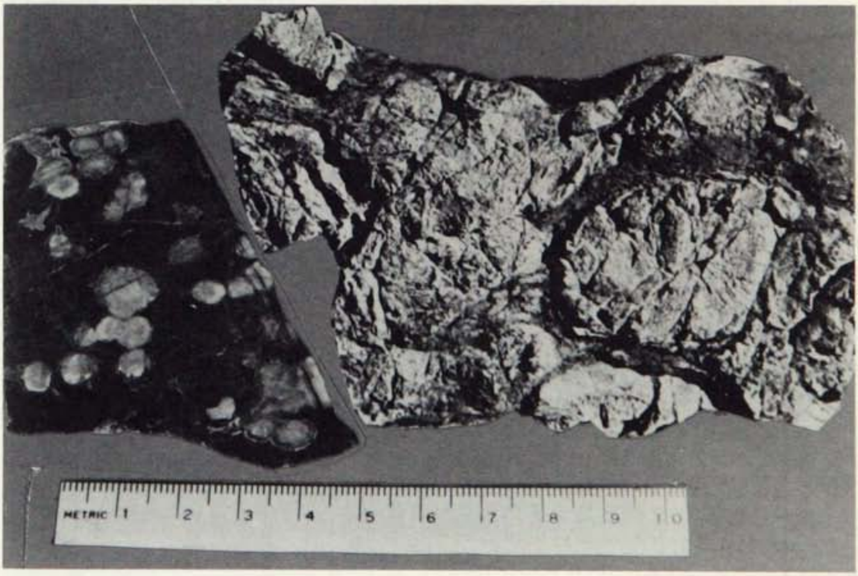

Figure 4. Variolites in pillowed metabasalt of Ely Greenstone. Larger variolites M-7132, sec. 1, 63 N/10 W; smaller M-7174, sec. 21, 63 N/11 W. Scale in cm and mm.

Table 2 — New chemical analyses (in weight percent) and norms of metabasaltic rocks and Keweenawan diabase

	M-7201	M-7228	M-7251	M-7258	M-7286	M-7360$_a$	M-7527	EG-16	EG-17	EG-26	EG-27	M-7129
SiO_2	51.20	50.14	51.06	39.71	48.15	49.55	51.45	49.30	50.90	49.65	51.30	48.10
TiO_2	1.47	1.59	1.44	0.87	0.84	0.98	0.98	0.79	1.33	0.78	0.76	1.49
Al_2O_3	14.91	13.54	13.85	19.70	13.80	16.05	11.60	14.68	16.05	15.44	14.29	15.88
Fe_2O_3	2.18	2.77	1.79	3.62	2.34	2.45	3.24	4.42	2.33	3.22	4.46	2.23
FeO	9.16	11.81	10.86	8.46	10.20	8.32	8.24	8.04	8.66	7.96	6.76	10.16
MnO	0.25	0.30	0.22	0.16	0.22	0.22	0.19	0.22	0.18	0.18	0.19	0.18
MgO	5.45	5.07	5.31	9.93	8.59	4.66	7.73	6.78	6.15	7.42	7.53	7.54
CaO	7.60	8.25	10.66	9.67	8.97	11.94	11.09	10.42	9.30	9.56	9.54	8.82
Na_2O	2.78	2.95	2.49	1.40	2.70	2.04	2.62	1.90	2.06	1.64	1.69	3.26
K_2O	0.00	0.25	0.25	0.04	0.10	0.62	0.08	0.12	0.76	0.32	0.16	0.49
H_2O^+	3.93	2.95	1.83	6.10	3.81	2.34	2.44	2.80	1.74	3.02	2.83	1.44
H_2O^-	n.d.	0.31	0.06	0.20	n.d.	0.12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	0.74	0.06	0.33	0.80	0.00	1.39	0.00	0.17	0.00	0.05	0.00	0.14
P_2O_5	0.14	0.24	0.13	0.07	0.16	0.09	0.22	0.08	0.20	0.13	0.12	0.16
Total	99.81	100.23	100.28	100.73	99.88	100.77	99.88	99.72	99.66	99.37	99.63	99.89
Q	7.3	3.8	3.2			3.1	3.7	5.4	4.8	5.6	9.6	
or		1.7	1.7		0.6	3.9	0.6	0.6	4.4	2.2	1.1	2.8
ab	24.6	25.7	21.5	12.6	23.6	17.8	22.5	16.8	17.8	14.1	14.7	28.3
an	29.8	23.6	26.4	50.6	26.4	33.9	20.3	32.2	33.1	35.0	32.0	27.5
di	7.1	14.2	22.2		15.5	22.1	28.2	16.7	10.3	10.9	13.0	13.0
hyp	24.5	23.8	19.2	4.4	20.6	13.4	17.3	19.8	22.9	25.6	21.1	5.6
Ol				24.6	7.7							16.0
Il	2.9	3.2	2.7	1.8	1.7	2.0	2.0	1.5	2.6	1.5	1.5	2.9
Mt	3.2	4.2	2.6	5.6	3.5	3.7	4.9	6.7	3.5	4.9	6.7	3.2
Ap	0.4	0.6	0.3	0.2	0.4	0.2	0.5	0.2	0.5	0.3	0.3	0.4
Analyst	K.R.	H.A.	H.A.	H.A.	K.R.	H.A.	K.R.	K.R.	K.R.	K.R.	K.R.	K.R.

Explanation for Table 2

Analysts: H.A.: Hiroshi Asari, Japan Anal. Chem. Res. Inst., Tokyo, 1967; K.R.: K. Ramlal, Univ. of Manitoba, 1968

Sample ♯: description (normative name); locality; formation

M-7201: pale gray-green, dense greenstone (quartz basalt); SW of Wood L. in SW ¼ Sec. 34, 64 N/10 W; EG

M-7228: dark green, dense, variolitic, pillowed greenstone (basaltic andesite) N. shore Garden L. in NE ¼ Sec. 20, 63 N/11W (Ely quad.); EG

M-7251: dark green, fine-grained, pillowed greenstone with few small labradorite phenocrysts and devitrification texture (basalt); Fernberg rd. nr E edge of quad., SW ¼ Sec. 8, 63N/9W; EG

M-7258: pale gray-green, fine-grained, pillowed greenstone (olivine basalt); Fernberg rd. old jct. with eastern Moose L. rd., S ½ Sec. 6, 63 N/9 W; EG

M-7286: gray-green, massive, fine-gr. greenstone with relict ophitic augite lumps (olivine diabase); Fernberg rd. ¼ mi. W. of BM 1419 in NW ¼ Sec. 9, 63 N/10 W; EG; see fig. 7

M-7360a: dark green, fine-grained, pillowed greenstone with relict labradorite laths (basalt); logging rd. S. from Fernberg rd. in SW ¼ Sec. 8, 63 N/9 W; EG

M-7527: gray-green, fine-gr., recrystallized, variolitic, pillowed greenstone with relict augite microphenocrysts (basaltic andesite); NW of Fall L. in NW ¼ Sec. 9, 63 N/11 W; NL

EG-16: medium- to pale green, fine-gr., pillowed greenstone with few small amygdules (quartz basalt); E. shore Triangle L. in SW ¼ Sec. 13, 63 N/10 W; EG

EG-17: dark green, massive, fine-gr. subdiabasic basalt, conformable beneath pillows with fresh labradorite and augite and pseudomorphs after olivine (basalt); E. shore Triangle L. in SW ¼ Sec. 13, 63 N/10 W; EG

EG-26: gray-green, massive, fine- to medium-gr. greenstone with relict ophitic texture (quartz basalt); E. shore Triangle L. in SW ¼ Sec. 13, 63 N/10 W; EG

EG-27: gray-green, massive, fine-grained greenstone with few small amygdules (quartz basalt); E. shore Triangle L. in SW ¼ Sec. 13, 63 N/10 W; EG

M-7129: dark green, fine-grained, massive diabase dike (olivine basaltic andesite); NW shore, W. end Moose L., NE ¼ Sec. 36, 64 N/10 W; Keweenawan; estimated mode 45% labradorite, 35% augite, 13% olivine, 5% magnetite, 2% rest incl. uralite, biotite, hisingerite, hornblende, quartz, calcite, epidote; see fig. 32

pecially large, pillow-like structures or lobes were recognized, in which the individual units are at least 10 feet long by 3 or 4 feet thick (see fig. 3). In these, the metabasalt has an uncommonly coarse texture (0.2-1.0 mm) compared to most of the other pillowed greenstones in the area, and it is inferred that the lava was very fluid during eruption and for some reason was not quickly chilled. In other places, smaller structures also thought to be pillows of highly fluid lava were seen (fig. 3); the texture is very fine-grained, but the pillow shapes are irregular and closely molded on each other as if more fluid than normal, and the rinds are very thin (2-4 mm). In all metabasalts showing the distinct, normal-sized, rounded pillows, the texture is aphanitic, or very fine-grained.

Locally the greenstone is made of a peperite or lava breccia of devitrified tachylyte fragments (fig. 5), and more rarely, basaltic tuff, agglomerate, or breccia (fig. 6). One tuff-breccia (NW¼ sec. 24, T. 63 N., R. 10 W.), with fragments up to 2 cm in diameter, was found to contain clasts of felty-textured basalt, devitrified tachylyte, and augite crystals. Such pyroclastic zones were too limited compared to the amount of exposure to map successfully. With a beginning of abrasive rounding of fragments, these rocks pass into volcanic conglomerate and graywacke.

It should be made clear that the structural features described above are readily visible on many exposures that have the right degree of weathering, but with an increase in lichen cover, shearing, and other detrimental factors* these features may be only marginally, if at all, apparent in spite of diligent study; they may well exist in many areas where they have not been recognized, even where outcrops are abundant.

Many outcrops of metabasalt, particularly near but not necessarily along major shear zones, are uncommonly pale in color and closely resemble many felsites. Instead of having the characteristic dark to medium gray-green color, these rocks are a pale green or light tan. Though aphanitic, they are in general slightly more granular than the felsites, and in many areas they show normal pillows and/or breccia structure identical to those of the darker metabasalts. The textures, mineral composition, and presence of pillows, as well as chemical analyses, indicate that these are metabasalts that have apparently undergone secondary bleaching by hydrothermal solutions (see table 2).

Small, chloritic metabasaltic dikes penetrate many greenstone outcrops. Probably they are more or less contemporaneous with the extrusive volcanism and could be feeders.

A few of the metabasalts sampled are porphyritic. Labradorite, about 1-2 mm long, is the most common phenocrystic mineral (retrograded to albite, An$_5$, in one specimen), and augite is rare. Large (2-4 mm) chlorite plates, pseudomorphous after magnesian biotite, were seen in several localities, but a mappable unit of this type could not be traced. Hornblende phenocrysts were found in one sample of variolitic greenstone. Most of the greenstones contain very thin laths (0.1-0.5 × 0.03 mm) of plagioclase

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* Such as *Simulium* sp.

Figure 5. Photomicrograph of devitrified tachylyte breccia (peperite) in Ely Greenstone, M-7586, sec. 20, 63 N/10 W.

Figure 6. Breccia of greenstone fragments associated with pillows of Ely Greenstone, M-7452, sec. 15, 63 N/11 W.

(labradorite where not retrograded) that typically show a random orientation, but in several thin sections a subparallelism, indicating flow during congelation, was found. One uncommonly fresh, granular basalt that intrudes pillow lavas (EG-17: see table 2) contains plagioclase zoned from about An_{70} to An_{55}.

Under the microscope most of the metabasalts show intense retrograde alteration, making the thin section semi-opaque. Minerals recognizable in most samples are sodic plagioclase, quartz, actinolite, chlorite, epidote, calcite, leucoxene, and opaques. Relict augite was seen in five samples, and calcic plagioclase in seven of 30 thin sections studied. One sample contains pseudomorphs after olivine. Mineral assemblages resulting from prograde metamorphism of the greenstones will be mentioned below; the prograde minerals include calcic plagioclase, hornblende, biotite, augite, magnetite, and epidote.

Intrusive metadiabase and other mafic intrusions. Tabular to irregular plutons of fine- to medium-grained metadiabase, having both concordant and discordant contacts, are common within the Ely Greenstone and the Newton Lake Formation (Green, Phinney, and Weiblen, 1966). These bodies are thought to be essentially contemporaneous with and consanguineous with the metabasalts, and probably were intruded at shallow depths within the volcanic pile; some may be feeder dikes. Some large sills as much as 1,000 feet thick follow rather uniform levels for several miles (see geologic map). Other, smaller bodies are not differentiated on the map, especially in areas of poor outcrop. The rock is tough, uniform, and massive, has more widely-spaced joints than do the metabasalts, and forms many of the higher topographic knobs in the area. The most common texture is relict poikilitic, in which relict augite oikocrysts (or actinolite pseudomorphs of augite) enclose small saussurite laths (fig. 7). The actinolite crystals and relict augite range in diameter from about 3 to 8 mm, and commonly protrude slightly on weathered surfaces. Other bodies have a hypidiomorphic-granitoid texture with sub- to euhedral plagioclase tablets and augite or hornblende prisms or actinolite pseudomorphs. Small phenocrysts of plagioclase and augite occur rarely. Interstitial quartz and granophyre are present in a few areas, and the large sill-like body south of Moose Lake is relatively coarse but variable (3-12 mm) and has local pegmatitic patches. One sample from the east shore of Ojibway (North Twin) Lake is a panidiomorphic-granular cumulate rock about 70 percent of which is augite crystals (fig. 8).

These rocks generally resemble the metabasalts in mineral composition. A new chemical analysis (M-7286, table 2) is similar, though not identical, to the analyzed metabasalts. Being coarser-grained, the minerals in the intrusive greenstones are more readily identified in thin section. The plagioclase is everywhere strongly saussuritized; actinolite, chlorite, epidote, opaques (some partly altered to leucoxene and sphene), calcite, and apatite are nearly ubiquitous. Quartz and granophyre are present rarely, and relict augite was found in several samples. Pseudomorphs, thought to have been

Figure 7. Photomicrograph of intrusive greenstone (analyzed) with relict ophitic augite oikocrysts, M-7286, sec. 9, 63 N/11 W.

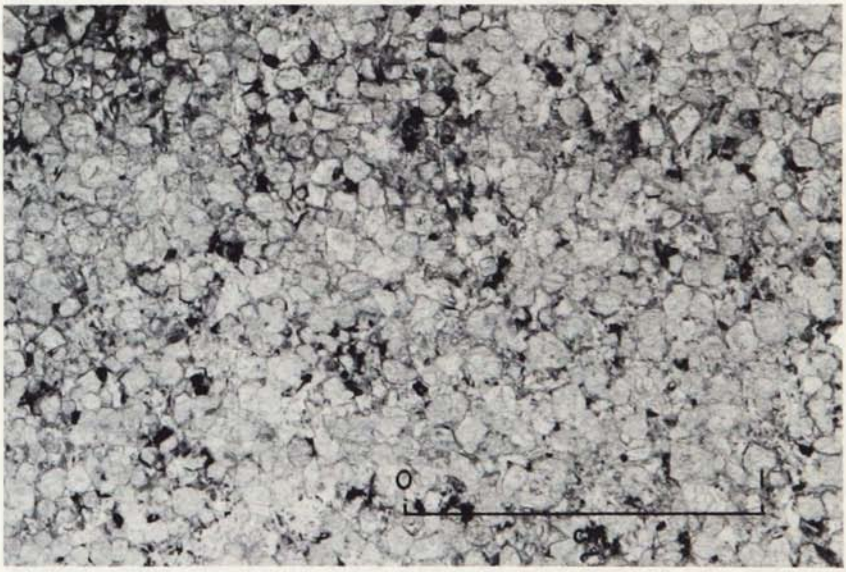


Figure 8. Photomicrograph of intrusive melagabbro with relict cumulus augites, M-7379, sec. 11, 63 N/10 W.

olivine, were seen in rare instances. Two samples have the mineral composition of a quartz diorite, two are quartz gabbros, one a granophyric metagabbro, and one an olivine-hornblende gabbro.

Other mafic intrusive rocks that cut the Ely Greenstone were penetrated by diamond drilling by the Garden Lake Iron Co. in the NE¼ sec. 22, T. 63 N., R. 11 W. One drill hole penetrated about 150 feet of a distinctive biotite diorite, not seen elsewhere in the area. This rock is generally porphyritic and has plagioclase and biotite phenocrysts about 2-4 mm long in a groundmass of these minerals plus chlorite, calcite, apatite, and magnetite. One sample shows abundant augite phenocrysts (and actinolite-magnetite pseudomorphs) as well. The plagioclase is untwinned, and strongly microperthitic; a small amount of interstitial microcline occurs in some specimens. This rock shows a strong foliation, at least some of which is due to shearing, and the core is cut by several zones of locally intense crushing. Red, porphyritic- to syenitic-appearing veins and dikes, probably related to those cropping out west of Pea Soup Lake, cut the diorite.

A rare biotite melagabbro was also cut by the same drill hole. It is mostly made of phenocrysts, 50 percent augite and 20 percent biotite, that appear to have formed as a crystal accumulate. The groundmass was estimated to contain 20 percent plagioclase, 4 percent actinolite, and 2 percent each apatite, magnetite, and calcite. The core penetrated this rock for at least 20 feet, but because of shearing and alteration, its contacts with the greenstone are not clear. It is also cut by the red syenitic veins.

Extrusive felsic rocks. Perhaps one or two percent of the formation consists of metamorphosed felsic volcanic rocks, excluding the dacite porphyry which is described separately under the section on intrusive rocks. Some of the felsites form thin but traceable units, and have been shown on the geologic map; others, because of faulting, lack of sufficient exposure, and the scale of mapping, are not shown. The felsites mapped near the Fernberg road between Pea Soup and Sourdough Lakes are consistently underlain by a thin bed of iron-formation. This pair of strata probably has been repeated by faulting here, although no direct evidence was seen.

The extrusive felsites are pale gray or pale tan, dense, and tough, and are thought to be flows. No pyroclastic texture was identified, but a local, angular breccia thought to be flow-breccia was seen on the Fernberg road just east of Madden Creek. Round amygdules are present in several outcrops. Some outcrops could not be distinguished from bleached metabasalt without microscopic study, although the felsites tend to be finer-grained. Most samples show trachytic texture with subparallel sodic plagioclase laths, and most have small (1-2 mm) plagioclase phenocrysts which, because of alteration, are not obvious megascopically. These rocks are predominantly sodic in composition; their mineralogy corresponds to dacite, rhyodacite, and andesite (see M-7288a, table 3). Quartz, albite, sericite, epidote, chlorite, carbonate, opaque, and apatite are characteristically identifiable in thin section, and actinolite was found in the meta-andesite. Microcline was found in only one section, where it occurs in the ground-

Table 3 — New chemical analyses (in weight percent) and norms of intermediate and felsic metavolcanic and hypabyssal rocks, and serpentinized peridotite

	M-7152	M-7194	M-7441	M-7548	M-7560	M-7288$_a$	M-7499	M-7509	M-7202	M-7112	M-7549
SiO_2	57.83	58.79	63.61	60.55	54.72	69.11	70.52	69.55	60.95	66.75	38.50
TiO_2	0.79	0.67	0.61	0.53	0.76	0.61	0.58	0.37	0.51	0.28	0.26
Al_2O_3	13.39	15.81	13.91	15.99	14.77	16.24	15.50	17.05	15.14	15.56	3.69
Fe_2O_3	2.44	3.70	1.64	2.44	2.37	1.10	0.60	0.62	4.34	1.42	6.65
FeO	5.07	4.09	3.90	3.13	4.92	1.37	1.26	0.45	1.16	1.20	7.76
MnO	0.20	0.10	0.09	0.08	0.11	0.02	0.03	0.01	0.07	0.03	0.23
MgO	2.69	4.44	4.00	3.50	3.77	0.98	0.52	0.68	4.38	0.92	30.10
CaO	7.16	2.86	4.27	6.95	7.94	2.63	1.90	1.77	3.32	3.18	2.69
Na_2O	3.84	5.59	5.23	4.14	3.29	3.36	5.59	5.84	5.48	5.60	0.13
K_2O	0.23	0.20	0.43	0.86	0.68	2.09	1.38	1.72	2.12	1.73	0.02
H_2O^+	3.44	3.33	2.27	2.17	3.16	2.19	1.86	1.81	1.83	1.42	9.39
H_2O^-	0.14	0.16	0.11	0.06	0.23	0.30	0.13	0.18	n.d.	n.d.	n.d.
CO_2	2.87	0.53	0.53	0.10	3.06	0.30	0.42	0.58	0.43	1.62	0.0
P_2O_5	0.24	0.14	0.14	0.11	0.17	0.17	0.14	0.09	0.13	0.07	0.08
Total	100.31	100.41	100.77	100.61	99.95	100.47	100.43	100.72	99.86	99.78	99.50
Q	21.4	11.9	16.4	14.8	11.9	35.5	28.4	24.8	9.2	20.7	
or	1.7	1.1	2.8	5.0	4.4	12.8	8.3	10.6	12.8	10.6	
ab	33.5	49.2	45.0	35.6	29.9	28.8	48.2	50.3	47.2	48.7	1.0
an	16.4	14.7	13.6	23.1	25.0	12.2	8.9	8.3	10.8	12.8	10.6
c	1.0	1.5				4.2	1.6	2.6			
di			5.8	8.9	12.9				4.1	2.4	2.8
hy	13.5	15.0	12.3	7.4	10.2	3.2	2.2	1.7	9.2	1.9	31.2
ol											42.6
mt	3.7	5.6	2.6	3.7	3.7	1.6	0.9	0.5	2.6	2.1	10.7
hm								0.3	2.7		
il	1.5	1.4	1.2	1.1	1.5	1.2	1.1	0.8	1.1	0.6	0.6
ap	0.6	0.3	0.3	0.3	0.4	0.4	0.3	0.2	0.3	0.2	0.2
cc	6.7										
Analyst	H.A.	H.A.	H.A.	H.A.	H.A.	H.A.	H.A.	H.A.	K.R.	K.R.	K.R.

Explanation for Table 3

Analysts: H.A. = Hiroshi Asari, Japan Anal. Chem. Res. Inst., 1967; K.R. = K. Ramlal, Univ. of Manitoba, 1968

Sample #: Description (normative name); locality; formation; comments

M-7152: dark green, subtrachytoid greenstone with amygdules of calcite and of chlorite (intermediate dacite); NW shore Wood Lake in SW ¼ Sec. 27, 64 N/10 W; NL; norm computed with calcite (remaining volcanic norms ignore CO$_2$)

M-7194: dark green, massive greenstone, rare amygdules (quartz andesite); E. end Wood L. in NW ¼ Sec. 25, 64 N/10 W; NL

M-7441: med. gray-green, bulbous-pillowed metavolcanic lava with albite phenocrysts, quartz, feldspar, amphibole, epidote, and chlorite groundmass (intermediate dacite); S. shore Witness L. at Twp. line, Sec's. 25/30, 64 N/9-10 W; NL; see fig. 19

M-7548: light gray-green, lineated tuff-breccia, unwelded (quartz andesite); W. side Newton L., in SE ¼ Sec. 27, 64 N/11 W; NL

M-7560: light greenish-buff, lineated tuff-breccia (quartz andesite); NE of Mud L. in SW ¼ Sec. 30, 64 N/10 W; NL; contains about 7% dissem. calcite

M-7288a: light gray, dense, massive felsite, few amygdules (rhyodacite); powerline near Fernberg rd. in SE ¼ Sec. 7, 63 N/10 W; EG; no K-spar detected

M-7499: light gray, dense, schistose felsite with plagioclase phenocrysts (rhyodacite); knoll WNW of Sourdough L. in NE ¼ Sec. 6, 63 N/10 W; KL; no K-spar detected

M-7509: white, dense, trachytic felsite with plagioclase phenocrysts, few possible amygdules (rhyodacite); ¼ mi. NE of B.M. 1425 in SW ¼ Sec. 14, 63 N/11 W; EG; no K-spar detected

M-7202: dark green, intrusive andesitic porphyry with abundant plagioclase, fewer hornblende phenocrysts (quartz trachyandesite); SW shore Tofte L., NE ¼ Sec. 10, 63 N/10 W; "adp" on geologic map; oxidation ratio of Fe in analysis questionable; see fig. 24

M-7112: medium gray, slightly sheared, dense porphyry with abundant plagioclase, fewer quartz, and altered mafic phenocrysts (rhyodacite); Moose Lake Road, SW/SE ¼ Sec. 6, 63 N/9 W; "dp" on geologic map; intrusive or extrusive?; no K-spar detected; see figs. 22, 23

M-7549: black, medium-coarse grained, poikilitic, serpentinized peridotite consisting of serpentinized olivine (cumulus), serpentinized enstatite (poikilitic), augite and uralite (poikilitic), chromite and biotite; quad. boundary W. of Newton L. in SW ¼ Sec. 33, 64 N/11 W; NL; fig. 30

mass. For identification of groundmass feldspars, x-ray diffractometry or sodium cobaltinitrite stain was used; no K-feldspar was detected in any of the six samples so tested.

In addition to the felsites just mentioned, an unknown proportion of the rock described as dacite porphyry under the section "Intrusive Rocks" is actually extrusive and interbedded with the Ely Greenstone. As cited above, evidence for this is twofold: (1) local, clastic (pyroclastic? flow-breccia?) structure, and (2) clearly recognizable clasts of this rock in conglomerate and grit interbedded with metabasalt flows of the Ely Greenstone. Such features are particularly apparent in the Jasper Lake-Gem Lake area, and the large mass of dacite with a long extension westward to Tofte Lake may represent a lava dome and flow. In other areas, however, the same rock type shows clearly intrusive relationships with the Ely Greenstone.

Meta-clastic rocks. Scattered at various horizons, but especially near the top of the Ely Greenstone, are thin (mostly less than 11 ft.) beds of immature meta-clastic rocks. They constitute perhaps one percent of the formation. Conglomerate, breccia, and graywacke are predominant; metasiltstone and argillite are found locally, especially in association with iron-formation. No single unit could be traced more than a mile within the quadrangle, although several lenses were found about 1,000 to 1,500 feet below the top of the formation, and one of these beds was traced for 1.5 miles southeast from near Moose Lake into the Forest Center quadrangle.

