MINNESOTA GEOLOGICAL SURVEY

SP-8 *Special Publication Series*

The Geology of the Isaac Lake Quadrangle, St. Louis County, Minnesota

W. L. Griffin and G. B. Morey

UNIVERSITY OF MINNESOTA
MINNEAPOLIS • 1969

GEOLOGY OF THE
ISAAC LAKE QUADRANGLE,
ST. LOUIS COUNTY, MINNESOTA

by

W. L. Griffin and G. B. Morey

PUBLISHED IN COOPERATION WITH MINNESOTA
DEPARTMENT OF IRON RANGE RESOURCES
AND REHABILITATION

CONTENTS

Page

Abstract 1

Introduction 2
Geologic Setting 5

Lower Precambrian Rocks 9
  Lithology 9
    Ely Greenstone 9
    Meta-sedimentary and meta-volcanic rocks 11
      Gneisses of Zone 2 12
      Gneisses of Zone 3 13
    Giants Range Granite 15
      Mode of intrusion 17

  Petrography 17
    Ely Greenstone 17
      Volcanic rocks 18
      Sedimentary rocks 18
    Soudan Iron-formation 19
    Meta-sedimentary and meta-volcanic rocks 19
      Gneisses of Zone 2 19
      Gneisses of Zone 3 23
    Giants Range Granite 29
      Porphyritic Granodiorite 29
      Mafic phases 30
      Biotite Granodiorite 31
      Dike rocks 32

  Metamorphic Petrology 32
    Mineral Assemblages 32
      Gneisses of Zones 2 and 3 32
    Retrograde Metamorphism 34
    Metamorphic Facies 35

  Structural Geology 35
    Fabric Elements 35
    Statistical analysis of macroscopic fabric elements 36
    Faults 38
    Joints and shears 40

Middle Precambrian Rocks 41
  Stratigraphy 41
    Pokegama Quartzite 41
    Biwabik Iron-formation 42
    Virginia Formation 46

Petrography 46
    Pokegama Quartzite 46
    Biwabik Iron-formation. 47
    Virginia Formation 51
Metamorphic Petrology 51
    Mineral assemblages 51
    Petrogenesis 53
Structural Geology. 55

Upper Precambrian Rocks (?) 55
Keweenawan (?) 55

References 56

ILLUSTRATIONS

Page

Plate 1 – Geologic map of the Isaac Lake quadrangle, St. Louis County, Minnesota .... (In Pocket)

Figure 1 – Index map showing location of Isaac Lake quadrangle in relation to the Messabi and Vermilion Ranges 3
2 – Map of the West Vermilion area showing the generalized regional geology 6-7
3 – Geologic sketch map showing boundaries of metamorphic zones (thin dashed lines) and mineral isopleths (dash-dot lines) in region of this study 10
4 – Area of the Isaac Lake quadrangle showing subareas used in statistical analysis of fabric elements 36
5 – Equal-area diagrams of foliation and lineation in subareas I-II and III 37
6 – Orientation of joints and shear planes in subareas I-III 40
7 – Orientation of granitic dikes in subareas I and II 41
8 – Bedding characteristics, textural features, and mineralogy of the Biwabik Iron-formation 44

TABLES

Page

Table 1 – Stratigraphic succession in the Isaac Lake quadrangle 8
2 – Modes of Argo gneiss 22
3 – Modes of quartzose gneisses of Zone 3 25
4 – Modes of amphibolitic gneisses 25
5 – Modes of coarse-grained biotitic gneisses............... 28
6 – Modes of leucotrondhjemitic orthogneisses 28
7 – Modes of porphyritic granodiorites 29
8 – Modes of mafic phases of the Giants Range batholith 30
9 – Modes of biotitic granodiorites 31
10 – Modes of granitic dike rocks 32
11 – Lithologic distribution of mineral associations in paragneisses from Zones 2 and 3 33
12 – Lithologic distribution of mineral assemblages in Ely Greenstone samples 34
13 – Middle Precambrian nomenclature and generalized lithologic section 43

GEOLOGY OF THE ISAAC LAKE QUADRANGLE, ST. LOUIS COUNTY, MINNESOTA

by

W. L. Griffin and G. B. Morey

ABSTRACT

The Isaac Lake quadrangle lies between the Mesabi and Vermilion ranges, and includes a segment of each. The Lower Precambrian rocks that characterize the Vermilion range underlie the northern 2/3 of the quadrangle, and include both the Ely Greenstone (with interbedded iron-formation) and an overlying sequence of interlayered meta-sedimentary and meta-volcanic rocks. These rocks strike northwestward and dip steeply northeast or southwest; they were folded and intruded by the Giants Range Granite during the Algoman orogeny (2.5 b. y.). The grade of regional metamorphism increases southeastward along strike from Tower into the Isaac Lake quadrangle; the Ely Greenstone and meta-sedimentary and meta-volcanic rocks within the quadrangle contain mineral assemblages characteristic of the upper amphibolite facies.

The well known Middle Precambrian Animikie Group of the Mesabi range uncomformably overlies the Giants Range Granite in the southeastern corner of the quadrangle and these rocks have been intruded by dikes of Keweenawan (?) age and metamorphosed by the Middle Keweenawan Duluth Complex.

The basalts and tuffaceous sedimentary rocks of the Ely Greenstone are metamorphosed to massive or schistose amphibolites, and contain thin lenses of cherty iron-formation. The overlying highly metamorphosed sedimentary and volcanic rocks have been informally divided into two units, the layered gneiss and the (overlying ?) Argo gneiss. The Argo gneiss consists of fine-grained weakly foliated biotite gneisses with rare thin mafic layers; these gneisses are metamorphic equivalents of greenschist facies slates and graywackes which lie along strike to the northwest. The layered gneiss comprises amphibolite and leucocratic biotite and hornblende gneisses, interlayered on all scales and well-foliated parallel to the compositional layering. Thick layers of very coarse-grained biotite gneiss within the layered gneiss apparently were partially mobile during metamorphism. The layered gneisses are correlative with less-metamorphosed volcanic and volcaniclastic rocks to the northwest. The higher-grade parts of the layered gneiss are migmatized by fine-grained leucotrondhjemites that were foliated by the regional metamorphism, recrystallized to gneissic textures, and cut by granitic dikes.

