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FIELD TRIP GUIDEBOOK FOR PRECAMBRIAN GEOLOGY OF NORTHWESTERN COOK COUNTY, MINNESOTA

PREPARED FOR THE ANNUAL MEETING OF
THE GEOLOGICAL SOCIETY OF AMERICA
AND ASSOCIATED SOCIETIES
MINNEAPOLIS, MINNESOTA, 1972

MINNESOTA GEOLOGICAL SURVEY
UNIVERSITY OF MINNESOTA
ST. PAUL, MINNESOTA 55108
GUIDEBOOK SERIES NO. 6

MINNESOTA GEOLOGICAL SURVEY
UNIVERSITY OF MINNESOTA
P. K. Sims, Director

FIELD TRIP GUIDE BOOK FOR

PRECAMBRIAN GEOLOGY OF NORTHWESTERN COOK COUNTY, MINNESOTA

Leaders

P. W. Weiblen and D. M. Davidson, Jr.

Special Papers

GEOLOGY OF COOK COUNTY, Paul W. Weiblen, D. M. Davidson, Jr., G. B. Morey and M. G. Mudrey, Jr.

NORTH SHORE VOLCANIC GROUP, John C. Green

Prepared for the Annual Meeting of

THE GEOLOGICAL SOCIETY OF AMERICA

and

ASSOCIATED SOCIETIES

Minneapolis, Minnesota, 1972

Available from the Minnesota Geological Survey, University of Minnesota, 1633 Eustis Street, St. Paul, Minnesota 55108. Price $3.00 (plus tax).

TABLE OF CONTENTS

GEOLOGY OF COOK COUNTY

Paul W. Weiblen, D. M. Davidson, Jr., G. B. Morey, and M. G. Mudrey, Jr.

INTRODUCTION

An exceptionally complete record of Precambrian history is recorded in the rocks exposed in Cook County, Minnesota. In northwestern Cook County, in the vicinity of the Gunflint Trail the Lower Precambrian is represented by a metavolcanic succession, which was intruded by the somewhat younger Saganaga Tonalite. These rocks are unconformably overlain by the Middle Precambrian Animikie Group, consisting of the Gunflint Iron Formation and the Rove Formation. In northeastern Cook County, a gently dipping angular unconformity separates Middle Precambrian and Upper Precambrian strata. There, a thin basal sandstone, the Puckwunge Formation, is overlain by volcanic rocks of the North Shore Group. The Logan intrusions and the Duluth Complex intrude and truncate Middle and Upper Precambrian rocks and comprise the major part of the Upper Precambrian section in northwestern Cook County.

Although the geology of Cook County was summarized by Grout and others (1959), geologic mapping since 1962 has considerably revised the earlier geologic interpretation. Because much of this work is unpublished as yet, a comprehensive summary is presented here. The discussion is meant to provide a framework for the specific aspects of the geology which the chosen stops illustrate. The geologic setting of Cook County is shown in Fig. 1, the general geology in Figs. 2 and 3.

LOWER PRECAMBRIAN

The Lower Precambrian rocks in Cook County are the eastern extension of the Vermilion district, a typical Archean metavolcanic-metasedimentary terrane. The district, as defined originally by Clements (1903), constitutes a narrow belt of rocks that extends from the vicinity of Tower, near Lake Vermilion, northeastward to the International boundary in the vicinity of Saganaga Lake in northwestern Cook County (fig. 3). The metavolcanic-metasedimentary sequence is bounded on the north by the Vermilion granite-migmatite massif, on the south by the Giants Range batholith, and on the east by the Saganaga massif. Rocks in much of the eastern part of the district are truncated by the Duluth Complex of Late Precambrian age.

Lower Precambrian rocks within the district trend eastward to northeastward, generally dip steeply, and dominantly constitute a northward-facing stratigraphic sequence. Folding of at least two generations was broadly contemporaneous with emplacement of the fringing batholithic rocks, and was followed by a major period of faulting that was regional in scope.

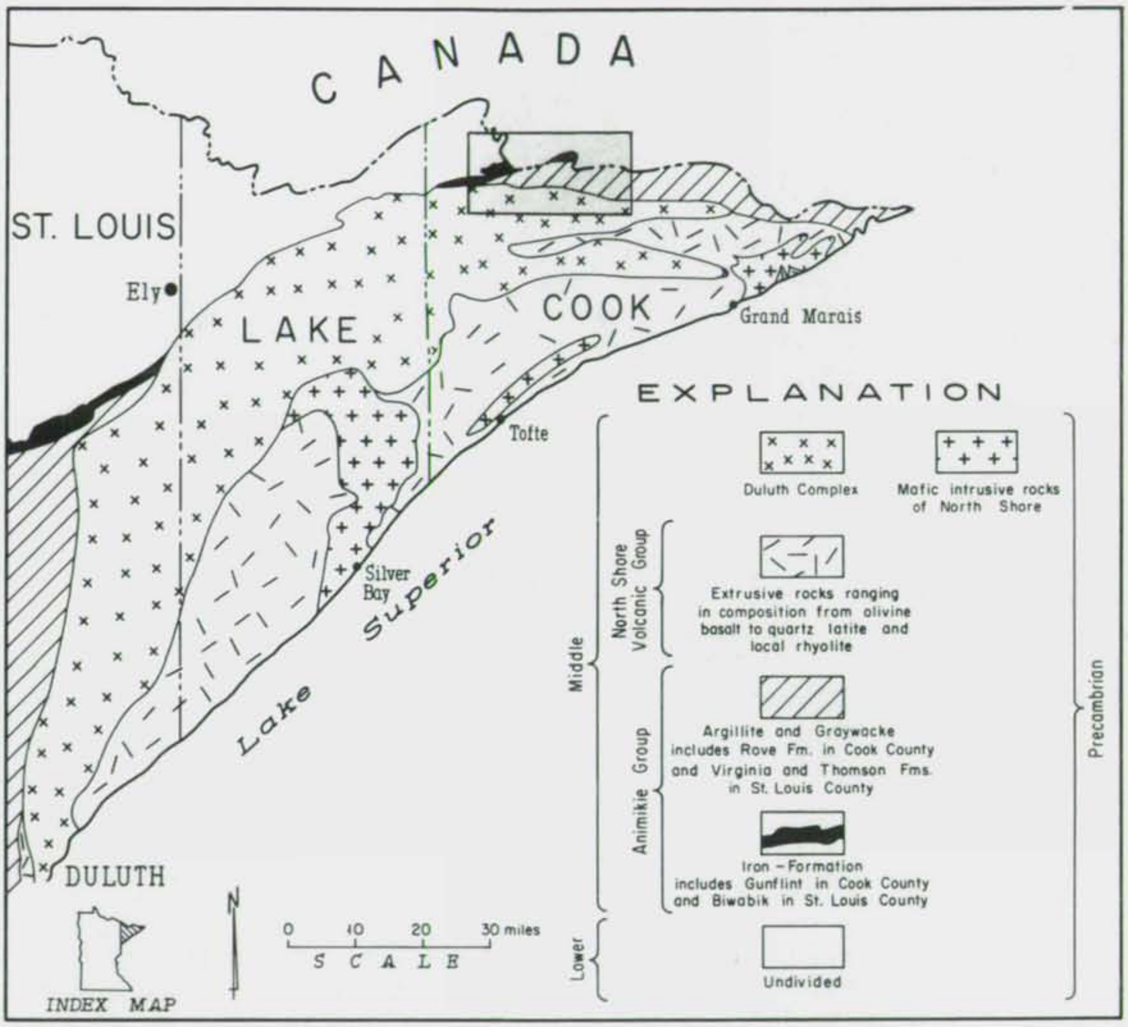

Figure 1. Generalized map of northeastern Minnesota showing the geologic setting of Cook County and the location of Fig. 3 (shaded).

The geologic history of the Vermilion district, insofar as known, has been summarized as follows by Sims (1972):

(1) The first recognized event was mafic volcanism, accompanied by some pyroclastic discharge and intrusion of synvolcanic hypabyssal rocks. The volcanism was mostly under water, and magmas were mainly of basaltic composition. The nature of the basement rocks on which the volcanic rocks were deposited is not known. Minor, banded iron-formations formed locally in depressions on the surface of the volcanics, probably directly from volcanic emanations.

(2) Deposition of the major Soudan Iron-formation and associated carbonaceous and tuffaceous sediments in the western part of the district during a quiescent period in the volcanism; mafic-intermediate volcanism continued in central part.

(3) Abrupt beginning of felsic pyroclastic discharge (volcaniclastic member, Lake Vermilion Formation) in the west and, locally, continuing mafic-intermediate volcanism. Several thin, discontinuous, banded iron-formations were deposited in areas of mafic volcanism, probably during quiescent periods. Late in the volcanism (Ely time), dacitic lavas were extruded locally. Contemporaneously, many hypabyssal intrusive bodies of felsic and intermediate composition intruded the volcanic pile.

(4) Clastic debris derived by erosion of the upper part of the volcanic edifice was deposited, in part contemporaneously with the felsic volcanism that produced the pyroclastic deposits of the Lake Vermilion Formation (in the west) and the Knife Lake Group (in the east).

(5) Mafic-intermediate volcanism was renewed in the central and eastern parts (Newton Lake Formation) of the district and sporadic mafic volcanism occurred during clastic sedimentation in the western part. Probably, some of the felsic volcanic deposits now designated as the Knife Lake Group were formed contemporaneously with the mafic volcanism.

(6) After an unknown interval of time, accumulated volcanic and sedimentary strata were folded and metamorphosed, virtually contemporaneously with early stages of emplacement of the batholithic rocks. Some faulting occurred approximately contemporaneously with emplacement of the batholiths.

(7) Near the end of major folding, small bodies of syenodiorite and related lamprophyres were emplaced. Probably, the Linden pluton, dated at about 2,700 m.y. (Prince and Hanson, 1972), was emplaced slightly later; its age provides a lower limit for the time of folding, metamorphism, and magma generation associated with the Algoman orogeny.

(8) Faulting occurred on a regional scale, deforming local parts of all rock bodies and producing widespread cataclasis. Some of the faulting represented renewed movements on previously formed faults.

The revised stratigraphy for the western part of the Vermilion district

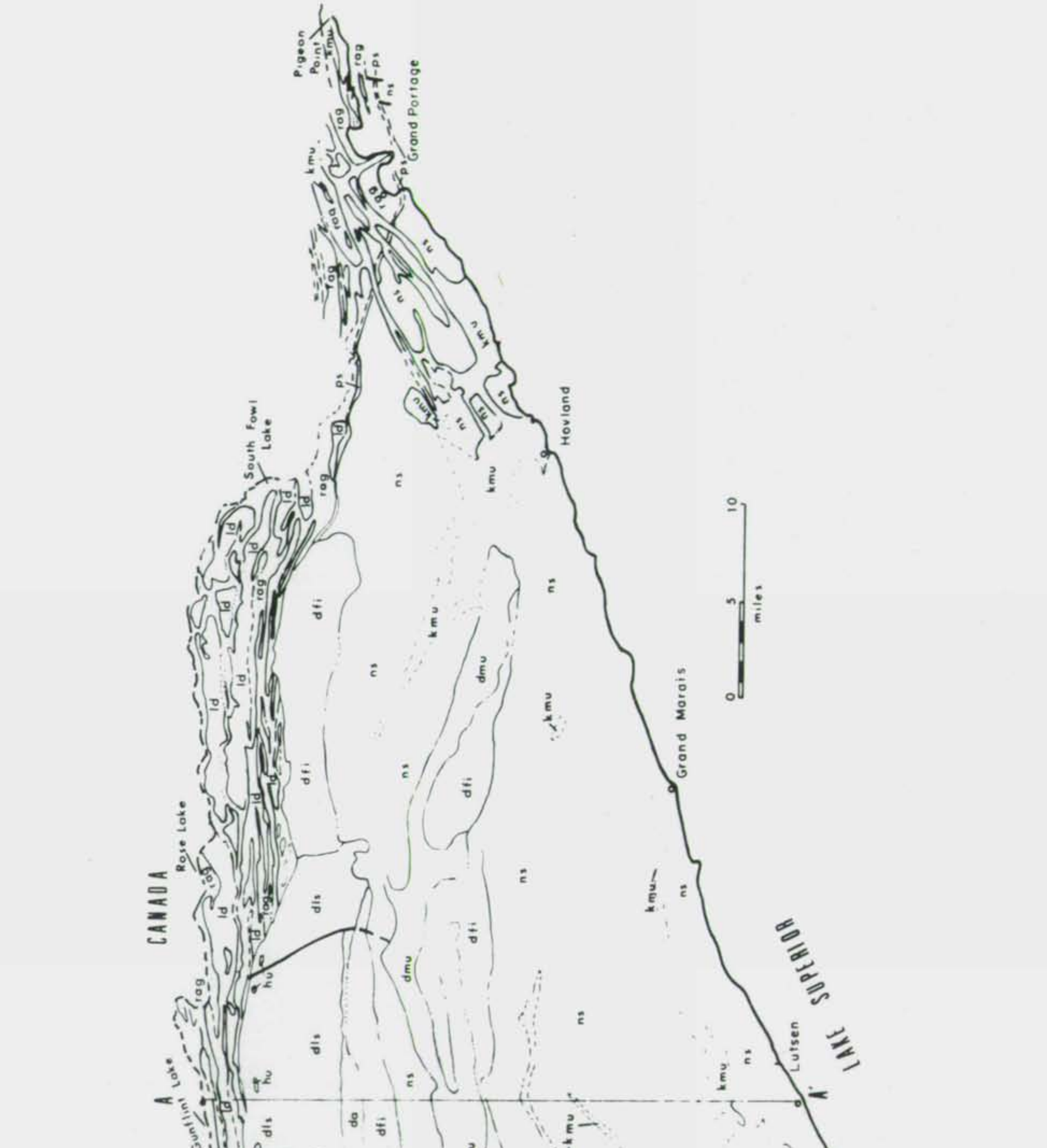

Figure 2. Geologic map of Cook County (modified from Green, 1972, in press).

EXPLANATION FOR FIGURE 2

Upper Precambrian

Middle Keweenawan

hu — Inclusions in Duluth Complex

DULUTH COMPLEX

kmu — Mafic hypabyssal rocks

dfi — Felsic series

dt dmu — Troctolitic-gabbroic series

da — Anorthositic series

dls — Nathan's layered series

Lower Keweenawan

ns — North Shore Volcanic Group

ld — Logan intrusions

Middle Precambrian

ps — Puckwunge Sandstone

rag — Rove Formation

gif — Gunflint Iron Formation

Lower Precambrian

kcg — Knife Lake Group

sgt — Saganaga Tonalite

gst — Metavolcanic and metasedimentary rocks

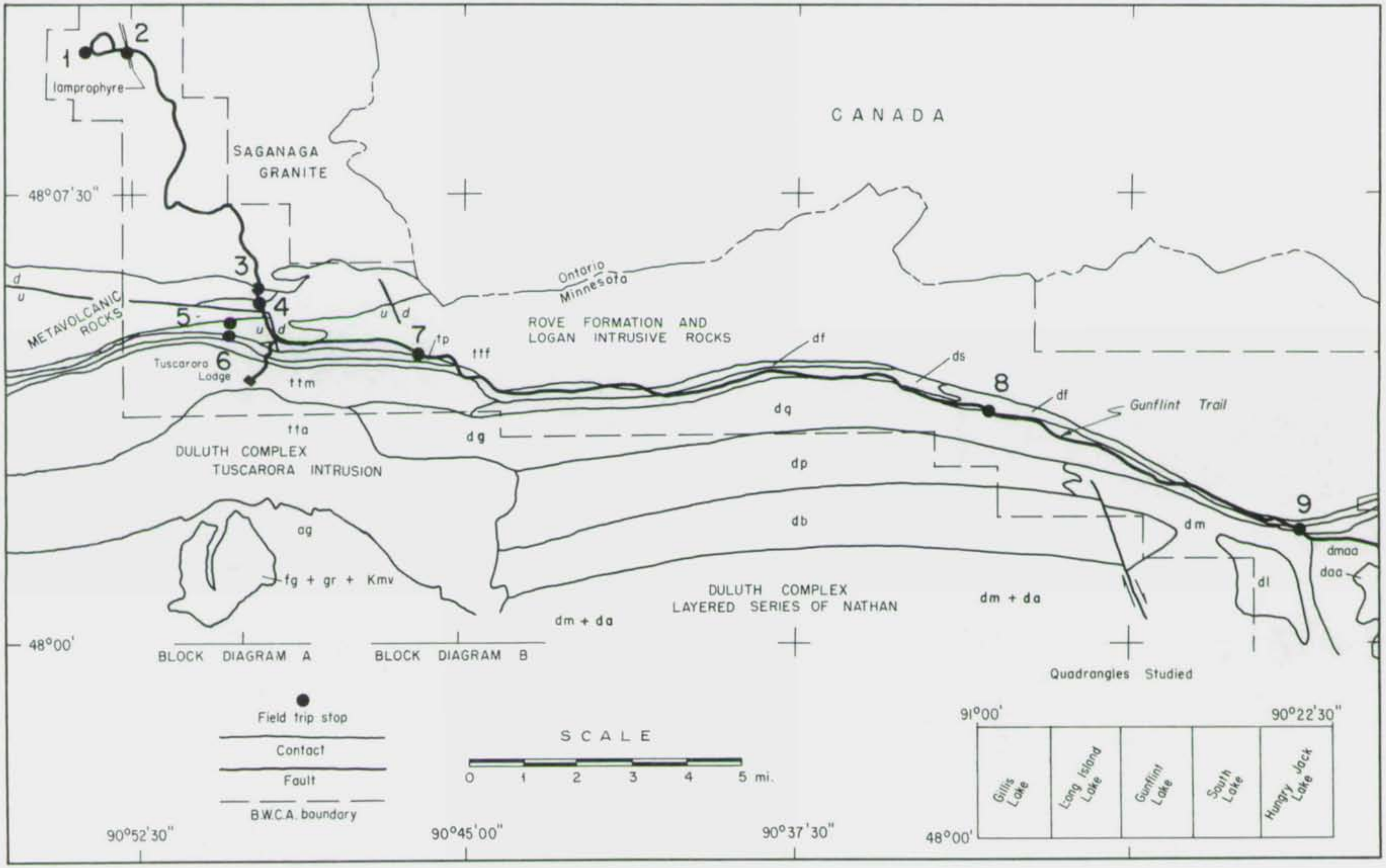

Figure 3. Generalized geologic map of northwestern Cook County showing location of the Gunflint Trail and field trip stops.

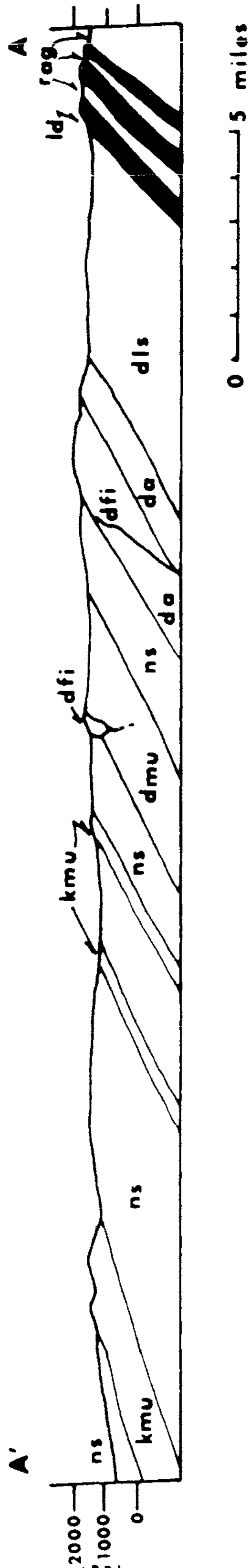

Figure 4. North-south geologic cross-section across central Cook County. Location of cross-section shown on Figure 2.

has important implications regarding the nomenclature and stratigraphy of the eastern part. Previously, all mafic metavolcanic rocks in the eastern part of the district were equated with the Ely Greenstone (Gruner, 1941, pl. 1) and all of the Knife Lake Group was interpreted as being younger than the Saganaga batholith. The emplacement of the batholith and its associated deformation was referred to as the Laurentian orogeny. However, mapping by Gruner (1941) showed that some conglomerates containing boulders of Saganaga tonalite that were previously assumed to represent the base of the Knife Lake Group were actually deposited well into Knife Lake time (post-Saganaga rocks at the Knife Lake Group). Moreover, the work of Harris (1968) along the north shore of Saganaga Lake has shown that the Saganaga batholith is intrusive into a metabasalt unit (Newton Lake Formation (?) in Minnesota) which stratigraphically overlies metasedimentary rocks assigned to the Knife Lake Group. The Knife Lake Group can be interpreted to consist of two rock successions of different ages, one younger than and one older than the Saganaga Tonalite. Therefore, on geologic grounds, the emplacement of the Saganaga Tonalite does not define a major break in the stratigraphic record in this area, but is a part of a continuous sequence of igneous activity and sedimentation.