The conglomerates (figs. 1, 5) contain angular to subrounded pebbles, and grade into what are considered to be volcanic breccias with increase in angularity and uniformity of volcanic composition. Locally up to one foot across, the clasts are mostly less than five centimeters in diameter, and consist predominantly of various types of greenstone, including both intrusive and extrusive varieties. Scoriaceous fragments are common in some areas, for example southwest of Tofte Lake, and indicate shallower submarine or subaerial extrusion of lava (fig. 9). Some of these have been flattened. Of less constant but common occurrence are pebbles of dacite porphyry (fig. 2), red, gray, and white chert, and felsite. One conglomerate that contains pebbles of dacite porphyry as well as of greenstone is clearly intruded by identical dacite porphyry (NW¼ sec. 7, T. 63 N., R. 9 W.; fig. 1). Still less common are andesite porphyry, hornblende-quartz diorite, and granite. The granitic clasts, clearly distinguished from dacite porphyry only in thin section, were found in the SE¼ sec. 8, T. 63 N., R. 10 W. They indicate the presence of an as yet unrecognized, potash-rich source area, and are made of both granophyric and coarser intergrowths and independent crystals of quartz, orthoclase, and plagioclase. The matrix of the conglomerates consists of sand- to clay-sized particles of the same materials, and resembles the graywackes described below.

The metagraywackes also have angular to subrounded clasts, recognizable grains of plagioclase and less abundant quartz, chert, hornblende, scoria, basalt, felsite, and opaque. K-feldspar and granophyre grains were found in the same locality mentioned above for granitic pebbles. Many of the grains and most of the matrix of the graywackes are altered beyond recognition. Plagioclase clasts, most of which resemble those from the dacite porphyry of this district, were found in an arkosic graywacke rather low in the stratigraphic section one-fourth mile south of the south end of Triangle Lake. Metasiltstones and argillites, some of which are associated with iron-formation layers, contain a few identifiable clastic quartz and plagioclase grains in a matrix that includes variable amounts of the same two minerals, chert, epidote, calcite, and chlorite.

In the higher-grade, recrystallized parts of the Ely Greenstone (mainly east and south of Twin Lakes), a few lenticularly laminated strata were found. These layers range in thickness from a few inches to several feet. A few of these cut across original structures in the metabasalts and are probably recrystallized shear zones; microscopic study supports this interpretation in some cases, although in others all original textures are destroyed. Most, however, are concordant, and are thought to be metamorphosed volcanic graywackes, tuffs, and breccias. In outcrops at the Fernberg lookout tower, immediately east of the map area, the volcanic nature of similar but less metamorphosed beds is evident. Suggestions of clastic and pyroclastic structure and/or texture were seen under the microscope in some, but their mineral composition is entirely metamorphic.

Iron-formation. Scattered in many outcrops throughout the area mapped as Ely Greenstone are thin lenses and irregular beds, from a fraction of an inch to a few feet thick, of gray, black, or reddish magnetic chert, generally

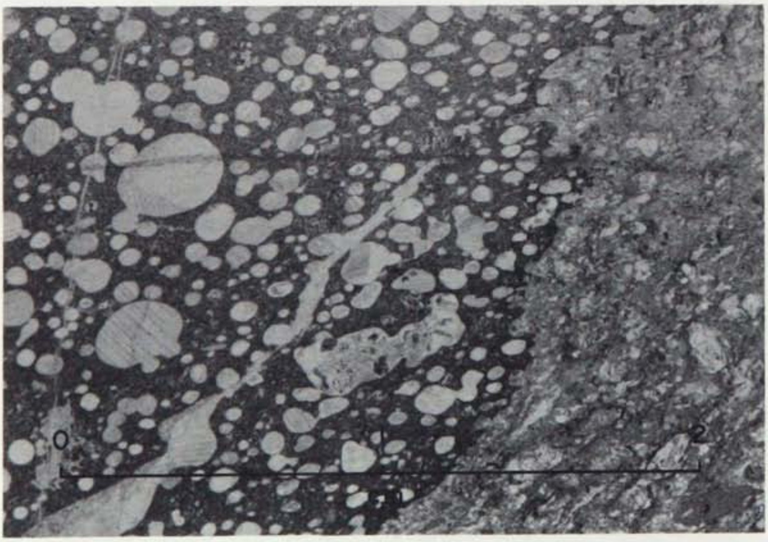


Figure 9. Photomicrograph of volcanic conglomerate with scoriaceous pebble, M-7404 b, sec. 10, 63 N/10 W.

associated with pillowed greenstone (fig. 10). Thicker strata of similar type, sufficiently large to indicate (with some exaggeration) on the geologic map, are more restricted, though the lack of outcrop in some areas has certainly kept some from being seen. These may range in thickness from a few to about 50 feet; most are less than 25 feet thick. Continuity of some of the thicker units north of Garden Lake, as shown on the geologic map, has been guided by old dip-needle traverses made available by the U. S. Steel Corp., and recent data of Jones and Laughlin Steel Corporation. Although Clements (1903) assigned most of the iron-formation outcrops to the Soudan Iron-formation, he recognized from the field evidence that some of these beds are within, and part of, the Ely Greenstone (p. 196).

The most conspicuous layering consists of major alternations between cherty and oxide-rich beds; these are normally 3 to 25 mm thick. These major layers, especially the cherty beds, are themselves finely, rhythmically banded in most exposures (fig. 10). The laminae, from 0.1 to 2 mm thick, are also formed from alternations of more and less iron-rich composition, but with less extreme changes than in the major bands. The quartz in the cherty beds is mostly from 0.01 to 0.04 mm in diameter, but slightly coarser in higher-grade areas. Magnetite, the principal iron oxide mineral, occurs as minute euhedra about 0.02-0.1 mm across, and probably also as very fine dust within the quartz grains in many specimens. The red, jaspery cherts contain fine hematite flakes, and rarely laminae of specular or steely hematite. Relict oolitic or pseudo-oolitic structures are common, consisting of

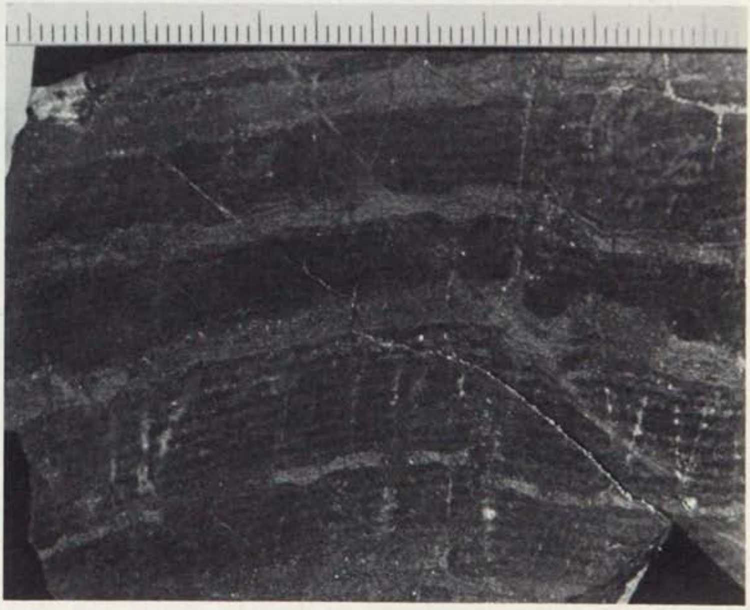


Figure 10. Rhythmically laminated chert-grunerite-magnetite iron-formation, Ely Greenstone, M-7657, sec. 14, 63 N/11 W. Scale in mm.

minute, round clear areas in the chert devoid of opaque crystals or dust. In several specimens, however, these each contained a small magnetite porphyroblast, and they may be purely metamorphic features. Two samples showed tiny clots of opaque dust in the chert.

Besides quartz and magnetite, most specimens also contain grunerite (fig. 11) and carbonate (both siderite and calcite or either). Scraps of stilpnomelane were found in a few samples, and muscovite, biotite, chlorite, and apatite were seen in at least one sample each. An unusual facies of iron-formation, composed nearly entirely of a fine-grained felted mass of grunerite, was found on the northeast end of the hill in the NE¼ sec. 14, T. 63 N., R. 11 W. (see table 4 for chemical analyses).

As has been mentioned above, fine-grained, clastic metasediments are associated with a few of the banded iron-formations. They are gray or green, thin-bedded or laminated, and typically more granular than the associated cherts. These have been seen stratigraphically beneath, and also above, the iron-formation stringers. They appear to grade vertically into chert, with increase in abundance and thickness of cherty laminae in the metasiltstones. They may be tuffaceous.

Figure 11. Bedding-plane of chert-grunerite-magnetite iron-formation, Ely Greenstone, showing radial sprays of grunerite. M-7210, sec. 8, 63 N/9 W. Scale in cm and mm.

Table 4 — New chemical analyses (in weight percent) and calculated mineral compositions of iron-formations and calcareous quartzite.

	M-7271	M-7314	M-7438	M-7511	M-7625	M-7553
SiO_2	58.30	81.40	62.60	39.60	59.10	67.90
TiO_2	0.00	0.00	0.00	0.00	0.13	0.00
Al_2O_3	1.24	0.76	0.72	1.06	4.21	1.40
Fe_2O_3	3.94	6.67	12.12	16.02	9.36	0.30
FeO	18.76	8.32	11.36	32.96	12.04	0.96
MnO	0.29	0.00	0.34	1.76	0.07	0.41
MgO	1.28	1.17	1.21	3.97	2.27	0.15
CaO	0.84	0.16	4.24	0.48	1.61	14.86
Na_2O	0.05	0.02	0.04	0.01	1.68	0.23
K_2O	0.00	0.00	0.00	0.00	0.00	0.16
H_2O^+	1.30	1.21	0.95	3.45	1.42	0.80
H_2O^-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CO_2	13.57	0.24	6.07	0.00	7.57	12.72
P_2O_5	0.35	0.08	0.20	0.40	0.16	0.00
Total	99.92	100.03	99.85	99.71	99.62	99.89
Q	57.9	74.5	58.6	3.6	47.6	65.7
or						1.1
ab	0.5		0.5		14.2	2.1
an		0.3			3.9	
grun		13.1	6.1	73.5		
cor	1.1	0.6	0.6			0.8
mt		9.7	17.6	11.6	13.7	0.5
hm	3.8			8.0		
il					0.3	
ap	0.8	0.2	0.5	1.0	0.3	
siderite	31.0	0.6	7.7		12.4	2.2
magnesite	2.7				4.7	0.3
calcite	0.8		7.2		1.2	26.5

Explanation for Table 4

Analyst: K. Ramlal, University of Manitoba, 1968

Sample ♯: physical description (mineralogy); locality; formation

M-7271: gray and white banded-laminated, nonmagnetic iron-formation (chert, siderite slightly altered to hematite, traces of pyrite and muscovite); island in Moose Lake in SW ¼ Sec. 29, 64 N/9 W; KL; see fig. 16

M-7314: dark gray, dense, magnetic iron-formation (chert, magnetite, grunerite); western Moose Lake road, E ½ Sec. 1, 63 N/10 W; EG

M-7438: gray, lean, banded, magnetic iron-formation (chert, partly oxidized ankerite, magnetite, grunerite, trace apatite); S. shore Twin (Ojibway) L., NE ¼ Sec. 13, 63 N/10 W; EG

M-7511: brown, fine-grained, non-cherty iron-formation (grunerite, magnetite, salmonsite?); 1503′ hill E. of Stub L. in NE ¼ Sec. 14, 63 N/11 W; EG; "norm" depends on hematite/magnetite ratio assumed

M-7625: dark gray, laminated, magnetic iron-formation with Fe-carbonate porphyroblasts (microcrystalline chert and plagioclase, magnetite, siderite, ankerite, chlorite); W. shore N. arm Wood L. in NW ¼ Sec. 26, 64 N/10 W; NL; see fig. 21

M-7553: light gray, calcareous, schistose quartzite (quartz, calcite, plagioclase, sericite, chlorite); ridge NE of Upper Pipestone Falls, SE ¼ Sec. 34, 64 N/11 W; NL

Knife Lake Group

General statement. The term "Knife Lake Group" has been used since 1951, when Grout and others changed to group status the complex "Knife Lake Series," which had been studied by Gruner (1941) between Moose Lake, in the northeast corner of the Gabbro Lake quadrangle, and the Saganaga Lake area. Earlier reports (A. Winchell, 1888; Van Hise and Clements, 1901) had used the term "Knife Lake slates," to which Clements (1903) had added the Ogishke conglomerate and Agawa iron-formation. This group of dominantly clastic rocks was observed at several localities to overlie greenstones, and all metaclastic sequences of any considerable extent in the district have since been assumed to be younger than "Ely Greenstone" (see discussion above). However, Gruner (1941) found the entire "Knife Lake" belt, including the rocks at Knife Lake itself (immediately northeast of the Gabbro Lake quadrangle; see pl. 1), to be cut by major faults into many blocks and slices, and a lack of distinctive, mappable marker beds made it impossible to correlate from one block to another. Therefore, for example, it is uncertain whether a clastic-metabasalt contact in one block (such as south of Saganaga Lake) has in fact the same lithostratigraphic position as that in another (such as in the Moose Lake area), and there may be more than one such sequence in the area Gruner mapped.

The rocks encompassed by Gruner in the Knife Lake Group include major successions of felsic and intermediate pyroclastic rocks and tuffaceous graywackes and arkoses, as well as abundant graywackes and slates that he did not identify as volcaniclastic. From his descriptions, these pyroclastic rocks (especially his units 8 — pink andesite conglomerates and agglomerates — and 12 — Ensign-Snowbank Lake agglomerates) closely resemble the major component of the Newton Lake Formation in the northern part of the Gabbro Lake quadrangle, from which they are separated by a bulge of the Basswood Lake part of the Vermilion batholith in the vicinity of Prairie Portage (see pl. 1). Clements had mapped these pyroclastic rocks as Ely Greenstone; in the northwestern corner of the Gabbro Lake quadrangle they are interlayered with metabasalts which are part of a very broad belt of mafic rocks that continues to the west, north of Ely. Therefore, these pyroclastic rocks have been separated in this report from the remainder of the Knife Lake Group.

Accordingly, the rocks for which the name "Knife Lake" is retained in this report are dominated by graywackes, slates, and phyllites, although significant areas are also underlain by pyroclastic rocks, volcanigenic sediments, and some lava flows. These Knife Lake rocks form a belt one to two miles wide that extends from Moose Lake (at the western limit of Gruner's mapping), west-southwest through Fall Lake and on through Shagawa Lake at Ely. They are thought to be equivalent to one or more of Gruner's units 1, 2, 5, or 10, but most likely to his unit 5 — "Well-banded slates and graywackes." Several strike-faults shown by Gruner trend southwestward through Moose Lake; faults are certainly present, as evidenced by the intensive shearing of rocks on shores and islands, but they probably are underwater and their position is uncertain; accordingly, they are not shown on the quadrangle map. Other longitudinal faults may also be present in land areas, but were not located because of inadequate outcrops (but see lineament map, pl. 2).

The Knife Lake Group in the Gabbro Lake quadrangle overlies the Ely Greenstone, apparently with little if any angular discordance, although polymict conglomerate is the most widespread basal unit. Along most of its length in the area, however, the contact is a fault, especially in the western half of the map. A fault south of Moose Lake has dropped Knife Lake metasedimentary rocks (on the south) against greenstone (on the north); here the entire sequence faces north, in contrast to Gruner's synclinal interpretation. The unfaulted, depositional contact at the base of the Knife Lake Group is best observed south of Moose Lake (secs. 31, 32 of T. 64 N., R. 9 W.) and west of Tofte Lake (secs. 9, 10 of T. 63 N., R. 10 W.).

The northern contact of the Knife Lake Group is shown as an inferred fault on the geologic map, but physical evidence of faulting, such as a sheared zone, was not seen at this position, and later mapping to the west and further consideration have led to the conclusion that the volcanic rocks of the Newton Lake Formation stratigraphically overlie the clastic rocks of the Knife Lake Group in this area. The actual contact was not seen in outcrop.

An accurate measurement of the thickness represented by the rocks in this belt cannot be made because of (1) the probability of longitudinal faults, (2) the lensing of mappable units, and (3) the paucity of top-sense observations (as control on isoclinal folding). The dominantly volcanic unit near the base has a probable maximum thickness of 2,500 feet; the clastic unit above must be a few thousand feet thick, perhaps as much as 5,000 feet. The thickest lens of basal conglomerate (south of Moose Lake) is about 500 feet thick; most of the conglomerates are less than 100 feet thick.

The belt of rocks mapped as Knife Lake along the North Kawishiwi River and Farm Lake are even more difficult to correlate with Gruner's mapped units (Gruner, 1941). Being dominantly metagraywackes and metaconglomerates, they may be equivalent to Gruner's units 3 and 5 ("Disappointment Mountain and Moose Lake greenstone conglomerates," and "well-banded slates and graywackes"), but they have been metamorphosed to a high grade and are in fault contact with both the Ely Greenstone and Gruner's units 3 and 5 southeast of Fernberg Hill (see pl. 1). Furthermore, the abundance of banded iron-formation west of Farm Lake, though surrounded by metasediments, suggests a closer relationship of the metasediments to Ely Greenstone deposition in that area than to Knife Lake (see interpretation of pl. 1). Here also the thickness is impossible to measure, but it must be on the order of a few thousand feet.

Low-grade clastic metasediments. Conglomerate is the most common basal unit of the Knife Lake Group observed to directly overlie the Ely Greenstone without an intervening fault. A few additional mappable lenses of conglomerate were also seen, such as those northwest of Moose Lake and west of Wood Lake. Except for chert, which tends to be angular, the pebbles, cobbles, and granules are mostly rounded. Metabasalts are the most abundant clasts, and in some areas, such as north of Jasper Lake, they are the only type present. Where such greenstone conglomerates also have a chloritic, basaltic-debris matrix, their conglomeratic nature is difficult to recognize except on certain properly-weathered surfaces. In addition to massive fine-grained basalts, medium-grained metadiabases are fairly common as clasts, as are cherts of various shades of red and gray and the common dacite porphyry. Other clasts recognized are andesite porphyry (with plagioclase, hornblende, and magnetite phenocrysts), other varieties of felsite porphyry (plagioclase and quartz phenocrysts), trachytic felsite, argillite, quartz, and granophyre. A fragment of fine- to medium-grained hornblende granodiorite was seen in a polymict conglomerate in the SW¼ sec. 33, T. 64 N., R. 10 W. In most cases the matrix is finer-grained and similar in composition, but a few outcrops have a calcareous cement.

Graywackes, argillites, and slates make up the bulk of the Knife Lake rocks. They are laminated and interbedded; graywacke beds range in thickness from a few millimeters to a few decimeters. The finer-grained rocks, where not excessively sheared, show fine laminations. Grain gradation was seen at several localities, and cross-bedding was observed in a few. These rocks are texturally and compositionally highly immature, indicating that they were weathered very little prior to deposition. The graywackes grade into arkosic wackes with increased feldspar, and much of the source material was certainly volcanic. It is difficult to make a clear distinction petrographically between volcanigenic graywackes and arkosic wackes, on the one hand, and truly tuffaceous rocks on the other hand, especially after the rocks were altered to their present extent (figs. 12, 13). The most feldspathic rocks, including those showing more or less clear volcanic structures, are described separately in a later paragraph.

The graywackes range in grain size from coarse to fine, and have clasts that vary in shape from angular to subrounded. Clastic grains of plagioclase (many of which are zoned) are most abundant, and K-feldspar (in four samples), hornblende (with actinolite overgrowths), augite, quartz, apatite, opaques, chlorite pseudomorphs after unknown minerals, dacite porphyry, other felsites, argillite, greenstone, chert, devitrified glass shards, granophyre, and granite (four specimens) were also identified. These are set in a pasty matrix made up largely of chlorite, epidote, opaque, calcite, actinolite, and sericite; pyrite, siderite, kaolinite, and rutile have also been identified. In several specimens quartz clasts constitute less than 5 percent of the rock.

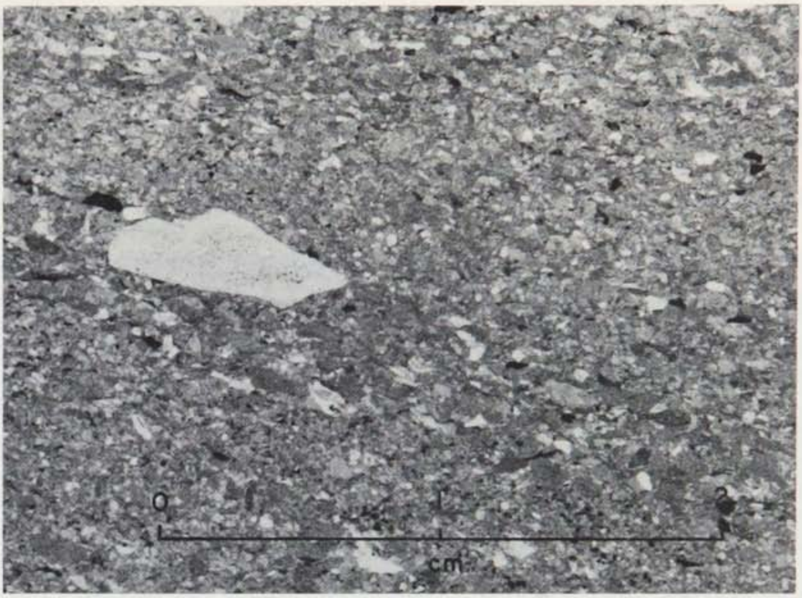


Figure 12. Photomicrograph of angular, gritty graywacke of Knife Lake Group. Note large chert clast and rare quartz; other clasts include greenstones, hornblende, plagioclase, and rare granophyre. M-7101, sec. 31, 64 N/9 W.

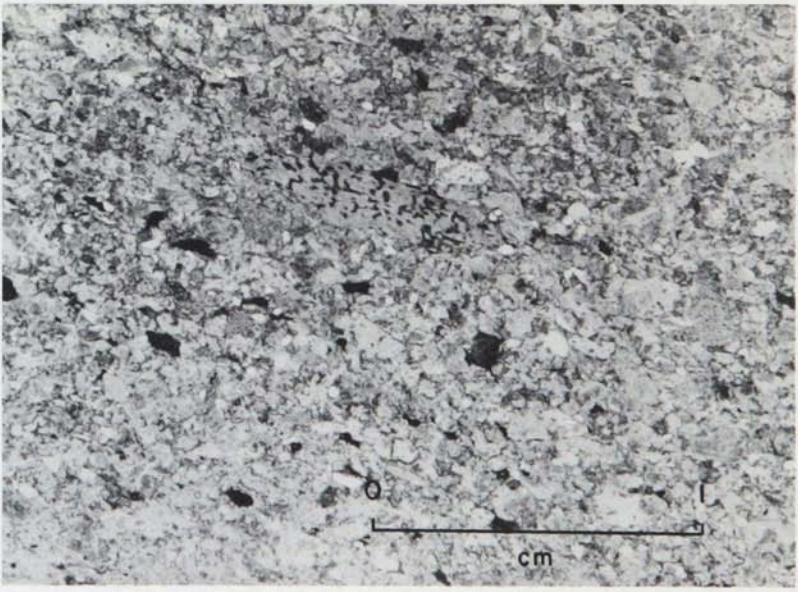


Figure 13. Photomicrograph of felsic tuffaceous graywacke of Knife Lake Group. Note abundant feldspar, rare quartz, and vesicular andesite clast. M-7200, sec. 10, 63 N/10 W.

Fewer clastic grains are recognizable in the finer-grained siltstones, argillites, phyllites, and slates. Clasts of plagioclase, quartz, amphibole, opaque minerals, and apatite were found, and optical and X-ray study indicates that muscovite, chlorite, and calcite predominate in the matrix, in various ratios.

Considerable recrystallization and some metasomatism have taken place in those areas within the Knife Lake belt that have undergone strong shearing associated with longitudinal faults. Graywackes and siltstones are now schistose, have considerable sericite, and locally have large amounts of introduced iron carbonate. Such rocks typically weather to an orange to tan crust, and although small quartz grains may be visible in hand specimen and in thin section, it is particularly difficult to distinguish sheared arkosic graywackes from sheared porphyritic felsites. A specimen from Wood Lake, identified in the field as a sideritic gneiss, was found by microscopic study to consist of about 35 percent clastic quartz and plagioclase of sand size in a foliated matrix containing about 58 percent siderite, 5 percent muscovite, and 2 percent opaques. Siderite-quartz veins, some containing disseminated pyrite, are also common in the sheared zones.

Carbonaceous material. An interesting though problematical occurrence of carbonaceous rock was discovered in fresh cuts along the north side of the Fernberg road just west of Madden Creek, as the road was undergoing improvement in July, 1963. The bedrock in this area is intensely sheared, at the confluence of at least two major faults, and most of the material within the sheared zone appears to belong to the Knife Lake metasediments and felsic volcanics, although Ely Greenstone crops out a short distance to the north and south. Within this phyllitic, rusty-weathering, siderite-impregnated zone is a 3- to 4-foot section, now (1969) largely slumped and covered, of graphitic layers alternating with rusty, clayey material, all sheared, broken, and deformed. Some parts of the carbonaceous material are soft and dull, whereas other parts, particularly on slickensides, are shiny and coal-like in appearance.

Metavolcanic rocks. A wide range of potassium-poor metavolcanic rocks is interbedded with the clastic rocks of the Knife Lake Group. Felsic varieties predominate, and are concentrated near the base of the section except in the area north and east of Gem Lake in the Forest Center quadrangle, where they appear higher in the section. These definite volcanic rocks, as mentioned above, pass laterally into clastic debris derived from them, and they are interpreted as the products of submarine eruption (see Fiske, 1969). Many of the rocks described above as clastic have predominantly volcanic, and in some cases pyroclastic, provenance. Many of these volcanic rocks have been sheared and somewhat recrystallized, and all have been altered by low-grade metamorphism, thus obscuring or erasing much structural and textural information.

Felsic dacite and rhyodacite constitute by far the bulk of the volcanic rocks of this belt (see M-7499, table 3), but exposures were also seen of mafic dacite, felsic andesite, mafic andesite, and metabasalt. Both massive flow rocks and fragmental breccias, tuff-breccias, and tuffs are present (figs. 14, 15); devitrified glass shards were seen in one specimen and many fragments that resemble pumice were seen. Some flows have scattered amygdules, and some of the metabasalts show pillow structures (*e.g.*, Moose Lake NW shore, SW¼ sec. 30, T. 64 N., R. 9 W.). Most of the volcanic rocks are porphyritic, and plagioclase is the most common phenocryst. Quartz is present in a few felsic porphyries, and hornblende crystals are common in a

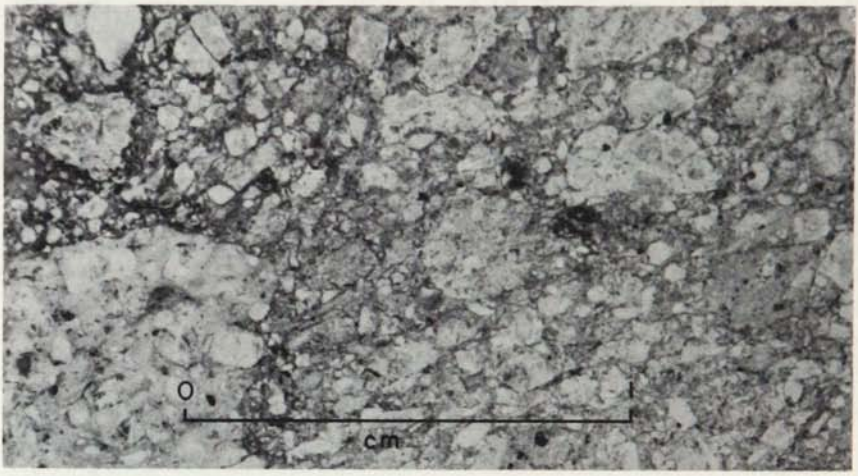


Figure 14. Photomicrograph of felsic tuff of Knife Lake Group, M-7366, sec. 35, 64 N/10 W.