The Algoman Giants Range Granite intrudes the older rocks and underlies the southern half and the northeastern corner of the quadrangle. It is predominantly a coarse-grained hornblende granodiorite or monzonite. The granite is strongly foliated parallel to its contacts and is generally conformable to the structure of the country rocks. The batholith is interpreted as a late-kinematic forceful intrusion, emplaced at relatively shallow depths.

Two major transcurrent faults strike northeastward across the quadrangle. The western one, here named the Waasa fault, offsets the granite-gneiss contact three and three-fourth miles. The eastern, or Camp Rivard fault offsets this contact about two miles. Contacts and fold axes within the gneisses appear to be offset even further, and other evidence also suggests that the faults were active both before and after emplacement of the granite. Numerous smaller faults are sub-parallel to the larger ones. Rocks north of the Waasa fault dip steeply northeast; those between the two faults generally dip steeply southwest. Statistical analysis of foliations and lineations suggests non-cylindrical folding about a northwest-trending axis. In the northwestern corner of the quadrangle there has been minor later crossfolding about an axis perpendicular to the axis of the major folding.

The Middle Precambrian Animikie Group, in the East Mesabi district of the Mesabi range consists of three comformable sedimentary formations, the Pokegama Quartzite at the base, the Biwabik Iron-formation, and the Virginia Formation at the top. They are exposed in the southeastern part of the quadrangle where they lie unconformably on the Giants Range Granite. The Pokegama Quartzite fills minor topographic irregularities in the older granite surface; accordingly, it is variable in thickness, ranging from near zero to approximately 30 feet. The Biwabik Iron-formation is approximately 400 feet thick and is subdivided into seven cartographic units on the basis of bedding characteristics, texture, and gross mineralogy. These units are readily correlated with those previously recognized by Wolff (1917) and Gundersen (1960). The Virginia Formation is not exposed in the quadrangle and is known only through diamond drilling.

The structure of the Animikie Group is relatively simple. The beds dip 5° – 15° SE, but the lower part of the Biwabik Iron-formation is warped by several small-scale folds whose axes trend north-northwest and plunge south-southeast at low angles. Structural closure on each fold seems to decrease upward so that near the top of the iron-formation the small-scale folds are no longer apparent.

The Animikie Group was intruded by gabbro dikes of possible Middle Keweenawan age, and metamorphosed by the Middle Keweenawan Duluth Complex. The formation is characterized by abundant prograde and retrograde cummingtonite with minor amounts of prograde fayalite, orthopyroxene, hedenbergite, and diopside.

INTRODUCTION

The Isaac Lake quadrangle was mapped as part of a broader study of the Precambrian rocks between the state's two most important iron ore ranges, the Mesabi and the Vermilion. The major purpose of this investigation is to determine through detailed geologic mapping and laboratory studies the stratigraphic and structural framework and the pattern of metamorphism and igneous intrusion in this complex geologic terrane. A better understanding of these rocks will aid ultimately in evaluating the economic potential of the older Precambrian rocks in and adjacent to the Vermilion range and in determining the effect of older structures on the deposition and alteration of the Biwabik Iron-formation.

The Isaac Lake quadrangle (Pl. 1) lies astride the geographic interval between the Vermilion and Mesabi ranges, and thus includes a segment of each (fig. 1). Accordingly, both Lower Precambrian and Middle Precambrian rocks are described in this report. Because many of the problems of the Lower Precambrian rocks are regional in extent, the geology of these rocks is discussed with respect to the broader area.

The Isaac Lake quadrangle is in east-central St. Louis County. Access to the area is moderately good. St. Louis county highway 21 crosses the center of the quadrangle in an east-west direction, and several secondary roads lead from it both to the north and to the south. The southern part of the quadrangle is largely within property owned by Reserve Mining Company and Erie Mining Company. Their cooperation during this project is gratefully acknowledged.

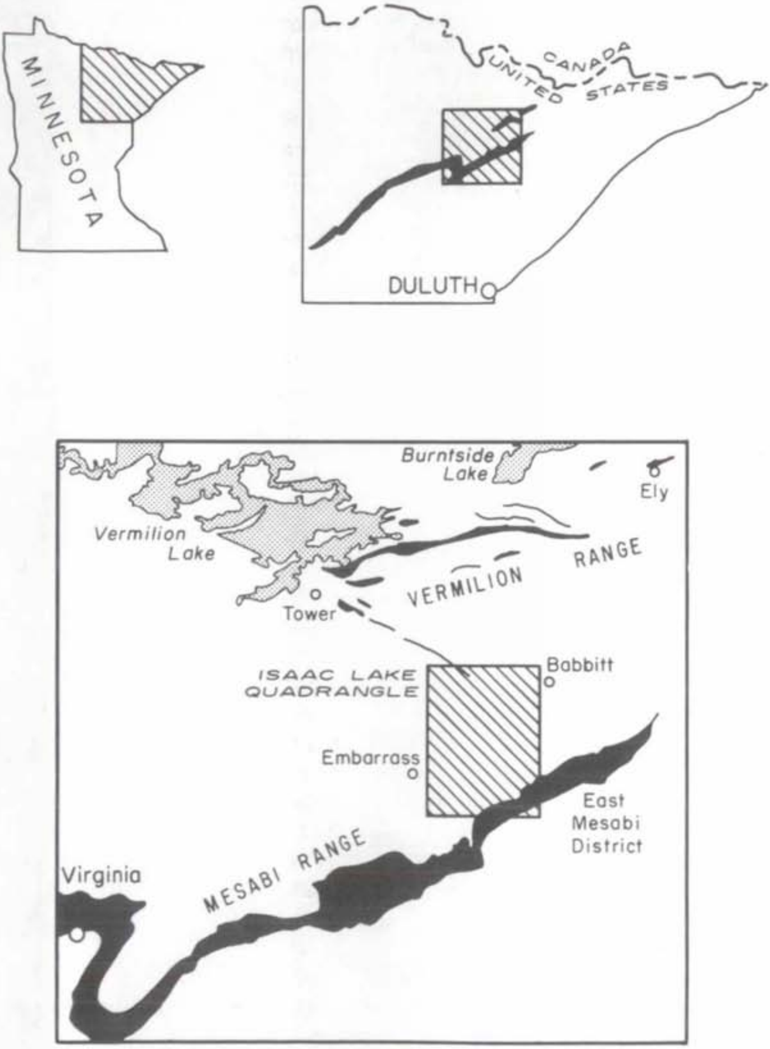


Figure 1. Index map showing location of the Isaac Lake quadrangle in relation to the Mesabi and Vermilion ranges.