The interpretation of the geologic history of the eastern part of the Vermilion district given above is consistent with the radiometric dating in the region. The age data indicate that there is no appreciable difference in the age of the Saganaga Tonalite and the granitic rocks comprising the Vermilion and Giants Range batholiths (Table 1). This led Goldich and others (1961, p. 73-74) to relegate the Laurentian orogeny to a minor status. With the interpretation presented here, the Saganaga batholith was emplaced, probably at shallow depths, and unroofed during the later stages of a volcanic-sedimentary cycle, to supply debris locally to still-accumulating volcanogenic sediments. The epiclastic deposits shed from the batholith probably were deposited with a time span of a few million years, and there need not have been a long time span between emplacement of the Saganaga and the older batholiths.

Descriptive Stratigraphy

The Vermilion district contains many major longitudinal faults that divide it into long segments or belts, each with distinct geologic characteristics. Consequently, the stratigraphic sequences in each segment cannot be correlated with each other in any simple way. Of particular interest here is the Gabimichigami segment of Gruner (1941) which extends from Gabimichigami Lake across the Gunflint Trail (figs. 2 and 3). It includes a metavolcanic assemblage consisting of metabasalt, metaandesite, agglomerate and tuff, hornblende andesite porphyry, and intercalated metagraywacke and slate. To the north, the Saganaga Tonalite has intruded and metamorphosed the volcanic succession. To the west it is overlain by or is in fault contact with post-Saganaga rocks of the Knife Lake Group: it is overlain to the south by younger rocks of Middle and Late Precambrian age.

The metavolcanic assemblage constitutes a homoclinal sequence which dips southward toward what Gruner inferred to be the axis of a southeastward-plunging synclinorium. Pillow-top directions indicate that the sequence also becomes stratigraphically younger to the south. However, some pillows top to the north, indicating folding, but poor exposure precludes detailed evaluation of the structure.

Previously, an unconformity was thought to separate the mafic and more felsic rocks; thus the succession was subdivided into two formations. The metabasalts were referred to as part of the Ely Greenstone, whereas the more felsic volcanic and clastic rocks were placed within the Knife Lake Group. Recent mapping (Morey and others, 1969) has shown these two lithologies to be gradational, and mapping in other parts of the Vermilion district (Sims and others, 1968; Morey and others, 1970; Green, 1970) has shown that specific rock types are not diagnostic of any particular stratigraphic horizon -- i.e., lithologic units are not time-stratigraphic units -- therefore no formal stratigraphic nomenclature is now used for these rocks.

Volcanogenic Rocks

Detailed mapping in the Long Island Lake quadrangle, reconnaissance mapping as far west as Fay Lake in the Gillis Lake quadrangle, and Gruner's work (1941) have indicated that the volcanogenic sequence consists of approximately 60 percent metabasalt and associated fragmental rocks, 30 percent metaandesitic agglomerate, conglomerate, tuff, and flows and 10 percent intercalated metagraywacke and slate.

Metabasalt and associated rocks: Over 95 percent of the metabasalt is extrusive and many of the flows exhibit pillow structure. The pillows are as much as three feet in diameter, although many have been deformed so that they are now two or three times as long as they are wide. Chilled rinds up to one-half inch thick are well developed and are typically lighter in color than the dark green or dark greenish-gray pillow interiors. Interpillow material is well developed locally and consists of tuffaceous material, chert, or pillow-rind fragments. In addition there are several tabular bodies, less than 200 feet long, of metadiabase associated with the metavolcanic rocks.

The metabasalt shows intense retrograde alteration; many thin sections are nearly opaque. Recognizable minerals include relict augite and calcic plagioclase, and secondary sodic plagioclase, actinolite, chlorite, epidote, calcite, quartz, leucoxene, and opaques. The tabular bodies of metadiabase have a relict poikilitic texture (actinolite pseudomorphs after augite) and a mineralogy very similar to that of the metabasalt.

Thin beds of texturally and mineralogically immature metaclastic rocks are locally intercalated with the metabasalt. Several beds are crudely graded and have a texture suggestive of a pyroclastic origin. Most layers, however, appear to be epiclastic with pebble- to silt-size clasts of locally derived metadiabase in a finer grained matrix of chert, plagioclase, hornblende, chlorite, and sericite.

Table 1 Summary of ages of rocks from the Saganaga Massif. from Hanson and others (1971), Catanzaro and Hanson (1971), Hanson and Malhotra (1971)

	Peterman and Goldich Rb-Sr Whole-rock isochron m.y. (Sr^{87}/Sr^{86} initial)	U-Pb Zircon and Sphene m.y.	K-Ar-m.y.	
Northern Light Gneiss	2740 ± 100	2750	2605	biotite
Saganaga Tonalite	2710 ± 560 (.7009)	2750	2690	hornblende
Icarus pluton	2690 ± 480	2730	2620	hornblende
Granodiorite of Gold Island	2670	-	2430	sericite
Lamprophyre KA-70	-	-	1755	biotite
Keweenawan dikes	-	-	1010	whole rock
Ely Greenstone 1/	2660 (.7005 - .7007)	-	-	
Newton Lake Formation 1/	2660 (.7005 - .7007)	-	-	
Knife Lake 1/	2660 - 2750 2/			

1/ Verbal communication, June 1972, B. Jahn

2/ Model age on composite sample and initial from Ely Greenstone

Table 2 Average modal analyses of the Saganaga Tonalite and Northern Light Gneiss

	1	2	3	4	5	6	7	8
Quartz	20.9	24.5	2.1	15.3	11.4	30.2	.5	11.4
Plagioclase	64.8	59.1	61.9	65.3	54.6	59.6	49.4	54.1
Microcline	1.5	6.1	1.6	3.4	20.2	3.0	19.4	10.4
Hornblende	6.5	4.1	25.8	11.4	tr.	-	15.1	17.2
Augite	tr.	-	-	-	-	-	8.8	1.4
Biotite	3.6	.5	1.4	2.3	6.0	4.7	2.8	1.5
Chlorite	.9	2.5	.9	.9	1.4	tr.	.5	2.1
Muscovite	tr.	-	tr.	tr.	-	1.6	-	-
Epidote	1.5	2.8	4.5	1.1	.4	.8	.5	.6
Opaques	tr.	.1	tr.	tr.	1.6	.1	1.0	.4
Sphene	.3	.1	1.1	.2	-	tr.	.9	.5
Apatite	tr.	.2	.5	.1	-	tr.	1.1	.4
Zircon	tr.	tr.	tr.	tr.	tr.	tr.	-	-
Carbonate	tr.	-	-	-	.8	-	tr.	tr.
Fluorite	-	-	-	-	3.6	-	-	-
An	24	29	26	24	10	24	34	34

Table 2 Continued

1. Saganaga Tonalite main phase, average of 20 from Trout Bay, Northern Light Lake, relatively non-cataclastic; by C. R. Hallford

2. Saganaga Tonalite main phase, average of 10 from Sea Gull Lake, strongly sheared; by C. R. Hallford

3. Border phase, average of 9 from Moosehead Point north of Trout Bay; by C. R. Hallford

4. Younger tonalite, average of 5 from Horseshoe Island, Saganaga Lake; by C. R. Hallford

5. Fluorite granodiorite, 1 modal analysis, from Gold Island, Saganaga Lake; by C. R. Hallford

6. Northern Light Gneiss, average of 21, from Northern Light Lake; by M. G. Mudrey, Jr.

7. West phase of Icarus pluton, average of 13, from Icarus Lake; by J. E. Kavanaugh

8. East phase of Icarus pluton, average of 12, from Icarus Lake; by J. E. Kavanaugh

Hornblende andesite porphyry and related rocks - There are two types of hornblende-biotite phenocryst bearing rocks. Both are light greenish-gray in color. One type lacks internal structure. The groundmass consists of plagioclase, lesser amounts of biotite, opaques, and rare quartz and secondary calcite. The other type has similar phenocryst and groundmass mineralogy but also contains angular to rounded, cobble-size clasts and is inferred to be a volcanic breccia or agglomerate.

Metagraywacke and slate - In the vicinity of Fay Lake in the Gillis Lake quadrangle (fig. 3), the more felsic volcanic rocks apparently interfinger, or are infolded with agglomerate of conglomerate, metagraywacke, and slate.

Amphibolite - The metamorphic effects of the Saganaga Tonalite on the metabasalt becomes apparent only within several hundred feet of the contact. Near the contact, the metabasalt becomes granular and contains recrystallized hornblende and calcic plagioclase, and along the contact the rock is strongly schistose. The schistosity parallels the granite contact, as does a well-developed foliation within the granite.

Saganaga Massif

Several types of leucocratic igneous rocks intrude the metavolcanic sequence of and adjacent to Saganaga Lake. Pioneering work by A. Winchell (1888) and Grout (1929, 1936) distinguished two major phases, the Northern Light Gneiss and Saganaga Granite. Recent mapping, chemical and age data by Goldich and others (1961, 1972) and Hanson and Goldich (1972) have clarified the relationships between these two units (Table 1). They also characterized a younger granodioritic intrusion, the Icarus pluton, and minor lamprophyre. All of these rock types are considered to be part of the Saganaga massif (Hanson and others, 1971).

Northern Light Gneiss: - Although no exposures of the Northern Light Gneiss have been reported in Minnesota, excellent outcrops of this foliated trondhjemitic gneiss are found in road cuts along Ontario provincial highway 588 from Whitefish, to Northern Light Lake. The gneiss is dominantly a fine-grained, quartz-rich leucotonalite of trondhjemitic composition (Table 2) containing lenses and layers of amphibolite and lesser amounts of metarhyodacite and metarhyolite.

Grout (1929) concluded that the Northern Light Gneiss formed by lit-par-lit injeciton of early granitic magma into metavolcanic rocks. Goldich and others (1972) consider the gneissic unit to represent metamorphosed volcanic pile of basalt and felsic lavas and felsic pyroclastic material. They recognize two periods of folding in the gneiss, but only one in the younger Saganaga Tonalite. Thus, they conclude that a period of deformation and metamorphism occurred before emplacement of the Saganaga Tonalite.

Saganaga Tonalite: - The Saganaga Granite of A. Winchell (1888) has been renamed the Saganaga Tonalite by Hanson and others (1971), inasmuch as plagioclase is the dominant feldspar.

The tonalite is a syn-to late-kinematic composite intrusion emplaced into older metavolcanic rocks and the Northern Light Gneiss. Inch- to foot-sized inclusions of both rock types are found within the tonalite. The main phase of the tonalite, which comprises 85 percent of the outcrop area, is a medium-grained, quartz "eye" hornblende-biotite tonalite. Other phases include: (1) younger fine-grained tonalite which lacks conspicuous quartz "eyes;" (2) a border phase which is up to several hundred feet wide found along the southern margin of the batholith and along the base of a roof pendant of the Northern Light Gneiss: (3) a red, coarse-grained biotite-fluorite granodiorite and pegmatite: and (4) a quartz-feldspar pegmatite which occurs as veinlets as much as 3 feet wide in the main phase.

Linear structural elements marked by an alignment of quartz "eyes" and/or elongate hornblende grains are well developed only in the border phase. Lineations in the border phase plunge gently southeastward. In contrast, primary lineations in the main phase are random.

The dominant (main) phase is a gray, medium- to coarse-grained tonalite characterized by large quartz aggregates that resemble phenocrysts. The quartz "eyes," commonly about 1 cm across, are aggregates of grains 1 to 2 mm in diameter that have different optical orientations. Quartz also occurs as an interstitial mineral. The quartz "eyes" probably are a primary igneous feature, for they occur in small tonalite dikes as well as in the larger bodies. Plagioclase (An_{20-28}) constitutes about 60 percent of the rock (Table 2); most is nonperthitic, unaltered, weakly zoned, and poorly twinned. Antiperthite increases in abundance as the borders of the batholith are approached, and is well developed in the more highly sheared parts.

Microcline is sparse and occurs as small, antiperthitic grains, as discrete zones at the borders of the plagioclase grains, and as interstitial grains. Hornblende, the dominant ferromagnesian mineral, forms euhedral subhedral discrete grains that are altered slightly to chlorite and epidote or occurs as aggregates with biotite, epidote, and chlorite. Some of the hornblende grains contain relict augite. Generally, augite is confined to the eastern part of the batholith, in the vicinity of Icarus Lake in Ontario. Apatite, epidote, sphene, and opaque oxides are the common accessory minerals.

Peripheral to the central core, the tonalite is more or less sheared and altered, and contains more microcline than the normal phase. The increase in microcline is interpreted as having resulted in part by exsolution from plagioclase, aided by shearing and the addition of water, and in part by the introduction of microcline together with carbonate and quartz into the shear zones (Goldich and others, 1972). The shearing is manifested by a reduction in grain size from approximately 4 mm to less than 0.02 mm in the groundmass and by the mechanical elongations and flattening of the quartz "eyes." The "eyes" have length to width ratios of as much as 7:1.

A fine- to medium-grained hornblende biotite tonalite intrudes the sheared "normal" tonalite in the vicinity of Horseshoe Island in Saganaga Lake. It is distinguished from the normal phase by being finer grained, in lacking quartz "eyes," and in having somewhat more hornblende (table 2). It contains numerous mafic inclusions. This tonalite is not sheared, whereas the immediate country rock is, indicating that it was emplaced after the main deformation of the normal phase.

The mafic border phase is a quartz-bearing hornblende diorite that is gradational with the quartz "eye" tonalite. This phase is well developed along the southern edge of the batholith in the Long Island Lake quadrangle (fig. 3) where it is as much as 1000 feet wide, and in the Moose Bay area in Ontario where it is found along the underside of a roof pendant of the Northern Light Gneiss. Foliations in the border phase and in the country rocks are everywhere similar. The variation in the modal composition of the border phase can be explained by partial assimilation of amphibolite. The optical properties of hornblende from the metavolcanic rocks and from the border phase are sufficiently similar to accept this hypothesis. However, the origin may be more complex, as suggested by Grout (1929) who first described the border rocks. Grout surmised that the border phase was the result of settling of mafic crystals to the chamber floor and brought to its present position by rotation about a north-south axis. Goldich and others (1972) find this explanation untenable, in part because of the low pressure Abukuma-type metamorphism of the Northern Light Gneiss (see below).

A sheared fluorite-bearing granodiorite and pegmatite (Grout, 1929) probably intrudes the Saganaga Tonalite on Gold Island, within Saganaga Lake. Exposures are limited to this island which lies along a line of islands consisting of strongly cataclasized Saganaga Tonalite. Apparently the rock is sheared to the same extent as is the main mass of the tonalite (Goldich and others, 1972).

Icarus Pluton: - The Icarus pluton is a composite intrusion which cuts both the Northern Light Gneiss and the Saganaga Tonalite in the vicinity of Ontario provincial Highway 588. The west phase of the Icarus pluton (Goldich and others, 1972; Kavanaugh, 1969) is an aegerine-hornblende syenodiorite that is cut by an east phase consisting of hornblende granodiorite (table 2). This intrusion is not cataclasized as is the country rock, and thus, its age places limits on the period of fracturing that is recorded in the Saganaga Tonalite.

Post-Saganaga Rocks of the Knife Lake Group

A tonalite-bearing conglomerate having clasts derived from the underlying Saganaga Tonalite is exposed at Cache Bay on Saganaga Lake just to the north of the International Boundary. At this locality, it consists entirely of cobbles and boulder of the Saganaga in a matrix of finer granitic detritus. McLimans (1971) estimates that about 74 percent of the conglomerate is granitic clasts and the remainder arkosic matrix.

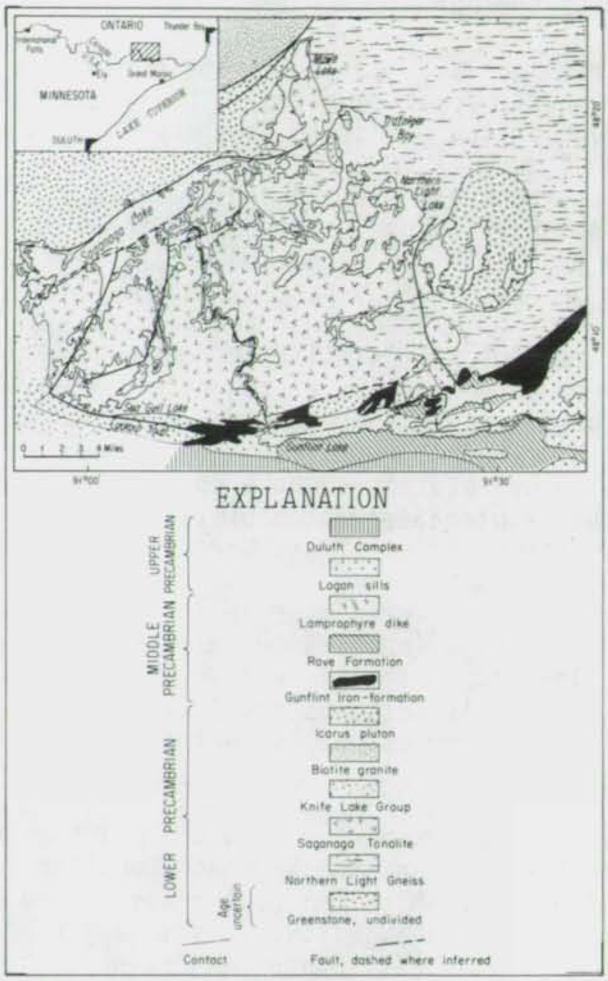

Figure 5. Generalized geologic map of the Saganaga massif (modified from Hanson and others, 1971).

Apparently the same conglomerate unit also is exposed at Ogishkemuncie Lake, the type locality of the Ogishke conglomerate, as originally defined by Winchell (1887). There, however, the conglomerate contains clasts of many rock types including tonalite, greenstone, andesite, rhyodacite, dacite porphyry, aplite, chert, jasper, shale, tuff, and other sedimentary rocks.

The size distribution of granitic clasts indicates that sediment transport was from east to west. McLimans (1971) concludes that deposition was accomplished by turbidity currents generated by slumping of detritus on a steep initial slope that formed as the Saganaga massif rose to the east.

Structure

Major faults bound the Saganaga massif on both the north and south margins, and lesser ones, some of which are shown on Figure 5 occur within it. The fault along the north margin follows the north shore of Saganaga Lake (Harris, 1968) and generally separates tonalite from greenstone. According to Harris, the breccia zone along the fault, consisting of broken metavolcanic rocks, tonalite, and peridotite cemented by quartz and calcite, is as much as several hundred feet wide. The fault along the southern margin previously named the Lookout fault (Sims and others, 1969), trends northwestward and is steeply inclined. A breccia zone consisting of highly sheared metabasalt in a matrix of quartz and calcite also occurs along this fault. In the vicinity of Sea Gull Lake, the fault separates tonalite from greenstone, but to the east, the fault transects greenstone and separates amphibolite on the Saganaga Tonalite side of the fault from greenstone on the other side. The faults that have been mapped within the massif are based largely on observed shear zones and to a lesser extent on topographic lineaments (Goldich and others, 1972). Strong cataclasis associated with the faults produced a cataclastic foliation and lineation in the tonalite. Along the bordering faults, the cataclastic foliation is steeply inclined and the lineation plunges 15° to 30° E. Within the batholith, the cataclastic foliation parallels the shear zones and generally has a northeastward strike and a gentle dip to the east.