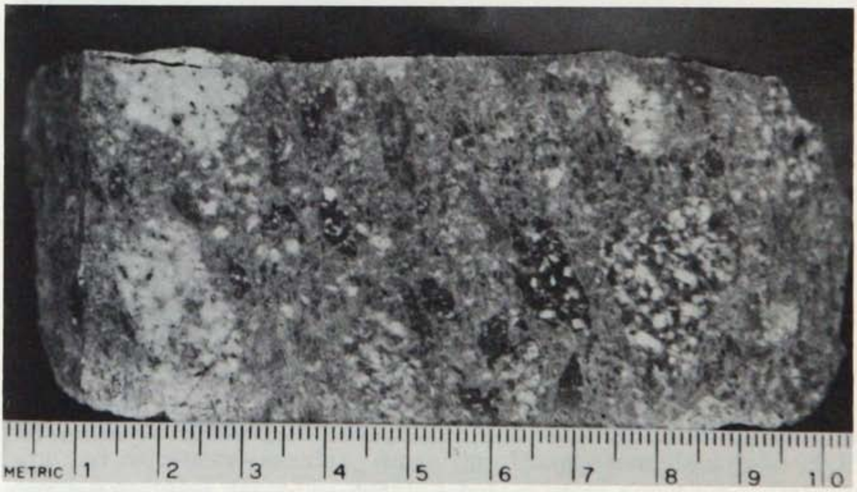


Figure 15. Felsic-intermediate tuff-breccia of Knife Lake Group, M-7367, sec. 35, 64 N/10 W. Sawn surface, 5 × 8 cm.

few rocks. Groundmasses of the lavas range in texture from dense and microcrystalline to trachytic and rarely spherulitic, and some specimens show feathery quench-structure intergrowths. In addition to plagioclase, quartz, and hornblende, minor K-feldspar was detected in a few specimens, and sericite, calcite, siderite, magnetite, apatite, actinolite, epidote, and kaolinite are common accessories and alteration products.

Iron-formation. Banded cherty and chert-carbonate iron-formation was found at four localities within the low-grade Knife Lake belt: (1) north side of island in SW¼ sec. 29, T. 64 N., R. 9 W., Moose Lake (fig. 16); (2) west end of Moose Lake, SE corner sec. 25, T. 64 N., R. 10 W.; (3) west shore of Wood Lake, just north of Madden Creek; and (4) southeast of Fall Lake in SE¼ sec. 11, T. 63 N., R. 11 W. The cherty beds are thin and rather lean, contain only a few magnetite-rich beds, and resemble the cherty beds typical of the Ely Greenstone. The carbonate-rich types are gray and locally stained brown by limonite weathering. They are composed of microcrystalline (about 0.01 mm) quartz and siderite in a ratio of about 1:2 or 2:3. Siderite-rich bands are finely laminated. Tiny magnetite grains are present in a few laminae, but some specimens are devoid of iron oxides. Where secondary oxidation has occurred, the siderite has been replaced by opaque and semi-opaque iron oxide products; this process, in an arrested stage, can be seen in several specimens. A chemical analysis is given in Table 4 (see also fig. 16). Another sideritic iron-formation locality was found in road cuts in a shear zone along the Fernberg road, about ¼ mile east of Madden Creek (NE¼ sec. 8, T. 63 N., R. 10 W.). Although the

Figure 16. Laminated chert-siderite iron-formation (analyzed) showing recent oxidation along joints and bedding planes, Knife Lake Gp. M-7271, sec. 29, 64 N/9 W. Specimen is 6 × 6 cm.

geologic map shows this area as Ely Greenstone, most of the material exposed here appears to belong to the Knife Lake, in that it contains abundant sericite, and relict quartz and feldspar grains. Mixed in with the phyllonite of these cuts are strongly crushed gray chert, gray hematite veined with specularite, red jasper, and gray sideritic chert that has a red-brown weathering rind.

Beds of iron-formation are considerably more abundant in the high-grade metamorphic area between Farm Lake and White Iron Lake and produce a very high (>35,000 gammas) magnetic anomaly (Meuschke and others, 1963). Although these strata are surrounded by metaclastic schists and gneisses, no iron-formation beds were found east of Farm Lake, within the main belt of Knife Lake gneisses. As indicated on Plate 1, these rocks may more properly be assigned to the Ely Greenstone, as also suggested by mapping to the west. These recrystallized iron-formations are also banded, but their grain size has increased to about ½-1 mm. They are composed principally of granoblastic quartz (60-85 percent), magnetite (5-30 percent), and grunerite (5-20 percent); the banding or lamination is an expression of small to large differences in the ratios of these three minerals. An iron-rich clinopyroxene, probably a hedenbergitic variety, constitutes as much as 3 percent of some samples, a small amount of apatite is typically present, and stilpnomelane (retrograde?) was seen in two specimens. Several prospect pits have been dug in this area, notably at the south edge of sec. 33, T. 63 N., R. 11 W.

Higher-grade rocks along North Kawishiwi River. Schists and gneisses, mainly clastic but containing some metavolcanic types, are exposed in a belt that extends east-west across the Gabbro Lake quadrangle along the North Kawishiwi River. Where not covered by water along the river or in Farm Lake, their northern contact is seen to be a fault of apparently large displacement against the lower part of the Ely Greenstone. Along the irregular southern margin of this belt, the schists and gneisses are intruded by the Giants Range batholith, and intimate, locally migmatitic mixtures of gneiss and granitic rocks are typical near this contact. A satellite body and several fault slices of granitic rocks also occur near the northern contact. The metamorphic rocks have been thoroughly recrystallized in the amphibolite facies. They are tentatively assigned to the Knife Lake Group because of their overwhelming clastic origin and because of a tenuous and faulted connection with Gruner's units 3 and 5 just east of the map area, south of Fernberg Hill.

The rocks of this belt are predominantly feldspathic gneisses that have a foliation expressed by both thick and thin beds and a preferred mineral orientation of biotite and hornblende. Layering and lamination are less distinct or absent in beds or outcrops of the coarser metaclastic rocks (metagrit and meta-conglomerate). Along the strongly tectonized zone of the North Kawishiwi River, the pebbles show extreme smearing and elongation, and the rocks have a very obvious rodding of clasts and a distinct mineral lineation. The small island in the SE¼ sec. 26, T. 63 N., R. 11 W., for example, consists entirely of an extremely stretched conglomerate. Granitic veins and quartz veins, many of ptygmatic form, are common in the belt (fig. 33). Some of the gneisses are so feldspathic and uniform in grain size that careful examination of outcrops is necessary to discover the relict bedding and so to distinguish these rocks from intrusive types; an example is near the east end of Murphy portage, at the north edge of sec. 28, T. 63 N., R. 10 W.

In spite of the extensive recrystallization, protoliths of most of this belt could be identified at least grossly from structures, textures, and/or mineral composition. Conglomerates are widespread and abundant in this belt. In most outcrops, the more felsic pebbles and cobbles are surrounded by a more mafic matrix, but in some areas amphibolite pebbles lie in a recrystallized felsic matrix, giving the rock some resemblance to an inclusion-rich granitic rock. Sorting is generally poor. It is not uncommon to find scattered pebbles and cobbles of various sizes in a gritty or metagraywacke matrix, rather than discrete beds of metaconglomerate alternating with beds of finer sediments; however, some examples of metaconglomerate beds were found, and pebble-rich outcrops are common. Rock types identified as clasts in these conglomerates include basalt and diabase (now amphibolite), dacite porphyry, felsite (probably), siltstone, quartzite (meta-chert?), hornblende granodiorite, biotite-hornblende tonalite, and biotite granite. The granitic cobbles are particularly abundant on ledges that overlook the river along the sec. 26-35 line, T. 63 N., R. 11 W. No provenance for these granites is known. The matrix of the conglomerates is similar to the metagraywackes described below.

Most of this high-grade belt is composed of recrystallized clastic rocks of sand size, but as noted above these grade into conglomerates. Cross-bedding was seen in several outcrops in the area north of South Farm Lake. The most common original rock type appears to have been arkosic (volcanigenic?) graywacke; nearly all the gneisses are highly feldspathic. Some of the more schistose, biotitic types probably were argillaceous or chloritic graywacke and possibly andesitic or basaltic tuff. Recognizable clasts are mostly plagioclase, but quartz, felsite, siltstone, apatite, hornblende, and zircon were also found. The plagioclase is mostly albite; oligoclase and andesine are uncommon. Minerals of the groundmass, and of laminated gneisses that have lost their clastic texture, are plagioclase, quartz, microcline, biotite, hornblende, epidote, chlorite (mostly as a retrograde alteration of biotite), garnet, cummingtonite, magnetite, sphene, apatite, allanite, zircon, monazite(?), calcite, pyrite, and kaolinite. In a few rocks, textures imply replacement of plagioclase by microcline along grain boundaries and fractures. In contact-metamorphosed metasediments adjacent to the Duluth Gabbro, near the east edge of the area, augite, hypersthene, cordierite, olivine, and orthoclase occur (see section on metamorphism below).

Fine-grained, laminated rocks just south of Pickerel Lake are interbedded with metagraywacke. Composed principally of plagioclase and hornblende, they probably are recrystallized chloritic argillites or fine-grained, basaltic tuffs. Somewhat coarser, more schistose rocks containing abundant biotite and quartz in other areas also probably originated as argillaceous sediments. No rocks aluminous enough to contain muscovite were found.

Recrystallized volcanic and rare intrusive rocks, most of which are porphyritic, also are present in this belt of high-grade metamorphism, although they probably constitute less than 5 percent of the total. Mineral compositions are indicative of intermediate rhyodacite, mafic, intermediate, and felsic dacite, andesite, and basalt. A hornblende andesite, exposed on the Farm Lake road in the SW¼ sec. 33, T. 63 N., R. 11 W., is adjacent to banded iron-formation and has pillow structure. Black, garnetiferous hornblende gneisses were found in a few outcrops west of Farm Lake as well as in the area to the west in the Ely quadrangle. In one exposure this rock shows intrusive relationships with the surrounding gneisses. Its protolith may have been peridotite.

Recrystallized, banded iron-formation is interbedded in the schists and gneisses west of Farm Lake, and has been described above.

Mafic sills. Two mafic, phaneritic sills, each a few tens of feet thick, were found within the low-grade Knife Lake belt. Both are pre-tectonic, and have been subjected to retrograde metamorphism.

One sill, located northwest of Moose Lake in the SE¼ sec. 30, T. 64 N., R. 9 W., is an altered, porphyritic, fine- to medium-grained syenodiorite. Phenocrysts of altered plagioclase and of actinolite-chlorite pseudomorphs after augite lie in a groundmass of saussurite, actinolite, chlorite, K-feldspar, epidote, apatite, and magnetite. The second sill forms part of the small ridge north of the mouth of Madden Creek in Wood Lake (NW¼ sec. 34, T. 64 N., R. 10 W.), and is a metadiabase. Not only is the ophitic structure preserved, but much of the original augite also remains. The remainder of the rock is composed principally of chlorite ± serpentine, actinolite, saussuritized plagioclase, epidote, and leucoxene.

Newton Lake Formation

General Statement. The belt of dominantly volcanic rocks that lies along the north boundary of the Gabbro Lake quadrangle, from Fall and Newton Lakes eastward to Washte Lake, has been distinguished as a separate stratigraphic unit in this report and on the map for reasons outlined in an earlier section. Clements (1903) included these rocks in the Ely Greenstone, but they closely resemble rocks that Gruner (1941) mapped to the east as Knife Lake. They lie north-northwest of the belt of predominantly metasedimentary, low-grade Knife Lake Group (as used in this report), along a rather straight contact that, although shown on the geologic map as an inferred fault, is now considered to be more probably a depositional contact except at its western end, northwest of Fall Lake. This change of opinion is based principally on two facts: (1) the lithology of the metavolcanic rocks north of the Knife Lake belt clearly differs from that to the south (the Ely Greenstone); and (2) although outcrops are poor over much of its length, the contact shows little evidence of the strong shearing that characterizes faults elsewhere in this area. Furthermore, several top-sense determinations in the volcanic rocks near the contact (from Wood Lake to Witness Lake) show younging away from the Knife Lake. Thus the northern volcanic belt is thought to overlie the Knife Lake stratigraphically, which in turn overlies the Ely Greenstone.

The name "Newton Lake Formation" has been proposed for this series of rocks (Morey and others, 1970). It is bounded on the south in the Gabbro Lake quadrangle by an apparently depositional contact with metasedimentary rocks of the Knife Lake Group of Gruner (1941), but from the center of Fall Lake westward for many miles its southern contact is faulted at an angle to structures within the formation. Its northwestern boundary is formed by a major fault (Vermilion fault) against higher-grade and intrusive rocks of the Vermilion batholithic complex. The formation strikes to the northeast into the Vermilion batholith. It is faulted off to the southwest by another large fault about eight miles west of Ely (see map, pl. 1). The eastern terminus is thus found in the vicinity of Prairie Portage (east end of Basswood Lake) or slightly southwest of that point, and its western, faulted-off terminus lies about 28 miles away near the southwest end of Burntside Lake.

A significant feature of this belt of rocks is the intertonguing, in the Newton Lake area, of metabasaltic lavas and intermediate and felsic volcanic rocks. Although part of the alternation of lithologies seen on the geologic map results from repetition of units across a synclinal axis, a sequence of two basaltic units alternating with two andesite-dacite units can be demonstrated by pillow structures in the northwest limb (see pl. 2). The felsic and intermediate rocks constitute the bulk of the formation in the eastern part of the quadrangle; a few mafic units are interbedded with the more felsic strata. The metabasalts, with associated mafic intrusions — in the western part — continue rather monotonously to the west across the Ely quadrangle. Although there are major faults in the Newton Lake area, there is no evidence that the contacts between these contrasting tongues of differing volcanic composition are faulted; instead, they are thought to represent contemporaneous accumulation of volcanic material from different sources. The presence of thin, felsic tuff beds in the mafic sequence supports this interpretation.

North of Ella Hall Lake, and northwest of Newton Lake, thick sequences of bedded, metaclastic and probably metatuffaceous rocks occur in this formation. Contacts with the metavolcanic rocks were not seen, and the inferred fault shown north of Ella Hall and Muskeg Lakes instead may be a depositional contact. In the northwest corner of the quadrangle the contact is probably depositional.

The internal structure of the Newton Lake Formation is not well known because of some fairly large gaps in exposure and few depositional top-sense criteria. However, from those pillow shapes that have been seen in the eastern and central part of the belt, it is clear that some isoclinal folds are present. In the Newton Lake area, and southwest along strike in the Ely quadrangle, pillows in metabasalt and andesite imply an isoclinal syncline having felsic and intermediate rocks in the core. The axial trace of the syncline passes along the west side of Newton Lake (pl's. 1 and 2). Strong lineations throughout this area plunge roughly northward, and may be related to the plunge of the syncline although they appear to be too steep. Other isoclinal folds in this formation have been mapped by the writer to the west in the Ely quadrangle (open file map, Minnesota Geological Survey).

Two major faults cut the Newton Lake Formation near the western edge of the map, and can be traced for many miles into the Ely quadrangle (pl. 1). The fault northwest of Newton Lake also passes northeastward into the Basswood Lake quadrangle, where it also continues for many miles. The fault at the south end of Newton Lake probably passes northeastward under or across the lake, but because of lack of exposures could not be traced. Many other faults, unrecognized on the ground, are probably present and complicate the internal structure of the formation.

A valid estimate of the thickness of this formation cannot be made at this time because of uncertainties of the extent of isoclinal folding, lack of marker beds and generally poor exposures, and the possible presence of internal faulting. However, about 4,500 feet of metabasalt is present in the northwest limb of the syncline west of Newton Lake, about 500 feet of siliceous marble and limy chert is present at Upper Pipestone Falls, more than 1,000 feet of laminated rock is probably included in the area north of Ella Hall Lake and also in the northwest corner of the quadrangle, and many thousands of feet of felsic and intermediate volcanic rocks are certainly present in the remainder of the area.

Although there are some gross similarities between this formation and the Ely Greenstone, several important differences exist which should be pointed out in order to demonstrate the lack of correlation between these two units: (1) felsic and intermediate rocks make up a very small proportion of the Ely Greenstone, whereas they constitute most of the Newton Lake Formation east of Newton Lake; (2) the felsic rocks in the Ely Greenstone differ in structure and composition from those to the northwest; (3) rhyodacite and dacite porphyry are common as small intrusions (and a large flow?) in the Ely, but, except for some pink, porphyritic rhyodacites north of Ella Hall Lake thought to be related to the Basswood Lake plutonic complex, are absent in the Newton Lake Formation; (4) the Newton Lake Formation, west of Newton Lake and to the west in the Ely quadrangle, is penetrated by numerous small serpentinized peridotite bodies, whereas ultramafic rocks have been found in the Ely Greenstone only in one area (west of Pea Soup Lake), and these have primary hornblende and no olivine or serpentine; (5) neither thick metasedimentary strata nor calcareous strata have been found in the Ely Greenstone, but both are present in the Newton Lake; (6) iron-formation is much less abundant in the Newton Lake Formation than in the Ely Greenstone.

The rocks of the Newton Lake Formation appear to be slightly more recrystallized than those in the bulk of the Ely Greenstone. Amphibolite-facies metamorphic rocks occur in the northwestern corner of the quadrangle and north of Muskeg and Ella Hall Lakes, near the Vermilion batholith complex. Many relict structures and textures, however, are still discernible. As is the case with the Knife Lake belt, recrystallization, sericite growth, and impregnation by ankerite are common in the Fall Lake area where the rocks have been affected by major faults.

Because of locally well-preserved bedding and lamination, grain-gradation and pillow structures, and a lack of primary welded structures, the volcanic and clastic rocks of this formation are considered to be of submarine origin.

Felsic and intermediate metavolcanic rocks. The major part of this formation from Newton Lake eastward consists of sodic, intermediate to felsic volcanic rocks and their clastic debris. Mineral and chemical compositions correspond to andesite and intermediate to felsic dacite, but where sericitized near faults at Fall Lake, K_2O contents have been determined at 3.05 and 3.38 percent (W. L. Griffin, written comm., 1967). In the more deformed zones the rocks are schistose or phyllitic, but elsewhere show little planar structure. Rodding and mineral lineation permeate much of this belt, being particularly strong near Newton Lake.

Where relict structures have been preserved, it is evident that most of these rocks are fragmental. Breccia and tuff-breccia are abundant (figs. 17, 18, 20), and finer-grained beds interlayered with these probably are tuffs. Some of the breccias are scoriaceous. Volcanic-arkosic wacke and volcanic graywacke were also identified (*e.g.*, east and northeast of Ella Hall Lake). West of Newton Lake, flow-banded, dacitic lava and lava-breccia are common, interbedded with pyroclastic rocks. Massive lavas of both felsic and intermediate composition are also widespread; some of these are amygdular, with one or more of the minerals chlorite, quartz, and calcite filling the cavities. Pillowed lavas having the composition of intermediate dacite (see table 3, fig. 19 and geologic map) and probably also of felsic dacite were seen in several layers between Witness and Ella Hall Lakes. The intermediate types characteristically have small plagioclase (and in some exposures quartz) phenocrysts and quartz or chlorite amygdules, and rather bulbous pillow shapes.

Many of the lavas and pyroclastic rocks are porphyritic. Plagioclase is by far the most common phenocrystic mineral; quartz is rare; hornblende or pseudomorphs thereof are not uncommon; microphenocrysts of magnetite and apatite were found in a few specimens. The tuffs, volcanic-arkosic wacke and graywacke contain clasts of albite, quartz, various felsites, and andesites with minor mudstone, chlorite, sericite, and apatite. Aside from phenocrysts and clasts, these volcanic rocks contain the following minerals, in approximate order of decreasing abundance: albite, quartz, chlorite, calcite, epidote, actinolite, sericite, sphene, magnetite, apatite, ankerite, pyrite, and zircon. K-feldspar was looked for by optical, staining, and X-ray diffraction methods, but none was found. Chemical analyses of two tuff-breccias are given in Table 3.

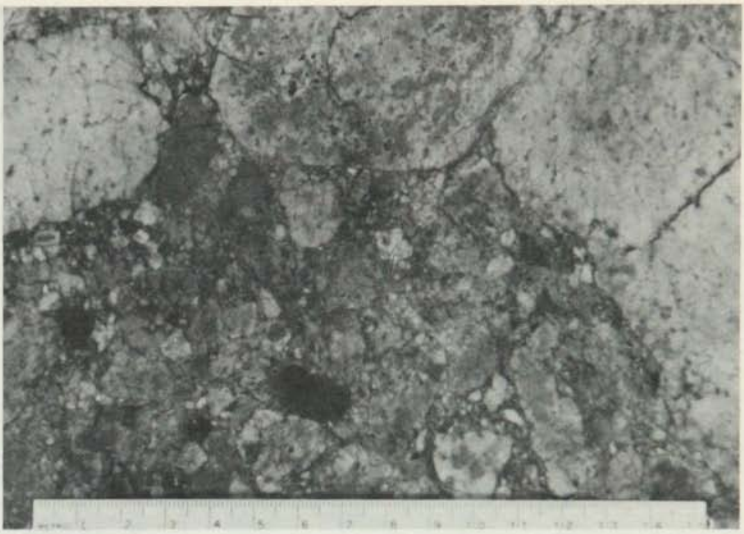


Figure 17. Dacite conglomerate or breccia of Newton Lake Formation, Ella Hall Lake. Rounded cobble at top is 6 cm across.

Figure 18. Andesitic tuff-breccia of Newton Lake Fm., M-7615, sec. 19, 64 N/9 W. Specimen measures 6 × 4.5 cm.

Figure 19. Pillowed dacite (analyzed) of Newton Lake Formation, M-7441, sec. 25/30, 64 N. 9/10 W.

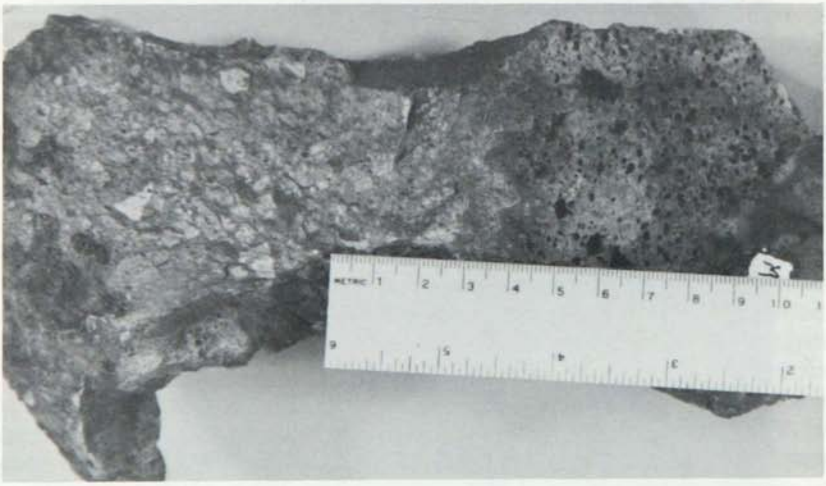


Figure 20. Vesicular andesite agglomerate or breccia, Newton Lake Fm., M-7661a, sec. 36, 64 N/11 W.

Mafic metavolcanic rocks. Dark rocks of basaltic and andesitic composition occur west of Newton Lake, and north of Muskeg and Ella Hall Lakes, and are interbedded with more felsic volcanic rocks near the base of the formation east of Newton Lake. In the area west of Newton Lake, the metabasalts, which predominate, strongly resemble those of the Ely Greenstone: pillow structure and massive fine-granular greenstone are common; variolites are present in some flows; pale, bleached pillowed flows were seen; and porphyritic texture is rare. All are somewhat more recrystallized than most of the Ely Greenstone. These metabasalts are cut by many irregular intrusions of metadiabase. Two or three thin (5-25 feet) strata of thin-bedded silicified felsic tuff(?) are interbedded with the metabasalts southwest of Newton Lake, and thinner stringers of chert and iron-formation are present but uncommon.

One of the variolitic, pillowed greenstones has been analyzed (table 2). It contains abundant, very small relict phenocrysts of augite. There has been considerable redistribution of elements within the matrix, however; the variolites are white or light gray and contain abundant fine-grained plagioclase, whereas the greenstone groundmass contains no feldspar but principally chlorite and actinolite. No radial structure is now apparent.

In the area north of Muskeg and Ella Hall Lakes the volcanic rocks have been intruded by many irregular bodies ranging from metagabbro to granodiorite, and also some smaller rhyodacite porphyries of apparently later, post-deformational age. The grade of metamorphism is higher than at Newton Lake; biotite and hornblende are common, and relict textures have been destroyed. The rocks have compositions ranging from basalt to dacite, with basaltic and andesitic types predominant. Many of them are laminated, some show probable breccia or agglomeratic structures, and nearly all are strongly lineated. Some of these rocks north of Muskeg Lake may be a continuation of the laminated rocks separated on the geologic map just north of Ella Hall Lake, but outcrops were too poor to trace them with certainty.

The mafic and intermediate rocks near the base of the formation, from Fall Lake east to Washte Lake, are mostly of andesitic composition although there are a few basalts. Many of these units are fragmental, ranging from tuff to breccia, but pillowed and massive flows are also present. Scoriaceous varieties are more common here than in other areas, particularly in some of the breccias or agglomerates (fig. 20). Amygdules occur in some of the pillowed and massive flows. A pillowed, amygdular flow and a massive, fine-granular flow have been analyzed (table 3). Another pillowed flow that was studied is also andesitic. Plagioclase phenocrysts occur in several flows. Nearly all the rocks contain albite, quartz, chlorite, calcite, sericite, epidote, magnetite, and sphene; some also contain tremolite-actinolite, and rutile that altered from ilmenite.