The Giants Ridge physiographic region (Wright, 1956, p. 10), which flanks the Mesabi range on the north, extends through the southern part of the quadrangle. The ridge, composed largely of granite, forms a divide that separates drainage north to Hudson Bay and south to Lake Superior. However, the Embarrass River, which parallels the north side of the ridge and drains most of the Isaac Lake quadrangle, transects the ridge near Aurora, Minnesota and flows south to Lake Superior via the St. Louis River. Altitudes within the quadrangle range from 1,850 feet above sea level on the ridge itself to about 1,400 feet above sea level on the Embarrass plain immediately north of the ridge. Most of the area, excluding the ridge, is characterized by flat discontinuous knobs separated by low ground that is commonly swampy. Although relief is not more than a few hundred feet, much of the country is rough and difficult to traverse.

The present surface owes much of its character to Pleistocene glaciation. Most of the bedrock is covered by irregular, thin to thick deposits of glacial outwash and ground moraine. This material was deposited during the Automba-Vermilion phase of the Wisconsin Glacial Stage (Wright and Ruhe, 1966, p. 36). Ice entered the area as two separate, but simultaneous, lobes; the Rainy Lobe to the north of and the Superior Lobe to the south of the Giants Ridge. The Vermilion Moraine was deposited in what is now the northern part of the Isaac Lake quadrangle at a still-stand of the Rainy Lobe (Elftman, 1898). As the ice waned, meltwater was trapped between the Giants Ridge and the Vermilion Moraine forming Glacial Lake Norwood (Winchell, 1901; Wright, 1956, p. 18). The lake drained southwestward through Embarrass Gap along the present water-course of the Embarrass River.

Because of the extensive glacial deposits, a pervasive cover of moss and lichens, and a thick growth of balsam, spruce, pine, poplar, and birch, the bedrock geology is difficult to study. Since the last large forest fire that burned over much of the area in 1917, large areas have become overgrown with second-growth brush that consists mostly of hazel-nut. Cedar, black spruce, tamarack, and alder predominate in the intervening swamps and low ground. Small farm clearings are scattered throughout the area, the largest concentration being in an east-west belt along the Embarrass plain.

The relatively high altitude in the Isaac Lake quadrangle results in heavy snowfalls and generally severe winters. The annual precipitation is about 30 inches, and the average snowfall is approximately 60 inches. Minimum temperatures approach 50°F. below zero and maximum temperatures 100°F. above zero. The January mean is about 7°F., that for July about 64°F., and the mean annual temperature is about 37°F.

Major publications that concern the general geology of the Vermilion district are U. S. Geological Survey Monograph 45 (Clements, 1903) and Minnesota Geological Survey Bulletin 21 (Grout, 1926). The geology of the Middle Precambrian rocks in this area is summarized in Minnesota Geological Survey Bulletins 17 (Grout and Broderick, 1919) and 43 (Gundersen and Schwartz, 1962).

Field work in the area covered by this report extended over a period of three summers (1964-1966). In 1964, Griffin began mapping the Lower Precambrian rocks exposed in the northern part of the quadrangle, in conjunction with a study of their metamorphism. This work continued through the summer of 1965 and a part of the summer of 1966. In 1966, Morey mapped part of the Giants Range granite and the Middle Precambrian sedimentary rocks as part of a re-study of these rocks along the Mesabi range. Methods of mapping differed from area to area within the quadrangle. Most of the area was mapped with the aid of aerial photographs, but the rocks on the Mesabi range were mapped by pace and sun-compass methods. On the range, outcrops were located with respect to ground control provided by Reserve Mining Company.

GEOLOGIC SETTING

The regional geologic setting of the area is shown in Figure 2. This area includes a thick sequence of highly deformed meta-volcanic, meta-sedimentary, and granitic rocks that are assigned to the Lower Precambrian. These rocks in turn are overlain along the Mesabi range and in areas further to the south by a thin, relatively undeformed sequence of Middle Precambrian rocks. In addition, small dikes of Upper Precambrian rocks intrude the Middle Precambrian sequence in and adjacent to the quadrangle. The stratigraphic relationships are summarized in Table 1.

The oldest rock recognized within the quadrangle consists of a thick sequence of basic extrusive rocks interlayered with minor quantities of pyroclastic or tuffaceous material. These rocks, called the Ely Greenstone, have been highly altered by various metamorphic processes, and contain chlorite as a common, diagnostic mineral formed by the alteration of primary ferromagnesian minerals.

The upper part of the Lower Precambrian includes a thick succession of interbedded slates, feldspathic and lithic graywackes, and conglomerates with lesser amounts of volcanic flows and pyroclastics. In the past, these rocks in Minnesota have been collectively referred to as the Knife Lake Group; however, because a correlation with rocks exposed around Knife Lake cannot be demonstrated, only informal rock names are used for those rocks occurring within the Isaac Lake quadrangle.

The above mentioned rocks were folded, metamorphosed, and intruded by massive granitic rocks about 2.5 billion years ago during the Algoman orogeny (Goldich and others, 1961, p. 68). This orogenic event produced a strongly foliated and metamorphosed sequence of rocks that now extends through the northern part of the Isaac Lake quadrangle. The granitic rocks are more-or-less exposed throughout the south-central part of the quadrangle.

After a prolonged period of erosion, the Middle Precambrian Animikie Group was deposited on an irregular erosion surface cut onto the Lower Precambrian rocks. The group consists of three conformable sedimentary formations; a basal quartzite (Pokegama), an intermediate iron-formation (Biwabik), and an upper argillite-graywacke sequence (Virginia). These rocks are only slightly deformed and dip 5-15°S.

The Upper Precambrian Duluth Complex and other associated gabbro-dike rocks were intruded into Middle Precambrian rocks approximately 1.1 billion years ago (Goldich and others, 1961, p. 96). Most of the complex is exposed to the south of the quadrangle, but a few gabbro dikes are known to cut the Animikie Group within the boundaries of the quadrangle. However, metamorphic effects resulting from the emplacement of the complex are particularly apparent in the Middle Precambrian rocks.

The last geologic event in the Isaac Lake quadrangle is recorded in the deposits of Pleistocene glacial material that now covers much of the bedrock.