All of the minor structural elements in the pre-Saganaga rocks along the south edge of the massif are consistent in orientation with mineral lineation developed in both the amphibolites and the border phase Saganaga Tonalite itself. Fracture cleavage is ubiquitous and commonly parallels the Lookout fault. Lineations formed by bedding/cleavage intersections plunge to the east-southeast and appear to reflect a southeast-plunging synclinorium. Because all structural elements along the south side of the massif are consistent with elements within the massif itself, it is inferred that deformation of the metavolcanic rocks, emplacement of the tonalite and subsequent uplift of the massif are related to the same tectonic event.

Near the western edge of Cook County, the west-northwest-trending folds in the Gabimichigami segment are truncated by a major fault that separates this segment from rocks folded on north-northeast-trending axes. Although exposures are poor, Gruner's (1941) map pattern in the southern part of the Gabimichigami segment implies that these rocks also were refolded about northeast-trending axes; hence, rocks in the Gabimichigami segment are characterized by at least two periods of folding. Similarly, Hanson and others (1971) and Goldich and others (1972) report two periods of folding in the Northern Light Gneiss, the youngest being a northeast-plunging synform. At the western edge of Saganaga Lake at Cache Bay, the Ogishke conglomerate dips westward as a result of tight folding (Gruner, 1941) on north- and northeast-trending axes that post-date emplacement of the Saganaga batholith; hence, the northeast-trending folds are inferred to be everywhere younger than the Saganaga Granite. It is interesting that the shear zones mapped by Hanson and others (1971) within the Saganaga Tonalite also have a northeast-trending direction. This shearing may be the result of the same stresses that folded the post-Saganaga Knife Lake rocks.

Grout (1936) interpreted the foliation and lineation in the Saganaga Tonalite as primary flow structures, and inferred that the tonalite and the Northern Light Gneiss had been tilted about 70° westward subsequent to deposition of the conglomerate at Cache Bay. In this interpretation, the eastern part of the Saganaga massif would represent the "roots" of a batholith, uplifted from a depth of some 15 miles. Goldich and others (1972), however, interpreted the internal structure in the sheared tonalite as secondary and as having formed mainly by shearing along the several faults. They concluded that the batholith rose approximately vertically, and after crystallization the tonalite and the Northern Light Gneiss continued moving upward as a diapiric mass. Faults formed along the contacts between the diapiric mass and adjacent greenstone, as well as within the batholith which was unfoofed, and shed detritus to the west to form the conglomerate at Cache Bay. Subsequently, these sediments were folded and faulted (Gruner, 1941) about east-northeast-trending axes. Thus, in this area folding preceded or was concurrent with the intrusion of the Saganaga Tonalite. Uplift and erosion followed. An erosional surface was developed on which conglomerates, graywacke and mudstone were deposited. These rocks were later folded, and this period of folding also affected rocks older than the Saganaga Tonalite and perhaps the tonalite itself. Hanson and others (1971) assign the first deformation to the Laurentian orogeny and the second to the Algoman orogeny. Although this orogeny can be geologically documented in the Saganaga Lake area, it is important to note that emplacement of the Saganaga Tonalite appears to post-date deposition of some Knife Lake detritus. Hence, the significance of the Laurentian as an orogenic event that separates dominantly mafic volcanism from dominantly clastic sedimentation is greatly diminished. Rather, the Laurentian appears to be part of a continuing sequence of events that culminated in the Algoman orogeny, and as such it has no special status.

MIDDLE PRECAMBRIAN

Although the Animikie rocks are believed to be younger than 2,000 m.y. (Hanson and Malhotra, 1971), uncertainties remain as to the actual time of deposition. Various attempts to determine that time have resulted in values ranging from 1,635 ± 24 m.y. (Faure and Kovach, 1969) to 1,900 ± 200 m.y. (Hurley and others, 1962). Although the value observed by Hurley and others includes an arbitrary and perhaps unnecessary correction for 20 percent argon loss, it nevertheless has been widely quoted in the literature as the time of diagenesis. Faure and Kovach also interpret the age they obtained as a time of diagenesis, and their data, if taken at face value, indicate that deposition and diagenesis of the Gunflint Iron Formation took place after metamorphism of presumably correlative rocks in east-central Minnesota (Goldich and others, 1961). Subsequent work, however, suggests several other possible interpretations. Misra and Faure (1970, p. 398) have shown that the apparent age of the Gunflint Iron Formation "...decreases from 1.7 b.y. at the eastern end to 1.2 b.y. ...at the western end..." and that this systematic variation "...may be related to metamorphic effects caused by Keweenawan diabase sills..." Although Misra and Faure conclude otherwise, their age may reflect partial re-equilibration resulting from Keweenawan igneous activity. A more interesting possibility has been suggested by Hanson and Malhotra (1971). Because the dike rocks they studied in northern Minnesota appear to have been metamorphosed about 1,600 m.y. ago, they suggested (p. 1110) that this event "...may have been associated with burial by overlying sediments of the Animikie Group..." However, the evidence for burial metamorphism is equivocal, and it may be that 1,600 m.y. was the time of a mild deformation younger than that of the Penokean orogeny. Thus, Faure and Kovach's age also may represent re-equilibration in response to this event; if so, the various mineralogic and textural features in the rocks of the Gunflint and Mesabi ranges, now ascribed to the Penokean orogeny, may be related to a post-Penokean event. Clearly, additional data are needed before this problem will be resolved, but it is significant that there are no data indicative of the Animikie Group being much older than 2,000 m.y. However, there is no unequivocal depositional age for these rocks.

Descriptive Stratigraphy

Gunflint Iron Formation

The Gunflint Iron Formation crops out in an east-northeast-trending belt that extends from Thunder Bay on Lake Superior to a point in Minnesota 12 miles west of Gunflint Lake where it is truncated by the Duluth Complex (fig. 3).

In Canada the iron-formation is only slightly, if at all, metamorphosed and consists of silica, iron oxides, iron carbonates, and greenalite. There, Goodwin (1956) recognized six sedimentary facies which serve to subdivide the iron-formation into four members (fig. 6): basal conglomerate member, Lower Gunflint member, Upper Gunflint member, and the Upper limestone member.

The Basal conglomerate member, or the Kakabeka Quartzite of Tanton (1931), is equivalent to the Pokegama Quartzite on the Mesabi range. It is as much as 10 feet thick, and is a polymictic conglomerate containing

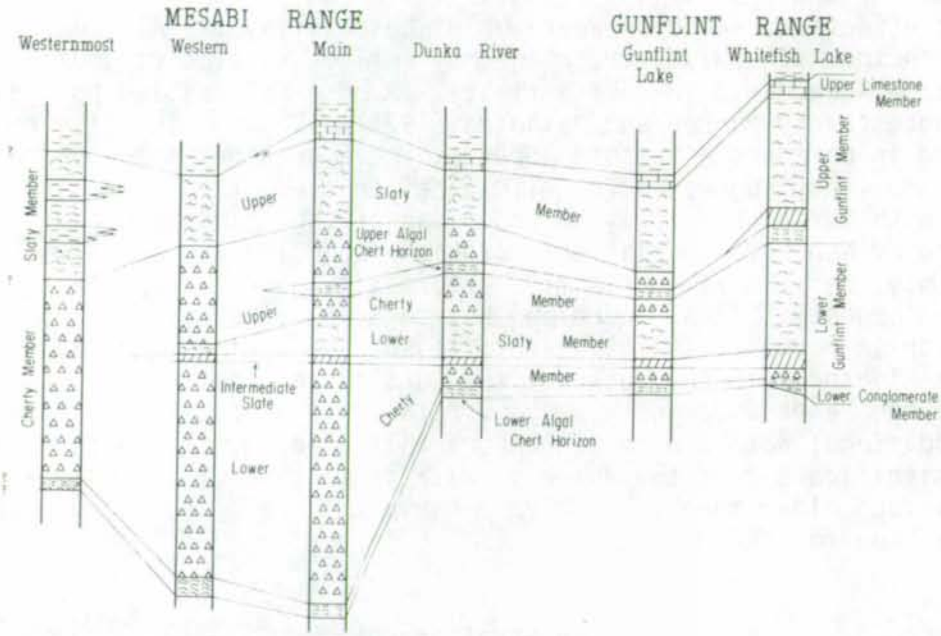

Figure 6. General correlation of lithostratigraphic units in the Biwabik Iron Formation of the Mesabi range, the Gunflint Iron Formation in Minnesota and the Gunflint Iron Formation in Canada.

clastic or Lower Precambrian metavolcanic rocks and granite in a matrix of quartz, feldspar, and lesser chlorite. In much of the western part of the Gunflint range, the unit is missing and the iron-formation directly overlies older rocks.

A lower algal chert facies consists of reef-like mounds of finely-laminated black, red, and white chert. Individual mounds are either isolated or connected by thin layers of granular or oolitic chert. Many of the mounds are stromatolitic, and the associated cherts contain an abundant microflora. A lower tuffaceous shale facies overlies the lower algal chert facies, and is composed of fissile black shale containing volcanically-derived material. Three facies comprise the upper part of the Lower Gunflint member. The lower west taconite facies is composed of wavy-bedded granule-bearing chert, carbonate, and sparse iron oxides; greenalite occurs as granules; siderite forms thin beds, and the proportion of magnetite and hematite, both as disseminated grains and thin beds, increases upward. This facies grades laterally eastward into the lower bedded chert-carbonate facies, consisting of 4- to 6-inch-thick beds of gray chert. Carbonaceous material and pyrite are common in the shaly layers. This facies in turn grades northeastward into the lower east granular taconite facies. The lower 2 to 6 feet of this facies is composed of interbedded granular chert and ankerite. The upper 10 to 20 feet consists of interbedded red or green mottled chert and dolomitic limestone.

The base of the Upper Gunflint member is marked by a granular cherty layer that is overlain by algal-bearing chert and, locally, by amygdaloidal basalt flows. The latter two units are overlain by granular chert and bedded jasper. The jasper beds grade upward into a tuffaceous shale facies consisting of "...black, tuffaceous shale and siltstone with considerable interbedded siderite and pyrite, together with extensive beds of volcanic ash" (Goodwin, 1956, p. 579). The ash contains ellipsoidal structures that resemble mudballs, and which are composed of concentric layers of small angular tuff fragments arranged about larger central clasts. The upper tuffaceous shale facies grades into an upper taconite facies and an upper bedded chert-carbonate facies. The upper taconite facies is composed of wavy beds of granular greenalite-bearing chert. This facies contains abundant hematite and magnetite in granules toward the top, and grades laterally eastward into the upper bedded chert-carbonate facies. The latter facies consists of intercalated gray chert and brown carbonate, consisting of siderite with lesser amounts of dolomite and/or ankerite. Brecciation and crumpling, apparently contemporaneous with deposition, are common in this facies.

The Upper limestone member marks the top of the Gunflint Iron Formation. Minor chert beds, illite, and volcanic shards are present, and tuffaceous shale is common, especially in the eastern part of the outcrop area.

The original mineralogic character of the iron-formation in Minnesota is obscured by a thermal metamorphic overprint produced by Upper Precambrian igneous rocks. Nevertheless, most of the textural aspects are well preserved. Therefore, a four-fold nomenclatural scheme, originally outlined in the Biwabik Iron Formation of the Mesabi range by Wolff (1917), which emphasizes various textural aspects was extended to the Gunflint Iron Formation by Broderick (1920) and subsequently has been retained in more recent studies (Morey and others, 1969; Sims and others, 1969).

The four-fold nomenclatural scheme originally outlined by Wolff and Broderick also consists of four members: Lower cherty, Lower Slaty, Upper cherty, and Upper slaty. Although the boundaries of these members do not coincide with those recognized by Goodwin (1956), the two schemes can be equated with only slight difficulty (fig. 6).

Lower Cherty Member: - The Lower cherty member is thin, ranging in thickness from 15 to 45 feet. Feldspathic quartzite that contains granite and greenstone pebbles is present locally at the base of the formation; these beds are equivalent to Goodwin's basal conglomerate member. A persistent magnetite-rich, silicate-bearing unit five to 15 feet thick occurs within this member and serves as an excellent marker-horizon. Most commonly it lies directly upon basement rocks, but locally it overlies either the feldspathic quartzite or a chert-cemented conglomerate containing fragments of algal structures; it, in turn, is overlain by a massive, chert-rich magnetite-poor unit about 15 feet thick.

Lower Slaty Member: - This member is 80 to 95 feet thick. The lowermost, nearly magnetite-free 10 feet is a black, thin-bedeed argillite composed dominantly of volcanically derived material. It is equivalent to the Intermediate slate on the Mesabi range and to the lower tuffaceous shale facies in Canada. The beds immediately above the Intermediate slate are massive and cherty and resemble the upper part of the Lower cherty member. This unit passes abruptly upward into cherty silicate-bearing beds with sparse magnetite intercalated with a few thinly-laminated silicate-rich beds. The remaining 50 feet is a thin-bedded to laminated rock containing various silicates and from 20 to 35 percent magnetite. A few cherty-silicate beds, definitely subordinate in amount are intercalated in this stratigraphic interval.

Upper Cherty Member: - There is a continuous gradation between the Lower slaty and Upper cherty rocks. The Upper cherty member, as presently defined, is approximately 50 feet thick. The lower part consists of irregularly bedded to lenticular cherty layers intercalated with thinly-laminated silicate-rich layers that increase in abundance upward. Thin irregular layers of magnetite are common in the cherty beds near the bottom of the member, but become less abundant upward. The top of the member, equivalent to Goodwin's upper algal chert facies, is characterized by several granular chert beds containing algal structures, conglomerate fragments, and abundant magnetite.

Upper Slaty Member: - The Upper slaty member is approximately 150 feet thick. Thick lenticular chert beds with disseminated magnetite characterizes the lower few tens of feet, but most of the member consists of a thin-bedded to laminated quartz-silicate rock interbedded with thinly laminated layers of graphitic argillite, and one to two inch thick beds of relatively pure chert. The upper 10 feet is nearly magnetite-free and consists of limestone and chert interbedded with argillite. This stratigraphic interval is equivalent to Goodwin's (1956) Upper carbonate member.

Rove Formation

The Rove Formation gradationally overlies the Gunflint Iron Formation and is intruded by Logan intrusions and truncated by various units of the Duluth Complex. The thickness of the formation cannot be determined accurately because of poor, discontinuous exposures, local faults, and the presence of intrusive igneous rocks that have inflated the stratigraphic section. Eight hundred feet of strata was described by Tanton (1931) above Lake Superior on Sibly Peninsula in Ontario, but only 20 feet is present 24 miles to the north. The thinning toward the north is attributed to tilting and erosion prior to an overstep of Upper Precambrian sedimentary rocks. Elsewhere the thickness of Rove Formation that was removed by pre-Upper Precambrian erosion is not known. However, in Minnesota the formation is calculated to be at least 3,200 feet thick (Morey, 1969).

On the basis of a study of many incomplete sections, Morey (1969) distinguished three lithostratigraphic units in the Rove Formation. These are, from bottom to top, lower argillite, transition sequence and thin-bedded graywacke. In general, the lower argillite consists of intercalated beds of argillaceous siltstone, silty argillite, and carbonaceous argillite. The transition sequence separates dominantly argillaceous rocks below from dominantly arenaceous rocks above. Thus, the thin-bedded graywacke consists of fine-grained graywacke and intercalated beds of argillaceous siltstone. The upper 700 feet of the formation is distinguished by the presence of gray, white, or pinkish gray beds of quartzite or feldspathic quartzite.

In the Long Island Lake, Gunflint Lake, Southlake, and Hungry Jack Lake quadrangles, the lower part of the formation is exposed and characterized by intercalated black to grayish black, locally carbonaceous argillite, argillaceous siltstone and fine-grained graywacke. In general the silt and sandstone beds become coarse-grained, thicker, and more abundant upward in the formation. In addition, there are several lenses and irregular bodies of limestone, dolomite, and chert and a number of calcite-dolomite concretions of various shapes and sizes scattered near the base of the formation similar to those described by Tanton (1931) and Moorhouse (1963) higher in the formation.

Morey (1969) has suggested the deposition started in a deep basin in which fine-grained sediment accumulated under reducing conditions. The siltstone and sandstone beds contain many primary sedimentary structures indicative of turbidite deposition. This type of deposition is less common upward in the section. The graywackes contain abundant framework grains of quartz, feldspar and "granitic" rock fragments (fig. 7) indicative of a granitic source area. Sedimentary structures including cross-bedding and various kinds of sole marks indicate that sediment transport dominantly was from north to south (fig. 8). These observations and the graywacke mineralogy led Morey (1969) to conclude that the source area was the Lower Precambrian terrane now exposed north of the outcrop area of the Rove

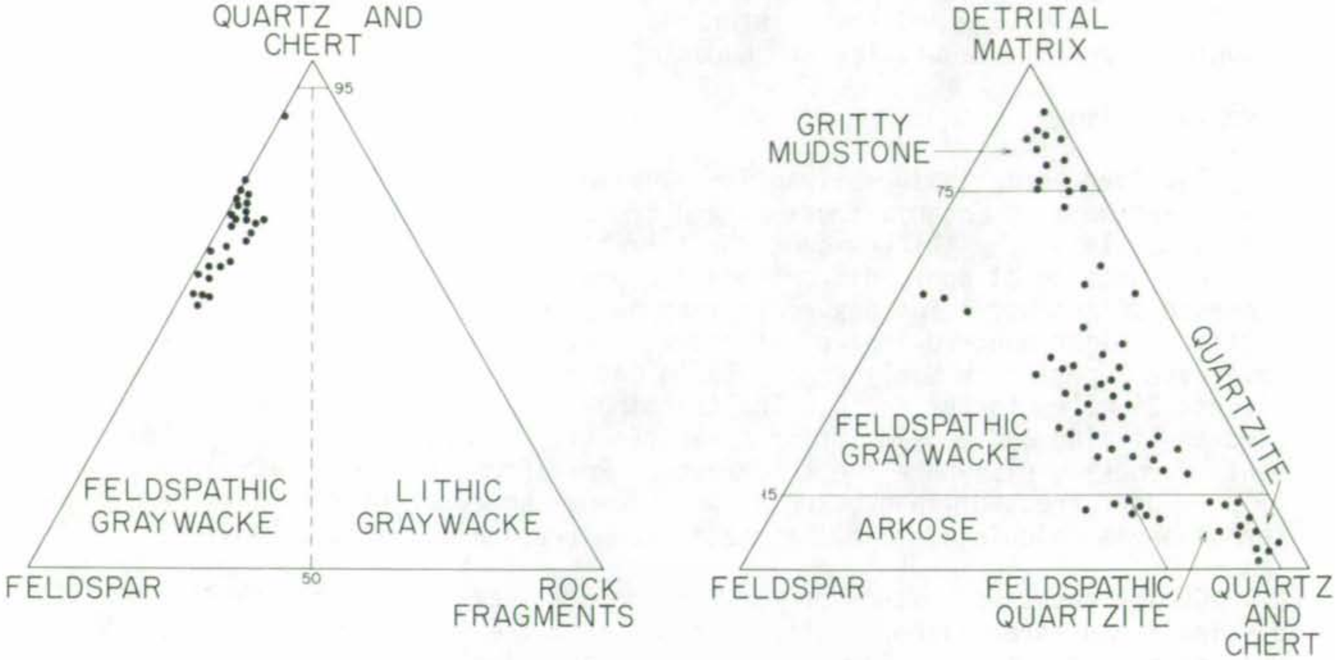

Figure 7. Mineralogic composition of unmetamorphosed Rove Formation (from Morey, 1969).