Clastic and volcaniclastic metasedimentary rocks. Although the principal areas of metasedimentary rock in this formation are north of Ella Hall Lake and in the northwestern corner of the map, minor units interbedded in the dominant volcanic rocks were seen and sampled just southeast of

Washte Lake (sec. 19, T. 64 N., R. 9 W.), east of Wood Lake (sec. 25, T. 64 N., R. 10 W.), ¾ mile northwest of Wood Lake (sec. 28, T. 64 N., R. 10 W.), northeast of Slumber Lake (sec. 29, T. 64 N., R. 10 W.), and southwest of Newton Lake (sec. 4, T. 63 N., R. 11 W.), as well as associated with iron-formation at Wood Lake (see below). They are mostly laminated graywackes, siltstones, and tuffs, all composed dominantly of quartz and plagioclase with minor chlorite, epidote and/or calcite. As in the older formations, some of these outcrops (where bedding was not visible) proved difficult to classify as either metavolcanic or metasedimentary, for they are generally recrystallized, fine-grained, and feldspathic and chloritic. However, most showed at least some compositional lamination. Even in these, however, it is difficult to determine the relative contributions of primary or reworked tuff or simple clastic erosion of volcanic material. A light-weathering bedded sequence, locally 5 to 25 feet thick southwest of Newton Lake, has a rather cherty appearance, but in thin section is seen to be a laminated felsic tuff or volcanic siltstone that has local graded laminations.

A coarse conglomerate is interbedded with pillowed metabasalt one-quarter mile west of the northwest end of Newton Lake. Although the mafic metagraywacke matrix and accompanying beds now are amphibolite as a result of metamorphism (mostly hornblende and poikiloblastic plagioclase), grit, pebbles, and cobbles of a variety of rocks are present in this matrix. These range from very mafic (principally hornblende and augite) to medium-grained, "normal" amphibolite, to syenite (?) to a variety of granitic rocks. Two of the samples studied are: (1) a massive, quartz-poor hornblende-biotite granodiorite, and (2) a foliated, coarser-grained, quartz-rich tonalite. The source area for these plutonic clasts is unknown.

The rocks north and northeast of Camp Lake (northwest corner of map) are nearly entirely laminated, mafic to "intermediate" metagraywacke, with rare conglomerate beds and metabasalt flows. In most outcrops the metagraywacke beds are strongly drag-folded, and in one area they are graded. Clasts identified in thin section are principally quartz and plagioclase, and include minor K-feldspar, microgranite, epidote, magnetite, apatite, and sphene; the matrix is composed of quartz, plagioclase, biotite, sericite, epidote, and chlorite.

At the north edge of the map, and in the area north of Muskeg and Ella Hall Lakes, the laminated rocks have a somewhat higher metamorphic grade, and recrystallization is more complete; no original clastic texture remains. These rocks are composed principally of fine-grained hornblende, biotite, plagioclase, quartz, and epidote.

Siliceous marble and limy quartzite. At Upper Pipestone Falls, between Fall Lake and Newton Lake, a layer of siliceous and calcareous rocks occurs within the dominant dacite. The layer is about 500 feet wide and at least one mile long; additional outcrops could not be found along strike to the northeast. It is composed of fine-grained, recrystallized cherty limestone and recrystallized calcareous chert. Bedding was seen in some exposures, but is not sharp. Several conglomeratic zones of cherty pebbles, cobbles, or granules in a limy matrix are present; these and other siliceous beds in the sequence form some of the rapids in the river. X-ray studies show the carbonate to be almost entirely calcite. A thin section of one sample, however, shows some small euhedral rhombs as well as anhedral carbonate; they probably are dolomite or ankerite. Other minerals present in small amounts are sericite, chlorite, magnetite, pyrite, and plagioclase. A chemical analysis of the rock is given in Table 4.

Iron-formation. Iron-formation is much less common in this formation than in the Ely Greenstone, but small stringers of barren to slightly magnetic, white or gray chert were seen here and there in the metabasaltic area west of Newton Lake. A bed at least 20 feet thick and a mile long of dark gray to black, well banded magnetite-chert iron-formation strikes across the northeastern part of Wood Lake, and another isolated outcrop of similar rock was found just to the north on the lake shore. In several exposures these iron-formations are intimately interbedded with more barren chert and laminated clastic rocks. Each of the two samples studied is finely laminated, but in one the laminations are lensy and discontinuous. The granoblastic quartz is about 0.01-0.03 mm in diameter, whereas the smaller magnetite euhedra range from about 0.005 to 0.01 mm; in one sample small magnetite porphyroblasts as large as 0.1 mm are present. Both samples contain about 5 percent chlorite flakes, and one sample contains 2 percent sericite. The sericite-bearing sample contains about 1 percent calcite and 3 percent siderite, whereas the other contains about 15 percent siderite, as minute rhombs, and ankerite, as porphyroblasts 2-3 mm in diameter. A chemical analysis of the latter specimen is given in Table 4; see also Figure 21.

A 2-4 foot bed of fine-grained, iron-rich rock is interbedded with a sequence of volcanic agglomerates on the southeast shore of Ella Hall Lake. Recrystallization has destroyed most of its original texture, but its compo-

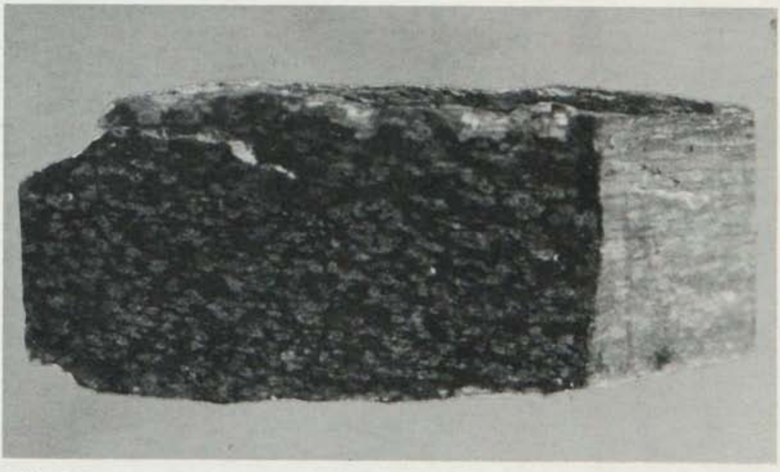


Figure 21. Carbonate-magnetite-chert iron-formation (analyzed) with ankerite porphyroblasts, Newton Lake Formation, M-7625, sec. 26, 64 N/10 W. Sawn surface is 7 × 3.8 cm.

sition and general microscopic aspect suggest that it was a siltstone, enriched in iron either during or after deposition. It is now composed of about 20 percent quartz, 30 percent albite, 22 percent ankerite, 20 percent pyrite (in small porphyroblasts), and 8 percent iron-rich chlorite.

Intrusive Rocks

Nearly one-half of the area covered by this report is underlain by intrusive rocks, the great majority of which constitute the eastern end of the Giants Range batholith of Algoman age. The remaining intrusive rocks include a wide variety of small dikes, sills, stocks, and fault slices that are also of Early Precambrian age, plus several rather straight and uniform post-metamorphic diabase dikes that are probably Keweenawan. The metamorphosed intrusive mafic rocks that are included in the stratified formations have been described above.

Porphyries and Microgranites of Early Precambrian Age

Porphyritic rhyodacite. Dikes and irregular small plutons of a distinctive porphyritic rhyodacite or dacite (rp and dp on the geologic map) are widespread in the Ely Greenstone, as well as in many other parts of the Vermilion district. In most exposures the rhyodacite clearly can be seen to intrude the Ely Greenstone, but in the Jasper Lake-Tofte Lake area it apparently flowed onto the surface during Ely Greenstone time. In this area some weathered surfaces show fragmental structure. Easily recognizable debris of this porphyry is found in most exposures of conglomerate within the Ely Greenstone, also implying extrusion and/or unroofing during Ely Greenstone time (fig. 1). One exposure, on the south shore of Moose Lake, is surrounded by rocks of the Knife Lake Group, which indicates that porphyry intrusion overlapped deposition of the Ely and Knife Lake units in this area. Some rather similar porphyritic rhyodacites north of Ella Hall Lake, near the northern edge of the quadrangle, are thought to be related to the nearby Basswood Lake pluton of the Vermilion batholith. Their textures approach those of intrusive granitic stocks just north of the map boundary at Good and Indiana Lakes, and they intrude rocks of the Newton Lake Formation, which is younger than the Knife Lake. Other pink porphyries with scattered orthoclase phenocrysts are limited to the south-central part of the outcrop belt of the Ely Greenstone (Twin Lakes-Greenstone Lake-Pickerel Lake area), and may be related to the Giants Range batholith, though there is no clear evidence for this.

Typically these rocks are whitish, pale tan, or pale green, and rarely medium or dark gray. They weather white. Some of those containing K-feldspar have a pink groundmass. Plagioclase, in euhedral to subrounded, blocky crystals 1-6 mm across, is the most abundant phenocryst (average 39 percent in 11 sections); in most specimens it is albite (An_{4-6}), but in some it is zoned with cores of oligoclase and albite rims. These phenocrysts are slightly to strongly altered to sericite, calcite, and kaolinite; where strongly altered they may be difficult to see megascopically. Quartz phenocrysts are also ubiquitous in these rocks, though less abundant than the plagioclase (average 8 percent). It occurs as generally equant, rounded crystals about 1 to 4 mm across, many of which show resorption embayments. Orthoclase phenocrysts, 3 to 10 mm across, are found as well in those areas labelled "rp" on the geologic map, and also in local areas within "dp" areas, such as east of Camp Twenty Lake. Where present at all, the orthoclase crystals, which are pink, euhedral, and less altered than the plagioclase, make up about 9 percent of the rock. Hornblende phenocrysts, 0.2-1 mm across, in large part retrograded to more or less well-defined pseudomorphs of calcite, chlorite, and epidote, also are ubiquitous, and constitute about 7 percent of the rock. Short, prismatic apatite microphenocrysts, about 0.1-0.3 mm long, are also characteristic, and are estimated to constitute about 1 percent of the rock. In some specimens they have brown, dusty cores. The groundmass of the porphyries is a microcrystalline, hypidiomorphic-granular or granoblastic aggregate of quartz and albite, and, in some specimens, minor K-feldspar. Sericite is widely distributed in the groundmass, and chlorite, epidote, calcite, sphene, magnetite, and pyrite are common. Zircon and actinolite are rare, and biotite and tourmaline are confined to areas that have undergone later metamorphism (see figures 22, 23).

A chemical analysis of a typical specimen (M-7112 of table 3) indicates a rhyodacitic composition, although no K-feldspar was detected; the K_2O must be almost entirely contained in sericite of the plagioclase phenocrysts and groundmass.

Porphyritic andesites. A few small bodies of a medium- to dark-green porphyry, which appear in hand specimen to be andesitic, cut both the Ely Greenstone and the Knife Lake Group; the major occurrences are near Tofte Lake and southeast of Moose Lake. The small body immediately northeast of Tofte Lake also consists of this rock, and is incorrectly labeled "dp" on the geologic map. The rock is crowded with blocky to tabular plagioclase phenocrysts, 1-5 mm long, which constitute an average of 37 percent of the rock. Where the phenocrysts are tabular, the rock shows a pronounced flow structure. Hornblende phenocrysts are next most abundant; they make up about 16 percent of these rocks, and occur as stubby prisms about 1-2 mm long (fig. 24). A few small quartz phenocrysts, about 1 mm in diameter, were found in some samples. Both sphene and apatite form microphenocrysts, each making up about 0.5 percent of the rock. The plagioclase phenocrysts are mostly albite, but some are zoned and have oligoclase cores and albite rims. The microcrystalline groundmass is made up principally of albite, quartz, and, in some specimens, K-feldspar; epidote, magnetite, chlorite, zircon, calcite, and pyrite are also typically present in small amounts.

A chemical analysis of a typical specimen (M-7202, table 3) shows a normative composition of a quartz trachyandesite; other facies, without K-feldspar in the groundmass, have the mineral compositions of hornblende dacite and hornblende andesite.

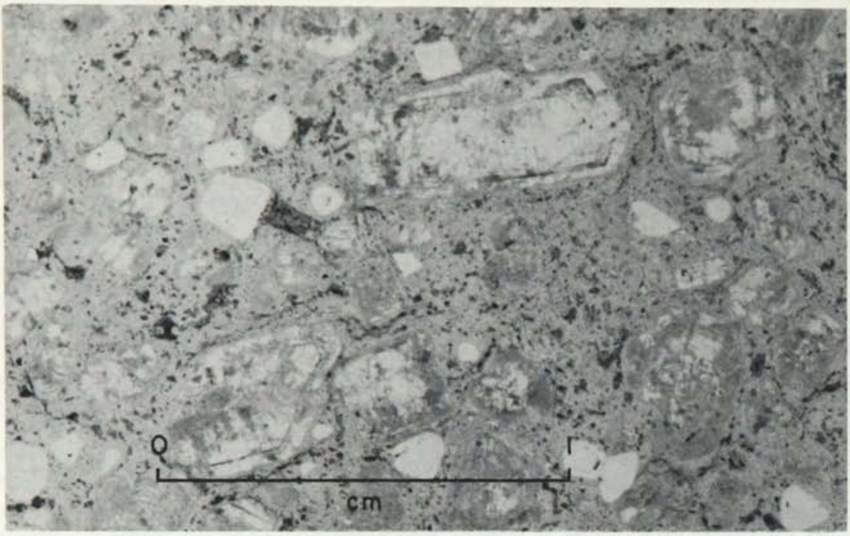


Figure 22. Photomicrograph of typical dacite porphyry (analyzed). Note large, zoned plagioclase, high-quartz euhedra, small, altered hornblende phenocrysts, and mafic xenolith. M-7112, sec. 6, 63 N/9 W.

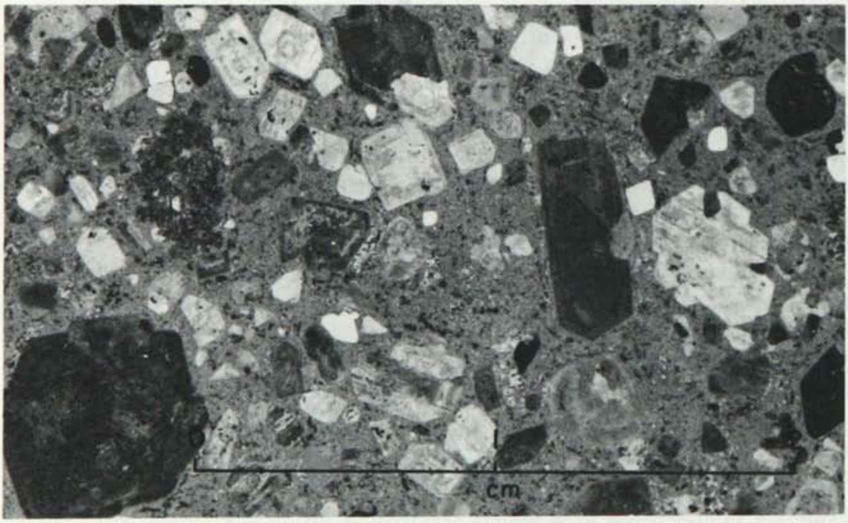


Figure 23. Same specimen as in Fig. 22, crossed polars.

Other porphyritic dikes. A great variety of dikes and sills, from 1 to 10 feet wide, cut all the stratified formations in the area. Nearly all are porphyritic and have aphanitic or fine-granular groundmasses; a few, described in a later paragraph, are aplitic or microgranitic in texture. Basaltic and diabasic dikes, clearly of Keweenawan age, are also described later, as are dikes that cut the Giants Range batholith. The porphyritic dikes here described show varying degrees of deformation and alteration, and it is difficult to assign most of them to a pre-, syn-, or post-metamorphic or -tectonic category (even the clearly post-metamorphic Keweenawan dikes show some alteration). All are tentatively assigned to the broad period of intrusion and deformation known in Minnesota as the Algoman orogeny, part of which may be contemporaneous with the deposition of some of the stratified rocks in this area. However, Hanson (1968) has identified post-Algoman, pre-Keweenawan dikes in other areas of northern Minnesota. Detailed isotopic studies of the dikes in the Gabbro Lake quadrangle should provide valuable information.

None of the dikes is sufficiently continuous or large to show on the geologic map, and no preferred orientation was noted.

Plagioclase is the most common phenocryst, occurring in at least 80 percent of the dikes. Hornblende, or pseudomorphs thereof, is next most common, followed by biotite (or chlorite pseudomorphs), which was found in about half the dikes. Quartz, orthoclase, and augite (or pseudomorphs) are

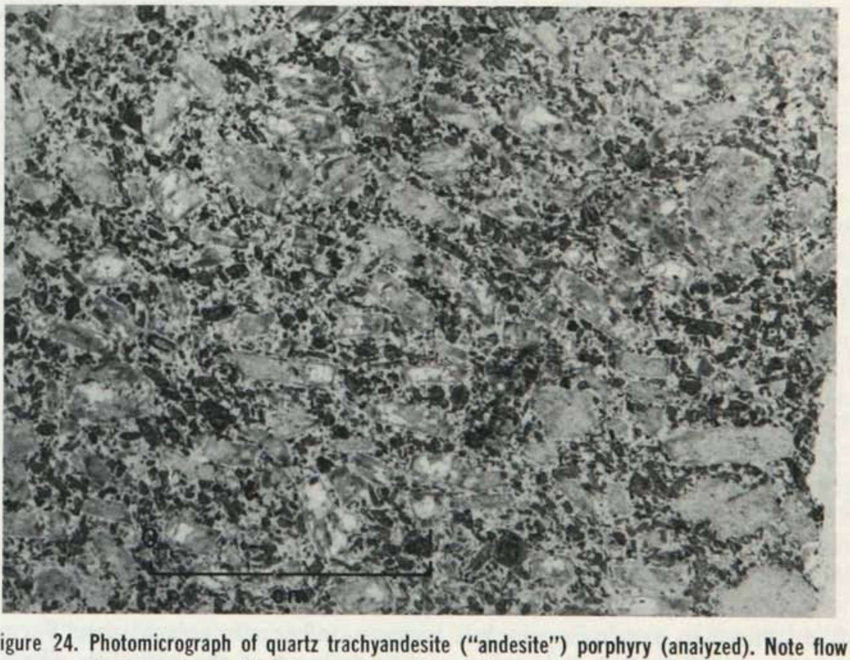


Figure 24. Photomicrograph of quartz trachyandesite ("andesite") porphyry (analyzed). Note flow structure, large plagioclase and small hornblende phenocrysts. M-7202, sec. 10, 63 N/10 W.

less common, and apatite and sphene phenocrysts are uncommon. Rock compositions range from mafic to felsic, with representatives from basalt through andesite, minette, trachyte, trachyandesite, latite, dellenite, dacite, and rhyodacite.

Microgranite dikes. Several small dikes and sills of microgranite were found in the map area, outside the zone of aplites and other granitic dikes that are closely associated with the Giants Range batholith. They are fine-grained, hypidiomorphic-granular in texture, and a few contain small phenocrysts; three samples show plagioclase, and one also has quartz phenocrysts. One dike has clearly finer-grained (chilled) borders. These dikes cut the Ely Greenstone, the Knife Lake Group, and the Newton Lake Formation. Many are conformable, and are in that sense actually sills. In the area southeast of Moose Lake, and at Jasper Lake, these dikes have been somewhat altered hydrothermally, and contain sericite, pyrite, and carbonate (calcite ± siderite or ankerite).

The dikes generally have the composition of biotite tonalite, although some may range to biotite adamellite depending on the abundance of K-feldspar. The plagioclase is albite and albite-oligoclase. The biotite is generally altered to chlorite, and in addition to the secondary minerals mentioned above, apatite, zircon, and rutile were seen as accessories.

Giants Range Batholith

General statement. The Gabbro Lake quadrangle includes the eastern exposed extremity of the Giants Range batholith, which extends for more than 100 miles to the west-southwest generally along the north side of the Mesabi range. Allison (1925) has presented the results of a survey over the entire batholith. The following discussion is concerned only with that part exposed within the Gabbro Lake quadrangle.

In this area, the batholith has intrusive contacts along its north side against high-grade metamorphic rocks tentatively assigned to the Knife Lake Group (described above). Both the intrusive rocks and the metamorphic rocks have been faulted against the Ely Greenstone along the North Kawishiwi River. To the west, in the Ely quadrangle, the Giants Range batholith intrudes the Ely Greenstone (see open file map, Minnesota Geological Survey). Along its southeastern contact, the granitic mass is overlain and contact-metamorphosed by the Duluth Complex. The granite-gabbro contact dips about 30° SE, according to data obtained by the International Nickel Company (Wager and others, 1969). Southeast of South Farm Lake, large masses of mafic gneiss and granoblastic rocks occur within the batholith. Relict structures such as pillows were not seen in these metamorphic rocks, and their origin is unknown; the rocks may be either the refractory remnants of large xenoliths or roof pendants, or cognate xenoliths or segregations related to the earlier crystallization history of the batholith.

In this map area two principal facies — informally termed the "Farm Lake" and "Clear Lake" facies — constitute most of the batholith. However, a large number of different lithic types are present in these major facies, many of which show gradational contacts with one another, and the batholithic rocks are cut by a wide variety of apparently cognate dikes. A general summary of sequential and structural relationships follows.

Although the Farm Lake and Clear Lake facies constitute most of the outcrops in the area, in no place were clear-cut intrusive relationships observed between the two. Instead, a wide zone extends from near South Farm Lake eastward to the South Kawishiwi River in which the two facies occur in an intimate, alternating mixture that suggests physical mixing of two contemporaneous viscous magmas, without homogenization. In fact, many of the lithic contacts within the batholith in this map area are of this type, as will be mentioned below.

The Clear Lake facies contains abundant areas of more mafic types, which obviously are related to and gradational into it. Intrusive relationships, such as dikes and inclusions, show these to be older than the major Clear Lake type. The Farm Lake facies also contains internal varieties — a non-porphyritic phase that lacks the typical large microcline phenocrysts and which has commonly associated mafic schlieren and segregations — and local, marked variations in quartz content. These Farm Lake varieties do not show clear intrusive relations to one another; dikes, inclusions, chilled borders, or other structural evidence indicative of an age sequence were not found. For example, in one outcrop (S½ sec. 1, T. 62 N., R. 11 W.) the visible quartz content changes from 0 to 20 percent over a distance of 2 inches, without any other associated textural or mineralogical change such as a chilled border.

Dikes and small irregular plutons of fine-grained and fine- to medium-grained biotite granite intrude both of the major facies mentioned above, particularly near the South Kawishiwi River. Also, a variety of intermediate and mafic dikes, all metamorphosed, intrude both major facies, and are particularly abundant in the area south of Farm and South Farm Lakes. Pegmatite and aplite dikes are the youngest phases, and cut all those mentioned above; aplites are clearly younger than pegmatites in some outcrops. In a single exposure a diorite dike can be seen to cut an aplite; elsewhere several younger, chilled, Keweenawan (?) dikes were found.

Many veins and dikes of Farm Lake and Clear Lake facies in adjacent gneisses of the Knife Lake Group are folded and boudinaged (fig. 33). Many aplites post-date at least some of the folding, but some have been broken and pulled apart after solidification. In one outcrop of Farm Lake facies, shearing is interpreted to have been followed by intrusion of aplite and still later fracturing. Small and large xenoliths and septa of banded gneiss are common along the northern contact with the Knife Lake Group, especially along the north shores of Farm, South Farm, and Clear Lakes and along the North Kawishiwi River to the east.

A mineralogic feature characteristic of nearly all phases of the batholith in this area, but especially of the Clear Lake facies, is plagioclase that is megascopically pink and strongly kaolinized. Accordingly, the feldspars are difficult to distinguish in hand specimen and plagioclase compositions are difficult to determine in thin section.

Estimated modes of typical specimens are given in Table 5.

Farm Lake facies: hornblende adamellite and monzonite. Most of the Giants Range batholith in the Gabbro Lake quadrangle consists of the Farm Lake facies — hornblende adamellite and monzonite — which also extends west and southwest to Birch Lake in the Ely 15′ quadrangle. Apparently this facies corresponds to the facies described by Allison (1925) as "intermediate type." The most abundant type is porphyritic and medium-grained (fig. 25); non-porphyritic varieties, in the southwest part of the area, will be described later. The rock typically has a flow foliation and generally a lineation formed by alignment of evenly distributed hornblende prisms and microcline phenocrysts. Large outcrops of this well-foliated, coarsely porphyritic rock give the impression of a rather viscous magma, as there is no evidence of settling of either type of phenocryst. The flow structures are fairly consistent in attitude over areas a mile or more across.

The common porphyritic variety is a pink hypidiomorphic-granular hornblende-biotite adamellite or monzonite. Microcline phenocrysts generally range in cross-section from ½ × 1 cm to 1 × 2 cm; the quartz content ranges from 10 to 25 percent and generally is 15 to 20 percent; one sample lacks quartz altogether. The quartz content is less than that in "typical" granitic rocks, which have close to the eutectic amount of approximately 30-35 percent quartz (Chayes, 1951). In some areas plagioclase also occurs as phenocrysts, and in some quartz as well forms grains sufficiently large to be called phenocrysts (about 5 mm). In some areas, the hornblende prisms are also slightly larger than groundmass grains and are thus porphyritic. Augite as well as hornblende was observed in one sample that lacked quartz. The Farm Lake facies has a color index that ranges from 10 to 20. Hornblende predominates over biotite, and the plagioclase is albite to sodic oligoclase.

In addition to quartz, microcline, plagioclase, hornblende, and biotite, these rocks contain small amounts of magnetite, sphene, apatite, zircon, and locally epidote and/or allanite. In one thin section the hornblende crystals contain relict cores of augite. Contact-metamorphic effects of the Duluth Complex are described in a later section.

In the area south and southwest of Crocket Lake (secs. 21, 22, 27, 28, 29, 32, 33, T. 62 N., R. 11 W.), much of the rock lacks the conspicuous pink microcline phenocrysts, but otherwise shows the texture and foliation typical of the Farm Lake facies. This non-porphyritic type is intimately mixed with typical Farm Lake-type porphyritic rocks in many outcrops, without clear intrusive relationships, and a mixing of viscous magmas is here also implied. This interpretation is supported by the observation in two outcrops of flow structure (*not* secondary foliation) that is continuous across contacts of these two phases, and is not parallel to the contacts. The geologic map distinguishes only those areas where the non-porphyritic type ("gae") predominates. Lacking the microcline phenocrysts, these nonpor-

Table 5 — Estimated modes of typical specimens of intrusive rocks of Giants Range batholith and of granitic rock west of Pea Soup Lake.