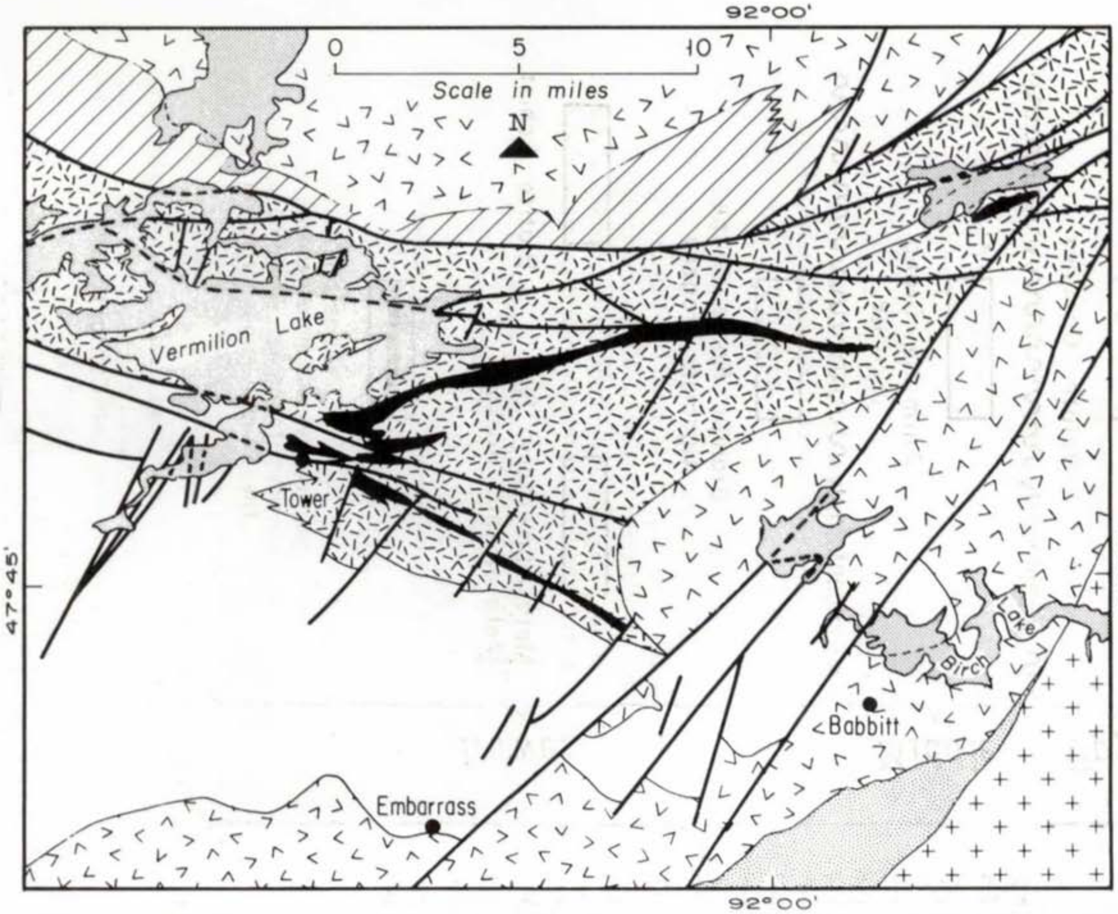


Figure 2. Map of the West Vermilion area showing the generalized regional geology.

EXPLANATION

PRECAMBRIAN

Upper

⊞ Duluth Complex

∽ unconformity ∽∽∽∽∽∽∽∽∽∽∽∽∽∽∽∽

Middle

▒ Animikie Group
undivided

∽ unconformity ∽∽∽∽∽∽∽∽∽∽∽∽∽∽∽∽

Lower

☐ Granitic Rocks of the Algoman Orogeny

☐ Metasedimentary & Metavolcanic Rocks

▨ Biotite Schist

▬ Ely Greenstone
locally with interbedded iron-formation including the Soudan Iron-formation

——— Contact

——- - - - Fault
dashed where concealed

Table 1 – Stratigraphic Succession in the Isaac Lake quadrangle (modified from Goldich and others, 1961, p. 5)

Era	Period-System	Major Sequence	Formation	Orogeny	Intrusive Rocks
0.6 b.y.					
Late Precambrian	Keweenawan				Duluth Complex (not exposed within area) unnamed dike(s)
1.7 b.y.				Penokean (not represented in area)	
Middle Precambrian	Animikian	Animikie Group	Virginia Formation Biwabik Iron-formation Pokegama Quartzite		
2.5 b.y.				Algoman	Giants Range Granite
Early Precambrian			Interbedded metasedimentary and metavolcanic rocks Ely Greenstone, undivided, with interbedded lenses of iron-formation		

LOWER PRECAMBRIAN ROCKS

The lower Precambrian rocks in the Isaac Lake quadrangle are the Ely Greenstone – including lenses of iron-formation – and overlain by a sequence of meta-sedimentary and meta-volcanic rocks. Both of these units are intruded by the Giants Range Granite of Algoman age. The Lower Precambrian rocks described here lie along a steeply-dipping fold limb which extends southeastward from Tower into this quadrangle. The fold limb is cut off within this quadrangle by intrusion of the Giants Range Granite and by the Waasa and Camp Rivard faults, which have large horizontal displacements. The Ely Greenstone crops out only in the northwestern corner of the quadrangle, whereas the meta-sedimentary and meta-volcanic rocks underlies most of the central part. The granitic rocks underlie the northeastern part and the southern one-third of the quadrangle, and also occur as small bodies intrusive into the meta-sedimentary and meta-volcanic rocks.

Mapping to the west of this quadrangle – in the Embarrass quadrangle (fig. 2) – has shown that the grade of metamorphism increases southeastward from Tower toward Babbitt (Griffin, 1967a). The sedimentary and volcanic rocks throughout most of the Vermilion range are metamorphosed to greenschist-facies assemblages. Rocks west of Tower likewise have greenschist-facies assemblages, but those south of Tower contain amphibolite-facies assemblages. Near Tower, primary structures are clearly visible in both volcanic and sedimentary rocks; to the southeast, the Ely Greenstone is metamorphosed to amphibolite and the overlying volcanic and sedimentary rocks are changed to layered gneisses, migmatites, and biotitic gneisses of the upper amphibolite facies.