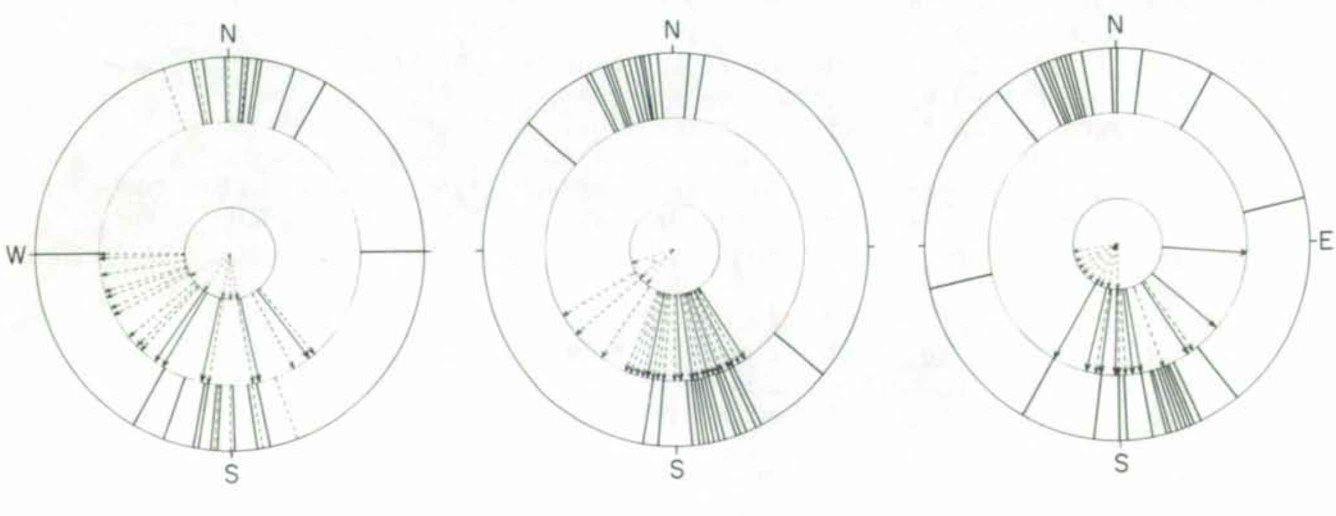

Figure 8. Summary of paleocurrent data in the Rove Formation. Outer circle shows groove casts (solid line) and flame casts (short dashed line); middle circle shows flute casts (solid line) and cross-bedding (short dashed line); inner circle shows ripple marks.

Formation.

Structure

The Animikie strata form a homocline that dips 10°-15° SE except where intrusive bodies, folding, and faulting have distorted or disturbed the beds. All of these structures, which have a profound effect on the cartographic distribution of the Animikie strata, are essentially Late Precambrian in age and are discussed below.

Metamorphism

In the Animikie rocks there is no textural or mineralogic evidence for a pervasive regional metamorphism beyond minor recrystallization of the clay-size detrital fraction. The obvious metamorphic effects in the Animikie strata are associated with the emplacement of the Duluth Complex and Logan intrusions of Keweenawan age.

The contact aureole of the Duluth Complex has not been studied in detail. Preliminary work in the Gunflint Iron Formation shows there are a number of metamorphic facies similar to those described from the Biwabik Iron Formation by French (1968), Bonnichsen (1969) and Morey and others (1972). Unmetamorphosed iron-formation like that described by Goodwin (1956) is found in Minnesota only in a small area between Gunflint and North Lakes. There the iron-formation consists of chert, iron carbonates, greenalite, abundant amounts of finely disseminated hematite, and traces of magnetite. However, west of Gunflint Lake, the iron-formation has been metamorphosed and three metamorphic zones have been distinguished by changes in mineralogy along the strike of the formation toward the Duluth Complex.

Zone 1, Slightly Metamorphosed Iron-formation

Slightly metamorphosed iron-formation occurs in the area immediately west of Gunflint Lake, It consists of quartz, iron carbonates, greenalite, minnesotaite, and stilpnomelane. Finely-divided hematite occurs in the east end of the zone, but disappears mid-way into it. Disseminated and interlocking grains of magnetite are abundant, especially as rims around granules. This part of the iron-formation is much like that described by French (1968) as "unmetamorphosed" Biwabik Iron Formation.

Zone 2, Moderately Metamorphosed Iron-formation

Moderately metamorphosed iron-formation occurs in a zone about 1.2 miles wide and extends to within 0.3 miles of the Duluth Complex. Grunerite-cummingtonite, hornblende and actinolite, as well as quartz and magnetite characterize this zone. As in zone 1, much of the magnetite is between 0.002 and 0.02 mm in diameter; a size-range similar to that observed in various other Lake Superior iron-formations. Small-scale pre-metamorphic sedimentary structures such as granules and oolites are partly obliterated but larger-scale primary structures and bedding features are little affected.

Zone 3, Highly Metamorphosed Iron-formation

Highly metamorphosed iron-formation occurs adjacent to the Duluth Complex and is characterized by a wholly metamorphic fabric. The rock is composed chiefly of quartz, magnetite, iron-rich pyroxenes, and fayalite. Very commonly, euhedral or subhedral grains of magnetite are poikilitically enclosed within large silicate grains. This magnetite is essentially the same grain size as in the lower grade rocks. However, a significant part of the magnetite is extensively recrystallized, and grains as much as several millimeters in diameter are concentrated along bedding planes. Actinolite is common in magnetite-rich layers, and both prograde and retrograde grunerite are abundantly present. In general, this zone is very similar to that described in the Dunka River area on the Mesabi range by Bonnichsen (1969).

Preliminary work on the contact aureole of the Duluth Complex in the Rove Formation reveals a complex mixture of rock types suggesting partial melting as well as mineral and textural variations due to original inhomogeneities and degree of metamorphism. The metamorphosed rocks are commonly layered and have a vague granoblastic texture. Individual layers contain: 1) cordierite and hypersthene with minor biotite and ilmenite, 2) hypersthene, plagioclase, biotite, and ilmenite, 3) augite, plagioclase ± minor olivine, biotite, and ilmenite, or 4) hypersthene, plagioclase, K-feldspar, and biotite. At varying distances from the contact but as much as several hundred feet away, the biotite is the only well developed metamorphic mineral in the pelitic rocks. Calcareous beds near the contact have a skarn-mineralogy consisting of wollastonite, diopside, tremolite, and grossularite garnet. Evidence for recrystallization in the Rove Formation, and development of the above assemblages is barely discernable in the field even adjacent to the Duluth Complex across the Tuscarora intrusion and Nathan's layered series. However, the Rove Formation is obviously recrystallized where it is adjacent to large masses of intermediate and granophyric rocks. For example, near Alder Lake in T. 64 N., R. 1 E. at the base of the northeast end of the Gunflint prong, gneiss-like textures are well developed. Originally quartzose layers are recrystallized to a granoblastic mosaic of quartz and feldspar and the originally pelitic layers now consist of recognizable pyroxene, magnetite, quartz, and feldspar (Morey, 1969).

The Logan intrusions have metamorphosed the Gunflint and Rove Formations also. The widths of the metamorphic aureoles are related to sill thicknesses and range from less than one foot to more than 30 feet. It is difficult to recognize unique metamorphic assemblages adjacent to sills in the Gunflint Iron Formation. For example, in zone 2, mineral assemblages characteristic of zone 3 occur in aureoles adjacent to the sills, and similarly in zone 1, minnesotaite, which is characteristic of zone 2 metamorphism, is found. In the Rove Formation thick sills have produced metamorphic assemblages that can be assigned to the pyroxene-hornfels facies whereas thinner sills have assemblages characteristic of the hornblende-hornfels facies. Locally andalusite (Morey, 1969; Grout and Schwartz, 1933; Grout, 1933) and chloritoid (Grant, 1970) have been identified in certain beds.

UPPER PRECAMBRIAN

In Minnesota, the terms "Late Precambrian" and "Keweenawan" have been used more or less synonymously. However, the Late Precambrian includes that period of time from about 1,600 m.y. to the time of Croixan deposition about 600 m.y. ago, whereas available data from Keweenawan flows and hypabyssal rocks in northern Minnesota all cluster around 1,100 m.y. However, K-Ar data on hypabyssal rocks range from 1,300 m.y. (Hanson and Malhotra, 1971; Wanless and others, 1970) to 900 m.y. The significance of these values is not well understood, but the rocks of Cook County could record events over as large a time span as 400 m.y. Regardless of the ultimate outcome of this problem, it seems clear that the Keweenawan comprises only one part of the Late Precambrian.

In early reports on the geology of the Lake Superior region, it was assumed that lava flows, associated interflow sediments, and most of the gabbroic intrusions represented a more or less short-lived igneous event, which was defined as comprising the middle part of the Keweenawan succession. This igneous event was thought to have been preceded by and followed by deposition of dominantly clastic strata. Hence, the Keweenawan system was divided into three units, Lower, Middle, and Upper. Thus, in Cook County a thick sequence of lavas (North Shore Volcanic Group), and a variety of basic intrusive rocks (Duluth Complex, Logan intrusions, and other hypabyssal diabasic rocks) were thought to comprise the Upper Precambrian. The Puckwunge Formation was assigned to the Lower Keweenawan whereas the remainder of the rocks were included in the Middle Keweenawan.

Detailed work within the Keweenawan type locality in the Keweenaw Peninsula of Michigan and in Minnesota has shown that the stratigraphic framework outlined above is no longer tenable. Hence, the classic boundaries within the Keweenawan are being reevaluated at this time. Of the various criteria that may be used, data derived from paleomagnetic studies appear to be most useful. Several paleomagnetic studies (DuBois, 1962; Beck and Lindsley, 1969; Books, 1969; Books and Green, 1972) have shown that the Keweenawan rocks are characterized by changes in the direction of magnetic polarity. In Minnesota, only one reversal in the volcanic and associated sedimentary rocks has been recognized, and this reversal, from reverse to normal polarity, is being used currently to define the Lower-Middle Keweenawan boundary (Green, 1971). The time-stratigraphic significance of this boundary is not well understood, but recent geologic studies have shown that the paleomagnetic method effectively groups various rock units having coherent petrologic and structural characteristics: the Puckwunge Formation, the lower most flows of the North Shore Volcanic Group in the Grand Portage area of Cook County, Nathan's layered

Series in the Gunflint prong part of the Duluth Complex, and the Logan intrusions in Canada have a reverse magnetic polarity. In contrast, the bulk of the North Shore Volcanic Group, certain other units of the Duluth Complex, the Reservation River diabase, and the Hovland diabase complex have a normal magnetic polarity. Thus, these latter units are currently being assigned to the Middle Keweenawan (Green, 1972).

Puckwunge Formation

In northeastern Cook County the Puckwunge Formation unconformably overlies the Middle Precambrian Rove Formation. It can be divided into two units: a basal conglomerate member and an overlying sandstone member. Sporadic exposures occur from just west of the McFarland Road north of Hovland eastward to Lucille Island in Lake Superior just south of Pigeon Point (fig. 2). The total thickness is not known, but at least 200 feet is exposed. Well rounded pebbles in the basal conglomerate consist of several varieties of quartz, quartzite, jasper, iron-formation, and chert. The matrix consists of sand-size detritus and as much as 48 percent carbonate.

The sandstone part of the formation is typically fine-grained and composed of well sorted, sub-rounded to well rounded grains (quartz, 80 percent; feldspar, 3 percent; granitic rock fragments, 1 percent; carbonate cement, 7 percent; silica cement, 5 percent; and chlorite-sericite, 3 percent). Paleocurrent analyses of cross-beds, troughs, and ripple marks indicate a southwesterly direction of sediment transport with the source area to the northwest. The lithology, depositional environment, and regional stratigraphy suggest that the Puckwunge Formation is correlative with the Lower Keweenawan Sibley Series in Ontario (Mattis, 1972). If the isolated exposures of Puckwunge Formation are in fact correlative with the Sibley Series in Canada, these rocks represent a period of sedimentation around 1,376 ± 36 m.y. ago (Franklin and Kustra, 1970) followed by possible uplift and erosion prior to the onset of volcanic activity in Early Keweenawan time.

Hypabyssal Intrusions

Logan Intrusions

Exposures of sill-like bodies and cross-cutting dikes of diabase and basalt in Middle Precambrian strata in northern Cook County extend from west of Gunflint Lake to Pigeon Point on Lake Superior. The sills thin and are less abundant toward the east and northeast; in the Thunder Bay district of Canada only a few sill-like bodies have been recognized (Geul, 1970). From Gunflint Lake to South Fowl Lake (figs. 2 and 3), the hypabyssal rocks form a series of easterly-trending ridges due to differential erosion of the intruded Rove Formation. In the Grand Portage-Pigeon River area (fig. 2), the sill-like intrusions are thin and inconspicuous, whereas vertical dikes of variable thickness are prominent. In the past,

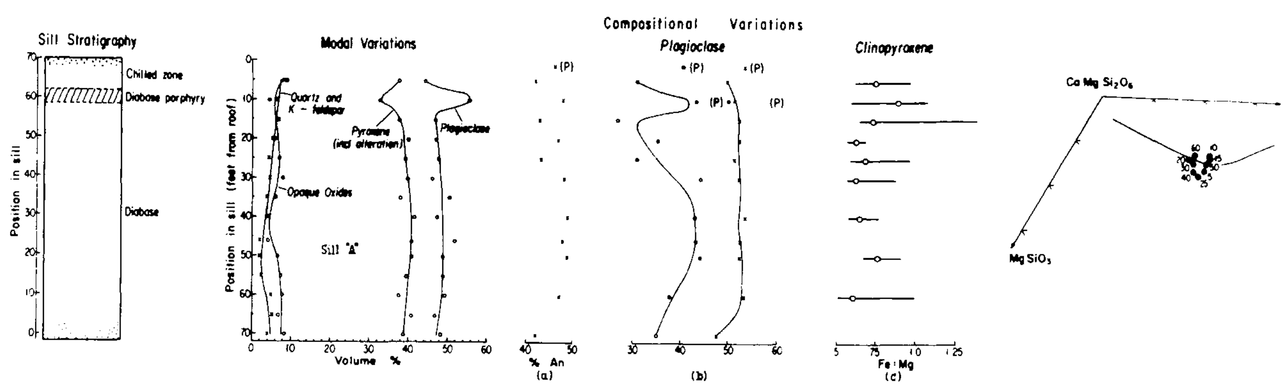

Figure 9. Modal and compositional variations across one sill in the Logan intrusions (from Weiblen and others, 1972; after Mathez, 1971).

Table 3 Chemical composition, in weight percent, of Logan intrusions, other rocks of similar composition, and related rocks of different composition.

	1	2	3	4	5	6	7	8
SiO_2	46.60	47.20	50.04	47.50	51.17	49.00	46.60	49.88
TiO_2	4.90	2.79	3.76	3.74	3.63	3.40	1.13	1.19
Al_2O_3	14.10	14.23	11.70	12.94	13.78	13.10	16.80	18.55
Fe_2O_3	2.22	5.61	2.28	3.94	1.70	2.87	2.43	2.06
FeO	11.30	9.86	13.51	11.52	10.97	13.00	10.60	8.37
MnO	0.21		0.15	0.22	0.18	0.22	0.20	0.09
MgO	5.80	7.21	4.20	5.62	5.37	5.60	9.60	5.77
CaO	12.10	8.32	7.16	8.38	9.32	7.45	10.30	9.70
Na_2O	2.27	2.57	3.47	2.39	2.79	2.52	1.82	2.59
K_2O	0.32	0.75	1.03	1.07	0.79	1.16	0.29	0.68
H_2O+		0.94	1.28	1.31		0.49	0.57	1.04
H_2O-			0.07	0.68		0.29		
P_2O_5			0.47	0.69	0.41	0.38	0.13	0.16
CO_2			0.25			0.14	0.10	
S			0.11			0.14	0.02	
	99.82	99.48	99.48	100.00	100.11	99.80	100.59	100.18

Table 3 Continued

1. Calculated composition for a Logan sill from near Rose Lake (see Weiblen and others, 1972, for details).

2. Calculated composition for a Logan sill by Mathez (1970, p. 74).

3. Chilled diabase from top of a Logan sill.

4. Diabase; Northland sill at Duluth (Schwartz and Sandberg, 1940, p. 1145, table 1, analysis 8).

5. Average composition of differentiated lava erupted on the east rift zone of Kilawa, Hawaii in 1955 (Wright and Fiske, 1971, p. 26).

6. Chilled diabase; Early mafic intrusions of Geul (1970, p. 14, table 3, analysis 2).

7. Olivine diabase dike; Pigeon River intrusions of Geul (1970, p. 14, table 3, analysis 5).

8. Composite sample of fine-grained olivine diabase from the Pigeon Point sill (Grout and Schwartz, 1933, p. 41, table 8, analysis 2).

all of these hypabyssal rocks have been collectively referred to as the Logan intrusions. Early workers (Tanton, 1931; Grout and Schwartz, 1933) recognized cross-cutting relationships which suggested intrusion over a considerable span of time. More recently, Geul (1970) distinguished in the Thunder Bay district two major petrogenetic types: (1) Early mafic intrusions of tholeiitic diabase and, (2) Pigeon River intrusions of olivine diabase. In Minnesota, Weiblen and others (1972) have suggested that the term Logan intrusions be restricted to diabasic rocks equivalent to Geul's Early mafic intrusions. The occurrence of such rocks in Cook County appears to be largely restricted to the Gunflint Lake-South Fowl Lake area. As can be seen in figure 2, they have a distinctive outcrop pattern and as described below are characterized by a well defined internal stratigraphy (fig. 9) and bulk composition (table 3). Thus, they may be the record of a unique igneous event in Late Precambrian time. Weiblen and others (1972) also believe that the olivine diabase of the Grand Portage-Pigeon River area is younger, and that the two kinds of rocks are part of a succession of events whose petrologic characteristics and relationships in space and in time were determined by tectonism in this area in Late Precambrian time (see below).

Texture: - Rock types include aphyric chilled margins, fine- to medium-grained diabase with ophitic clinopyroxene enclosing plagioclase, plagioclase cumulates, and granophyre (Mathez, 1971). Chilled margins form sharp contacts with country rocks. Diabase grades in grain size from fine to medium toward the center of sills. Clinopyroxene remains ophitic even though the grain size changes. Plagioclase crystals enclosed in clinopyroxene rarely exceed 5 mm in length whereas phenocrysts may be as much as 10 cm long in some of the thicker sill. Diabasic rocks with plagioclase phenocrysts grade into accumulations of essentially coarse-grained plagioclase. Such accumulations are found in the upper parts of some thick sills and their origin has been attributed to the floating of plagioclase (Grout and Schwartz, 1933, p. 50).

Mineralogy: - Minor olivine (<1 percent) is found in the lower part of some sills. There is only minor variation in the modal mineralogy and mineral compositions across the sills as shown in figure 9. Plagioclase, both as phenocrysts and as small grains (40-50 percent) enclosed in pyroxene is generally highly sericitized. Clinopyroxene (30-40 percent) is commonly altered to amphibole within single oikocrysts. The remnant pyroxene varies in composition from subcalcic augite through augite and has a mottled birefringence which resembles that of the complex lunar pyroxenes. Ilmenite and minor magnetite (5-10 percent) are ubiquitous throughout the sills; ilmenite is commonly skeletal. Biotite is a ubiquitous constituent. Granophyric intergrowths consisting of quartz, sodic plagioclase, and orthoclase are common in the upper part of the diabase where they impart a pink mottling which can be recognized in hand specimen. Separate occurrences of granophyre in mappable units are rare, although several bodies are of mappable size.

Structure and Metamorphism: - The sill-like geometry of the Logan intrusions between Gunflint Lake and South Fowl Lake reflects the planar character of the intruded Animikie strata. Individual sills as much as

1,100 feet thick can be traced along strike for several miles. However, branching and merging of individual sills is common and many individual sills thicken and thin down dip. Some sills terminate against joint and possibly fault planes and these features are occupied by minor interconnecting dikes which together with the sills form a box-work configuration in three dimensions.