	M-7133	M-7272	M-7504	M-7599	M-7300	M-7460	M-7459	M-7669
Quartz	10	10	25	tr.	3	15	3	28
K-Feldspar	68	34	30	4	30	15		30
Plagioclase	15	40	34	74	50	50	47	35
Sericite		X	X	X			X	X
Biotite	(?)	1	(?)	5		2	3	6
Chlorite	1	2	4	X	X	1	X	X
Hornblende		10	6	10	15	15	45	
Fe-Ti opaque	3	tr.	½	3	1	½	tr.	tr.
Pyrite	1							
Sphene	X	1	tr.	2	½	½	1	
Apatite	½	tr.	½	2	½	tr.	1	tr.
Zircon	tr.	tr.		tr.	tr.	tr.	tr.	tr.
Epidote	X	1½	tr.		X	1		
Allanite		tr.						
Monazite				tr.				
Fluorite	tr.							
Calcite	1½							

X = present as alteration but amount not estimated

(?) = probably originally present but now completely altered

Explanation for Table 5

M-7133: red granitic rocks west of Pea Soup Lake. Massive, reddish quartz syenite with moderate cataclastic texture, Fernberg road, SE of Stub Lake, Sec's. 14/23, 63 N, 11 W. Most of plagioclase grains show peripheral K-spar replacement.

M-7272: Giants Range batholith, Farm Lake facies (quartz-poor). Medium- to coarse-grained, pink, flow-foliated, porphyritic hornblende-quartz monzonite, southwest shore of Farm Lake, 62 N, 11 W; fig. 25

M-7504: Giants Range batholith, Farm Lake facies (quartz-rich). Medium-grained porphyritic adamellite, hill southeast of big swampy lineament, SE ¼ Sec. 1, 62 N, 11 W.

M-7599: Giants Range batholith, Farm Lake facies ("non-porphyritic"). Medium-grained, weakly porphyritic hornblende-biotite diorite, ½ mile N. of Minn. Rte 1, W. edge of quadrangle, SE ¼ Sec. 29, 62 N, 11 W.

M-7300: Giants Range batholith, Clear Lake facies. Medium-grained, allotriomorphic-granular hornblende monzonite, N. Kawishiwi River 1 mi. SE of Uranus L., NW ¼ Sec. 26, 63 N, 10 W; see fig. 26

M-7460: Giants Range batholith, Clear Lake facies. Medium-grained hornblende granodiorite with mortar texture, S. Kawishiwi River about 2/3 mi. S. of Clear Lake, NE ¼ Sec. 5, 62 N, 10 W; see fig. 26

M-7459: Giants Range batholith, Clear Lake facies, mafic phase. Medium-grained hornblende diorite, island in bay of S. Kawishiwi River S. of Clear Lake, NE ¼ Sec. 5, 62 N, 10 W.

M-7669: Giants Range batholith, fine-grained biotite granite. Fine- to medium-grained biotite adamellite, SW corner of Bruin Lake, N ½ Sec. 18, 62 N, 10 W.

phyritic rocks also tend to have less quartz than the typical Farm Lake facies, although the mafic minerals occur in similar amounts. Representative samples have the compositions of syenodiorite and quartz syenodiorite.

In these areas of non-porphyritic, Farm Lake-related rocks, intermediate and mafic schlieren, xenoliths(?), and segregations are also common. Although abundant, the individual bodies are too small to show on the geologic map. In several exposures, veinlets of hornblende can be seen to cut across the granitic rocks, and one outcrop has the appearance of syenite "boulders" in a hornblende matrix. These mafic zones have sharp to diffuse contacts with the surrounding porphyritic and non-porphyritic granitic rocks. In some outcrops the relationships imply hornblende segregation after the country rock had been solidified and fractured, but in others the hornblende concentrations appear to be cumulate segregations of crystals; this interpretation is supported by textures seen in thin sections and megascopically. These mafic and intermediate phases have compositions ranging from hornblende diorite to hornblende melagabbro. In a few outcrops, mixed porphyritic and non-porphyritic Farm Lake-facies rocks are cut by a dark, fine-grained diorite, which is obviously younger. A very distinctive dark diorite containing pink feldspar and abundant larger-than-normal, euhedral hornblende prisms was seen at several places in areas dominated by both the Farm Lake and Clear Lake facies. Its diffuse contacts and its texture imply that it may be the result of recrystallization of cognate xenoliths.

Clear Lake facies: hornblende monzonite and adamellite. The northeasternmost exposed part of the batholith is made of a fine- to medium- and medium-grained, allotriomorphic-granular, pink hornblende-biotite facies, most of which ranges in composition from adamellite to monzonite to granodiorite and syenodiorite. One specimen is a tonalite. Color index is generally 10 to 20. The grain size is typically smaller and quartz is less evident megascopically than in the Farm Lake facies (fig. 26). As a result of the typical pink, somewhat altered feldspars, these rocks megascopically resemble syenites. Quartz content actually ranges from 3 to 35 percent (estimated), but typically is 10-20 percent. Much of this facies contains small plagioclase phenocrysts, but they are not conspicuous and the contrast with the Farm Lake facies is rather clear. The plagioclase is albite to sodic oligoclase, and in a few sections is antiperthitic. The potassium feldspar is normally well-twinned microcline, but in some specimens untwinned K-feldspar also is present. The microcline is finely microperthitic in about half the sections studied. The ferromagnesian minerals are more commonly altered

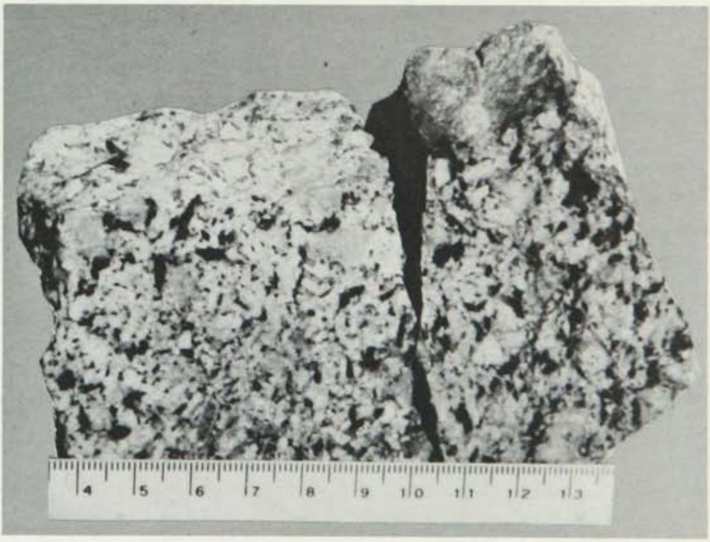


Figure 25. Textures characteristic of Farm Lake facies of Giants Range batholith. Note grain size, K-feldspar phenocrysts, slight foliation of hornblendes, euhedral feldspars and hornblende, lack of large quartz grains. M-7139 and M-7272, S. of Farm Lake.

than in the Farm Lake facies: hornblende alters to chlorite and epidote, whereas biotite alters to chlorite. In one syenodiorite sampled, augite constitutes 10 percent of the rock; the augite is rimmed by hornblende, apparently indicating a magmatic reaction relationship.

In addition to the major minerals, the Clear Lake facies contains accessory apatite, zircon, magnetite, sphene, and epidote. Calcite is not uncommon, and allanite was found in one section, and tan-brown tourmaline in two others. Large (½-2 mm) grains of an unidentified dark brown, glassy, metamict mineral were found to be common in the sheared granitic rock in two localities along the North Kawishiwi River; NW¼ sec. 28, and SE¼ sec. 22, T. 63 N., R. 10 W. Minute cracks radiate from the grains, indicating expansion concomitant with metamictization.

The Clear Lake facies has varying degrees of foliation and lineation expressed as alignment of hornblendes. Although this appears to be a primary flow structure in most areas, it grades locally into a secondary foliation as a result of shearing. This is particularly true along the North Kawishiwi River, where the batholith and several separate thin, granitic slices have been strongly crushed and smeared by movements associated with the major North Kawishiwi fault that separates it from the Ely Greenstone. In some places where strongly sheared, the granitic rocks take on an intense brick-red or orange-red color; the same effect has been seen by the writer in Pipestone Bay of Basswood Lake to the north along another major fault.

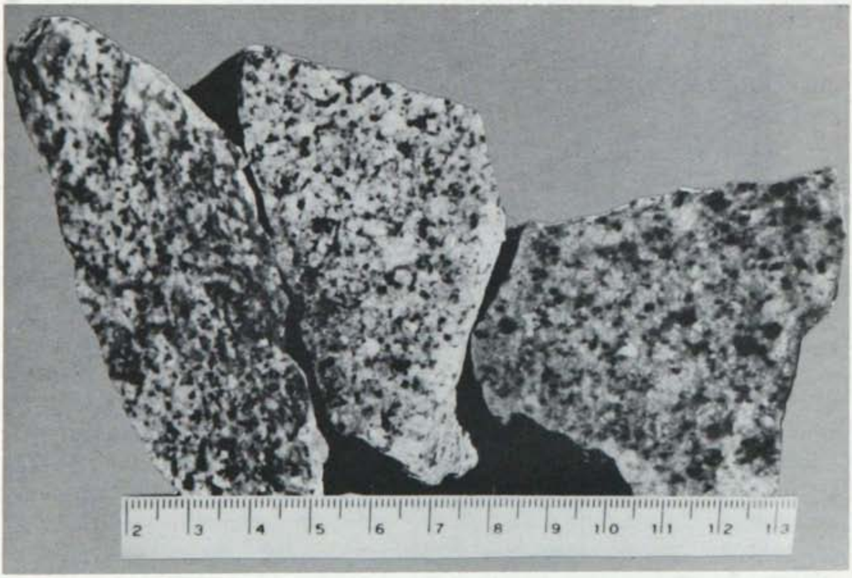


Figure 26. Textures characteristic of Clear Lake facies of Giants Range batholith. Note finer grain, lack of phenocrysts, lack of obvious quartz grains. M-7300 (sec. 26, 63 N/10 W), M-7460 (sec. 5, 62 N/10 W), M-7532 (sec. 30, 63 N/10 W).

In addition to the inhomogeneities in quartz and feldspar content mentioned above, there are many local variations in mafic mineral content, giving abundant mafic and intermediate varieties. Particularly inhomogeneous areas occur along the South Kawishiwi River south of Esquagama and Clear Lakes, and about one-half mile east of Clear Lake. The larger bodies that were found are shown on the geologic map. Compositionally, they are mostly hornblende-(biotite) diorite and quartz-poor tonalite. Biotite, largely chloritized, is greatly subordinate to hornblende, and a few samples contain a trace or a few percent of microcline. The plagioclase has albite to oligoclase rims, but the cores are altered. One sample contains 35 percent augite that is rimmed by hornblende. A hornblendite, containing about 6 percent interstitial antiperthite and 4 percent microcline-microperthite, was found near the Clear Lake end of the Clear Lake-North Kawishiwi portage. Although the contacts of these mafic and intermediate bodies are not sharp or chilled, intrusive relationships were seen in several outcrops that establish their age of consolidation as earlier than the more felsic "normal" Clear Lake facies. For example, in one outcrop a dioritic variety contains inclusions of a finer-grained, more mafic type, but is itself enveloped in the "normal" granodiorite and is cut by granite pegmatite.

Equigranular biotite adamellite and granodiorite. The youngest mappable phase of the Giants Range batholith in this area is a pink, fine-grained to fine- to medium-grained, non-porphyritic biotite adamellite and granodiorite that occurs as dikes, sills, and small, irregular intrusions that cut both major facies. This rock unit is more common in the area underlain by the Farm Lake facies, and is particularly abundant in the vicinity of the South Kawishiwi River. The rock has a hypidiomorphic-granular texture, with rare, weakly porphyritic feldspars, and a locally developed, weak foliation; its general aspect, however, is uniformity and finer grain size, especially in contrast to the Farm Lake and Clear Lake facies. In contrast to the major facies, it also has abundant quartz (25-35 percent), no hornblende, and a more felsic composition (color index 5-8). Thus, in both structure and composition the rock fits an interpretation of a late-stage residual product of the Farm Lake (and perhaps the Clear Lake) magma. Although it might also be interpreted as a rheomorphic product from the effect of the nearby Duluth Complex, this investigator does not subscribe to this hypothesis because (1) the rock type is too abundant and widespread; (2) although common along the South Kawishiwi River, it is not concentrated in the immediate vicinity of the gabbro contact; and (3) its plagioclase has undergone the same strong alteration as that in much of the rest of the Giants Range batholith. Although it is difficult to determine the composition of the plagioclase cores, the clearer rims are albite and albite-oligoclase. The K-feldspar is mostly untwinned, but in some sections typical microcline twinning has developed in some grains. Accessory minerals are magnetite, apatite, sphene, and zircon; epidote and allanite are less common.

Aplite, pegmatite, and syenite dikes. Aplite and pegmatite dikes cut all the previously described phases of the Giants Range batholith. As mentioned above, many of the aplites are younger than at least some of the folding and shearing, but some have been broken and pulled apart after solidification. Rarely, pegmatites are cut by aplites, but in most outcrops the two appear to be more or less contemporaneous. In one exposure an aplite dike has pegmatitic selvages, with perpendicular quartz and feldspar. Most aplite dikes are ½-inch to 1½ feet thick. The pegmatites range in thickness from an inch to several feet, but rarely are more than 10 feet thick.

The aplites are allotriomorphic-granular and fine- to medium-grained. They have approximately equal proportions of quartz, plagioclase (oligoclase), and microcline; accessory minerals are hornblende and/or biotite (much altered), apatite, epidote, sphene, and zircon. The pegmatites range in grain size from about 1 cm in the smaller dikes to about 25 cm in some of the thicker dikes. Most are granitic or adamellitic in composition, and contain quartz, albite, and microcline perthite as major components and biotite, secondary sericite, magnetite, zircon, apatite, and secondary chlorite as lesser, local components. One pegmatite west of Clear Lake contains tourmaline and magnetite. Syenitic or monzodioritic pegmatites were found locally in the area underlain by the Clear Lake facies. Besides plagioclase and orthoclase, these contain small amounts of hornblende, epidote, apatite, sphene, chlorite, and quartz.

A distinctive trachytoid augite syenite was found as a dike at three localities — two in sec. 1, southeast of South Farm Lake, and another in the NE¼ sec. 7 on the South Kawishiwi River south of Esquagama Lake. It is pink, has strongly aligned, platy microcline-microperthite showing Carlsbad twins as the major mineral, and a phaneritic matrix of anhedral microcline, plagioclase, augite, hornblende, and sphene.

Late mafic and intermediate dikes. A variety of mafic and intermediate dikes, from about 10 inches to 5 feet thick, cuts the Farm Lake and Clear Lake facies of the batholith. They are particularly abundant in the area south of Farm and South Farm Lakes, and thus are found principally in the Farm Lake facies. Their textures and structural relations are complex, but imply that they are genetically related to the development of the batholith. The dikes have more or less recrystallized, metamorphic textures, yet most have a foliation parallel to their contacts and many are cut by aplites and pegmatites; clearly they were intruded along fractures in already solidified batholithic rocks. Some have discontinuous streaks of varying mafic content parallel to their contacts, and some are clearly compound. Their contacts are sharp against the enclosing granitic rocks. At one such contact, examined in thin section, the granite appears to have been remelted in a zone about one half mm wide; it has at least been recrystallized to a much finer grain size than it had originally. One compound diorite dike cuts an aplite, but this is the only such relationship seen. Elsewhere a more massive metabasaltic dike cuts a streaky dioritic dike. Figure 27 shows some of the structural relationships. It is evident that these dikes were intruded shortly after the granitic rocks had solidified, but while they were still hot, and before at least most of the aplites and pegmatites were formed.

Compositionally these dikes are mostly hornblende diorites, but there is enough microcline to make some of them syenodiorite or even monzonite, and enough quartz in a few to make them tonalite. Augite cores are present in the hornblendes of one tonalite. A few percent of biotite is found in most of these dikes, and apatite, magnetite, sphene, and epidote are nearly ubiquitous.

Mafic xenoliths and/or segregations. Southeast and south of South Farm Lake, in the area of the Farm Lake facies and mixed zone, many outcrops of amphibolitic rocks were found. They are fine- to medium-grained or medium-grained, massive or gneissic, and have a generally allotriomorphic-granular texture. Their genetic relations are obscure; it is unclear whether they are mafic segregations or phases related to and metamorphosed by the batholith, or simply xenoliths of some mafic protolith such as Ely Greenstone. Most of the amphibolites contain about 45-50 percent plagioclase (andesine to labradorite), 20-50 percent hornblende, a small amount of quartz, 5-15 percent biotite, and minor apatite and opaque oxides. Two samples, from different places in the large body near the south shore of South Farm Lake, are ultramafic, each containing about 70 percent augite. One of these also contains 10 percent hornblende, 5 percent apatite and 5 percent microcline (fig. 28); the other contains 22 percent hornblende and 5 percent plagioclase. These appear more likely to be early segregations than xenoliths.

Granitic Rocks Outside the Giants Range Batholith

Red granitic rocks west of Pea Soup Lake. Several small exposures of red granitic rocks were found along and near the Fernberg road west of Pea Soup Lake, especially in sec. 13, the S½ of sec. 12, the southeastern part of sec. 14, the N½ of sec. 23, and the NE¼ of sec. 22, T. 63 N., R. 11 W. Exposures are generally poor in this area, and the contacts shown on the

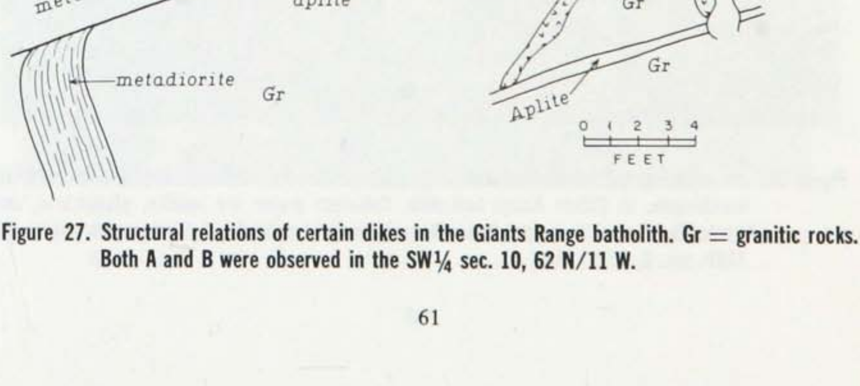


Figure 27. Structural relations of certain dikes in the Giants Range batholith. Gr = granitic rocks. Both A and B were observed in the SW¼ sec. 10, 62 N/11 W.

geologic map are generalized. Many small granitic dikes cut the country-rocks — greenstones, amphibolites, gabbros, and ultramafic rocks — and appear to represent the latest intrusive activity (before the Keweenawan) in the local area. Intrusion breccias, consisting either of greenstone intimately veined by red stringers or red granitic material choked with angular greenstone xenoliths, were seen in several road cuts during realignment of the Fernberg road. In one cut (NE¼, NE¼, sec. 22), a fault separates a granitic body from greenstone; both rocks become progressively sheared to phyllonites within a few feet of the contact.

The granitic rocks are red or pink, fine- to medium-grained, and hypidiomorphic-granular. Some of the finer-grained dikes contain small, lighter-colored feldspar phenocrysts in a brick-red groundmass. The ratios of quartz, plagioclase, and K-feldspar vary greatly between different samples, but quartz is nowhere as abundant as in typical granites. According to these mineral ratios, samples that were studied are adamellite, quartz syenite, monzonite, tonalite, and quartz syenodiorite. For a typical mode see Table 5. Besides containing dominant plagioclase (albite, commonly antiperthitic), poorly twinned microcline-microperthite, and quartz, the rocks have minor

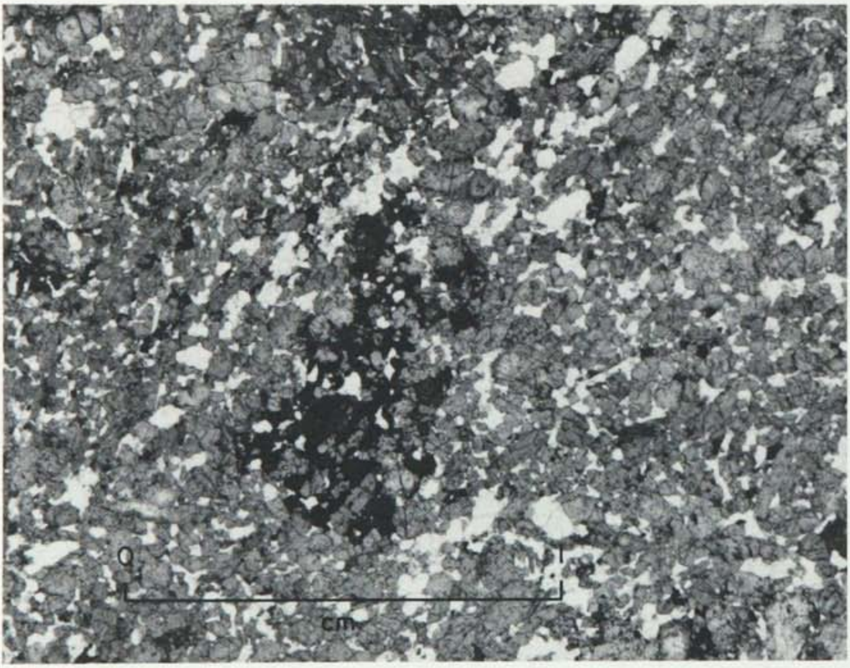


Figure 28. Photomicrograph of melagabbro segregation (?) with cumulus augite and poikilitic hornblende, in Giants Range batholith. Colorless grains are apatite, plagioclase, and microcline; large, dark-gray to black grains are hornblende, lighter gray is augite. M-7280, sec. 2, 62 N/11 W.

hornblende (or its alteration products), biotite (or pseudomorphs), magnetite, epidote, apatite, sphene, calcite, chlorite, pyrite, and sericite. Fluorite was observed in one sample and augite in another. A few samples exhibit the sericite-calcite-ankerite-pyrite impregnation which characteristically occurs in sheared zones of this area. Centripetal replacement of plagioclase crystals by microcline, without myrmekite, is common.

Granitic fault slices near Fall Lake. Immediately southeast of Fall Lake, in T. 63 N., R. 11 W., granitic rocks occur as long, narrow bands with fault contacts against the enclosing low-grade metasedimentary rocks of the Knife Lake Group. It is possible that the two bands as mapped may be continuous with each other. They are intensely sheared at their borders, and impregnated with ankerite and calcite. The adjacent metasediments show no contact-metamorphic effects. The granitic rocks are fine- to medium-grained, hypidiomorphic-granular hornblende-biotite tonalities that have about 20-25 percent quartz. One specimen has large muscovite plates that may be secondary. The plagioclase, hornblende, and biotite are largely altered to sericite, epidote, and chlorite. The shear foliation is vertical, and parallel to the bedding and cleavage of the surrounding Knife Lake rocks (see fig. 29).

Other, isolated granitoid bodies. Exposed along the northwestern side of the large point in the western end of Ella Hall Lake is a small mass of altered biotite tonalite. It is fine- to medium-grained, has a weak foliation of

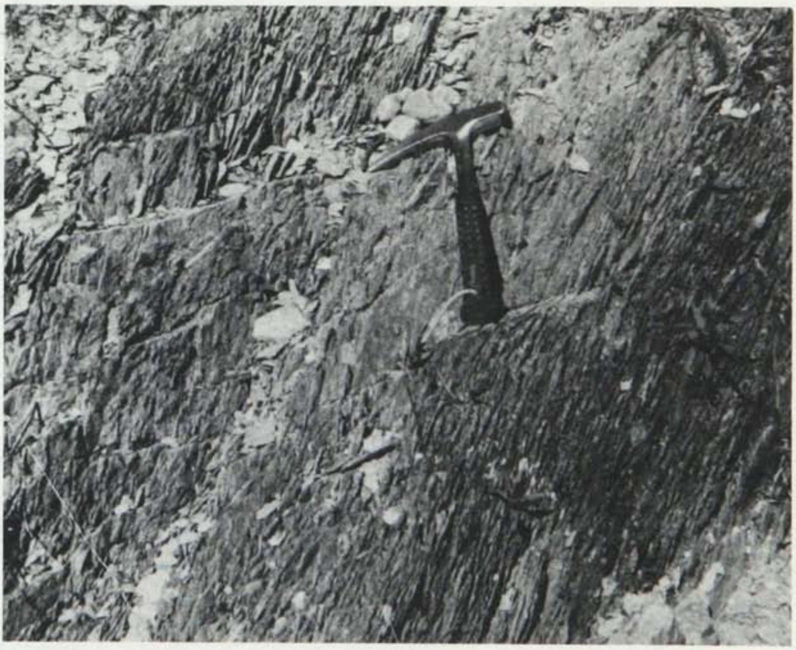


Figure 29. Sheared granitic rock of fault-slice in Knife Lake Group, SE shore of Fall Lake, sec. 16, 63 N/11 W.

subhedral to euhedral plagioclase crystals, and has undergone considerable quartz veining, calcite impregnation, and alteration of biotite to chlorite. Apatite, sphene, magnetite, and zircon are accessory minerals. Its relationship to the surrounding volcanic rocks is obscure.

A fine-grained, porphyritic tonalite, too small to be mapped, was found on the Fernberg road (old alignment) 0.3 miles SE of Uncle Judd's Creek in sec. 8, T. 63 N., R. 9 W. It has sodic plagioclase phenocrysts and pseudomorphs after either hornblende or biotite, in a fine-grained groundmass of albite, quartz, sericite, calcite, and chlorite; traces of K-feldspar, opaques, and apatite are also present.

Another small exposure of fine-grained, porphyritic tonalite was found approximately on the section-line halfway between Ella Hall and Hula Lakes, T. 64 N., R. 10 W.; it intrudes andesitic and dacitic volcanic rocks. The phenocrysts are sodic plagioclase that has micrographic overgrowths, and rare, equant quartz crystals. Biotite is altered to chlorite, muscovite, and opaque oxides; secondary carbonates are common.

In the area of higher metamorphic grade north of Muskeg and Ella Hall Lakes several bodies of reddish felsic to intermediate rocks have intruded the amphibolites of the Newton Lake Formation. One sample examined, from north of Muskeg Lake, is a medium-grained hornblende tonalite that has a hypidiomorphic-granular texture but is somewhat recrystallized. The hornblendes, which are strongly pleochroic, are large, euhedral, and poikilitic, enclosing abundant quartz and magnetite blebs. The plagioclase is subhedral to euhedral and albitic, and contains abundant epidote granules. Apatite, ilmenite, and magnetite are also present. These rocks may be outlying early phases of the Vermilion batholith complex of the Basswood Lake area.