During the mapping, three metamorphic zones were distinguished on the basis of degree of recrystallization and degree of deformation (fig. 3). The zones are defined as follows:

Zone 1: Relict volcanic and clastic textures preserved; little or no disruption of sedimentary layering, no migmatization.

Zone 2: No relict textures preserved; layering generally continuous though locally distorted; no migmatization.

Zone 3: No relict textures preserved; layering tends to be discontinuous and lenticular on all scales; most metamorphic rocks are intruded by fine-grained leucotrondhjemites.

The Lower Precambrian rocks in the Isaac Lake quadrangle lie entirely within Zones 2 and 3 (fig. 3) as defined above.

Lithology

Ely Greenstone

The relatively low-grade rocks of the Ely Greenstone to the northwest of the quadrangle consist of extensive massive or pillowed mafic volcanic flows and interbedded volcaniclastic sedimentary rocks. Primary structures in the volcanic rocks include vesicles, amygdules filled with calcite or epidote, and ellipsoidal pillows one-half to three feet in length having epidotized rims. The pillows have a characteristic domical outline and generally show well-defined tops and bottoms. However, many outcrops of the flows are either massive or schistose. Dikes and sills of coarse-grained meta-diabase are common, and some outcrops are diked by intrusive rocks associated with the overlying meta-volcanic rocks.

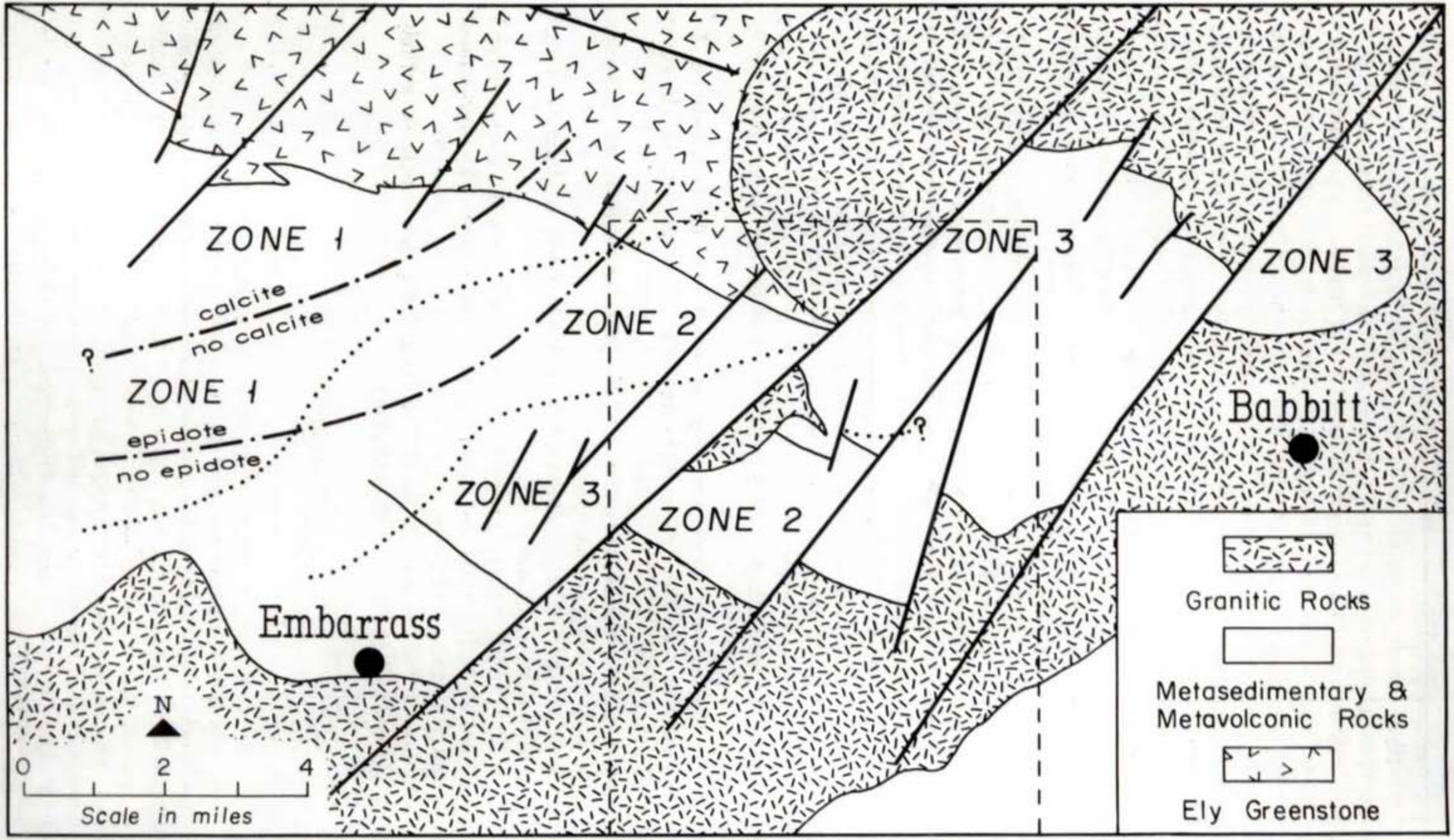


Figure 3. Geologic sketch map showing boundaries of metamorphic zones (thin dashed lines) and mineral isopleths (dash-dot lines) in region of this study.

The associated sedimentary rocks include thin-bedded, possibly tuffaceous types as well as fine to coarse conglomerates and breccias composed of basaltic pebbles. Thin-bedded sedimentary rocks are difficult to distinguish from locally schistose volcanic rocks unless conglomerates also are present. Sedimentary rocks of both types are most abundant near the top of the Ely Greenstone in the quadrangle, where they locally are associated with lenses of iron-formation. The sedimentary rocks commonly contain stringers of epidote parallel to bedding.

Mineral lineations – elongate crystals of amphibole – are poorly developed in the rocks to the northwest of the quadrangle, but become progressively better developed with increasing grade of metamorphism. In the lower-grade rocks both foliation and lineation are more strongly developed in the sedimentary than in the volcanic rocks, but at higher grades both structures are pervasive. No small-scale folding was noted in outcrops of the Ely Greenstone.

The only primary structures visible in higher-grade rocks of the Ely Greenstone are rare, strongly distorted pillows. The foliation is generally parallel to pre-existing bedding or pillow elongation and movement along the foliation has resulted in stretching of the pillows to narrow lensoid outlines.