Despite the predominance of intrusive rocks (80 percent of a 2,700 foot section in the South Lake area), there is only minimal evidence of disruption of Animikie strata. Xenoliths are relatively small (less than 20 cm) and restricted to contact zones in the sills. Furthermore, metamorphic aureoles are thin as described in the section on metamorphism of Middle Precambrian strata above (Morey, 1969; Weiblen and others, 1972). This evidence suggests passive, sequential emplacement of the sills.

Olivine Diabase and Other Hypabyssal Intrusions

The diabasic intrusions in the Rove Formation east of South Fowl Lake (fig. 2) have an outcrop pattern which is distinctly different from the Logan intrusions described above. The sills are thinner and a northwest-trending dike set is prominent. Except for the sill on Pigeon Point (Bayley, 1893; Daly, 1917; Grout and Schwartz, 1933; Mudrey and Weiblen, 1971; 1972), little is known about these rocks beyond the early descriptions (Grout and Schwartz, 1933). Recent mapping by Mudrey in the Pigeon Point quadrangle reveals that in addition to the Pigeon Point sill several sills on the mainland consist of olivine diabase. Estimates of the bulk composition of these sills from mineral compositions and modes indicate that it is similar to that of Geul's (1970) Pigeon River intrusions.

Olivine diabase dikes and sills, which cut lavas of the North Shore Volcanic Group, are exposed in the vicinity north of the Reservation River, Grand Marais, Tofte, Lutsen and central Cook County (fig. 2, Green, 1972a). Near Tofte, massive inclusions of anorthosite (An_{60}) in olivine diabase are well exposed on Carlton Peak which rises 700 feet above Lake Superior. These have been compared by Phinney (1968) with other occurrences in the Keweenawan in Minnesota. They are clearly distinct from the plagioclase porphyry zones of the Logan intrusions (Weiblen and others, 1972).

Several rock types other than olivine diabase have been recognized as being intrusive into the North Shore Volcanic Group (Green, 1972a). These include ferrogabbro, fayalite-syenodiorite and granophyric red monzonite in the vicinity of Hovland (fig. 2) (Jones, 1963) and porphyritic trachybasalt (Leveaux porphyry, Green, 1972a) between Taconite Harbor and the Cascade River (fig. 2). Green (1972a, b) includes the olivine diabases and these latter intrusions in the Middle Keweenawan on the basis of field relations and magnetic polarity (normal where measured).

Additional mapping and petrologic studies such as those of Mathez (1971) and Ernst (1960) are needed to characterize these rocks in detail. They are obviously an important link to Keweenawan petrogenesis.

Table 4 Summary of presumed stratigraphic relations of Upper Precambrian intrusive rocks in Cook County

Informal designation	Unit/Location	Principal rock type	Magnetic polarity	Host rock	Reference
Late minor intrusive hypabyssal rocks	Olivine diabase dikes and sills of the Grand Portage area (Pigeon Point sill and Pigeon River intrusions of Geul, 1970) (kmu)	Olivine diabase, olivine gabbro, ferrogabbro and granophyre	Normal	Animikie strata (gif and roa) Puckwunge Formation (ps) and North Shore Volcanic Group of reverse polarity (nsm) normal (nsu)	Weiblen and others 1972; Mudrey and Weiblen, 1972
	Diabase of Tofte Lutsen area	Ophitic olivine diabase; local gabbro and anorthosite inclusions	?	North Shore Volcanic Group flows of normal polarity (nsu)	J. C. Green, 1972
	Grand Marais intrusions (kmu)	Olivine diabase	?	North Shore Volcanic Group flows of normal polarity (nsu)	J. C. Green, 1972
	Diabases of central Cook County (kmu)	Olivine diabase	?	North Shore Volcanic Group flows of normal polarity (nsu)	J. C. Green, 1972
	Hovland diabase complex	Olivine gabbro, ferrogabbro, fayalite-syenodiorite, granophyre	Normal	North Shore Volcanic Group flows of reverse polarity (nsm)	Jones, 1963; Green, 1972
	Reservation River diabase complex (kmu)	Olivine diabase, syenodiorite and granophyre	Normal	North Shore Volcanic Group flows of reverse polarity (nsm)	Green, 1972

Table 4 Continued

Informal designation	Unit/Location	Principal rock type	Magnetic polarity	Host rock	Reference
	See host rock description	Granophyre and adamellite (df), and undivided gabbroic and intermediate rocks (dgi)	?	North Shore Volcanic Group (nsm, nsu) Brule Lake sill (dmu), anorthositic series of north central Cook County (da), and intermediate rocks and layered series of Nathan in the Gunflint prong	Davidson (1972) and Babcock (1959)
Felsic series (granophyre and intermediate rocks of Taylor (1964) at Duluth	These rocks may be genetically related to their local host rocks and thus of different stratigraphic position, or some may be the record of a late, felsic intrusive event				
Troctolitic-gabbroic series (layered series of Taylor, 1964 at Duluth)	Tuscarora intrusion	Troctolite (dt) poikilitic gabbro (dat) and hornfels inclusions (hi)	?	Lower (kcg, ksc, gst), Middle Precambrian (gif and rog) at base; anorositic series (da) at top	Morey and others, 1969; Weiblen and others, this report
	Brule Lake sills in the "Brule River prong"	Troctolite, olivine gabbro (dmu) and granophyre (df)	?	North Shore Volcanic Group (nsu) and anorthositic series (da) layered series of Nathan (1969)	Davidson, 1972
Anorthositic series (anorthositic gabbro of Taylor, 1964 at Duluth)	Anorthositic rocks of north-central Cook County (da)	Anorthosite, gabbroic-troctolitic anorthosite, and anorthositic gabbro	?	North Shore Volcanic Group (km)	Davidson, 1972

Table 4 Continued

Informal designation	Unit/Location	Principal rock type	Magnetic polarity	Host rock	Reference
	Layered Series of Nathan (1969) in the "Gunflint prong"	Oxide gabbro, troctolite, anorthositic rocks, granophyre, and hornfels inclusions	Reverse	Animikie strata (gif and rog) North Shore Volcanic Group (nsu)	Nathan, 1969 Beck and Lindsley, 1969
Early intrusive hypabyssal rocks	Logan intrusions (ld)	Plagioclase-pyroxene oxide diabase having granophyre segregations	Reverse	Animikie (gif and rog) and Lower Keweenawan strata (ps, nsm)	Weiblen and others, 1972; Robertson and Fahrig, 1971
	Grand Portage dike swarm	basalt, trachybasalt, and rhyolite	Reverse	Animikie strata (gif, rog) North Shore Volcanic Group of reverse polarity (nsm)	Green, 1972

Duluth Complex

The Upper Precambrian (Keweenawan) Duluth Complex is a sequence of generally discordant intrusive rocks extending northeastward from Duluth to Hovland, Minnesota (fig. 1). In northeastern Cook County the complex bifurcates into two sheet-like masses referred to as the northern or "Gunflint prong" and the southern or "Brule River prong" (fig. 2). Reviews of the early literature and recent work are given by Phinney (1972), Bonnichsen (1972) and Davidson (1972). The detailed results of recent mapping and study of the northeastern part of the complex are presented by Nathan (1969), Morey and others (1969), Johnson (1970), and Davidson (1970, 1971). These studies show that the complex may be divided into three principal rock series, (1) anorthositic series, (2) troctolitic-gabbroic series, and (3) felsic series (table 4).

Rocks of the anorthositic series were apparently emplaced as large, crystal-liquid masses in which cumulus plagioclase is the predominant mineral. These rocks range in composition from anorthosite through gabbroic-troctolitic anorthosite to anorthositic gabbro, depending on the amount and type of interstitial mafic minerals. This series has been loosely referred to as "anorthositic gabbro" (Taylor, 1964). An extension of a large mass of this series in the central part of the complex is exposed in northwestern Cook County (figs. 2 and 3).

Rocks of the troctolitic-gabbroic series are generally layered and contain both plagioclase and olivine as cumulus minerals with poikilitic pyroxene and oxides. Rocks of this type occur in three mappable intrusions in Cook County: the Tuscarora intrusion, Brule River sills, and Nathan's layered series (fig. 2). Possible genetic relationships are discussed below.

Rocks of the felsic series predominantly are granophyric adamellites which occur both as large, sub-horizontal sheet-like intrusions and small, irregular-shaped masses. These rocks intrude both the anorthositic and troctolitic-gabbroic rocks. Rocks gradational between gabbroic and felsic types, containing iron-rich silicates and alkali-feldspars are found associated with felsic rocks, but exposures are limited except for a large intrusive mass at the east end of the "Gunflint prong" (fig. 2) (Nathan, 1969; Babcock, 1959). These rocks have been commonly referred to as intermediate rocks, ferro-granodiorite, or ferro-gabbro (Taylor, 1964), but are included in the felsic series in this report.

Exposures of Nathan's layered series, the Tuscarora intrusion, and the felsic series of the east end of the "Gunflint prong" are included as stops on this field trip, and therefore are described in some detail below, whereas rocks of the anorthositic series are only briefly discussed.

In addition to the three principal rock series, inclusions ranging in size from a few centimeters to mappable masses up to seven kilometers across occur throughout the complex (Phinney, 1972; Bonnichsen, 1972; Davidson, 1972). The inclusions probably include metamorphosed equivalents of all of the following: (1) the footwall rocks; (2) overlying Keweenawan

Table 5 Various designations for units of Nathan's layered series

Nathan (1969) Unit	Group	Green (1972) in press	Fig. 2	General
db dc	I			
dd, e, f, h, i, k dg	II			Troctolitic -
dm dl, n, o	III	dgg	dls	gabbroic ? Series
dp dq	IV			
dt, u, v, w	VI			
dj ds	II V	dgn	dls	Anorthositic Series
da	I	dgt	dls	Troctolitic-gabbroic Series
daa dmaa	VIII	df dgi	dls	Felsic Series
dx, y, z	VII	hi	hu	Inclusions

sedimentary and volcanic rocks; and (3) a variety of gabbroic rocks of earlier intrusions in later intrusions. The most easily recognizable type of inclusion is metamorphosed iron-formation which has retained its original bedding and the mineral assemblage quartz -- magnetite. The most common inclusions are plagioclase-cordierite-hypersthene and plagioclase-augite hornfels. Bonnichsen (1972) postulates that the former are derived from Middle Precambrian argillite and graywacke and the latter from mafic volcanic rocks. The extent and nature of the reactions of country rocks with Duluth Complex magmas has not been elucidated in any detail.

Layered Series of Nathan

Nathan (1969) mapped a series of sheet-like intrusions across the northern or Gunflint prong of the complex in the Gunflint, South Lake and Hungry Jack Lake quadrangles (figs. 2 and 3). To the west, in the Long Island quadrangle, the layered series is truncated by the Tuscarora intrusion (troctolitic-gabbroic series) and other associated rocks, and this truncation is marked by an irregular northwest-trending scarp. To the east, the layered series is truncated by rocks of the felsic series whose age is unknown.

For the most part, the layered series consists of a sequence of conformable sheets having a regional dip of 15-25° to the south. The sheets thicken to the west and are locally interrupted by minor cross-cutting stock- and dike-like bodies. On the east side of the Hungry Jack Lake quadrangle a northwest-trending fault offsets the series with an unknown amount of displacement, but as much as 140 feet of vertical displacement of the northeast side is inferred (fig. 3).

This layered series as described by Nathan (1969) consists of troctolitic, gabbroic, and associated felsic rocks. Several of the major units represent unique occurrences in the Duluth Complex of oxide-rich and two pyroxene gabbros. For the most part, fine-grained rocks do not represent chilled margins of large bodies but occur as separate intrusions or inclusions of mappable size. Planar orientation of minerals is common, indicating flow or crystal settling. Differentiation resulting from these processes can be demonstrated within some units, however the layered series does not form a regular stratigraphic sequence. Intrusive relationships for 27 different units were established using cross-cutting structures, fine-grained margins, inclusions and thermal effects, the latter being principally a development of dark-clouded plagioclase near intrusive contacts (Nathan, 1969, p. 99). On the basis of field relationships, mineralogy and composition, Nathan concluded that the 27 units could be combined into eight cogenetic groups. On the 1:250,000 Two Harbor geologic map, compiled by Green (1972b), many of Nathan's units cannot be shown. Table 5 shows the distribution of Nathan's units within the units shown by Green. If all of the oxide rich, gabbroic and troctolitic rocks are included in the troctolitic-gabbroic series, Nathan's units and his group designations fit the general rock series outlined above, with one exception. On the basis of textural and field relations, Nathan considers a plagioclase-rich (83 percent) unit (dj) to be part of the oxide-rich group of rocks, but Green grouped this unit with another anorthositic unit (ds) of Nathan's and designated both dga on the basis of the mode. This illustrates the difficulties involved in mapping within the complex. Textures and modes are the principal criteria used in correlating rocks. However, genetic and stratigraphic relationships can be reliably established only from exposures of intrusive relations or readily interpretable outcrop patterns.

The general series classification may be misleading because stratigraphic and genetic implications have been attributed to it elsewhere in the complex (Phinney, 1972; Bonnichsen, 1972; and Davidson, 1972). The oxide cumulates of Nathan's layered series are clearly older than the troctolitic rocks of the Tuscarora intrusion (fig. 3) and the available paleomagnetic data agree with this conclusion (Phinney, 1972). However, other gabbroic units, notably Nathan's unit dm (see below), could be equivalent to the upper gabbroic unit of the adjacent Tuscarora intrusion (fig. 3). Because of such uncertainties, an understanding of the sequential intrusion of various units in Nathan's layered series, and the relationship of these units to other units within the complex must await extension of the work begun by Nathan (1969), refinement of paleomagnetic criteria, and a better resolution in absolute age determinations so that they can be used to establish a chronologic sequence of igneous events.

Detailed rock descriptions and interpretations of the layered series by Nathan (1969, p. 38-185) are summarized below. Nathan devised a useful nomenclature which is retained in this summary. The descriptive rock names have several textural prefixes that characterize the primary mineral assemblages. A size classification for these rocks, based on visually-estimated mean grain diameters, is: 10 mm, very coarse-grained; 4-10 mm, coarse-grained; 1-4 mm, medium-grained; 1/2-1 mm, fine-grained; 1/2 mm, very fine-grained. Four basic fabrics are recognized. A "granular" rock has only equidimensional minerals. If elongate grains are present and are randomly oriented, the rock is "decussate," if the grains define a plate, the rock is "foliated," and if the grains are aligned, the rock is "lineated." All rocks are named by the characterizing primary mineral assemblage, in order of increasing abundance; the primary mineral assemblage refers to early crystallizing phases in contrast to late interstitial phases. If a significant part of the primary assemblage was transported in the magma the rock is referred to as an allocrystallate, a cumulate being a special case in which gravity settling has occurred. Rocks formed by crystallization in place are called autocrystallates. Subscripts are used to indicate modal composition. Thus, a descriptive rock name for a troctolite formed by gravity settling could be a fine-grained foliated olivine$_{20}$-plagioclase$_{70}$cumulative with minor interstitial augite$_{5}$and oxides$_{5}$.

Group 1

da db dc

The oldest unit (da) in the layered series now appears in the upper part of the section as dilated septa as much as 200 feet thick. It is a fine-grained foliated olivine$_{25}$-plagioclase$_{63}$ cumulate with minor pigeonite$_{9}$ and augite$_{3}$ which are also cumulus in the middle of the unit. This unit grades into a 1,000 foot-thick sheet of medium-grained, foliated augite$_{15}$-pigeonite$_{26}$-plagioclase$_{59}$cumulate (db). A very fine-grained olivine$_{10}$-augite$_{27}$-plagioclase$_{61}$ rock (dc) occurs as masses of various shapes and sizes near the base of the layered series. Nathan speculated that it might represent a chilled margin of the Group 1 intrusive rocks.

Group 2

dg dd de df dh di dj dk

This group comprises the major oxide-rich part of the layered series. The main unit (dg) is a coarse-grained foliated ilmenite-titanomagnetite$_{11}$-augite$_{19}$-olivine$_{14}$-plagioclase$_{56}$cumulate. Within this unit the following sequence of crystallization appears: (1) ilmenite-olivine-plagioclase; (2) ilmenite-titanomagnetite-olivine-augite-plagioclase; and finally (3) apatite-pigeonite-titanomagnetite-ilmenite-olivine-augite-plagioclase. Very fine-grained foliated olivine-oxide-augite-plagioclase (dd) and fine grained granulo-decussate augite-plagioclase (de) rocks occur in unit dg as inclusions as much as 400 feet across. A number of mappable units are gradational with unit dg: (1) at the base of the complex, a fine- to coarse-grained decussate augite-olivine-plagioclase autocrystallate (df) grades into rocks having a texture and mineralogy similar to that in unit dg, and may be the base of the cumulates of unit dg. Unit df shows sulfide mineralization similar to unit ttf of the Tuscarora Intrusion (Johnson, 1970, p. 68). (2) A fine-grained, olivine$_{20}$-plagioclase$_{66}$-olivine cumulate with minor augite$_{5}$-oxide$_{4}$-apatite occurs as a thin sheet (dh) within unit dg. (3) A fine-grained decussate, oxide$_{23}$-augite$_{28}$-plagioclase$_{45}$ autocrystallate containing minor olivine$_{2}$ and apatite$_{2}$ intrudes unit dg and is presumed to be a late differentiate (di). (4) Unit dg grades upward into 100-200 foot-thick discontinuous sheets of coarse-grained, foliated pigeonite$_{4}$-augite$_{6}$-plagioclase$_{83}$ cumulates containing minor potassium feldspar$_{2}$ and quartz$_{1}$ (dj). A fine-grained granular plagioclase, quartz, orthoclase rock (dk) occurs as dikes cutting other Group 2 rocks.

Group 3

dm dl

Unit dm, the upper part of the layered series, is a 2,000 foot-thick sheet of coarse-grained decussate pigeonite$_{13}$-augite$_{24}$-plagioclase$_{59}$ autocrystallates and cumulates containing minor oxides$_{2}$, quartz$_{2}$ and potassium feldspar$_{1}$. This unit is thought to have been emplaced along foliation planes and thus to have dilated the earlier units. Variations in grain size and modal mineralogy suggest that this unit may be a multiple intrusion. A related intrusion may be unit dl, a medium-grained decussate pigeonite$_{17}$-augite$_{20}$-plagioclase$_{60}$ rock containing minor oxide, quartz, and potassium feldspar, which occurs as a small stock about 1-1/2 miles across in the central part of the Hungry Jack quadrangle. Another related intrusive unit is a fine-grained

dn granular oxide$_{19}$-plagioclase$_{41}$-augite$_{40}$ rock (dn) which occurs as a sheet 6 feet thick and 4 miles long in the northern part of the South Lake quadrangle. Felsic dikes which intrude unit dm
do were given a separate designation (do) and may represent a late-stage differentiate of unit dj or partially fused country rock (Nathan, p. 115).

<u>Group 4</u> The next intrusive unit (dp) occurs as a concordant sheet as much
dp as 1,200 feet thick between units dg and db. It is a fine-grained foliated augite$_{32}$-plagioclase$_{58}$ cumulate with olivine-hypersthene$_{7}$ and trace amounts of oxides. Plagioclase and augite occur in a granular fabric, hypersthene as oikocrysts, and olivine as phenocrysts. The absence of late-stage interstitial material suggests the unit formed by flow or crystal settling with exchange between the magma and the inner cumulus melt. Near the top of unit dp, a 100-foot-thick sheet of medium-grained foliated olivine$_{17}$-
dq plagioclase$_{83}$ cumulate (dq) is gradational with unit dp.

<u>Group 5</u> In the southwestern part of the Gunflint Lake quadrangle a heterogeneous assortment of pyroxene-plagioclase and olivine-plagioclase rocks possibly related to unit tta of the Tuscarora intrusion truncate the layered series. A typical example is a medium-grained decussate tironals$_{5}$-olivine$_{5}$-augite$_{15}$-plagioclase$_{75}$
dr autocrystallate (dr). Near the base of the layered series a medium-grained foliated augite$_{17}$-plagioclase$_{77}$ rock with minor
ds oxide$_{3}$-pigeonite$_{2}$ and olivine (ds) is intruded as a sheet 300 feet thick between units df and dg. Unit ds is highly altered with montmorillonite after plagioclase, and amphibole and chlorite after pyroxene. Locally chalcopyrite and bornite occur within interstitial, altered pyroxene.