Ultramafic, Mafic, and Intermediate Plutonic Rocks Outside the Giants Range Batholith

Ultramafic rocks in the Newton Lake area. Four small bodies of serpentinized ultramafic rock were found in sections 27, 33, and 34 just west of Newton Lake (T. 64 N., R. 11 W.). Three of these are shown on the geologic map; the fourth lies in the major fault zone at the northwest end of the lake. "Pipestone Falls," at the outlet of the lake 0.2 miles north of the quadrangle boundary, may have been named for the serpentine in this zone. These rocks are generally black or very dark-green, but weather to a spotty, pale gray-green, and are medium- to coarse-grained and poikilitic. In thin section, one is seen to consist of about 47 percent rounded subhedral olivine pseudomorphs and about 2 percent small opaque spinel (probably chromite) euhedra, all enclosed in large ($\sim$1 cm diameter) poikilitic pseudomorphs of enstatite and augite and 1 percent magnesian biotite. Before serpentinization the rock was evidently a harzburgite. Most specimens retain unaltered relics of some of the augite intercumulus crystals (fig. 30). Several similar bodies, some considerably larger and some associated with faults, have been found during recent mapping by the writer in the Newton

Lake Formation just to the west, in the Ely quadrangle (Minnesota Geological Survey open file map). The body that lies on the edge of the map in sec. 33, and has been described above, has also been chemically analyzed (see table 3).

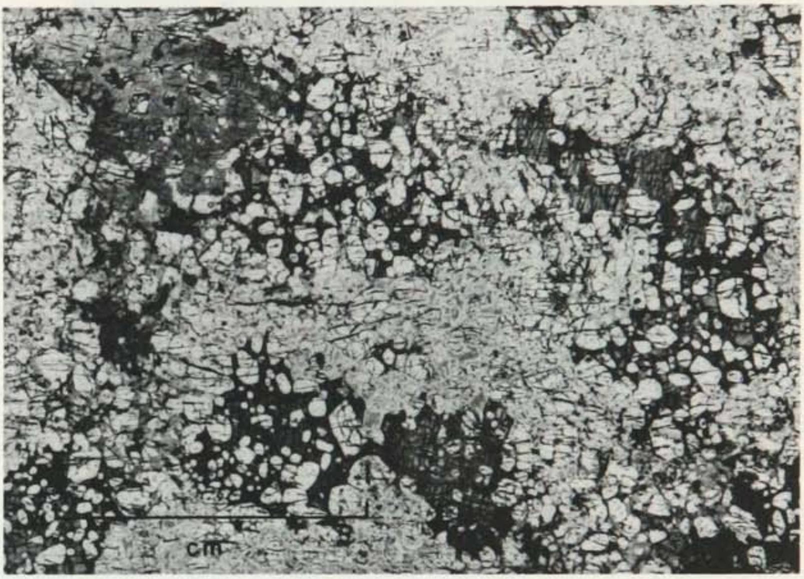


Figure 30. Photomicrograph of partly serpentinized peridotite (analyzed), Newton Lake Fm. Pale ovals are serpentinized olivine crystals; dark mesostasis is relict augite. M-7549, sec. 33, 64 N/11 W.

Mafic and ultramafic rocks west of Pea Soup Lake. North of the Fernberg road, in sections 12, 13, and 14, T. 63 N., R. 11 W., is a lowland area in which most of the scanty outcrops are of massive to gneissic, fine- to medium-grained plutonic rocks, which contrast with the obviously supracrustal and low-grade metabasalts in the surrounding area. They are shown on the geologic map as "amphibolite" (ea), but further petrographic study has shown them to be dominantly magmatic hornblende melagabbros and ultramafic rocks, though they have evidently been retrograde-metamorphosed to varying degrees. Two samples studied are augite-hornblende rocks; augite has cumulus textures in both, whereas the strongly pleochroic brown hornblende is poikilitic in one and subhedral and probably cumulus in the other (fig. 31). Small amounts of biotite, interstitial magnetite, and apatite are also present, and one sample contains 2 percent plagioclase. A sample of hornblende-augite-biotite gabbro, which has about 45 percent plagioclase, was also studied; except for the large amount of plagioclase, its texture and mineralogy are similar to the ultramafic rocks. Alteration to actinolite and epidote along fractures is common. These rocks are veined by the pink granitic rocks described above, with associated retrograde effects.

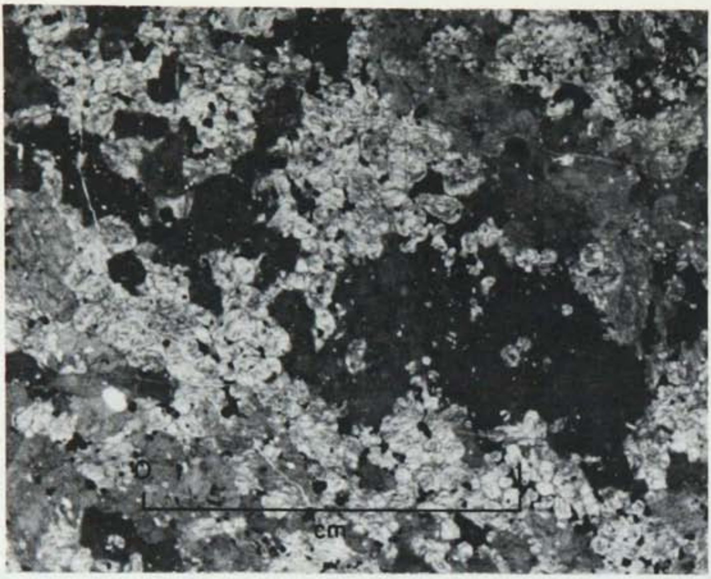


Figure 31. Photomicrograph of hornblende-augite rock with cumulus texture, from mafic-ultramafic rocks intruding Ely Greenstone ("ea" on geologic map). Augite is pale gray, hornblende is various shades of darker gray, magnetite is black. M-7656, sec. 14, 63 N/11 W. Scale is approximate.

Mafic and intermediate rocks in the Newton Lake Formation. Abundant metadiabase and metagabbro, very similar to those in the Ely Greenstone (described above), intrude this formation west of Newton Lake. Many outcrops of intermediate to mafic rocks occur in the area north of Muskeg Lake, but most bodies are not distinguished on the geologic map. Their textures range from massive to gneissic, and from obviously magmatic to metamorphic; it is difficult to distinguish in many cases between "amphibolite" and "hornblende gabbro" or "diorite." The feldspar is a red or pink strongly altered plagioclase; interstitial quartz is present in some outcrops; K-feldspar is rare. The hornblende is strongly pleochroic, and in some specimens it appears to have replaced augite. Biotite, which is sparse, is largely altered to chlorite, and magnetite is partly resorbed.

A metadiabase sill, from the east end of Wood Lake (sec. 26, T. 64 N., R. 10 W.), consists principally of large, equant, poikilitic actinolite pseudomorphs after augite, which enclose strongly saussuritized plagioclase laths.

Mafic sills in the Knife Lake Group. Granular, mafic sills were found in two locations in the Knife Lake metasediments: on the small point-ridge just north of the mouth of Madden Creek at Wood Lake, and on the ridge just northwest of Moose Lake in the SE¼ sec. 30, T. 64 N., R. 11 W. The sill at Wood Lake is a sheared and altered metadiabase with relict, ophitic augite. That at Moose Lake is a fine- to medium-grained, retrograded porphyritic syenodiorite or syenogabbro, with actinolite-chlorite pseudomorphs after what were most likely augite phenocrysts in a groundmass of the same minerals, saussuritized plagioclase, microcline, altered biotite, epidote, apatite, and magnetite.

Porphyritic biotite diorite northeast of Garden Lake. A diamond-drill hole of the Garden Lake Iron Co., in the NE¼, NE¼ of sec. 22, T. 63 N., R. 11 W., penetrated considerable porphyritic biotite diorite. Of four samples examined in thin section, all have 15-25 percent biotite, mostly as phenocrysts. Plagioclase phenocrysts are also found in most specimens; they are only rarely twinned but are antiperthitic. One specimen that has 50 perment augite phenocrysts together with 20 percent biotite phenocrysts, is a mela-syenodiorite. Calcite, magnetite, apatite, and chlorite are present in minor amounts in all samples. This distinctive rock cuts the metabasalt of the Ely Greenstone, but is locally strongly sheared. It has not been observed at the surface.

Keweenawan Diabase

Several dikes of black, tough basalt and diabase cut rocks of the Ely Greenstone, Knife Lake Group, and the Giants Range batholith. Although some are partly altered, most are rather fresh (see fig. 32 and analysis M-7129, table 2). They have chilled contacts that cross-cut structures in the

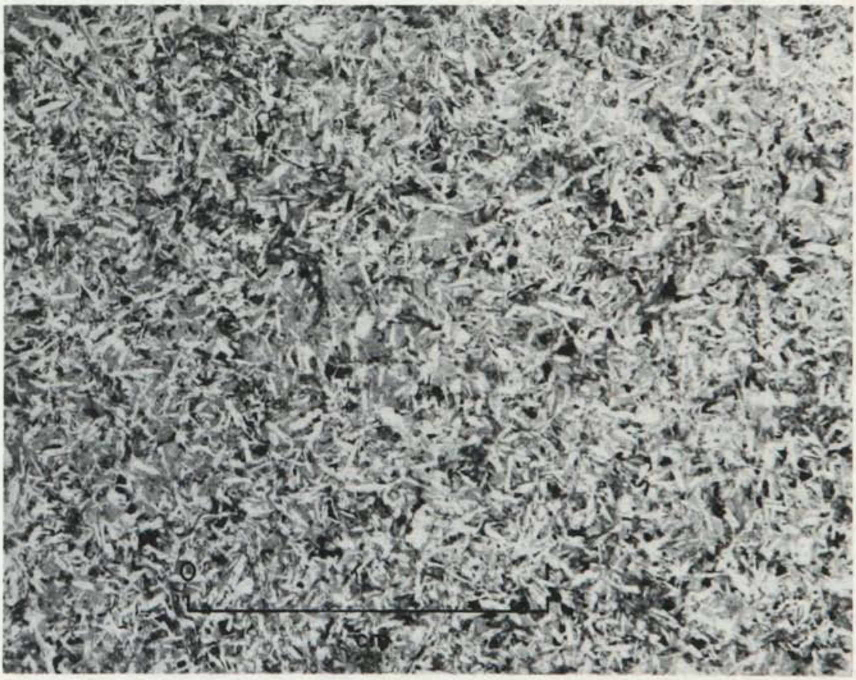


Figure 32. Photomicrograph of Keweenawan olivine diabase dike (analyzed), that cuts Knife Lake Group. M-7129, sec. 36, 64 N/10 W.

country rocks which were produced during the principal (Algoman) deformation. They are considered to be Keweenawan in age, and to have intruded during some unknown stage in the eruptive and intrusive activity of the North Shore Volcanic Group and the Duluth Complex. Because of their proximity to the gabbro and general parallelism to its trend, they are most likely related to either intrusion of the Duluth Complex (or a part of it), or to crustal warping resulting from the formation of the complex. They may have been feeders for now-eroded Keweenawan lavas.

The dikes range in thickness from 3 to 4 inches to 50 feet. The thinner ones are typical of the dikes in the Giants Range batholithic rocks. Most of the thicker dike exposures are thought to be segments of a large dike that may be continuous for at least 6½ miles, and which extends from the northeast corner of the map southwestward along the shore of Moose Lake to southeast of Sourdough Lake. In most outcrops the dikes trend about N. 65° E., but several trend between N. 30° W., and N. 60° W., and one trends N. 80° W. Observed dips are all within about 10° of vertical. In many outcrops of N. 65° E.-trending dikes, the intrusion was essentially concordant to the vertically dipping country rocks; by definition these should be called sills.

The thicker dikes are a fine- to medium-grained olivine diabase (fig. 32). The plagioclase is strongly zoned and has cores of labradorite-bytownite and rims of sodic andesine. One typical specimen has been chemically analyzed (M-7129, table 2). It contains abundant olivine as well as ophitic augite and traces of biotite.

Some of the thinner dikes are finer-grained and porphyritic; they contain small labradorite phenocrysts, a few augite phenocrysts, and possibly also olivine phenocrysts (altered) in an intergranular to intersertal matrix.

Amygdules containing chlorite and quartz occur in some of the Keweenawan dikes.

A few non-porphyritic mafic dikes, which from structural relationships evidently are post-deformational, are altered to such a degree that their geologic age was not inferred; they could range in age from late Algoman to Keweenawan.

STRUCTURE

General Statement

In those parts of the earth's crust that have been as mobile as the Vermilion district, it is essential to develop an understanding of the structural relationships at the same time as the stratigraphy; each type of evidence is needed for a valid elucidation of the other. In the Gabbro Lake quadrangle many conclusions as to stratigraphic relations have been based on interpretations of rock structures. Three types of structures have been of particular importance: primary depositional structures that show top senses (particularly lava pillows), intrusive relations of hypabyssal and plutonic rocks, and sheared and crushed zones that indicate faulting.

The metavolcanic rocks, which make up the bulk of the sequence in this area, have behaved with relatively high competence compared to the pelitic rocks of the Knife Lake Group or the banded chert and iron-formation beds. Deformation within the metavolcanic formations has thus been primarily by localized shearing and faulting, leaving most of the rocks undeformed, and with only rare and widely-spaced major folds. Even the bedded rocks show relatively few minor folds, although local alternations of top sense indicate more folding to be present than is directly evident in the Knife Lake Group.

Penetrative deformation, without the formation of folds or actual fault-plane dislocations, is important in some localized zones and areas.

Although the well-stratified formations generally have fairly straight, though vertical bedding, minor folds and other structures do indicate differences in tectonic style. Chert and cherty iron-formation beds within the greenstones locally show intense folding, generally parallel or concentric, and commonly disharmonic. The fold axes are nearly everywhere steep.

In the low-grade metasedimentary rocks of the Knife Lake Group, and those within the upper part of the Ely Greenstone, minor folds are of the shear or slip-fold type, associated with the development of an axial-plane cleavage. Some thickening of beds in the axial zones of these folds has occurred, and rarely such a fold has been faulted off along its axial plane. One-half mile northeast of Gem Lake a small quartz vein, cutting pelitic phyllite, has been fractured into blocks and each block has slipped sideways along the fractures. Other lineations of *b* tectonic type (intersections, wrinkles) are also moderately common.

In the more recrystallized rocks along the North Kawishiwi River (Knife Lake Group) and in the northwest corner of the quadrangle (Newton Lake Formation) the tectonic style is somewhat different, involving much more flowage through recrystallization and less slip along discrete cleavage planes.

The metasedimentary schists that constitute much of the Newton Lake Formation in sec. 28, T. 64 N., R. 11 W. (NW corner of map) are strongly folded; many thin-bedded outcrops exhibit folds that are from a centimeter to a foot in wavelength. Drag folds, evidently on the flanks of larger structures, and sets of folds having no preferred movement sense, and apparently from the axial zones of larger folds, are common. The schistosity is parallel to axial planes, and most of the folds plunge either vertically or to the northeast. Some of the laminated, hornblendic metasediments or metatuffs north of Ella Hall Lake also show good drag folds with nearly vertical plunges and east-northeast-trending axial planes.

The most extensive recrystallization, and the most rock flowage, has occurred in the high-grade Knife Lake schists and gneisses near the Giants Range batholith. Although straight bedding is well-preserved, and cross-bedding is still visible in the metagraywacke beds in several outcrops, minor folds are locally common and many granitic veins and quartz veins show boudinage or pinch-and-swell structure. Smaller veins show ptygmatic deformation in many places (fig. 33). Axial-plane cleavage is rather poorly developed. North of Farm and South Farm Lakes the folds generally plunge north to northwest; east of South Farm Lake they tend to plunge south; and west of Clear Lake they plunge to the southeast. Locally variable plunges are also common, however, indicating that the competence of local rock masses, as well as an areal stress field, has been a factor in determining orientation of the fold axes.

Structural relationships within the Giants Range batholith and between the batholith and country rocks have been described in an earlier section.

The major structural elements of the stratified rocks are emphasized in Plate 3, and interpretive structure sections are presented in Plate 4.

Faults

In his study of the Knife Lake district immediately east of the Gabbro Lake quadrangle, Gruner (1941) realized the great significance of faulting in the development of the earth's crust in this area. In addition, during the writer's first field season in the Gabbro Lake quadrangle it soon became evident that faults were both widely distributed and of profound importance in reconstructing the geologic relationships; this observation has been amply repeated and recognized in all the more recent work in the Vermilion district (*e.g.* Sims and others, 1968).

The direct evidence for faulting in the area is principally the physical state of the rocks. Although the rocks in most outcrops are massive or contain only primary structures such as flow-foliation, in many places they

Figure 33. Granitic veins and ptygmatic folds in metaclastic gneiss of Knife Lake Group, northeast of Clear Lake, sec. 29, 63 N/10 W.

show varying degrees of schistosity or fissility that locally culminate in soft, flaky, phyllitic rock. Associated with such a structural transition is a gradual deformation or eradication of primary structures, such as pillows or variolites or pyroclastic texture.

A particularly good example of such a fault contact is found in a road cut on the north side of the Fernberg road in the NE¼, NE¼ sec. 22, T. 63 N., R. 11 W., where granitic rock is faulted against greenstone. Because of the susceptibility to erosion of such phyllonites, however, actual fault contacts are rarely exposed, but are commonly expressed topographically by a trenchlike lineament visible on the ground and on aerial photographs.

Such trench-lineaments identified on aerial photos have been compiled in Plate 3. Many of them coincide with discontinuities in mapped rock units (such as near Madden Lake and along the North Kawishiwi River), and have supported the inference of many of the faults shown on the geologic map. There are many parts of the quadrangle, however, where there is so much cover by lake waters, bogs, or glacial deposits that any topographic expression of faulting that may exist in the bedrock surface is now invisible (such as west of Kempton Lake or east of Newton Lake). On the other hand, some strong lineaments are present where there is no discernible offset of rock units. This may be the result of a paucity of mappable beds by which dislocation could be demonstrated, but it may also be a result of the development of some planes of crushing and erosional weakness without a net displacement large enough to be shown at the scale of the map. Another possible explanation may be that displacement on some faults was essentially vertical, approximately parallel to the dip of the strata, thus producing no visible offset.

Fall Lake and Moose Lake occupy depressions eroded principally out of phyllitic rocks of the Knife Lake Group, and much of the intervening country is a lowland having relatively little outcrop. Most outcrops on the shores and islands of these lakes are strongly sheared; it may be inferred that major faults probably underlie them and perhaps pass along strike through the belt, although their exact location was not determined. Gruner (1941) shows several faults that trend along the length of Moose Lake, inferred on similar evidence. A similar situation may exist for Newton Lake, which occupies a strike-basin into which at least one major fault (showing large displacement just to the west in the Ely quadrangle) projects.

In the Ely Greenstone, particularly along the great east-west dislocation along the North Kawishiwi River and west into the Ely quadrangle, the rocks have reacted to intense stress by the development of innumerable small, randomly oriented fractures rather than the phyllonitic shearing typical of the rocks in other parts of the area. These fractures, spaced only a few millimeters apart (see fig. 34), make it difficult to collect hand specimens in many places, but these rocks are apparently no less resistant to erosion than the undeformed greenstones. It is probable that this type of strain took place under different conditions of either load (shallower?), or rate of stress (more rapid), or both.

Within one-fourth to one-eighth of a mile of the North Kawishiwi fault, rocks of the Giants Range batholith are strongly crushed and have a marked secondary foliation, and several fault-slices of granite lie in the fault zone (see geologic map). In many outcrops in this zone the crushing-foliation lies at an angle of 20°-40° counterclockwise from that of the nearby fault, suggesting that the deformation was induced in the granitic rock by left-lateral movement between the major granitic and greenstone blocks. In one outcrop near Murphy Portage (NW¼ sec. 28, T. 63 N., R. 10 W.), the granite has been crushed to a phyllonite, and then folded sharply (fig. 35). Minor crushing and mylonite veinlets and zones, from a centimeter to a meter wide, cut granite outcrops in widely scattered localities elsewhere in the batholith (fig. 36).

The granitic rocks that crop out near the southeast shore of Fall Lake also appear to be slices faulted into their present position in the Knife Lake metasediments. The surrounding slates and graywackes show no evidence of higher metamorphism, and the granites themselves are strongly sheared and foliated around their margins, to the extent that they are difficult to recognize as intrusive rocks; in outcrop and even in thin section they could be mistaken for schistose arkosic wacke (fig. 29). Furthermore, abundant iron carbonate has been introduced and quartz veins cut the rocks, as is com-

Figure 34. Photomicrograph of crushed, irregularly fractured metadiabase of Ely Greenstone at North Kawishiwi Fault, M-7593, sec. 28, 63 N/10 W.

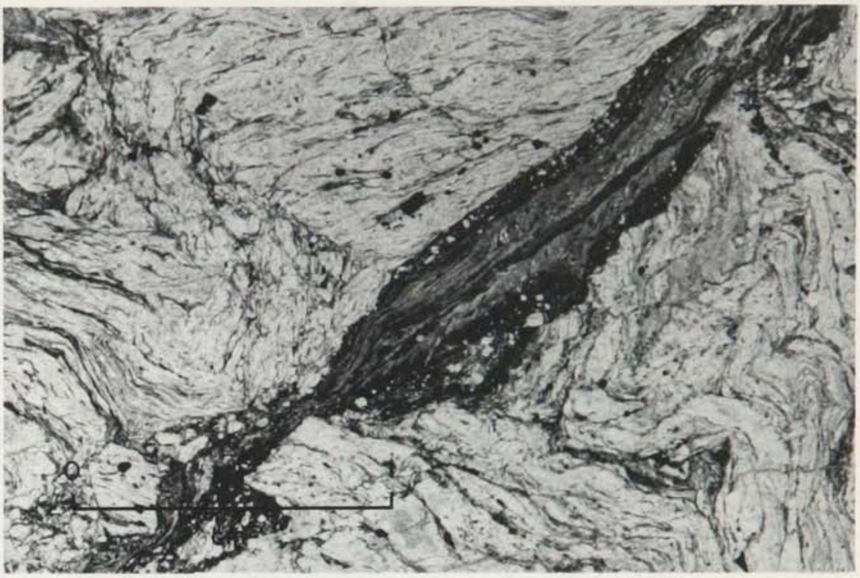


Figure 35. Photomicrograph of crumpled mylonite of Giants Range granite along North Kawishiwi Fault, M-7594, sec. 28, 63 N/10 W.

Figure 36. Photomicrograph of mylonite zone in Giants Range batholith, M-7489, sec. 15, 62 N/11 W.

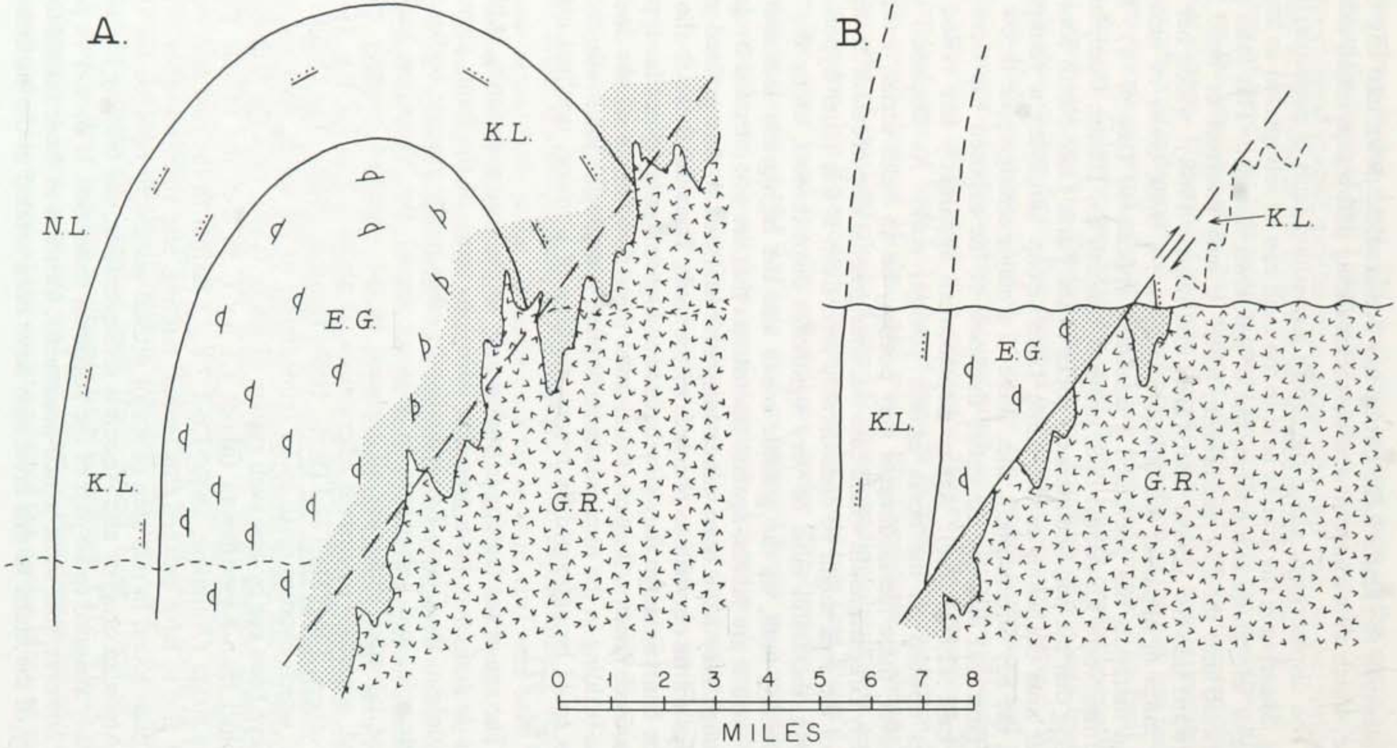
mon elsewhere in this trend. This rock can be best seen at the north side of the cove at the town of Fall Lake public landing, NE¼ sec 16, T. 63 N., 11 W. Less-crushed granite can be seen about one-half mile to the northeast, southeast of the road to the U. S. Forest Service campground.

Many of the faults that were mapped must continue beyond their limits shown on the geologic map, but without direct evidence further extensions were not drawn. This would include the east-west fault that terminates on the map one-half mile north of Jasper Lake and which to the east has faulted Ely Greenstone upward against Knife Lake metasediments. The fault that passes through Greenstone, Madden, and Tofte Lakes probably continues farther northeast into the Knife Lake Group. Probably this is also true for the fault that strikes from Pea Soup Lake northeastward through Wood Lake; this fault, or a branch of it, probably also passes southwest and west roughly along the Fernberg road or just south of it. There is undoubtedly a further extension of the fault that offsets the faulted Ely Greenstone/Knife Lake contact west of Stub Lake, but it was not located. The important fault near the south shore of Moose Lake where Ely Greenstone is sheared off against rocks of the Knife Lake Group is shown ending abruptly at a porphyry intrusion, but it probably continues to the northeast (see Plates 1 and 2). On the other hand (as discussed above under "Stratigraphy"), two of the contacts shown on the geologic map as inferred faults may actually be disconformable or only slightly unconformable depositional contacts, as strong shearing was not found at these places: these are the contact between the Knife Lake Group and the Newton Lake Formation from Fall Lake northeastward to Washte Lake, and that between mafic volcanics and metasediments (to the north) and felsic volcanics of the Newton Lake Formation (to the south) north of Muskeg and Ella Hall Lakes.