The rocks of the Ely Greenstone in the Isaac Lake quadrangle (Zone 2) are primarily schistose meta-sedimentary rocks or strongly foliated flows. Only one outcrop of pillowed basalt was found. Many outcrops contain internally laminated lensoid epidote-diopside-plagioclase nodules ranging in length from 1/2 – 12 in. and in width from 1/4 – 6 in. The larger nodules are very coarse-grained; most of these nodules are isolated, and the foliation wraps around them. At several places, however, strings of such nodules are connected by thin epidote layers, suggesting that they originated by boudinage of calcareous layers in thin-bedded sedimentary rocks. Continuous calcareous layers 3 – 6 in. thick are common in some outcrops. Where the nodules can be seen in three dimensions they are necked in two directions (chocolate-bar boudins). In some outcrops thin granite sills have similar boudinage structure. Quartz crystals are found locally in the neck between two nodules. Similar structures have not been found in the overlying meta-sedimentary and meta-volcanic rocks.

Aeromagnetic surveys (Bath, Schwartz and Gilbert, 1965) suggest that the Soudan Iron-formation of the Vermilion range turns at Tower and continues southeastward along the limb of the fold into the Isaac Lake quadrangle. However, it has been found that in outcrop, the rocks responsible for the magnetic anomaly are not part of the Soudan Iron-formation, but are layers and lenses of red or black chert, 1-6 feet thick, having thin stringers of magnetite and iron silicates. This cherty iron-formation is intercalated with thin-bedded mafic sedimentary rocks and pillow lavas. Though individual lenses are small and discontinuous, the zone of scattered iron-formation lenses is about 100 feet wide and sufficiently continuous to be traced by magnetic instruments from sec. 26, T. 61 N., R. 14 W. to sec. 18, T. 61N., R. 14 W. This zone is approximately three-tenths of a mile stratigraphically below the top of the Ely Greenstone. Thus, no outcrops of Soudan Iron-formation were found within the Isaac Lake quadrangle.

Meta-sedimentary and Meta-volcanic Rocks

Primary structures other than compositional layering are visible only within the meta-sedimentary and meta-volcanic rocks of Zone 1, northwest of Isaac Lake quadrangle. Toward the southeastern end of this outcrop belt, in the Embarrass and Isaac Lake quadrangle (fig. 3), only coarse structures such as bedding and conglomerate pebbles are distinguishable through the metamorphic overprint.

The sedimentary and volcanic rocks of Zone 1 – to the northwest of the quadrangle – consist of interbedded graywacke and slate, conglomerate and contain interlayered volcanic flows and associated hypabyssal intrusive rocks. Amphibole-bearing sedimentary and volcanic rocks predominate in the Soudan quadrangle and the northern part of the Embarrass quadrangle, but pass along strike to the west into generally more biotitic graywacke and slate. This biotitic facies apparently underlies the amphibolitic rocks in the Tower quadrangle, but higher in the succession is transgressive over the amphibolitic rocks from west to east.

Medium-grained unmigmatized layered gneisses of Zone 2 – lacking relict sedimentary or volcanic textures – occur in the central part of the Embarrass quadrangle and the northwestern part of the Isaac Lake quadrangle (fig. 3). Apparently they pass along and across strike into the more highly deformed, migmatized layered gneisses of Zone 3, but the transition areas are covered by extensive swamps.

The [Knife Lake] gneisses of Zones 2 and 3 consist of layered amphibolitic and biotitic gneisses, are overlain (?) to the south by a unit of fine-grained biotitic gneisses, herein named the Argo gneiss. On the basis of their spatial relations and similarities in structure and mineralogy, the layered gneisses are believed to be metamorphic equivalents of the amphibolitic volcanic and volcaniclastic rocks to the north and northwest. The Argo gneiss is believed to be the metamorphic equivalent of the biotitic graywackes and slates which lie along strike northwest of the Argo gneiss outcrops in the Embarrass quadrangle. The gradual transition from biotitic graywackes and slates to fine-grained biotite gneiss is visible in rail cuts northwest of Embarrass. On state highway 135 a fault apparently separates graywacke-slate from biotitic gneisses.

Gneisses of Zone 2. Rocks of Zone 2 lack relict volcanic or clastic textures, although layering is common and typically continuous through large outcrops; migmatites are absent in this zone. These gneisses occur between the sedimentary and volcanic rocks of Zone 1 and the migmatized gneisses of Zone 3 (fig. 3). This zone includes two areas of layered gneiss and most outcrops of the Argo gneiss.

The outcrops of the layered gneiss are in the northwest part of the Isaac Lake quadrangle, south of the easterly trending moraine. The area is separated from higher-grade rocks to the southeast by a covered interval. The outcrops show interbedding of thick layers (2-50 feet) of medium- to coarse-grained mafic (amphibolitic) and felsic (quartz-plagioclase-biotite-hornblende) gneisses. Many individual layers are internally laminated on all scales with respect to mineralogy and grain size. Primary structures were not noted. Recrystallization has totally obliterated the original clastic or volcanic textures. Foliation and mineral lineation are well-developed; all foliation is parallel to lithologic layering.

The only folds noted in the northwest part of the Isaac Lake quadrangle were minor open asymmetric drag folds with the fold axes parallel to hornblende lineations.

The Argo gneiss, a fine-grained biotitic gneiss, crops out to the south of – stratigraphically above (?) – the layered gneisses in the central part of the Isaac Lake quadrangle. It is informally named for a group of typical exposures in roadcuts 1/2 mile west of Argo cemetery on St. Louis County highway 21. Most outcrops of the Argo gneisses lie in Zone 2 as defined above. No relict textures were observed, layering is essentially continuous over large outcrops, and no outcrops are intruded by leucotrondhjemite. The contact between the Argo gneisses and the layered gneisses has not been observed, but beds of Argo-type gneiss near the top of the layered gneisses in the central part of the quadrangle suggest that the contact is gradational. The unit consists of fine- to medium-grained, even-textured massive to thinly bedded – 1 in.-2 ft. – quartz-plagioclase-biotite gneisses with sporadic 1/2 in.-1 1/2 ft. hornblende (-biotite) -rich layers. The finer grain size, even texture, and brownish color distinguish these gneisses from the quartzo-feldspathic members of the layered gneisses. Some outcrops adjacent to the granite in NE 1/4 sec. 17, R. 13 W., T. 60 N. are coarser-grained and have a swirled, uneven texture, but retain the darker color and distinctive appearance of the unit. The lack of mafic layers confirms the identification. These outcrops have been assigned to Zone 2.