<u>Group 6</u> A number of oxide-rich stock- and dike-like bodies 3/4 miles across occur near the base of the Complex in the South Lake quadrangle. Nathan recognized four varieties: (1) medium-grained granular olivine$_{16}$-oxide$_{73}$ rocks with a minor amount of plagioclase
dt and augite (dt). The ilmenite and titanomagnetite occur as primary phases; the latter generally has exsolved coarse ilmenite lamellae with intra-titanomagnetite granules which have in turn exsolved to a fine reticulate intergrowth of magnetite and hercynite. (2) On Little Iron Lake in the South Lake quadrangle
du a medium-grained granular plagioclase$_{21}$-oxide$_{24}$-olivine$_{49}$ (du) rock having minor hypersthene and augite forms a 1/2 mile long composite sheet within unit dt. (3) A coarse-grained granular plagioclase$_{8}$-oxide$_{23}$-pigeonite$_{24}$-augite$_{44}$ rock containing minor olivine occurs as small discordant masses in the South Lake quad-
dv rangle (dv). (4) Two occurrences of a coarse-grained decussate
dw oxide$_{10}$-augite$_{31}$-plagioclase$_{55}$-autocrystallate (dw) were mapped within unit dg. This unit exhibits an amphibole alteration similar to that in unit ds, but is considered to be part of group 6 rocks because of its large oxide content.

Group 7 Several fine-grained decussate rocks occur as discontinuous thin sheets along the base of the complex and as small stocks and dikes higher in the section. They may represent either fused fractions of country rock or contaminated melts, but all are thought to be intrusive. They consist of: (1) fine-grained decussate $oxide_7$-$augite_{22}$-plagioclase rock having minor $olivine_2$-

dx $quartz_2$ and potassium feldspar (dx); (2) fine-grained decussate

dy $oxide_5$-$hypersthene_{11}$-$augite_{31}$-$plagioclase_{55}$ autocrystallate (dy); and (3) fine-grained $augite_3$-$oxide_9$-decussate $quartz_{10}$-ortho-

dz $clase_{15}$-$hornblende_{29}$-$plagioclase_{34}$ rock (dz).

Group 8 The youngest intrusive unit within the layered series occurs as dikes and stocks as much as 1-1/2 miles across in the Hungry Jack Lake quadrangle. This unit, a medium-grained granular $quartz_{18}$-alkali $feldspar_{77}$ rock with minor $augite_3$ and $oxide_2$

daa (daa), truncates unit dm. Across an interval over a mile wide at the east end of unit dm, there is a progressive increase in the amount of late stage interstitial material that has a compo-

dmaa sition similar to unit daa. This unit (dmaa) might be a late stage differentiate of dm. Nathan found however that unit dx has been intruded and altered by daa. Therefore, it is presumed the dm was cold when unit daa was intruded and that the gradational zone represents melt from daa that was introduced into unit dm.

Anorthositic Series

Unfortunately, rocks of the anorthositic series do not crop out in the area of the field trip despite the fact that they constitute the predominant lithology in the complex. Coarse grain size and random foliation patterns characterize the anorthositic rocks. Gabbroic varieties predominate over troctolitic varieties. Reported plagioclase compositions range from An_{48}-An_{70}. Based on field relations, this series was emplaced early in the history of the complex.

In the Long Island Lake quadrangle, gabbroic anorthosite appears to concordantly overlie the troctolitic-gabbroic series (fig. 3). Although no intrusive relationships have been found, metasedimentary hornfels inclusions and evidence of sulfide mineralization is found in the poikilitic augite troctolite below the anorthositic rocks. On the basis of these observations and the marked increase in plagioclase content (75 to 85 percent plagioclase An_{55-60} in contrast to the 50 to 70 percent in underlying troctolitic rocks), the anorthositic rocks (ga, fig. 1) are considered to be an extension of the older anorthositic series mapped to the west by Phinney (1972).

Troctolitic-Gabbroic Series (Tuscarora Intrusion)

In the Long Island quadrangle (fig. 3) a sequence of rock types common to other parts of the Duluth Complex appears in the following succession away from the base: (1) fine-grained poikilitic augite gabbro (ttp),

(2) a fine-grained granoblastic gabbro (hornfels) (th), (3) a fine- to medium-grained troctolite (ttg-ttm), (4) interlayered troctolite and poikilitic gabbro (tta), (5) anorthositic gabbro (ag), (6) ferrogranodiorite (tg), (7) granophyre (gr), and (8) metamorphosed flows (kmv). Although the outcrop pattern suggests a simple differentiated layered sequence, the stratigraphic position of units tp, ag, tg and gr have not been unequivocally established. However, units ttf, ttm, and tta are clearly parts of a separate troctolite intrusion that truncates part of Nathan's layered series (fig. 3). Designations used by Green (1972; fig. 2) are indicated in Table 6.

Units ttm, ttf, and tta: The main unit of the Tuscarora Intrusion is a medium-grained troctolite (ttm, fig. 3), consisting of 65-70 percent cumulus plagioclase (An_{55-60}), and 10-15 percent cumulus olivine (Fo_{50}). Relative amounts of poikilitic augite and iron-titanium oxides vary locally. Orthopyroxene mantles olivine and occurs in symplectic intergrowth with plagioclase. Biotite is associated with the iron-titanium oxides. Planar orientation of plagioclase and modal-mineral layering are locally well developed and mutually concordant.

The troctolite is distinctly finer grained at the base, and a separate unit (ttf) has been mapped in which the grain size is roughly half of that in the overlying troctolite; it is this unit that contains the copper-nickel sulfides described below.

The troctolite grades into an upper unit which consists of interlayered poikilitic augite gabbro and troctolite (tta, fig. 3). The poikilitic augite consists of about 70 percent plagioclase (An_{50-60}), 15-20 percent augite, and 5-10 percent ilmenite and is medium- to coarse-grained with well developed augite orthocrysts as much as 1-1/2 inches across. The troctolite within the layered interval is similar to that in unit ttm. Contacts between layers are generally sharp and in general conformable with layering in the troctolite. Interlayering occurs on a scale of several inches to several feet, and is undulatory with wave lengths of ten to twenty feet and amplitudes of two to three feet, but the gross structure is nearly flat-lying.

Unit ttp: A belt of fine-grained rocks occurs beneath unit ttf. It consists of fine- to medium-grained augite troctolite with 60-70 percent cumulus plagiocaase (An_{50}), 5-10 percent cumulus olivine (Fo_{35}), 15-20 percent poikilitic augite, 5-10 percent iron-titanium oxides, and minor orthopyroxene-plagioclase symplectite. The upper contact of this unit with overlying troctolite has not been observed and it is not clear from outcrop data if it is a separate intrusion or the basal unit of the overlying rocks. Johnson (1970, p. 76) concluded from drill core data that it is a separate intrusion.

Unit th: Several areas of fine-grained, granoblastic gabbro consisting of 50 to 60 percent short tabular plagioclase, 30 to 40 percent rounded augite, minor subhedral iron-titanium oxides, olivine, and blades of biotite are exposed on topographic highs. These rocks may be a remnant capping over the troctolite; however, there is no noticeable chilling

Table 6 Various designations of units in the Tuscarora Intrusion and associated rocks

Weiblen and others, 1972 (Fig. 3)	Green, 1972 in press	Fig. 2	General
gt	dt	dfi	Felsic
fg	di		Series
tta	dat		Troctolitic-gabbroic
ttm	dt	dt	Series
tif			
ta			
th	hu	hu	Inclusions
kmv	nm		
Ag	da	da	Anorthositic Series

of the troctolite next to the hornfels and they more likely represent large inclusions.

Felsic Rock Units Associated with the Tuscarora Intrusion

In the Long Island Lake quadrangle, ferrogranodiorite and granophyre intrude rocks of the anorthositic series. It is not clear from the field relations whether these rocks are genetically related to the troctolitic (ttm, tta) or the anorthositic (ag) rocks or to either of them.

Unit tg: This unit is restricted to a topographically high area in the southwest corner of the Long Island Lake quadrangle (fig. 3). It is a medium-grained ferrogranodiorite which contains 50 to 60 percent cumulus plagioclase, 10 to 15 percent amphibole, minor clinopyroxene, and varying amounts of quartz, potassium feldspar, and magnetite. Contacts with the underlying anorthositic gabbro and overlying granophyre are gradational over tens of feet. The former could represent replacement by intrusive ferrogranodiorite or differentiation within the anorthositic gabbro. Further study is needed to clarify the stratigraphic relationships.

Unit gr: The ferrogranodiorite grades into and is cut by fine- to medium-grained granophyre. It consists of quartz, plagioclase, potassium feldspar and magnetite. The texture ranges from granophyric to granitoid.

Unit kmv: The granophyre intrudes black fine-grained metavolcanic rocks which are interpreted to be remnants of Middle Keweenawan flows. The groundmass is highly altered. Acicular blades of ilmenite are common and plagioclase phenocrysts are clouded similar to intruded rocks in the layered series.

Rocks of the Felsic Series at the East End of the Gunflint Prong

The east end of Nathan's layered series (fig. 3) is cut by several felsic intrusions (dmaa and daa -- detailed descriptions given above in the section on Nathan's layered series). The genetic relationship of these rocks to other units of the layered series is not clear (Nathan, 1969). Nathan attributes the extensive occurrence of interstitial granophyre, the development of hornblende, and the sericitization of plagioclase in the intruded gabbroic rocks (dmaa) to alteration by the magma of unit daa. No detailed mapping has been done in the eastern end of the "Gunflint prong" but samples from four traverses were described by Babcock (1959, 1960). He concluded that the area can be divided into two distinct units (fig. 3): (1) undivided gabbroic rocks having variable amounts of granophyre, and (2) an overlying felsic unit consisting essentially of granophyre with inclusions of gabbro and intermediate rock. Babcock concluded that the two units were genetically related. He envisions early crystallization and accumulation of plagioclase and pyroxene in the lower part of a magma chamber, with entrapment of interstitial felsic material to form the lower unit. The upper unit of predominantly felsic rocks is considered to be the product of continued differentiation.

Composition of cumulus plagioclase cores, An_{45-55}, is more sodic than typical gabbroic rocks, An_{50-70}, of the complex. More detailed compositional data is needed, but this suggests that the initial magma was relatively differentiated at the time of emplacement. This could account for the extensive occurrence of interstitial granophyre in the lower unit and the large volume of granophyre in the upper unit.

Inclusions

A variety of intrusions are found in all the units of the Duluth Complex in Cook County. In Nathan's layered series, mappable masses of metamorphosed sedimentary rock, presumably derived from the Rove Formation, consist of granular chlorite-feldspar-quartz hornfels, and biotite-cordierite hornfels (Nathan, 1969). Inclusions in the Tuscarora intrusion (th) have been described above. In the southwest corner of the complex, medium- to fine-grained, subhorizontal bodies, ranging in thickness from less than 3 to more than 30 meters occur, and appear to be remnants of a unit which once capped the Duluth Complex (Davidson, 1972). The rocks now have a granoblastic texture and consist of plagioclase (An_{36-58}), hornblende, augite, oxides, biotite, and minor amounts of alkali feldspar, quartz, and apatite. Davidson (1972) refers to these rocks as granofels, and on the bases of a ubiquitous granoblastic texture and proximity to relatively unmetamorphosed North Shore Volcanic Group rocks, considers them to be contact metamorphosed equivalents of the latter.

Mineralization

Three types of mineralization are found in the Duluth Complex in this area: (1) low grade copper-nickel concentrations are associated with the basal rocks of the Tuscarora intrusion and several of the layered series intrusions (Johnson, 1970), (2) ilmenite- and titanomagnetite-rich rocks occur in several units of Nathan's layered series, and (3) several types of fissure veins, deposits of copper, lead, zinc and lesser amounts of silver and cobalt.

With regard to the mineralization in the Duluth Complex, the unpublished Ph. D. thesis of Johnson (1970) warrants special mention. The thesis summarizes the results of an exploration program conducted by the Cleveland-Cliffs Iron Company and the Amerada-Hess Corporation from 1966-1969. This program assessed the economic potential of the base of the Duluth Complex in a 20 mile corridor along the Gunflint Trail adjacent to the Boundary Waters Canoe Area. The drilling program (10 holes) provides a unique opportunity to assess the effects of drilling on the area in comparison with other activities such as logging and recreation. More importantly the release of geophysical, drill core, and assay data, along with Johnson's study represents a major contribution by a mining company to the concern for the environment of the area. The correlation of geophysical and drill core data, discussed below, makes possible a more accurate evaluation of mineral resources in adjacent areas and in other areas of similar geology using less expensive and disruptive preliminary investigations.

Copper-Nickel: Discontinuous areas of gossan and visible sulfide mineralization within unit ttf of the Tuscarora Intrusion have been mapped across the Long Island quadrangle. Similar isolated exposures have been found in unit tta at the contact with anorthositic gabbro. The sulfide assemblage, consisting of chalcopyrite, pyrrhotite, and minor pentlandite occurs interstitially to plagioclase and olivine. Because of the smaller grain size of the troctolite a distinct interstitial texture, like that found in the sulfide mineralization in the Kawishiwi area in the Gabbro Lake quadrangle, is not apparent in hand specimen. Drilling across the quadrangle (Johnson, 1970) has indicated a tabular, possibly continuous volume of low grade ore (0.3 percent combined copper-nickel) about 50 feet thick in unit ttf. A thinner 10-20 foot-thick zone, 50-100 feet above the lower mineralized zone, has a higher combined copper-nickel content that approaches one percent (Johnson, p. 84). The mineralization can be correlated with a detectable resistivity anomaly on the order of 700 x 10^3 ohmcentimeters in the troctolite (ttf, ttm).

Titanium: The primary titanium oxide phases are ilmenite solid solution (Fe_2O_3-$MgTiO_3$-$FeTiO_3$) and titanomagnetite intergrowths described above. Johnson (1970, p. 87) estimates that Ti recovered from ilmenite in unit ttf in the Tuscarora Intrusion could add $1.50 per ton to sulfide ore from this unit.

The largest titanium concentrations, however, are in units dt and du at Little Iron Lake in the Gunflint Lake quadrangle and other isolated exposures in the South Lake quadrangle. Unfortunately, most of these occurrences at the surface do not exceed about 35 feet in maximum dimension.

A large low-grade titanium resource also is contained within unit dg (fig. 3). Oxide-rich layers as much as 5 feet thick are common, although individual layers seem too thin and discontinuous to be mined separately. Unit dg should be considered in its entirety for commercial evaluation with the potential of developing a very large tonnage of low-grade ore. The unit is very heterogeneous and field exposures are scarce and discontinuous, so only widespread systematic drilling will reveal which parts have the greatest promise.

Fissure Vein Deposits: Several types of fissure vein deposits occupy fractures that cross-cut rocks of the Animikie Group and associated Logan intrusions, and are composed of minerals containing cobalt, lead, zinc, and copper, and lesser amounts of silver. Since discovery in 1846, the Thunder Bay District in Ontario has been a sporadic producer of silver, and ore valued at more than $4,770,000 has been shipped, most of the yield prior to 1900. Similar deposits have been found in Cook County, but as yet none have proved commercial.

Most of the veins contain only gangue minerals consisting of variable proportions of the gangue minerals calcite, barite, quartz, and fluorite.

The principal ore minerals include argentite, galena, and sphalerite; less common ore minerals are arsenides, sulfosalts, and copper and nickel sulfides. Small quantities of native silver have been reported from several veins.

At the east end of Loon Lake southeast of Gunflint Lake (fig. 2) an irregular five to seven foot wide easterly-trending vein cuts Logan diabase and Rove argillite. These veins are composed of massive arsenopyrite containing up to 3 percent cobalt, as well as minor amounts of calcite, quartz and pyrite. Drilling to locate the vein at depth is currently being conducted by Mr. Russel Blankeburg and Roger Whitside.

At the Green Prospect near Mineral Center, west of Grand Portage, a sulfide-bearing olivine diabase has been fractured and hydrothermally altered so as to resemble fissure vein deposits in the district. Primary sulfides consist of pentlandite, pyrrhotite and chalcopyrite, but secondary copper sulfides, particularly chalcopyrite, are most abundant in the "vein" at fracture intersections. In addition, supergene chalcopyrite and violarite replace some of the pentlandite in unaltered diabase. A sulfide concentrate from this locality assayed at 18.26 percent copper, and 0.52 percent nickel.

On Susie Island south of Pigeon Point, calcite and barite are the principal gangue minerals, but unlike other fissure vein deposits in the district, much of the calcite contains minute inclusions of chalcocite and exsolved bornite.

A more complete summary on these veins is given by Mudrey and Morey (1972) and Mudrey (1972).

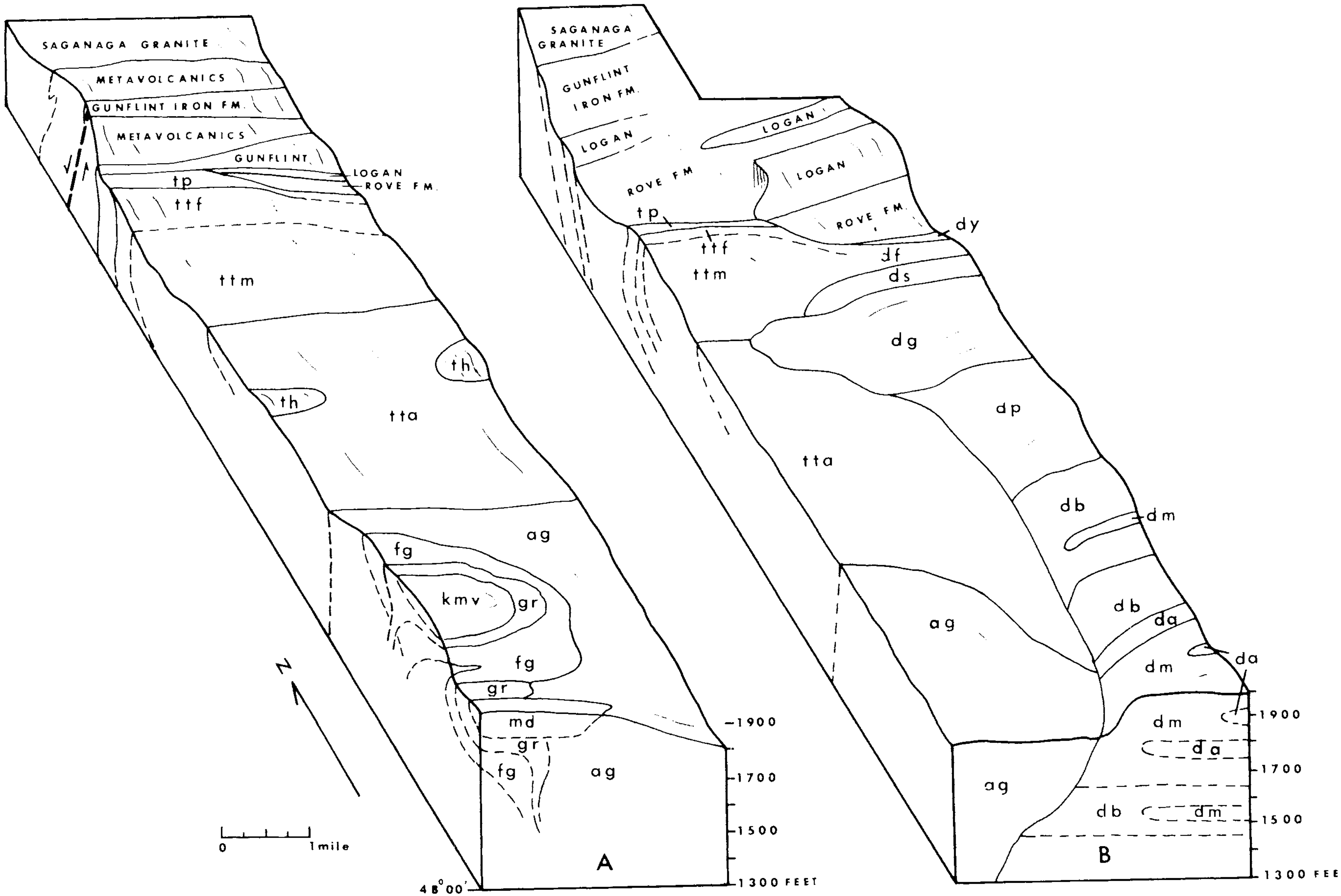

Figure 10. Structural block diagrams showing the inferred geologic relationships of rock units in the Long Island Lake and Gunflint Lake quadrangles (see Figure 3).