The faults in this quadrangle are thought to be approximately vertical. Only one actual fault plane (described above, in road cut) was seen, but many minor slickensided surfaces are visible in outcrops and road cuts, and nearly all have dips of greater than 60°. Slickensides are common on such surfaces, but show a wide variety of movement directions, even within some local groups of slip surfaces. Horizontal components of apparent displacement, as shown by offsets of rock units, range up to two miles (fault between Rookie and Moose Lakes) or perhaps much more (North Kawishiwi fault). The sense of displacement is left-lateral for most of the faults, but apparent displacement of two miles in a right-lateral sense has occurred on the fault between Pea Soup and Wood Lake. A large vertical component probably is present in several faults, especially those by which stratigraphic units have been repeated across their strike, such as the fault north of Gem and Jasper Lakes, the fault passing through Wedge Lake, a probable, though unmapped fault passing west from Jewell Lake (west of Twin Lakes), and another passing southwest from Sourdough Lake. These vertical displacements have generally had the effect of elevating older rocks on their north sides. However, at the eastern edge of the area a block of metasediments of the Knife Lake Group has been faulted down into Ely Greenstone, which shows unequivocal northeast-facing pillow tops on all sides.

The displacement along the North Kawishiwi fault is particularly puzzling. Shearing in the granite next to the fault can be interpreted as implying a major left-lateral component, but of unknown distance. This fault passes westward into the Ely quadrangle, where it may intersect or bend southwestward into the Waasa fault (Sims and others, 1968), which has about four miles of apparent left-lateral movement; a thick cover of unconsolidated materials has prevented a confident conclusion (see pl. 1). To the east, the North Kawishiwi fault projects beneath the Duluth Complex. Assuming that the metasedimentary rocks in the Farm Lake-North Kawishiwi River area do belong to the Knife Lake Group (implying a younger age than the Ely Greenstone), then there is a major stratigraphic throw along this fault that includes the entire thickness of the exposed Ely Greenstone (at least 12,000 feet). Again, displacement apparently has raised older rocks upward on the north against younger rocks. As discussed above, however, these metasediments may possibly be an older series, underlying the Ely Greenstone, in which case the stratigraphic displacement in the middle of the area might be considerably less. Even if this latter hypothesis is correct, there still must be very significant displacement, along the North Kawishiwi fault, as the granitic rocks and the high-grade metasediments they intrude are faulted against greenstones that are not intruded by granite, although they have been increasingly recrystallized to fine-grained amphibolites within one-half to one mile of the fault. Thus the rocks to the south of the fault, although they may have been higher stratigraphically, appear to have come from a deeper crustal level than those north of the fault. As cross-bedding in the metasediments implies younging to the south, the relations could be explained by reverse faulting of a major, isoclinal anticline (see fig. 37).

The age of the faulting is known only within very wide limits. Although some faulting may have preceded intrusion, many of the faults clearly cut and deform the Giants Range batholith, other minor granitic bodies in the quadrangle, and (elsewhere in adjacent areas) the Vermilion batholith. These intrusive rocks are all assigned to the Algoman orogeny and are dated, according to current information, at about 2.5 to 2.7 b.y. (Goldich and others, 1961; Hart and Davis, 1969; Hanson, 1968). The Duluth Complex, which overlies these rocks immediately to the south, does not appear to have been cut by any such system of major faults; thus the faulting must be older than Keweenawan (about 1.1 b.y.). In fact, the Middle Precambrian strata (Animikie, about 1.6-1.7 b.y.) farther to the east and west appear also to have escaped this intense faulting, and since no other evidence has been found in this area of major crustal instability between the time of the Algoman orogeny and Animikie sedimentation, the faulting is most reasonably assumed to be part of the Algoman tectonism. It should be pointed out, however, that some trench-lineaments, identical to those associated with many of the faults in this area, also have been eroded in the surface of the



A.
N.L.
K.L.
E.G.
K.L.
G.R.
B.
K.L.
K.L.
E.G.
G.R.
0 1 2 3 4 5 6 7 8
MILES

Duluth Complex (see geologic map and pl. 3), which implies that perhaps minor movement continued to take place even through Keweenawan time.

Folds

Although on a broad scale the entire sequence north of the North Kawishiwi fault faces north and thus forms a homoclinal, vertical sequence, each formation has been internally folded to some extent as well as sliced by faults.

In the eastern half of the area the Ely Greenstone shows a broad, arcuate structure convex to the north. This is continued to the east in the Forest Center quadrangle, where the Ely/Knife Lake contact approaches a north-south strike. This arc has the form of a broad, vertically-plunging anticline, faulted off across the bottom (south side). On its western flank, there has been some rotation between the many fault-blocks, having the net effect of a swing in strike from east-northeast to east to northwest, north, and even north-northeast in the area north of the Fernberg road and southeast of Fall Lake. Abundant top senses from pillows indicate that this forms a rather tight, vertically-plunging syncline facing northeastward. One-half mile east of Stub Lake there is an abrupt reversal of pillow tops, with a west-facing sequence one or two thousand feet thick, followed to the west by east- to southeast-facing pillows to the limit of the map. Either a major fault or a sharp, isoclinal synclinal axis separates these rocks from those to the south of Fernberg road, at and east of Garden Lake, all of which face north (see pl. 2).

Depositional structures that unambiguously indicate stratigraphic younging were not found in many exposures of the Knife Lake Group, although some graded beds and cross-beds were noted. Because of this fact, and the lack of good marker beds, no folds are shown on the geologic map. However, a few south-facing depositional structures were found in widely scattered localities, implying some internal folding within these metasediments. A small anticline, with a horizontal axis and vertical axial plane, was seen in one outcrop about one-half mile southwest of Witness Lake.

In the felsic, intermediate, and metasedimentary facies of the Newton Lake Formation a similar situation was found: very few top determinations were made (except in pillowed dacite-andesite flows), and there are few marker beds by which folds could be mapped. A few south-facing structures were seen; thus, there must be some internal folding. In the Newton Lake area, on the other hand, there are both interbedded thick units of basaltic

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Figure 37. Hypothetical structure sections in North Kawishiwi River area, looking east. N.L. = Newton Lake Fm; K.L. = Knife Lake Group; E.G. = Ely Greenstone; G.R. = Giants Range batholith; heavy dashed line = North Kawishiwi fault; wavy line = present erosion surface; stippled = metamorphic aureole of Giants Range batholith. A: after major folding and intrusion of batholith during Algoman orogeny. B: present structure, after displacement along North Kawishiwi fault assuming significant dip component.

and more felsic volcanic rocks, and abundant pillows in the metabasalts that give good top senses. These observations show an isoclinal syncline to be present, with its axial trace trending northeastward through the NW¼, NW¼ sec. 9, T. 63 N., R. 11 W., probably through the felsic-intermediate band along the west side of Newton Lake and curving around to the northwest at the northern edge of the quadrangle. This synclinal axis has been confirmed by mapping to the southwest in the Ely quadrangle. There are strong lineations throughout the Newton Lake area that plunge 60°-75° to the northeast or north. These may show the direction of axial plunge of the syncline, but they physically resemble tectonic a-direction features (rodding, streaking, stretching) more than they resemble b-axis features. In fact, because of the isoclinal nature of this fold, it is likely that it plunges at a considerably smaller angle.

Penetrative Deformation

In certain areas the rocks have undergone significant, continuous deformation in addition to failure and displacement along discrete fault planes and folds. This internal, penetrative strain takes two general forms: (1) an intense shearing, with the production of a conspicuous secondary foliation with or without lineation; and (2) an elongation or stretching, that forms streaking, rodding, and other forms of lineation, in many cases without visible foliation. The net strain produced in these ways is large, but probably considerably less than that caused by faulting.

Zones of shearing are common throughout the area, but tend to be narrow as compared to intervening undeformed regions, at least in places of abundant outcrop. They are not sharply bounded, but there is a gradual increase in the intensity of shearing as primary structures and textures tend to be obliterated. This was noted by Clements more than 60 years ago (1903, p. 138). Undeformed metabasalt pillows in the Ely Greenstone, for example, commonly have diameter-to-thickness ratios of 1.5:1, 2:1 or rarely 3:1, but where the greenstone has a strong schistosity or fissility the pillows, where still recognizable, may attain ratios of 5:1 or more, and there is commonly an elongation produced, though it is less marked than the flattening. Upon shearing, the metabasalts become dark-green, chloritic schists or phyllites; andesitic volcanic rocks become medium-green, and felsic rocks become pale-green or silvery, sericitic phyllites. Although relict feldspar phenocrysts generally can be recognized, the shearing typically destroys the groundmass texture, making it very difficult to differentiate "primary" volcanic rocks from feldspathic volcanigenic metasediments.

Many of the sheared zones noted in the field are shown by a double strike symbol on the geologic map. As would be expected, several of them are associated with mappable faults.

The linear-stretching type of strain is particularly common in two broad zones: in the Knife Lake metasediments along the North Kawishiwi River, and most of the area underlain by the Newton Lake Formation. Although planar shearing like that just described also occurs in the Newton Lake rocks, there are very few outcrops in which a strong lineation is not visible. In both areas the lineation involves a stretching-out or smearing-out of textural elements such as pebbles and smaller clasts (in the Knife Lake) or pyroclastic fragments and amygdules (in the Newton Lake). A large proportion of the metasediments east of Farm Lake are conglomeratic, and excellent examples of elongated pebbles are particularly abundant in sec. 26, T. 62 N., R. 11 W. as well as in many other places. Elongation ratios of as much as 5:1 appear to be common. Most lineations plunge steeply, and most have a northerly direction although there are local exceptions. Some of the recrystallized Ely Greenstone on the north side of the North Kawishiwi fault also shows a strong, steep linear structure, and it may be related to at least one phase of movement along the fault.

Late Kink-folds

A remarkable feature of the belt of Knife Lake rocks from Fall Lake northeast to Moose Lake, and beyond the quadrangle boundaries in both directions, is a system of kink-folds (chevron folds) and associated fractures that is superimposed on all the other structures so far described. They are most obvious in strongly sheared, phyllitic rocks or laminated, fine-grained slates, and can be readily seen in many outcrops in Moose and Fall Lakes. They are not confined to the Knife Lake Group, but some are found in sheared zones of the Ely Greenstone and Newton Lake Formation that are not far from the Knife Lake belt (such as along the Fernberg road south of Sourdough Lake). These small folds typically have straight limbs, with obtuse angles between the limbs, and short limbs generally between one and five cm across that pass like ribbons across a rock cleavage surface. The fold crests are sharp, and the axial planes commonly contain a fracture. The individual folds tend to die out within a few feet along the axial plane in a direction perpendicular to the axis, whereas others form nearby. Most of the kink-folds seen are horizontal or have shallow plunges to the east-northeast or west-southwest, but in some places vertically-plunging sets were found. In several outcrops conjugate sets of kink-folds are present whose orientations imply a principal stress either east-northeast and horizontal (parallel to the length of the belt of late deformation) or, in other sets, vertical. The long limbs are much longer than the short limbs, and little net deformation is thought to have occurred. As these flexure folds formed by elastic bending of the phyllitic rocks, followed by failure along the axial planes without plastic flow or axial-plane slip, and as they deform the products of the major deformation in the area (phyllites and phyllonites), they are assumed to have formed at a considerably later time and at a higher tectonic level than both the shearing and drag-folding that also affected these rocks. Thus these kink-folds must be either very late Algoman, or possibly younger.

METAMORPHISM

All the stratified rocks covered by this report have undergone alteration, but there is extreme variation in its degree within the area. Precise mapping of metamorphic zones has been hindered, however, by at least five factors: (1) the compositions of the rocks, which make most of them rather insensitive mineralogically to slight changes in physical conditions; (2) local concentrations of heat, probably associated with intense shearing as well as minor intrusions; (3) a marked lack of textural and therefore probably mineralogical equilibrium in most of the rocks; (4) the fine-grained and commonly aphanitic nature of the rocks; and (5) limited sampling (though 292 thin sections were studied). Retrograde reactions have locally destroyed earlier, high-grade metamorphic minerals, but an attempt has been made to interpret such rocks with respect to their highest metamorphic grade. Much more widespread are relict magmatic minerals that have not equilibrated under the local metamorphic conditions.

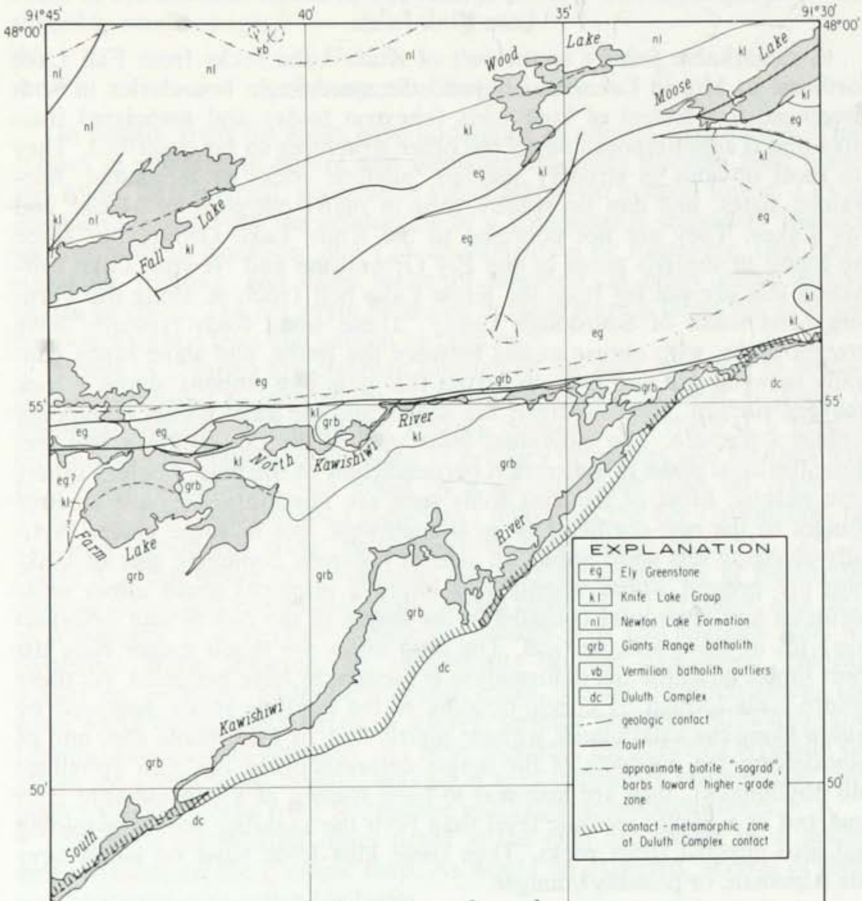

Figure 38. Generalized metamorphic zones of Gabbro Lake quadrangle.

Most of the area is underlain by rocks of very low metamorphic grade, assignable to the chlorite zone of the greenschist facies, and many rocks are nearly unmetamorphosed. This includes the broad band from Garden and Newton Lakes on the west, east-northeastward to Triangle, Hula, and Moose Lakes (see fig. 38). This broad belt includes most of the metasediments of the Knife Lake Group, many of which are pelitic; they contain chlorite and sericite but lack biotite and other higher-grade minerals. Most of the psammitic, psephitic, and volcanic rocks do not contain enough K_2O to form biotite, but even those that do have not developed this mineral, containing K-feldspar and chlorite instead. In many of these coarser metasediments there has been almost no recrystallization at all, even of the clastic matrix, and many unstable, relict minerals and textures are still present in the clasts, such as augite (some with actinolite overgrowths) and strongly zoned volcanic plagioclase. Most of the volcanic rocks in this zone are altered (saussuritization, kaolinization) but very little recrystallized, so that in many specimens the minerals are semi-opaque in thin section. Where some recrystallization has taken place the minerals are mainly albite, epidote, chlorite, actinolite, calcite, opaque oxides, and leucoxene. Relict, unstable labradorite and augite are preserved in several localities; the relict plagioclase is more common in basalts whereas the augite (rimmed by actinolite) is more common in metadiabases. Little scraps of stilpnomelane were found at two localities (south of Rookie Lake and southeast of Sourdough Lake) in conglomerate that contains small amounts of K-feldspar, and on the west side of Triangle Lake in iron-formation, but it is absent elsewhere in this low-grade zone. Besides relict biotite in local intrusive rocks, small amounts of metamorphic biotite were found in the country rocks in two areas that are near intrusions: one-half mile north of Pea Soup Lake, near the ultramafic "amphibolite" area, and at two outcrops on Greenstone Lake, near rhyodacite porphyry intrusions. These occurrences are probably attributable to local, low-grade, contact-metamorphic effects.

Recrystallization has been more thorough along the northwest side of Fall Lake and in some of the more sheared zones to the north and east in the Newton Lake and Knife Lake rocks, but higher-grade minerals were not produced. This recrystallization has tended to clarify most of the minerals, such as plagioclase, epidote, and actinolite, and to coarsen to a mosaic or foliated texture the groundmasses of felsic rocks.

Rocks of higher metamorphic grade are confined to four areas that fringe the major low-grade belt just described. Along the northern edge of the quadrangle, from Camp Lake eastward to north of Ella Hall Lake, the rocks of the Newton Lake Formation are decidedly more recrystallized than to the south, and many of them contain biotite, strongly pleochroic amphibole (assumed to be hornblende), or both, depending on the rock composition. There are no pelitic rocks here, and none of the biotite is porphyroblastic. Epidote is common, and the plagioclase is generally sodic. One recrystallized pebble in a metaconglomerate northeast of Camp Lake consists of hornblende, clinopyroxene, quartz, and oligoclase. The hornblende-rich rocks (metabasalts and stratified meta-tuffs or mafic metagraywackes) are nearly black, in marked contrast to the greenish-gray color of the lower-grade mafic rocks to the south. These rocks have been subjected to the conditions of the epidote-amphibolite zone, and locally to the amphibolite facies (Turner, 1968). The higher grade of metamorphism in this area is attributable to proximity to the intrusive rocks of the Vermilion batholith, which crops out a short distance to the north in the Basswood Lake quadrangle (see pl. 1).

A second area of higher metamorphic grade lies in the vicinity of Gem Lake, south of Moose Lake. Here rocks of the Ely Greenstone and Knife Lake Group as well as dacite porphyry have been recrystallized to a greater degree than to the west, and microscopic biotite is fairly common; the biotite is nowhere porphyroblastic. Hornblende occurs with biotite in a few areas, and a diopside veinlet was found one-fourth of a mile west of Gem Lake. At Uncle Judd's Creek in the SE¼ sec. 32, T. 64 N., R. 9 W., a spotted pelitic phyllite of the Knife Lake Group (with biotite flakes in the matrix) contains small pseudomorphs after cordierite, and abundant cordierite has been found in similar rocks farther to the southeast in the Forest Center quadrangle. This area of higher grade, mostly in the upper greenschist facies but locally gradational into the hornblende hornfels facies, may be caused by an unexposed, subjacent, westward extension of the Snowbank Lake stock (see pl. 1). It is noteworthy that these higher-grade rocks all lie south of the strike-fault along Uncle Judd's Creek, implying that the metamorphism preceded this faulting.

The most extensive area of higher metamorphic grade lies along the North Kawishiwi River and northwest of Farm Lake. It includes all of the strip of metasedimentary rocks here assigned to the Knife Lake Group, and also a narrow band, approximately one-fourth to one-half mile wide, of the Ely Greenstone along the north side of the North Kawishiwi fault. The belt of higher-grade rocks north of the fault broadens near the eastern edge of the quadrangle (east of Triangle Lake) and merges with the higher-grade area centered around Gem Lake (just described) near where the Fernberg road (old alignment, as on the geologic map) crosses the map boundary, thus including the fault-bounded area of metasedimentary rocks. All the rocks in this zone have undergone extensive recrystallization, and all original aphanitic textures, such as clastic matrix, have been destroyed; they are now gneisses and schists.

In the metasedimentary rocks of this North Kawishiwi River belt the most common assemblage is quartz-oligoclase (or andesine)-biotite-hornblende-epidote-microcline; these rocks are too rich in Ca and too poor in Al to contain muscovite or other peraluminous silicates. Only two specimens were found to contain a biotite-chlorite-muscovite-epidote assemblage, and both show textural evidence of retrograde effects. The metabasaltic rocks typically show the assemblage plagioclase-hornblende-epidote-biotite-quartz. Clinopyroxene was found at a few localities in this area, both concentrated in laminae in bedded gneisses and recrystallized mylonites — where it occurs with hornblende and plagioclase with or without quartz and epidote — and also as diopside in cross-cutting veinlets and replacements between breccia fragments or conglomerate pebbles. Southwest of Farm Lake traces of clinopyroxene, probably hedenbergitic, were found in recrystallized iron-formation, accompanying quartz, magnetite, and grunerite. Other iron-formation samples that also consist mainly of the three latter minerals, have traces of apatite, biotite, muscovite, and stilpnomelane. The last mineral may be a lower-temperature, retrograde reaction product, as it occurs as reaction scraps around magnetite grains and along cracks in one specimen, but as plates cutting grunerite in another. Cummingtonite is rare, but was found in four samples in the following assemblages: cummingtonite-Mg-hornblende-Mg-biotite-plagioclase-magnetite (laminated schist east of Triangle Lake); cummingtonite-biotite-almandite-chlorite-quartz-plagioclase-opaque oxides (metasedimentary schist southwest of Farm Lake); cummingtonite-Fe-hornblende-almandite-biotite-(quartz or plagioclase) (amphibolites, northwest of Farm Lake). These localities and assemblages are also the only ones in which garnet was found in the area.

According to the mineral assemblages, this large region from Farm Lake up the North Kawishiwi River can be assigned to the amphibolite facies. The metamorphism south of the fault is obviously related to the effects of the Giants Range batholith, which intimately intrudes these rocks. The area west of Farm Lake is actually a salient between two lobes of the batholith (pl. 1). The cause of the recrystallization north of the fault is much less clear. Because it so closely parallels the fault, frictional heating from fault movement might be implicated, but the present relationships could also have been produced by a complex sequence of faulting, then granitic intrusion and metamorphism, followed by more movement along the fault (see fig. 37).

The fourth area of high-grade rocks is a narrow contact-metamorphic zone, one-fourth to one-eighth of a mile wide or less, adjacent to the lower (northwestern) contact of the Duluth Complex. Some of these rocks, here and elsewhere along the contact, have been studied by Schwartz (1924) and Grout (1933). Near the eastern edge of the quadrangle the gabbroic rocks intrusively overlie a narrow band of metasedimentary rocks (Knife Lake) that is in fault contact with metabasaltic rocks of the Ely Greenstone. Farther southwest, only the Giants Range batholith has been affected by the Duluth Complex. The stratified rocks have typical fine-grained, hornfelsic texture and locally, a few megascopic poikiloblasts of hornblende, quartz, or K-feldspar. The mineral assemblages in the metabasalts are generally Ca-plagioclase-hornblende-augite-hypersthene-magnetite-ilmenite. One sample farther (about one-fourth of a mile) from the contact contained pale clinoamphibole-diopside-plagioclase-biotite-magnetite, and lacked the typical hornfelsic texture. In the metasediments (clearly identifiable as such by relict bedding and clastic grains), the assemblages are typically plagioclase-hornblende-biotite-hypersthene-augite-magnetite. In one sample olivine is also present, in addition to the above minerals; in this rock textures imply that the biotite may be a retrograde product. In another sample poikilitic quartz and orthoclase occur, with plagioclase, hornblende, and strongly pleochroic biotite; opaques are absent. Almandite, Al-silicates, and cordierite were looked for but not found in the samples studied. Some of these rocks appear to have been basified during this metamorphic pulse, as inferred previously by Grout (1933, p. 1018).

In the granite adjacent to the gabbro contact several metamorphic effects are evident. In some specimens the rock is recrystallized enough to change the primary hypidiomorphic texture of the leucocratic minerals to xenomorphic, although phenocrysts are preserved; in others, some of the newly formed ferromagnesian minerals are poikiloblastic. The plagioclase (oligoclase) typically contains antiperthitic blocks and patches of microcline; it appears as though the feldspars have reacted with each other as the temperature was raised, followed by exsolution on cooling. The K-feldspar (either orthoclase or microcline) is microperthitic; myrmekite is found between the two feldspars in some areas, and in others a replacement intergrowth is found with corroded plagioclase cores partly replaced by orthoclase in optical continuity. The quartz is poikiloblastic in one sample. One specimen only one or two hundred feet from the contact in the South Kawishiwi River shows the typical primary ferromagnesian assemblage hornblende-biotite-magnetite, but the hornblende is pale and contains tiny magnetite grains. In the three other samples studied the ferromagnesian assemblage is now pale hornblende (with magnetite grains)-augite-hypersthene-biotite-magnetite. The hypersthene contains exsolution lamellae and is probably inverted from pigeonite. Some of the hypersthene is partly altered by retrograde reactions to a mixture of biotite and actinolite. In one granite outcrop (the small hill just north of the Spruce road northwest of Filson Creek in NE¼ sec. 24, T. 62 N., R. 11 W.) a trace of copper sulfides has been introduced into the rock, most probably from the gabbro that once immediately overlay it.

The mineral assemblages in the contact aureole of the Duluth Complex are characteristic of the transitional zone between the amphibolite, the hornblende-hornfels, and the pyroxene-hornfels facies. Many of the rocks have too many phases to satisfy the requirements of the phase rule, and probably contain minerals produced over a certain range of conditions and preserved in the rock because of the relative rapidity of the heating and cooling. According to the recent estimate of Turner (1968, p. 366), these rocks would thus have recrystallized in the range of 600-675°C and under pressures of roughly 1.5 to 2.5 kb, equivalent to a depth of from 15,000 to 30,000 feet. This overburden would have consisted principally of the Middle Precambrian sediments that were still preserved by Keweenawan time, plus the Keweenawan lavas that had been erupted by the time of this particular phase of intrusion of the Duluth Complex, plus the already intruded part of the complex. Oxygen-isotope ratios in the same contact metamorphic zone about 9 miles to the southwest (Perry and Bonnichsen, 1966; Bonnichsen, 1969) imply maximum temperatures of 700-750°C.

ECONOMIC GEOLOGY

Except for sand and gravel from surficial deposits, there has been no profitable mineral production from this area. However, there are three types of deposit that may have some economic potential: serpentinized peridotites in the Newton Lake Formation, banded iron-formation in the Ely Greenstone, and base-metal sulfide veins and disseminations in the stratified formations.