Parallelism of the abundant small biotite flakes defines a foliation which everywhere is parallel to bedding. Broad open folds having wavelengths of several feet are visible locally, and others may be inferred from small outcrops of shallow-dipping rocks. One such fold in a roadcut west of Argo Cemetery has resulted in boudinage of a one-foot-thick mafic layer into large pods elongated parallel to the fold axis; these boudins in turn show necking structures perpendicular to their long dimension at several places. Smaller folds, especially in granite stringers, are locally present. Smaller mafic layers and thin granitic sills are commonly boudined.

The striking differences in texture and mineralogy between the Argo gneisses and the layered gneisses suggest different sedimentary parentages for the two units. Only a few outcrops of meta-sedimentary rocks in Zone 1 are along strike from the Argo gneisses. These are all graywackes and slates and are finer-grained, more biotitic, and more aluminous than the amphibolitic graywackes to the north. In addition, the only rocks containing garnet crop out in this area. It seems likely that these sedimentary rocks represent a change of facies from the less mature sedimentary rocks to the north. They might well yield finer-grained, more biotitic metamorphic derivatives. If this is the case, the rare mafic beds may represent tuffs or other influxes of volcanic material. Along the railway line south of the east-west moraine, there is a gradual transition from biotitic slates and graywackes to Argo-type biotite gneisses. On highway 135, slates and graywackes are separated from biotitic gneisses by a narrow valley; this valley probably is underlain by a fault contact (pl. 1).

Gneisses of Zone 3. Coarse-grained layered amphibolitic and biotitic gneisses, intruded and locally migmatized by leucotrondhjemite orthogneisses, underlie the east-central part of the Embarrass quadrangle, the central part of the Isaac Lake quadrangle, and several square miles around the west end of Birch Lake. The gneisses are dark plagioclase-hornblende-quartz amphibolites and leucocratic quartz-plagioclase-biotite-hornblende gneisses; all have well-developed foliation and lineation resulting from aligned hornblende crystals. In general, the different rock types are interlayered on the scale of inches to several feet, but several large outcrops of massive amphibolite were noted. Locally, either rock type may predominate, but the amphibolitic gneisses are generally thicker and more abundant.

In the layered gneisses foliation is parallel to lithologic layering and is defined by a preferred orientation of biotite plates and/or hornblende crystals, tabular plagioclase, and elongate quartz eyes. Generally the amphibolitic gneisses have a well-developed lineation, and some biotitic gneisses have parallel streaks of biotite on foliation planes. There has been considerable differential movement along foliation planes, especially within amphibolite layers.

Small-scale folds are present in many outcrops, especially in those rocks that are strongly migmatized. Isoclinal folds of thin quartzo-feldspathic layers within thick amphibolite layers typically have amplitudes of 1-3 feet. In some cases the fold nose is detached from its limbs and forms an arrowhead-shaped pod within apparently undeformed amphibolites. More rarely, thin amphibolites are folded within the quartzo-feldspathic gneisses. Asymmetric folding is less common, and generally is associated with shearing. Dikes of Giants Range Granite are commonly folded, apparently by slip along foliation planes. Quartz pods, generally elongated parallel to the hornblende lineation, are very common along the foliation of the gneisses. Where quartz seams cross the foliation, they commonly are folded.

Boudinage is very common, and results in apparent angular to lensoid "inclusions" of amphibolite within quartzo-feldspathic gneiss. Many such tectonic inclusions show internal bedding which is oblique to the elongation of the boudin. Boudins were observed to develop by oblique fracture of thin amphibolite beds, by necking of amphibolitic layers or groups of layers, or by simple cross fracturing of thin layers. Wispy schlieren of hornblendite in quartzo-feldspathic gneisses may have resulted from similar disruption of thin mafic beds. Quartz veins and some Giants Range Granite sills also show boudinage structure.

Low amplitude symmetrical folds that have roughly horizontal axial planes were seen in many vertical exposures, and were interpreted as incipient boudinage. The wave lengths range from 1 to 4 feet, amplitudes from 3 to 18 inches. The axes are parallel to aligned amphibole needles and to the plunge of other fold axes.

Locally in the layered gneisses there are thick – 10-50 feet – conformable layers of well-foliated very coarse-grained quartz-plagioclase-biotite gneisses, some containing eyes of quartz elongated parallel to the foliation. Thinner layers and lenses 1-3 feet thick are scattered throughout the layered gneisses and commonly send out apophyses into them. Large inclusions of amphibolitic gneiss within some of the thick layers appear to have been broken and rotated within the "granitic" gneiss. Other outcrops show thin conformable septa of amphibolite that are crosscut and injected by the coarse-grained biotitic gneiss in which they are enclosed. One such cross-cutting dike has been found as an off-shoot from a thick conformable layer of the coarse-grained gneiss. These layers are themselves cut by the leucotrondhjemites. Their metamorphic textures and relations to the layered gneisses suggest that these coarse-grained biotitic gneisses are paragneisses whose composition was suitable for them to become partially mobile under high-grade conditions.

A great deal has been written on the origin of layered ("banded") gneisses (cf. Dietrich, 1960). In this area, it is difficult to regard the lithologic layering as anything but relict sedimentary bedding; all of the varieties of layering found in the gneisses have counterparts in the lower-grade volcaniclastic meta-sedimentary rocks to the northwest. Some thick amphibolite layers, and the coarse-grained biotitic gneisses, may represent volcanic flows. The metamorphic mineralogy is similar to that in the lower-grade meta-sedimentary rocks. The differences in texture tend to obscure these basic similarities, but the mapping and petrographic study leave little doubt that these gneisses are metamorphic derivatives of volcanic and volcaniclastic rocks similar to those along strike to the northwest.

Most outcrops of the layered gneisses show some degree of migmatization by a leucocratic medium-grained trondhjemite that is white on weathered surfaces. The leucotrondhjemite commonly occurs as sills one inch to 2 feet thick that are difficult to distinguish from leucocratic meta-sedimentary rocks; however, most sills, if followed sufficiently far, can be seen to cut across the layering at oblique angles. Others branch out into several sills, or expand into pod-like masses. Irregular crosscutting dikes 1-18 inches thick also are common. Some of the migmatites are agmatitic – resemble intrusion breccias – this type is most common within thick amphibolite layers. The areas of most intense migmatization and injection are outside the Isaac Lake quadrangle, around Birch Lake and in NW 1/4 sec. 9, T. 60 N., R. 14 W. In the latter area, most outcrops contain only the leucotrondhjemite having frayed inclusions of paragneiss aligned parallel to the regional foliation.