Evolutionary History of Keweenawan Rocks

The Keweenawan rocks in the Lake Superior region give rise to the northern part of the Midcontinent Gravity High. This structural feature extends from Lake Superior southward to Kansas and is interpreted by some (e.g. Zietz and King, 1970) to be the result of igneous activity associated with continental rifting. Clearly, crustal evolution in the Lake Superior region during Late Precambrian time is characterized by a substantial thickening of the crust through the emplacement of igneous rocks (Green, 1972) (fig. 11) (Halls and others, 1971; Halls, 1971; Wold and Ostentino, 1966). We believe that the geometry of the evolving structure was controlled largely by pre-existing crustal dislocations, and that these structures also affected substantially the various igneous processes which took place as rifting proceeded. Therefore, a brief description of Lower and Middle Precambrian structures follows.

The pre-Keweenawan structural fabric in northeastern Minnesota trends generally in a N. 70°-80° E. direction and is characterized by a fracture system consisting of joints and faults trending N. 20°-30° E., N. 45° W., and N. 70°-90° E. (Morey, 1969; Sims, 1972). Apparently, faults along these directions formed in the Early Precambrian, prior to emplacement of the large granitic batholiths (Griffin and Morey, 1969), and movements continued in time to well beyond the final period of granitic plutonism. Subsequent movements on these faults also occurred in Middle and Late Precambrian time (Morey, 1972). On the Mesabi range, for example, the Biwabik Iron Formation is offset locally by faults which have substantial displacements in the Lower Precambrian rocks. Similarly, the Lookout fault (fig. 3), on the south side of the Saganaga massif, is a dominantly Lower Precambrian structure in which displacement is north side up (see above section on Lower Precambrian structure). However, the Lookout fault and a north-northwest-trending subsidiary fault also separates the Gunflint Iron Formation into outcrop areas (fig. 3). Movement on the Lookout fault in this case is south side up (fig. 3), away from the fault. The iron-formation is only slightly deformed, except just east of the Gunflint Trail where the iron-formation and several concordant Logan sills are folded into a southeast-plunging anticline that has a steeply-dipping north limb and a gently-dipping south limb. The axis of this structure, which obviously is post-Logan in age, projects into the trace of the Lookout fault and it is inferred that the fault extends to the east-southeast for some distance beneath the Animikie strata. Most likely folding of the supracrustal rocks was related to movement on the fault, but that movement east of the subsidiary fault was not sufficient enough to displace the overlying strata.

A north-northwest-trending set of faults parallel to the subsidiary fault mentioned above also displaces Animikie strata, Logan intrusions, and Nathan's layered series (fig. 3); these faults parallel a well developed fracture direction in the Lower Precambrian terrane. Although north-northwest- and east-northeast-trending topographic lineaments are apparent in the Tuscarora intrusion, no evidence of displacement has been observed in this younger intrustion in the Duluth Complex. Therefore, it seems likely that tectonism and igneous activity were more or less contemporaneous events in the area.

To judge from available data, the fracture system in northwestern Cook County is part of a narrow east-northeast-trending fracture zone that extends from near Gunflint Lake to Thunder Bay on Lake Superior. In Canada, this fracture zone has been referred to as the "black slate belt" by Oja (1967). A second and more or less parallel fracture zone to the southeast coincides with the present north shore of Lake Superior and is best observed along a string of islands extending from Grand Portage River northeastward to beyond Silver Islet. Oja (1967) has referred to this fracture zone as the "gray argillite belt." A third subparallel fracture zone is inferred to extend along the north side of Isle Royale and Michipicoten Island in Lake Superior (Halls and West, 1971). As in the Lookout fault, movement on other faults within each of these fracture zones is dominantly south-side up. In addition, the "black argillite" and "gray argillite" belts divide the south-dipping strata into three segments; north of the "black argillite belt," Middle and Upper Precambrian strata are nearly flat-lying, whereas south of the "gray argillite belt," the Upper Precambrian strata dip as much as 20°. The geologic cross section in Figure 11 is bounded on the north and south by these two belts. Consequently, dips are variable but generally are in the range of 10°-15°, except locally where the structure has been modified by igneous intrusions. Of importance here is the fact that again, these structures have an orientation similar to that which characterizes the Lower Precambrian terrane.

In the southern part of Cook County, Lower and Middle Precambrian rocks and their associated structures are covered by a thick sequence of Upper Precambrian rocks; hence, no direct correlation of older and younger structures can be made. However the general cartographic distribution of various rock types, and their relation to available gravity and magnetic data, suggest that the Keweenawan rocks also are separated into two distinct segments by a N. 20° E.-trending structural high in the pre-Keweenawan basement (fig. 1). In the vicinity of Cook County, this feature extends from Beaver Bay on the shore of Lake Superior north-northeast toward the west end of Gunflint Lake. To the south-southeast, it coincides with a similar-trending structure which, on the basis of gravity and magnetic data, White (1966) postulated to be present beneath the Lake Superior basin. White was unable to determine if the structure he recognized was the result of arching or block faulting, but regardless of origin, the trend of this structure parallels that of known Lower Precambrian faults (Gruner, 1941; Hanson and others, 1971), and we suggest that this structure also had its origin in Early Precambrian time.

As a current working hypothesis we envision that the dynamics and geometry of the emplacement of the Keweenawan rocks to be the result of rifting, the configuration of which was controlled primarily by the presence of the older structures described above. This structural framework consists essentially of east-northeast-trending faults and the north-northeast-trending "arch" in the basement rocks on the west side of Cook County. The resultant motion on these two elements is effectively to the southeast, and the crescent-shaped outcrop pattern of Keweenawan rocks most likely reflects void spaces created by this tensional movement. In the rifting process, arching followed by block faulting is considered to be the normal sequence of events (Illies, 1970). This style of deformation established a mechanism for developing tensional structures such as voids in layered strata. In turn, these voids, which thin away from structural highs, permit the passive emplacement of igneous material.

Given the above hypothesis and available geologic data, we can postulate the following sequence of events in the igneous history of Cook County. The first recognizable event is believed to be the eruption of pyroxene porphyry lavas in the Grand Portage area and the emplacement of the Logan intrusions between Gunflint and South Fowl Lakes (fig. 2). Mathez (1971) concluded that the Logan intrusions were emplaced under a load pressure of between 0.5 and 1 kilobar. This implies a thin cover and does not necessitate the presence of a substantial thickness of Keweenawan lavas. The bulk composition of the Logan rocks is similar to Hawaiite (Weiblen and others, 1972). The differentiated nature of the magma (<5 percent MgO) indicates either a small degree of partial melting of source rock or differentiation of a tholeiitic parent. Phinney (1969) has shown that some lavas of the North Shore Volcanic Group can be derived by differentiation of parent magmas at depth with plagioclase plus minor pyroxene and olivine crystallization. This suggests a model involving the derivation of a parent magma at depth and crystallization of plagioclase-rich cumulates at some intermediate depth to give rise to units of the Duluth Complex. Logan magmas could have been tapped off such chambers just prior to crystallization of ilmenite (Weiblen and others, 1972).

The source from which the tholeiitic magma was initially derived and the location of the intermediate magma chambers is not clear; however, a decrease in the relative abundance of Logan rocks eastward from Gunflint Lake implies that the magma source was near there rather than in the Grand Portage area as suggested by Grout and Schwartz (1933). Furthermore, a magma source in west-central Cook County is consistent with the conclusion reached by Weiblen and others (1972) that the emplacement of the Logan magma was localized by the east-northeast-trending arch described above. Therefore, we suggest that movement on this structure created tensional voids which thinned to the east and localized the passive emplacement of the magma.

The Logan intrusions and enclosing Animikie strata are locally folded and tilted so as to define the north limb of the so-called "Lake Superior syncline." Clearly, the change in direction from movements of a north-northeast-trending axis to subsequent tilting on an east-northeast-trending axis must reflect a fundamental change in the evolution of the postulated Keweenawan rift system. The reason for this change is not known, but nevertheless this deformational episode resulted in the structural configuration depicted in the northern part of the cross section shown in Figure 11. We conclude that, more or less contemporaneously with progressive tilting, a substantial thickness of lava was extruded over northern Cook County. Evidence for this is the fact that although Nathan's "Layered Series" was emplaced at about the same stratigraphic level as the Logan intrusions, these rocks are characterized by textures indicative of slower cooling at greater depth. An accumulation of a thick pile of lavas at that time appears to be a simple mechanism for generating the necessary cover.

We believe that the locus of the troctolitic-gabbroic series rocks of the Brule River prong also was controlled by tensional voids created by movements, in this case, along pre-existing east-northeast-trending structures. If the Brule River rocks are younger than the layered series, as postulated by Davidson (1972), there is a suggestion that the magma sources and intermediate chambers migrated southeastward with time (fig. 11c). Such a suggestion is consistent with the inference that subsidence was more pronounced to the southeast and continued there for a longer period of time.

The Tuscarora intrusion is younger than Nathan's "Layered Series" (Davidson, 1972). It occupies a position to the west of the layered series. Igneous layering within the intrusion is relatively flat-lying, whereas the Animikie strata, Logan intrusions, and Nathan's Layered Series are flexed about an east-northeast-trending axis. To us, this is additional evidence that tectonism occurred concurrently with the emplacement of successive units of Keweenawan igneous rocks and that the tectonic style varied from place to place relative to various basement dislocations. In addition, these observations constitute additional evidence that the Lower Keweenawan rocks were deformed during the emplacement of Middle Keweenawan rocks.

Olivine diabases near Grand Portage and in central Cook County occur predominantly as dikes (fig. 3). These dikes were emplaced along east-northeast and north-northwest-trending fractures that comprise part of the "gray argillite belt". This suggests that faulting -- if this was the dominant deep seated movement -- had progressed to higher crustal levels in the later stages of Keweenawan tectonism and igneous activity. Furthermore, the undifferentiated composition of these rocks (Weiblen and others, 1972) is consistent with high-level emplacement of magma from a deep source without differentiation in intermediate chambers.

The generalized structural model outlined here for the successive, passive emplacement of Keweenawan igneous rocks has many implications. One involves restraints on the possible relationships among specific extrusive, hypabyssal and cumulate Keweenawan rocks. Problems related to this aspect of Keweenawan petrogenesis are currently being studied.

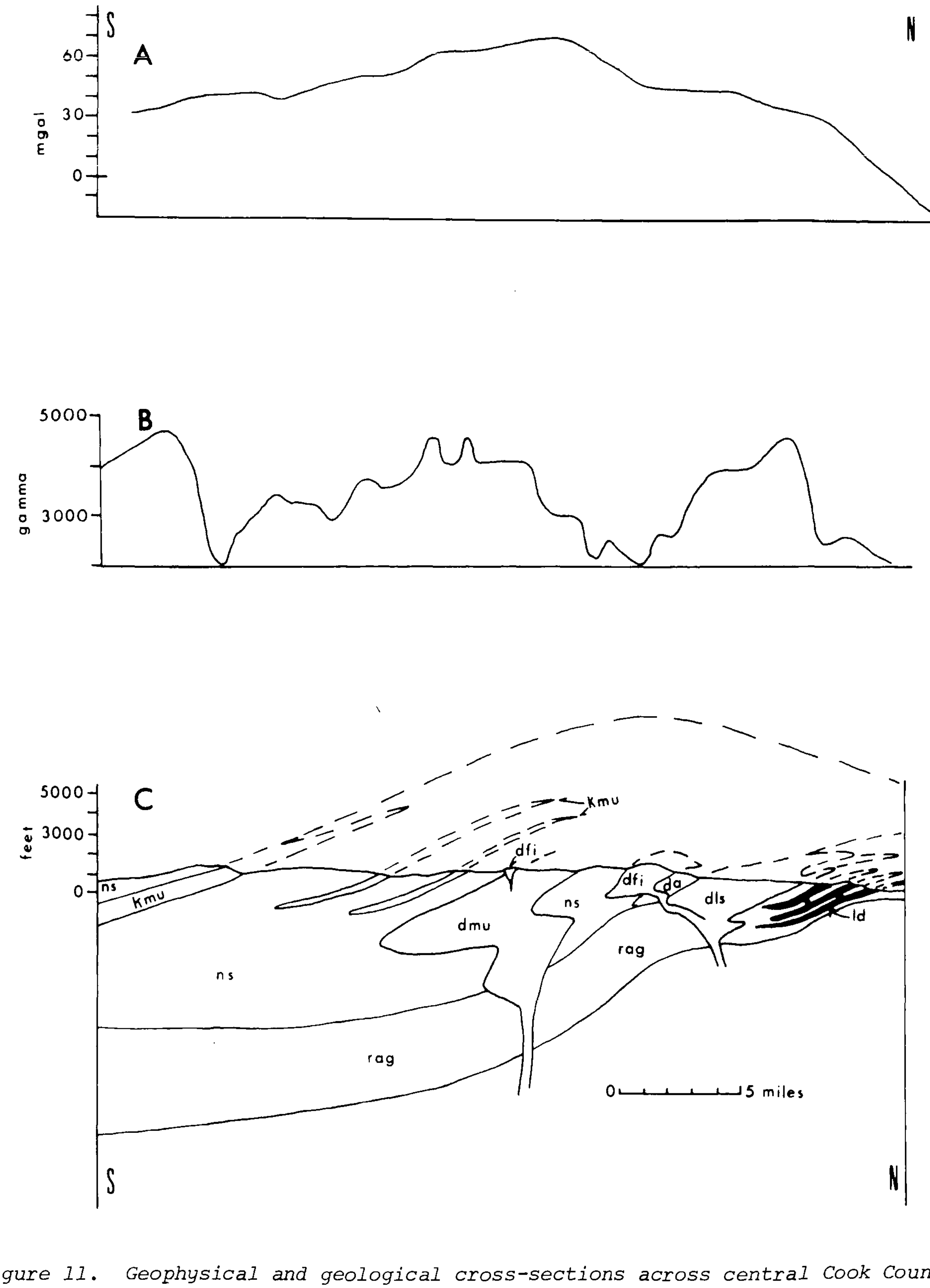

Figure 11. Geophysical and geological cross-sections across central Cook County. (See Figs. 2 and 4). A. Simple Bouguer anomaly profile (from Ikola, 1970). B. Total intensity aeromagnetic profile (from U. S. Geological Survey Geophysical Investigations Map GP-639 (1968). C. Diagrammatic geologic cross-section (see Fig. 2 for location and explanation of symbols and text for discussion).

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ALTERNATIVE STOPS IN THE NORTH SHORE VOLCANIC GROUP

Adapted from

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STRUCTURE

The general structure of the North Shore Volcanic Group is that of a great nest of dishes tilted gently to the southeast into Lake Superior. At the northeast end the strata at the base strike slightly north of west and dip about 10-12° south, whereas at the southwest end, 155 miles away, they strike north and dip about 25° east. In between the strikes gradually converge along the shore of Lake Superior as higher stratigraphic levels are reached, until the flows strike parallel to the shore in the vicinity of Schroeder, Tofte, and Lutsen in southwestern Cook County. Here the highest stratigraphic units are exposed, and the dip is approximately 12° to the southeast.

The lavas are intruded by a great variety and bulk of intrusive rocks, including several large diabasic sills at Duluth, the Beaver Bay Complex, the Hovland and Reservation River diabase complexes and the Logan intrusions. Where these intrusions are discordant and abundant they have deformed the lavas considerably, with local strongly divergent strikes and steep to overturned dips. Along with the thick glacial cover inland, they also have made difficult to impossible the long-distance tracing of stratigraphic units in the lava series. Several major flows or groups of similar flows, however, can be traced inland from the lakeshore for at least 15 to 25 miles. Faulting is common in the flows near the areas of abundant intrusions (such as from Silver Bay to Little Marais). These faults appear to be of minor displacement and are mostly transverse and steeply dipping with no strongly preferred strike or displacement, but a few longer strike-faults have been found, one of which probably extends for at least five miles.

The thickness of the lava succession has been measured and estimated by Sandberg (1938) and Grogan (1940) as 23,148 feet between Duluth and Split Rock River (which marks the beginning of the Beaver Bay Complex) by adding the individual flow thicknesses intersected along the lakeshore. Whether this conforms to the true thickness of the pile at Split Rock River is not known. Northeast of the Beaver Bay Complex, about 5,000 feet of lavas are estimated from recent mapping to form the lakeshore section between Silver Bay and the uppermost flows at Tofte. Northeast of Tofte and Lutsen, where the flows are parallel to the shore, lavas totalling about 16,500 feet have been measured down to the Reservation River diabase near Hovland. Below (northeast of) this is an older section of about 5,000 feet of lavas, for a total on this limb of about 21,500 feet.

Estimates of volcanic rock thicknesses by constructing cross-section profiles vary between 11,000 and 18,000 feet at Tofte, above the Duluth Complex, depending on assumed dips between 12° and 20°. Although the average dip at Tofte is about 12°, there is very little control on dips near the base of the section as the few inland outcrops rarely expose flow contacts. Farther northeast at the Cascade River, about 15,000 feet of lavas above the Duluth Complex are calculated with an average dip of 12°; another thick section, possibly as much as 5,000 feet thick, occurs there beneath the complex.

GENERAL DESCRIPTION

The North Shore Volcanic Group bears many resemblances, both physically and chemically, to plateau lava sequences of various geologic ages. Similarities to the Tertiary plateau lavas of eastern Iceland are particularly striking. The lavas are almost entirely subaerial, showing highly vesicular (now amygdaloidal) upper portions and massive interiors, and various types of jointing, surface features, and textures depending on their specific composition. Evidence of submarine extrusion is almost entirely limited to the base of the section both at Grand Portage and at Nopeming, west of Duluth. At Nopeming, the lowest flow is pillowed and on Grand Portage Island the lowest flow shows spheroidal forms that could possibly be pillows, but excellent, thick-rinded, vesicular pillows constitute a flow on the lakeward side of the island a few flows above the base of the section. Unequivocal but less well formed pillows and pillow-breccia have been seen only rarely higher in the section. These could have formed in local lakes or stream beds on the lava surface. The flows are in general tabular, and since some indivdual flows or flow groups can be traced along strike for at least 20 miles, the general impression is that of a broad, rather flat volcanic terrane. In contrast to the situation in eastern Iceland, however (Walker, 1964), no clear evidence of volcanic centers, representing shield or composite volcanoes contemporaneous with the plateau volcanism, has been found as yet. White (1960) has drawn attention to the remarkable extent of some Keweenawan flows (especially in Michigan) and with ample justification calls them flood basalts.

Interflow sediments make up a minor part (1-3 percent) of the section. They are principally red, cross-bedded sandstones that occur sporadically as beds a few inches thick between flows; however, a few local accumulations more than 100 feet thick are found. Conglomerate is rare. Some sand has filtered down into cavities in the upper parts of flows, and also forms a matrix for flow-top breccia in others. These sediments appear to have been deposited by scattered temporary streams winding across the volcanic surface. There is little evidence of erosion. Pyroclastic deposits are extremely scarce, but welded tuff and mixed sand and shards have been reported from the Cascade River in Cook County (Johnson and Foster, 1965) and basaltic to andesitic breccia, other than flow top breccia, is present in a few localities.