Only four exposures of serpentinized peridotite were found in this map area, but they are rather common in the Newton Lake Formation in the Ely quadrangle immediately to the west. The great majority are not completely serpentinized, but contain considerable relict pyroxene, which is mainly augite. Relict olivine was found in one outcrop west of Brown's Lake. Only traces of either slip-fiber or cross-fiber asbestos were seen, none of them in the Gabbro Lake quadrangle. No chromite bands were found, though accessory chromite is generally present. Trace-element analyses performed in 1968 by the U. S. Geological Survey on seven typical samples (one from the Gabbro Lake quadrangle) are on open file with the Minnesota Geological Survey; no particularly promising concentrations appear to be present.

Rare, thin iron-formation stringers occur in the Newton Lake Formation and in the Knife Lake Group, but they are more abundant and thick in the Ely Greenstone. This area was extensively prospected for iron by mapping, dip-needle surveys, pitting, and drilling in the late 19th and early 20th centuries; by 1902 nearly 12,000,000 long tons of ore had been produced from the Ely Trough only 4 to 5 miles to the west (Clements, 1903, p. 242-243). The last mine in the Vermilion district, the Pioneer mine at Ely, closed in 1967. In the late 1910's and early 1920's the Section 30 mine, 1½ miles west of the quadrangle boundary, produced nearly 1,500,000 tons of ore, but operations ceased in 1923 (Lindgren, 1963, p. 12). Old test pits are common in the woods throughout the Ely Greenstone belt, but no iron-formation could be found on many of the dumps. One of the larger prospects, about three-fourths of a mile south of Gem Lake, was known as Howard's mine, but the owners never recouped their investment. The most recent activity was in the 1950's, when the area for two or three miles east of Garden Lake was examined by Jones & Laughlin Steel Corporation and the Garden Lake Iron Co. The iron-formation layers that occur within this quadrangle appear to be too narrow to warrant further exploration; it should be emphasized that their thickness as shown on the geologic map has been greatly exaggerated.

Small veinlets and disseminations of sulfides are found locally in all the major rock units of the quadrangle except the Giants Range batholith. They are most abundant in the Ely Greenstone, particularly in the relatively more crushed and sheared zone along the Fernberg road, from the west side of the quadrangle to Moose Lake. About 30 polished sections were studied by the writer and James Riehle, in addition to hand-specimen and occasional X-ray examination. The U. S. Geological Survey has performed trace-element analyses on 12 samples; these are available in open files at Minnesota Geological Survey offices.

The mineralogy of the sulfide-bearing specimens is rather simple. Pyrite constitutes at least 80 percent of the sulfides in the great majority. The pyrite grains typically have a few tiny blebs of chalcopyrite; in some samples independent chalcopyrite grains are present. In three of the samples studied microscopically, chalcopyrite constitutes more than 10 percent of the total sulfides. In a few localities pyrrhotite is the dominant sulfide. Traces of sphalerite were seen in several samples, and a small amount was found megascopically in cherty iron-formation on the island in Moose Lake in the SW¼ sec. 29, T. 64 N., R. 9 W. Galena and precious metals were looked for but not found.

In the greenstones and more felsic volcanic rocks, the mineralization is primarily in the form of tiny stringers and veinlets and irregular disseminations, commonly in fractured or sheared rock. In the felsic intrusive rocks (dacite porphyry, microgranite, and syenitic rock near Pea Soup Lake), tne sulfides — mainly pyrite — tend to be more evenly distributed and locally constitute as much as 5 percent of the rock. They are typically accompanied by sericite and carbonate alteration and probably also were introduced. Many outcrops of banded iron-formation are pyritiferous, but only rarely do they show any other base-metal sulfides in more than trace amounts; the pyrite, though mobilized and recrystallized, may be at least in part of sedimentary origin. It varies widely in concentration, forming up to 30 percent of some samples, and nearly massive, barren pyrite is found in iron-formation in the Fernberg road cut north of Garden Lake about one-third of a mile west of the quadrangle. A couple of masses of barren pyrite were seen in glacial drift in the large gravel pit next to Madden Creek, but their source is unknown.

QUATERNARY DEPOSITS

Bedrock in most of the area mapped is covered by thin to thick deposits of Quaternary age, including glacial till, glaciofluvial sand and gravel, and peat. Lakes, including the broad and sluggish Kawishiwi River branches, also cover a large area. Bedrock exposure ranges from a maximum of about 30-40 percent (such as in the vicinity of Madden Lake, or in a burned area south of South Farm Lake) to zero (as between Newton and Muskeg Lakes). Although no serious attempt was made in this study to map or examine the surficial deposits, the following observations may be of some interest for future work.

At various intervals, probably throughout Recent history (Heinselman, 1969), forest fires have burned over parts of this region. When this has happened, erosion of the drift cover was accelerated by removal of the vegetation and humus, and many high areas have been cleaned off and lower areas covered. This is commonly attested to by the presence of a lag deposit of large, rounded (exfoliated in part) boulders, with no till or gravel matrix, perched on high bedrock areas especially overlooking abrupt slopes; charred stumps and uniform timber stands show the areas of most recent burning where a soil substrate still exists.

Glacial striations were observed and measured at many localities in the area. They show a south-southwest movement direction, ranging from S. to S. 40° W. (see pl. 2). Average bearing for the 70 measurements is S. 17° W. The late Wisconsin ice in this area is assumed to belong to the Rainy Lobe (Wright and Ruhe, 1965).

Glacial till forms most of the surface, and it was not distinguished on the geologic map. Along with abundant, locally derived rocks, it contains many granitic erratics that resemble various phases of the Vermilion batholith of the Basswood Lake district and Canada to the north. Casual observations suggest the existence of a boulder train or fan extending south and southwest from the distinctively-textured granite of Good and Indiana Lakes, which are just north and northwest of Hula Lake in the adjoining Basswood Lake quadrangle. Phyllitic rocks similar to those of the Knife Lake Group are also common on the surface and to the south of its outcrop area. In several localities, however, boulders up to several feet in diameter of feldspathic, gabbroic rocks identical to common varieties of the Duluth Complex were found several miles northwest of the complex, implying a direction of ice movement at some stage that was different from that so far assumed for this area (see pl. 2).

Glaciofluvial sand and gravel cover a small part of the area, and because of the possible economic significance of these deposits, an attempt was made to indicate their general locations on the geologic map. Because of their relatively well-sorted texture these tend to be rather well-drained areas, and commonly are found to support an open white birch (*Betula papyrifera*) forest. Of particular note is a long, somewhat discontinuous ridge of sand and gravel, perhaps an esker, that extends for 7 miles from north of Ella Hall Lake (just north of the map boundary) to the southwest, including Mile Island in Fall Lake, into the Ely quadrangle. An interesting deposit in the SW¼ sec. 8, T. 63 N., R. 10 W. south of the Fernberg road, was largely excavated during recent realignment and paving of that road. An examination of the pit during removal operations showed a 4-5 foot waterlaid sequence on top, consisting of three feet of gravel overlying 1 to 2 feet of sandy beds; this overlies about 30 feet of apparently unsorted drift, which in turn overlies about 30 feet of waterlaid mixed silt, sand, and gravel beds.

PETROCHEMISTRY OF THE VOLCANIC ROCKS

Twenty-one new analyses of Lower Precambrian volcanic and hypabyssal rocks are presented in Tables 2 and 3, together with analyses of a metaperidotite and a dike of probable Keweenawan age. Of these, eight samples are of clearly extrusive metabasalts (mostly pillowed), three are of probably shallow-intrusive metabasalts and metadiabases, six are of andesites (two pillowed, two tuff-breccias, one intrusive), and four are rhyodacites (Na-rhyolites), all of which appear to be flows though this is difficult to prove.

The samples were selected to represent as many as possible (within the limits of funding) of the important varieties, both on the basis of chemical and petrographic characters, with particular attention to the most abundant types. Several different types of pillowed lava were selected, both from the Ely Greenstone and the Newton Lake Formation. Two varieties of spherulitic pillowed greenstone were sampled, one of them from the extensive flow north of Garden Lake. Pale, medium, and dark greenstones were analyzed, and a few massive (non-pillowed), granular varieties were also selected, one of which is certainly intrusive. Two obviously pyroclastic rocks and four apparently massive felsic rocks were chosen, including a typical sample of the widespread "dacite porphyry." Several of the greenstones (EG-numbers) were from a detailed traverse across Twin and Triangle Lakes in a typical Ely Greenstone sequence. The samples were then further screened for textural uniformity and minimal obvious calcite or other possible alteration products that might have involved introduction of components other than H_2O. Several of the greenstones selected contained appreciable relict calcic plagioclase and/or augite. Although all the samples analyzed are altered to some extent, only four of them contain more than 1 percent CO_2, and 12 contain less than 0.5 percent CO_2. All contain more than 1.4 percent H_2O. For those rocks that contained calcite, it is difficult to judge the relative contribution of internal and external sources for the CaO of the calcite; standard, dry CIPW norms have been calculated assuming an internal source(thus ignoring CO_2) except for M-7152, which has calcite amygdules. If there has been metasomatic interchange involving other components, its effect, both qualitative and quantitative, is unknown, and it is assumed to be nil for the purposes of this discussion.

Most of the metabasalts are quartz-normative, and all are hypersthene-normative. Although compositional names are given to these rocks in the tables according to their calculated norms and Table 1, many of the rocks (especially in table 3) could be called andesite according to common usage (Chayes, 1969).

Wilson and others (1965) have discussed some of the chemical characteristics of ten suites of Archean volcanic rocks from other parts of the Superior Province of the Canadian Shield. Although they found minor but probably significant differences between some of these belts, in general the 261 Archean rocks they analyzed showed similarities to the typical orogenic calc-alkaline trend, according to several parameters, and marked differences from such other petrogenetic series as the spilite-keratophyre, the oceanic alkali-basalt-trachyte, or the tholeiite-granophyre associations.

The 21 new analyses presented here fit rather well with the data of Wilson and others, and extend their generalizations to the Vermilion district, which they had not sampled. Although the alkali-CaO curves for the suite show considerable scatter, they intersect in the range 60-64 percent SiO_2, to give an alkali-lime index of calc-alkalic to calcic. A plot of the Niggli values *alk* vs. *si* (fig. 39) shows that the Vermilion district rocks lie along or on the calcic side of a line Wilson and others (1965, p. 169) found

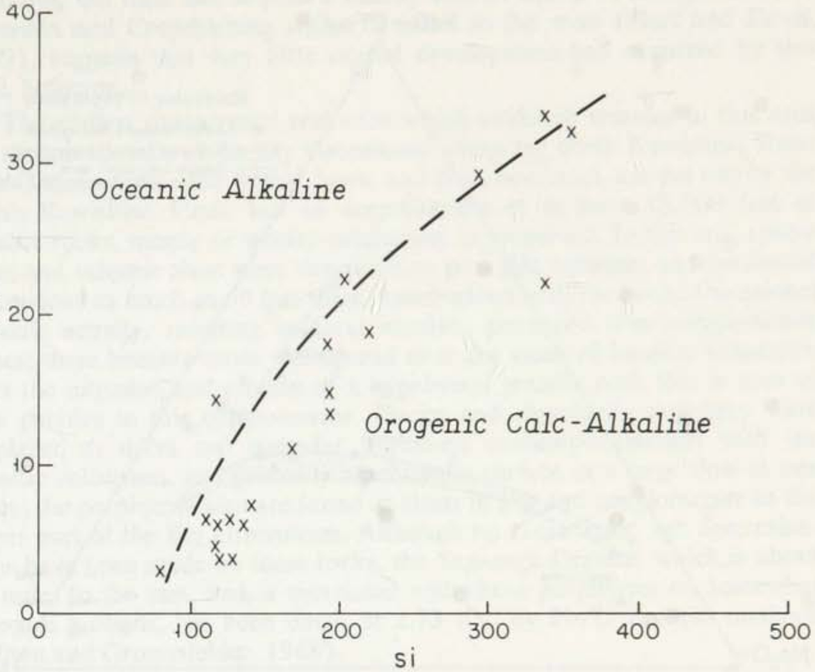

Figure 39. Niggli alk/si values of analyzed Lower Precambrian volcanic rocks of the Gabbro Lake quadrangle (x), with line of Wilson and others (1965) separating oceanic alkaline from orogenic calc-alkaline groups.

to separate oceanic alkaline from orogenic calc-alkaline series. An alkalies-iron-magnesia diagram (fig. 40) shows the Gabbro Lake quadrangle rocks to have a wide range in Fe/Mg ratios but no clear trend of iron enrichment, unless the range of basaltic compositions is the result of strong, early but discontinued concentration of iron. The general trend of composition resembles that of the orogenic basalt-andesite-dacite-rhyolite series, as exemplified by the Cascades suite (Turner and Verhoogen, 1960, p. 285), but at higher Fe/Mg ratios; but it is still lower in Fe/Mg than the tholeiitic suite of Thingmuli volcano, Iceland (Carmichael, 1964, p. 448).

As with many other Archean volcanic rocks, these new analyses support petrographic evidence of a notable lack of K_2O concentration during the development of these rocks. Figure 41 shows the $K_2O/(K_2O + Na_2O)$ ratio plotted against silica, for the Cascades as well as the Gabbro Lake quadrangle rocks; the great majority of the new Archean analyses show a considerably lower ratio than do those of the Cascade suite. No K-rich rhyolites have been found, to my knowledge, in the Vermilion district, either petrographically or by chemical analysis, although several are reported by Wilson and others (1965). The high Na/K ratio might be interpreted as an indication of excess Na_2O and thus affinities to the spilite-"keratophyre"

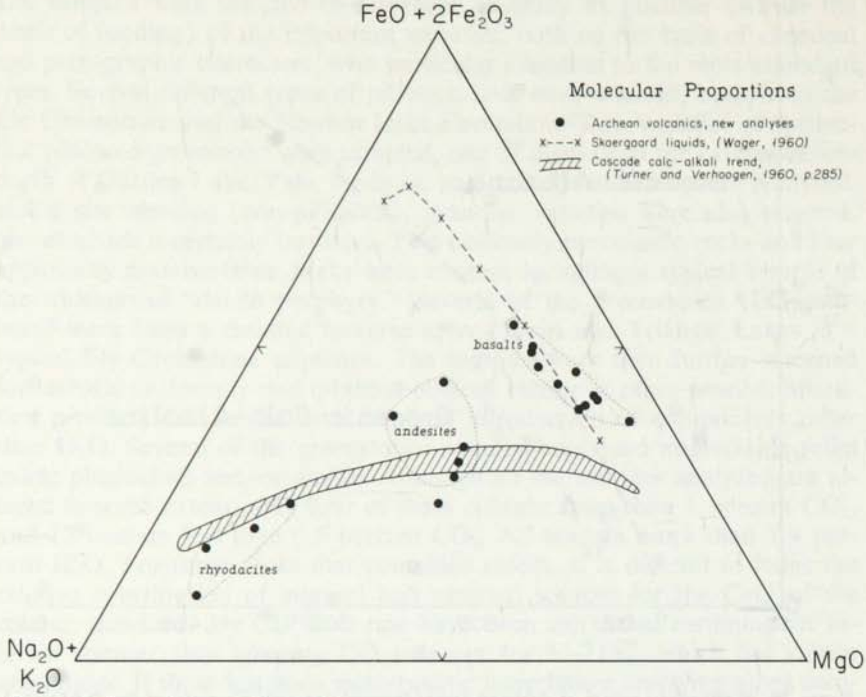

Figure 40. Iron-enrichment diagram for new analyses of Lower Precambrian volcanic and hypabyssal rocks (dots) compared to trends for Skaergaard liquids and Cascade volcanics.

kindred, which also contains abundant pillowed basalts, but as Figure 42 shows, the new analyses all plot with lower Na_2O values than spilites. Furthermore, and again supporting the data of other Archean volcanics (Wilson and others, 1965, p. 173), the TiO_2 contents of the metabasalts from the Gabbro Lake quadrangle average 1.08 percent, in contrast to an average for spilites of 3.32 percent TiO_2 given by Turner and Verhoogen (1960, p. 262); the intermediate and felsic Archean rocks contain considerably less than the metabasalts.

Wilson and others (1965, p. 174-5) infer from the chemical similarities of their Archean rocks to the calc-alkaline group that the Lower Precambrian volcanic rocks were erupted in a continental or at least a continental-margin environment. The same inference should apply to the Gabbro Lake quadrangle rocks, and it is supported by the presence of granodioritic, plutonic pebbles and cobbles in conglomerates interbedded with these lavas, as described above.

GEOLOGIC HISTORY

The presence of cobbles of granitic or tonalitic rocks in conglomerates is interpreted to indicate the existence of a granitic crust prior to volcanism in Ely Greenstone time. The location of the source of the granitic cobbles is unknown, but their size implies a nearby source. Initial Sr-isotope ratios of Keewatin and Coutchiching rocks 70 miles to the west (Hart and Davis, 1969), suggests that very little crustal development had occurred by this time, however.

The earliest supracrustal rocks for which evidence remains in this area are the metabasalts of the Ely Greenstone along the north Kawishiwi River near Conchu Lake. The lowest flows, and their basement, are cut out by the North Kawishiwi Fault, but an accumulation of at least 12,000 feet of basaltic rocks, mostly or wholly submarine, is preserved. In this sea, sparse chert and sideritic chert were deposited to give thin stringers and laminated successions as much as 50 feet thick, interbedded with the lavas. Occasional tectonic activity, resulting in local erosion, produced thin conglomerate lenses; these became more widespread near the close of basaltic volcanism after the intrusion and erosion of a hypabyssal granitic rock that is seen as rare pebbles in this conglomerate. Dacite and rhyodacite porphyry were emplaced as dikes and irregular intrusions contemporaneously with the basaltic volcanism, and probably reached the surface as a large flow at one place; the porphyries also are found as clasts in grit and conglomerate in the upper part of the Ely Greenstone. Although no radiometric age determinations have been made on these rocks, the Saganaga Granite, which is about 30 miles to the east, and is correlated with these porphyries on somewhat insecure grounds, has been dated at 2.73 b.y. by Pb/U isotopic methods (Tilton and Grunenfelder, 1968).

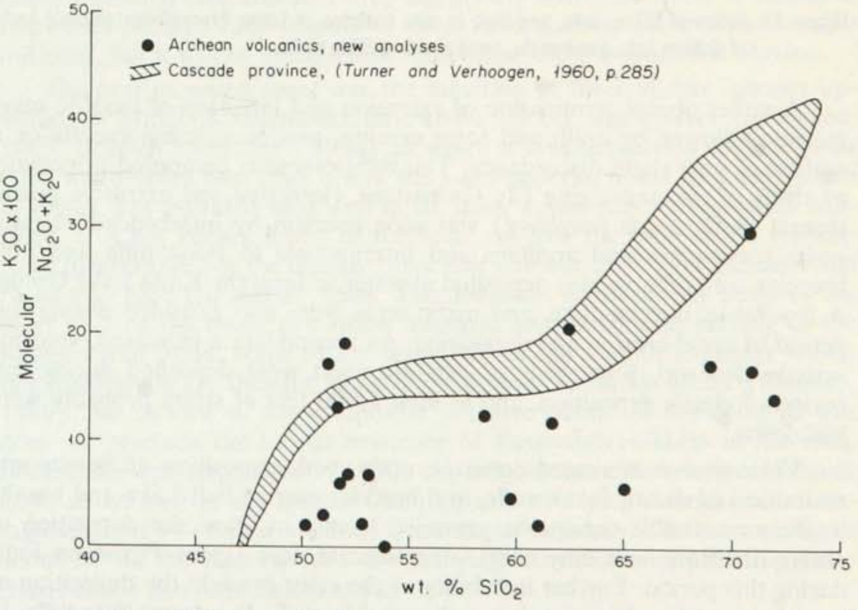

Figure 41. Ratios of SiO_2 to alkali ratio in new analyses of Lower Precambrian volcanic rocks (dots) and Cascade volcanics.

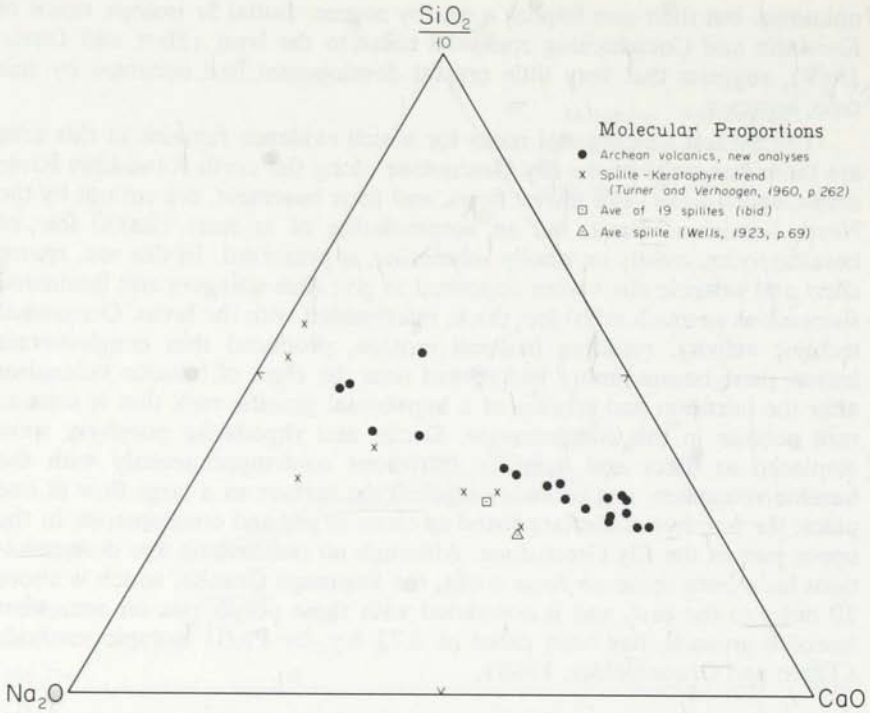

Figure 42. Ratios of silica, soda, and lime in new analyses of Lower Precambrian volcanic rocks of Gabbro Lake quadrangle, compared to spilitic rocks.

A rather abrupt termination of extrusion and intrusion of basaltic magma was followed by uplift and some erosion, producing conglomerate on a surface of only slight discordance. This conglomerate, composed principally of clasts of the underlying Ely Greenstone (intrusive and extrusive greenstones, chert, dacite porphyry) was soon overlain by interbedded volcanigenic graywackes and argillites and intermediate to felsic tuffs and tuff-breccias, all probably also deposited in water to form the Knife Lake Group. A few felsic, intermediate, and mafic lavas were also extruded during this period of rapid erosion and deposition. As accumulation increased, volcanic activity declined. Rare beds of sideritic chert were deposited during this period of clastic deposition, and at least 5,000 feet of strata probably were laid down.

Volcanism commenced again abruptly, with deposition of dominantly andesitic and dacitic lavas, tuffs, and breccias east of Fall Lake and basalts to the west. Stable conditions prevailed locally to allow the deposition of cherty limestone and limy chert conglomerate near Upper Pipestone Falls during this period. Further instability of the crust brought the deposition of a thick sequence of graywackes and probably mafic to intermediate tuffs, in part interbedded with the volcanic rocks beneath. These dominantly metavolcanic rocks, above the Knife Lake Group, of which at least 5,000 feet are preserved in this quadrangle, are called the Newton Lake Formation.

There is no record of further supracrustal deposition during Early Precambrian time in this area, and the next complex sequence of events constitutes the Algoman orogeny. Major folding and faulting, producing nearly uniformly vertical strata, probably preceded the plutonic intrusion of the Giants Range and Vermilion batholiths; this in turn was followed by more intense faulting, that produced in particular the North Kawishiwi and other major faults which clearly cut the intrusive rocks. Age determinations on Algoman intrusions give about 2.5-2.7 b.y. (Hedge and Walthall, 1963; Hanson, 1968; Goldich, 1968; Hart and Davis, 1969). K/Ar dates on micas of 2.5-2.4 b.y. (Goldich and others, 1961) probably indicate time of cooling and uplift following the orogeny.

A very large amount of erosion took place in the interval between the Algoman orogeny and the gradual sinking of the Animikie marine basin that took place sometime in the range 1.85-1.635 b.y. ago (Peterman, 1966; Faure and Kovach, 1969); the Animikie deposits overlie with sharp angular unconformity the folded, faulted and intruded Lower Precambrian rocks. Although not present in the Gabbro Lake quadrangle except as xenoliths in the Duluth Complex, the Animikie sediments are found both to the northeast (Gunflint, Rove Formations) and to the southwest (Pokegama, Biwabik, Virginia Formations), and undoubtedly once covered this area.

The Penokean orogeny which immediately followed Animikie sedimentation (Goldich and others, 1961) apparently had little effect in this area other than perhaps a few degrees of tilting toward the south. Further erosion followed, but it was of much lesser extent than the pre-Animikie erosion.

The next recorded event was the initiation of the immense igneous upwelling of Middle Keweenawan time about 1.1 b.y. ago (Silver and Green, 1963; Goldich and others, 1961) in which a lava succession several miles thick was erupted into what is now the Lake Superior basin, and the Duluth Complex was intruded near and at its base, apparently as the basin subsided. It is not known if any of the lavas covered the area of the Gabbro Lake quadrangle, but the diabase dikes that now cut the Lower Precambrian rocks may have fed surface flows. The dominant northeasterly trend of the dikes may be the result of tension fractures associated with sinking of the Keweenawan basin. Some of the hornfelses in the Duluth Complex within this quadrangle are thought to be derived from Animikie strata (Phinney, 1969), but in view of the compound intrusive nature of the complex this does not preclude the former existence of Keweenawan lavas in the area. Bonnichsen (personal comm., 1970) reports contact-metamorphosed basalt flows at the base of the Duluth Complex and overlying Animikie iron-formation about 14 miles west of the quadrangle boundary. The present dip of about 30° of the base of the Duluth Complex in this area probably dates from Middle and Late Keweenawan time.

Since Keweenawan time the map area has probably been above sea level and undergoing erosion, except for possible Early Paleozoic and Cretaceous transgressions of which no direct evidence exists in the immediate area. By the time of Pleistocene glaciation an erosion surface had been established that cut across Lower, Middle, and Upper Precambrian rocks; the ice sheets scoured off nearly all the weathered material, especially along zones of weakness, and deposited ground moraine and locally glaciofluvial stratified drift over much of the area. In the approximately 15,000 years since the Rainy Lobe moved south-southwestward over this area (Florin and Wright, 1969, p. 698), growth of forest vegetation, organic filling of smaller depressions, forest fires, and attendant minor redistribution of the Pleistocene mantle have been the dominant processes.

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