With the exception of a high potassium content in some mafic and intermediate members and the relative abundance of rhyolite, the compositions of the lavas are also very similar to those of plateau lava series in Iceland and elsewhere. The most abundant lava type is olivine basalt of several varieties; one widespread, important, and distinctive variety is mottled (ophitic), and is similar to what has been called olivine tholeiite in other areas. These typically have ropy surfaces and were very fluid. Rough columnar joints are common. Other olivine basalts are coarser grained having some diabasic or other characteristic textures. For example, in the Tofte-Lutsen area, high in the section, a group of olviine basalts occur which have abundant, small (1-3 mm) bytownite phenocrysts or crystal clots. At the base of the section both at Duluth and on Lucille Island east of Grand Portage are distinctive basalts that contain abundant phenocrysts, 2-3 mm across, of augite and (serpentinized) olivine: these are particularly atypical in having ferromagnesian instead of plagioclase phenocrysts. Another moderately abundant and distinctive rock type is a "quartz-tholeiite" which is aphanitic or very fine grained and slightly more siliceous and viscous than the olivine basalts. The quartz-tholeiites characteristically have a rubbly or brecciated top in which the highly vesicular fragments are set in a matrix of washed-in red sand or rarely calcite and zeolites. They also commonly show narrow oxidation bands, 1-3 mm thick, along subhorizontal flowage planes. This quartz-tholeiite grades into more potassium-rich varieties (trachybasalt, trachyandesite) that can be distinguished only by chemical analysis and microscopic study; patches of interstitial K-feldspar are present in these rocks but are invisible in hand specimen.

Rocks of intermediate composition are nearly all porphyritic and have phenocrysts of plagioclase, augite, magnetite, and in some specimens iron-rich olivine; they have the compositions of andesite, trachyandesite, and intermediate quartz latite. These flows are commonly brown or red and irregularly jointed or have platy, subhorizontal joints. Most are aphanitic, but one atypical flow, called the Manitou trachybasalt (Green, 1972) is exceptionally thick (at least 300 feet) and granular; it can be traced for 5 miles although it originally continued for an unknown distance in both directions.

The felsic lavas are anomalously abundant for a simple differentiation series from a basaltic parent magma. They are red, pink, or light gray, and have the composition of quartz latites. These flows tend to be much thicker than the other types; the thickest is 1,300 feet, a few miles east of Grand Marais; the 3,500-foot Brule River rhyolite west of Hovland may be a lava dome. Their top surfaces mostly are strongly flow-banded, vesicular, and contorted, but not brecciated, and their bases are commonly flow-banded and locally brecciated. Spherulites are sparingly present. Joint blocks range from large columns 4 feet across in the thickest flows to subhorizontal platy joints; small tectonically-produced parallel fracture sets a few mm apart commonly break up the cooling-joint fragments into small pieces. Most of the felsites are porphyritic and have quartz and feldspar phenocrysts (oligoclase-andesine and/or orthoclase) but others are only weakly porphyritic or aphyric. Poikilitic quartz surrounding stout alkali-feldspar laths ("snowflake texture") is a common microscopic texture in the thicker flows. Evidently, even these siliceous lavas have flowed a great distance; one lava or flow group can be traced for at least 23 miles west from the Devil Track River, north of Grand Marais.

ALTERATION

The lavas have been strongly but irregularly affected by secondary solutions that have deposited low-temperature minerals in vesicles, fractures, and other cavities. In addition, some of the original minerals in the lavas also have been altered. For example, no fresh olivine has been detected in any of the lavas, although it is common in the intrusive diabases. A broad zonation of alteration is apparent; at Duluth and at Grand Portage (in the lower parts of the lava sequence), much of the groundmass pyroxene has been converted to actinolite (although many larger grains of augite are unaffected) and some plagioclase has been saussuritized. Here also the amygdule minerals are characteristically quartz, prehnite, calcite, epidote, and chlorite, the same basic assemblage as is found in the Portage Lake Lava Series on the Keweenaw Peninsula (Stoiber and Davidson, 1959). In and northeast of Duluth, K-feldspar also is found locally, and laumontite becomes abundant. Higher in the section, various zeolites, along with calcite, are dominant except in the quartz tholeiites and similar lavas where agate, crystalline quartz and chlorite are common. The most abundant zeolites are laumontite, stilbite, heulandite, thomsonite, and scolecite, but analcite, natrolite, mesolite, mordenite, and apophyllite also have been found. Saponite is common in olivine basalts. Andradite garnet has been discovered in several localities in amygdules and veins from a wide range of lava types (basalt to rhyolite) and levels in the sequence, and traces of native copper have been found at several localities. Thus, the secondary zonation in the North Shore Volcanic Group spans both the deeper-level, high-temperature type of the Keweenaw Peninsula and the higher-level, cooler type characteristic of the lower parts of the Tertiary plateau lavas of eastern Iceland as described by Walker (1960). Walker's upper, zeolite-free zone is apparently not represented in Minnesota. According to his estimates, the presently exposed top of the lava sequence on the north shore of Lake Superior could have been approximately 5,000 feet below the surface during mineralization. Although no detailed work has been done, no clear cross-cutting relations of zeolite zones to stratigraphy within the lavas have been recognized as yet, but the evident Upper Precambrian, postvolcanic unconformity which probably follows the north shore of Lake Superior must have post-dated the mineralization, inasmuch as it does cross-cut the zeolite zones.

It should be stressed that none of the flows have been entirely converted to secondary minerals. In fact, plagioclase and augite typically are unaltered or only locally altered in most of the mafic and intermediate rocks, although no fresh olivine has been discovered. Typically, there also has been some oxidation of the opaque minerals, especially of magnetite, and pigeonite is commonly oxidized at its borders. In many intermediate and felsic lavas, plagioclase phenocrysts have been albitized and/or zeolitized; some of this alteration could be deuteric. Fresh, undevitrified volcanic glass is still present in some samples, notably in a basalt from about two miles west of the mouth of the Brule River.

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APPENDIX

ALTERNATE STOPS

STOP A-1. Two Harbors City Park (Two Harbors quadrangle). Quartz Tholeiite basalt. Just before leaving town, turn toward lake at road to city camp ground and Wa-Ke-Ya Motel. Drive past Burlington Bay, and up a hill. Park at hilltop picnic area, walk E to shore, then S. Well exposed contact between amygdaloidal, weathered (ex-laumontite) top of one basalt and massive basal part of an analyzed fine-grained, aphyric quartz tholeiite (50 percent SiO_2, 0.6 percent K_2O). Local thin sand lenses near and at contact; traces of Cu have been found. The tholeiite shows occasional small quartz-agate and chlorite amygdules and typical incipient sheeting-fractures with thin bands of oxidation. Upper zone of this thick tholeiite can be examined to S. toward power plant; it becomes rubbly, vesicular, brecciated, with abundant laumontite. Return to Hwy. 61.

STOP A-2. Gooseberry Falls State Park (Split Rock Point quadrangle). Smooth Surfaced Olivine Basalt. Below highway bridge are good exposures, in and between falls, of columnar-jointed olivine basalt lavas with amygdaloidal tops, and smooth, gently billowing surfaces.

STOP A-3. Shovel Point (Illgen City quadrangle). Palisade Head Porphyritic Rhyolite. Search for unmarked trail 0.45 mile SW of Illgen City jct. leading to shore at Shovel Point in Baptism R. State Park. Here is well exposed the upper-middle part of the thick (>300 feet) porphyritic rhyolite (quartz latite) that also forms Palisade Head to the SW and the road cuts at Illgen City. Take care on clifftop. View to SW over underlying lavas ("Baptism basalts") and some mafic intrusive bodies, to Palisade Head. Follow trail down dipslope to end and NE corner: view NE toward overlying quartz tholeiite flows. Return on same trail.

STOP A-4. Anorthosite Stop (Illgen City quadrangle). Anorthosite in syenogabbro. After crossing Kennedy Creek come to deep vertical cut in an irregular discordant intrusion (part of Beaver Bay complex) of altered syenogabbro that contains a great, massive block of rather pure anorthosite. After examining this, walk or drive SW downhill to lower cut that is composed of a sequence of several basaltic lavas with an interflow sediment bed - all of which have been overturned, probably as a result of forceful intrusion of nearby diabases. These basalts show a variety of structures, including some lobes that look like pillows and at the NE end some red scoria-rubble that is characteristic of the top part of the fine-grained tholeittes, basaltic andesites, and trachybasalts.

STOP A-5. Good Harbor Bay overlook (Good Harbor Bay quadrangle).

Thomsonite-bearing basalt and interflow sediment. In this large road cut one of the major cliff formers of the "Sawtooth Range" overlies a thick (130 feet) section of interflow sediments. The Terrace Point basalt is dominantly a massive, fine-grained ophitic basalt that characteristically contains thomsonite in amygdules, but in its lengthy exposure (including in this cut) several flow units of varying character show complex relations with the major, massive part of the flow.

The interflow sediment is here mainly thin-bedded siltstone and silty shale, but by walking up the bed of Cutface Creek at the bottom of this hill one passes outcrops of the basal contact of the sediments resting on the amygdaloidal-scoriaceous top of an andesite flow and eventually reaches large banks cut into well bedded sandstone showing abundant ripple marks.

ROAD LOG AND STOP DESCRIPTIONS

INTRODUCTION

Mileages for this trip are listed by stop as distances in miles along Minnesota 12 (The Gunflint Trail) going both northwest from Grand Marais and southeast from Trails End Campground, a round-trip distance of about 120 miles. Figure 1 indicates the location of the Gunflint Trail as well as the general geology of the area. A larger scale geologic map of the field trip area together with all the field trip stops is shown in Figures 2 and 3, while the cross section on Figure 2 and the block diagrams of Figure 4 represent the gross structural relationships between the units encountered on the field trip.

Going SW From Trails End	Going NE From Grand Marais	
0.0	54.7	STOP 1. End of Trail Campground - Main Phase of Saganaga Tonalite (SW1/4, NE1/4 sec. 31, T. 66 N., R. 4 W. Munker Island 7.5-minute quadrangle. The main phase of the Saganaga batholith at this stop is a medium-grained hornblende-quartz eye tonalite having quartz$_{20}$-plagioclase (An$_{27}$)$_{60-70}$-hornblende$_{6}$-microcline$_{3-5}$ and accessory muscovite, biotite, chlorite, epidote, sphene, apatite, allanite and opaques. The apparent lineation of the quartz-"eyes" is 25-30° ENE. This structure is parodied in the hornblende-biotite inclusions. These inch-to-foot sized inclusions probably are related to the metabasalt south of Seagull Lake. The bay leading north to Saganaga Lake was considered by Grout (1936) to be a shatter zone. It is here interpreted as a fault in the tonalite. At this stop, a vaguely developed secondary east-northeast-trending foliation is marked by shears and epidote veinlets, and may be related to faulting.
0.1	54.6	Y in road at End of Trail Campground.
0.5	54.1	Plymouth Youth Center turnoff. Outcrops along the paved road are typical Saganaga Tonalite without mafic inclusions.
1.25	54.7	STOP 2. Gunflint Trail near the Campground - Lamprophyre dike in Saganaga Tonalite (SW1/4, NE1/4 sec. 31, T. 66 N., R. 4 W. Munker Island 7.5' quadrangle) The lamprophyre dike at this stop is 50 feet wide, and can be traced to the north shore of Saganaga Lake where it is found to cut the northern boundary fault (Harris, 1968, p. 21). This observation sets a lower age limit for faulting and uplift to the west for the Saganaga Tonalite. Goldich and others (1961, p. 52) dated a biotite (KA-70B) from a small island to the north at 1.75 b.y. Sundeen (1936) reviewed the petrography of the lamprophyre dikes in the Saganaga Lake area and found biotite, hornblende, and pyroxene as the mafic phenocrysts in a groundmass of either plagioclase or "orthoclase." This dike contains plagioclase$_{50}$-

pyroxene$_{15-20}$-pyroxene$_{15-20}$-biotite$_{5-10}$ and hornblende$_5$. Accessory minerals include quartz, apatite, magnetite, chlorite, carbonate, sphene, pyrite, zircon, serpentine, talc and perovskite.

7.7 47.0 STOP 3a. Saganaga Tonalite - Border Phase (NE1/4, SW1/4 sec. 22, T. 65 N., R. 4 W., Long Island Lake 7.5' quadrangle).

The moderately foliated hornblende diorite exposed at this stop is typical of the border phase of the Saganaga batholith. The foliation is defined by a layering characterized by various proportions of dark and light minerals; it is nearly vertical and strikes N. 70° W. Elongate hornblende needles within the foliation plane define an elongate lineation that plunges gently to the east.

A transition from the border to the main phase involving an increase in quartz - with the development of quartz-"eye" structure - and a decrease in hornblende can be seen in a number of outcrops on either side of the Gunflint Trail to the north of this stop.

7.7 47.0 STOP 3b. Metabasalt and associated rocks (SW1/4, SE1/4 sec. 22, T. 65 N., R. 4 W., Long Island Lake 7.5' quadrangle).

In the general vicinity of this stop, vaguely pillowed metabasalt and thin bedded to laminated pyroclastic material typical of the mafic part of the volcanic succession are exposed. Layering is nearly vertical and strikes in a northwesterly direction. Fracture cleavage also is near vertical and strikes in a northeasterly direction parallel to the trace of the Lookout fault.

The mafic rocks are cut by conformable layers of the fine-grained phase of the Saganaga Tonalite. Locally a thin layer of iron-formation composed of magnetite and chert unconformably overlies the older rocks.

Iron-rich strata typical of the lower part of the Gunflint Iron Formation are exposed on the steep north-facing slope immediately to the south of these exposures.

8.0 46.7 STOP 4. Along Magnetic Rock Trail - metamorphosed Gunflint Iron Formation of Zone 2 (S1/2, SE1/4 sec. 22, T. 65 N., R. 4 W., Long Island Lake 7.5' quadrangle).

Thin bedded, fine-grained, chert-amphibole-magnetite-bearing strata assigned to the upper part of the Lower Slaty member are exposed along Magnetic Rock Trail at this locality. These exposures are near the transition between moderately and strongly metamorphosed iron-formation; small, poorly developed pyroxene porphyroblasts can be seen, especially in the more massive beds at the top of the member.

Along the power line trail to the south, the iron-formation is locally deformed with beds dipping northward at 15°.

Approximately 75 feet farther to the south a northwesterly-trending, medium-grained diabase sill cuts slaty iron-formation. Approximately 200 feet to the south the slaty beds again dip to the south and are interlayered with coarse-grained magnetite-rich cherty beds. On the same knob, algal chert-bearing beds characteristic of the Upper cherty member also are exposed.

8.25 46.45 STOP 5. Along the Kekekabic Trail - Metamorphosed Gunflint Iron Formation at Zone 3. (NE1/4, NE1/4 sec. 27, T. 65 N., R. 4 W., Long Island Lake 7.5' quadrangle).

The Kekekabic Trail more or less parallels the base of the Gunflint Iron Formation and the north-facing slope immediately south of the trail contains exposures of the Lower slaty member. The iron-formation everywhere in this area has been extensively metamorphosed and now consists of various assemblages of quartz-cummingtonite-grunerite-fayalite-magnetite and quartz-cummingtonite-grunerite-pyroxene-magnetite.

Tests pits can be seen along the trail. Most are in the lower magnetite-rich part of the Lower cherty member. Various sulfides, especially pyrrhotite, also are associated with the magnetite at this locality.

8.25 46.45 STOP 6. Paulson Mine railcut- Basal Contact of the Duluth Complex (SW1/4, NE1/4 sec. 28, T. 65 N., R. 4 W., Long Island Lake 7.5' quadrangle).

The Paulson Mine railcut exposes the base of the Duluth Complex from the Kekekabic Trail to the Tuscarora Lodge road, a distance of about one and one quarter miles. Contacts between beds of the Upper cherty member of the Gunflint Iron Formation and fine-grained poikilitic augite troctolite, unit tp of the Duluth Complex, are exposed at the west end of the railcut. Also at the west end truncation of a thin sill of the Logan intrusion can be seen. About half-way along the railcut, metaargillite and metagraywacke of the Rove Formation are in contact with the base of the Duluth Complex. The contact aureole here is narrow with no visible recrystallization of Rove strata except within a few feet of unit tp. This is inferred to be a reflection of the thickness of unit tp of between 100 and 1,000 feet. The dips of the Gunflint and Rove Formations vary from 15-60° to the south along this part of the contact. At the east end of the Paulson Mine cut along the Tuscarora Lodge Road to the north about 200 feet of unit tp is exposed in contact with fine- to medium-grained mineralized troctolite (ttf). The troctolite is cut by felsic dikes.

8.7 46.1 Tuscarora Lodge Road.

11.6 43.2 STOP 7a. Scenic overlook on the Gunflint Trail above Gunflint Lake - copper-nickel mineralization at the base of the Tuscarora intrusion (SE1/4, SW1/4 sec. 30, T. 65 N., R. 3 W., Long Island Lake 7.5' quadrangle).

The basal unit (ttf) (fig. 3) of the Tuscarora intrusion is exposed on the northeast side of the Gunflint Trail at the overlook. The fine- to medium-grained troctolite shows no regular increase in grain size away from a contact with unit tp and the contact or inclusion (?) of a Logan sill. Visible chalcopyrite, pyrrhotite, and pentlandite occur interstitial to plagioclase and olivine in the troctolite. This is a typical example of the copper-nickel mineralization of unit ttf, which was found by Cleveland-Cliffs Iron Company (in five holes along the base of the complex) to occur with apparent continuity in a 150-foot-thick interval near the base of unit ttf. The combined nickel-copper content is about 0.3 percent in this interval. A slightly richer zone 10 to 20 feet thick was intercepted about 50-150 feet above the lower zone.

11.6 43.2 STOP 7b. 2000 feet northeast of STOP 7a - Logan intrusions and the Rove Formation (SE1/4, SE1/4 sec. 30, T. 65 N., R. 3 W., Long Island Lake 7.5' quadrangle).

Thin bedded argillite is exposed on the north face of a ridge capped by diabase. The argillite is recrystallized to a biotite-bearing hornfels over an interval of a few inches at the contact. The diabase is typical of fine- to medium-grained diabase in thin sills and in the lower parts of thick sills.

23.2 31.5 STOP 8. Northwest arm of Poplar Lake on the Gunflint Trail (Center, NW1/4 sec. 1, T. 64 N., R. 2 W., South Lake 7.5' quadrangle - fig. 15).

At this stop, typical exposures and intrusive relationships of four of Nathan's units will be examined. On the north side of the unit df, (fig. 3), a fine-grained decussate augite-olivine-plagioclase rock (troctolite) similar to unit ttf of the Tuscarora intrusion intrudes unit dc, a very fine-grained granular olivine-augite-plagioclase rock (gabbro) which may represent a chilled margin of the oldest unit of the layered series (da). About 50 feet north of the Trail at the east end of the northwest arm of Poplar Lake, a small mass of unit dt, a medium-grained granular olivine oxide rock, occurs within unit dc. A small isolated exposure of unit ds with uncertain contact relationships occurs between units dc and df about 500 feet northwest of Poplar Lake and 400 feet north of the Gunflint Trail. South of the Gunflint Trail there are exposures of the large oxide-rich sheet unit dg (coarse-grained, foliated oxide, augite, olivine, plagioclase rock).

25.8 28.9 Service Station (Texaco).

29.9 24.8 STOP 9. Gunflint Trail south of Bear Cub Lake-Late granitic rocks of the Duluth Complex (SW1/4, NW1/4 sec. 13, T. 64 N., R. 1 W., Hungry Jack 7.5' quadrangle).

Unit daa, a medium-grained granular quartz-feldspar rock, is exposed as a dike in unit dm on the north side of the Gunflint Trail. The main mass of daa occurs south of the Trail as a stock one and one half miles across. Unit dm, a cumulate sheet of pigeonite-augite-plagioclase rock has visible interstitial quartz and alkali feldspar in an aureole as much as one mile wide around the stock of daa. This interstitial material is interpreted as replacement associated with the intrusion of unit daa.

0.0 54.7 Grand Marais. Intersection Gunflint Trail with Highway U. S. 61.