All the sills of trondhjemite are foliated parallel to the layering of the country rocks. Crosscutting dikes of trondhjemite are studded with 1 in. oligoclase megacrysts, but the rock generally has a granular appearance. Thin sections show that the megacrysts are porphyroblasts set in a poorly foliated granoblastic groundmass; the rocks are now leucotrondhjemite orthogneisses. The lack of any relict igneous textures suggests the original igneous rocks were quite fine-grained. Many of the dikes and sills are folded, some apparently by movement along the foliation. Dikes of Giants Range Granite commonly cut the leucotrondhjemites but never are cut by them. The relations in outcrops indicate a magmatic origin for the leucotrondhjemite. The migmatization is part of the early metamorphic history of the area; the trondhjemites were intruded, folded and recrystallized to gneisses prior to intrusion of the Giants Range Granite. Their ultimate origin is one of the major petrologic problems of the area and will be discussed in more detail below.

Giants Range Granite.

The Giants Range Granite crops out along the southern edge of the quadrangle and underlies the northeastern corner (pl. 1). These outcrops constitute a small part of a large batholith extending 20 miles northeast of the area and more than 100 miles to the southwest, and having an average outcrop width of 10 miles. Over most of its extent, however, little is known of the structure or lithology of the batholith. Allison (1925) gave a brief survey of the batholith, but some of his conclusions were based on meta-sedimentary rocks which he erroneously believed to be border phases of the granite. The granite has an intrusive contact with both the Ely Greenstone and the meta-sedimentary and meta-volcanic rocks; it is unconformably overlain by Middle Precambrian rocks.

The contact of the granite with the Ely Greenstone in the northeastern part of the area is poorly known because of a lack of exposures. The available outcrops indicate that the contact describes a great sweeping curve extending into the core of the synclinal trough formed by the greenstone. The shape and location of this contact have been confirmed by gravity studies (R. Ikola, oral comm., 1968). The contacts along the southern margin are poorly known, but apparently follow the structure of the gneisses in a general way.

A large isolated body of Giants Range Granite occurs along the Waasa Fault in the west-central part of the Isaac Lake quadrangle. The granite is a medium-grained hornblendic variety in which the mafic minerals are chloritized. However, the entire body has a very pronounced foliation parallel to the regional foliation in the country rocks. This foliation has in turn been cut by zones of shearing and silicification parallel to the Waasa fault. It is unclear whether this body is a separate fault-controlled intrusion or whether it is a boss which has been faulted off the main body of the granite. The manner in which it cross-cuts the country rock, unlike the remainder of the batholith, and the occurrence of small granitic bodies along several of the small faults parallel to the Waasa fault, suggest this body was at least partially intruded along a fault.

Several small bodies of granite occur in the gneisses of Zone 2 in the northern part of the quadrangle. One of these, in NW 1/4 sec. 36, T. 61 N., R. 14 W., actually is a series of thick lenses parallel to the layering of the gneisses; the lenses are strongly sheared and foliated along their length, and apparently have been forcefully intruded. The high-grade gneisses are extensively diked by Giants Range Granite.

Although many types of derivative dikes have been noted, two major rock types make up the bulk of the batholith in the area of this study: (1) a coarse-grained hornblende granodiorite, and (2) a fine-grained biotitic quartz monzonite. The coarse hornblende granodiorite is similar to the Intermediate phase of Allison (1925) but with an increase in quartz content grades locally into the Embarrass phase (Allison, 1925; Leith, 1903). It is pink or red, has large (1/4-1 1/2 in.) oblong euhedral grains of microcline and elongate hornblende prisms, and locally contains large rounded grains of blue quartz. The large euhedral crystals of microcline show apparent oscillatory-zoning rings on some weathered surfaces. The feldspars, and less commonly the hornblende, define a good foliation; lineations are less well developed. Border phases are generally more mafic.

The biotitic quartz monzonite makes up much of the western part of the batholith (Allison, 1925), but in this area occurs only as scattered small intrusions and dikes. It is gray to light pink in color, fine- to medium-grained, and even-textured. Pods of this phase near Birch Lake commonly contain abundant gneiss inclusions. Where relations can be observed, the biotitic phase is younger than the hornblende granodiorite.

Several general varieties of granitic rocks have been observed as dikes in the gneisses and the batholithic granodiorites. In order of decreasing age these are:

(1) Hornblende granodiorite and trondhjemite similar to the batholithic rocks. These are generally found in the gneiss and are cut by the regional foliation, folded, and show boudinage structures.

(2) Pink feldspathic quartz monzonite containing 1/16-1/8 in. square euhedral crystals of microcline. Commonly the dikes have foliated margins; where they occur in the gneisses they may or may not be cut by the regional foliation.

(3) Fine-grained biotitic granodiorite or quartz monzonite, as described above.

(4) Red fine-grained aplites. These dikes are especially common near Birch Lake, where they are parallel to the major faults and commonly are sheared along their length.

Pegmatites apparently were intruded throughout this time sequence and later; they cut and in turn are cut by most of the other dike rocks. Many pegmatites and dikes of types (1) and (2) in the gneisses are folded.

Preferred orientation of the feldspars defines a foliation in most outcrops of the coarse-grained hornblende granodiorite. The foliation of the granodiorite is parallel to the observed contact with the older rocks; this parallelism was observed as far as two miles from the contact. Where the foliation has been mapped near inferred contacts, it probably parallels the trend of the contact. Narrow zones of foliated granite locally crosscut the regional foliation of the batholith. These zones are parallel to the major faults and appear to be healed shears, which affected the granite before it was completely solidified.

Many gneiss outcrops near the granite contacts are intruded by two or more generations of granitic dikes. In many outcrops the first dikes emplaced are intruded parallel to the layering of the gneisses; later dikes may transect the layering. Dikes are very abundant only within 1/4 mile of the contact.

In some areas the country rocks near the contact have been coarsened and feldspathized by the granite. All of these effects, however, are limited to narrow zones near the contact of the gneisses with fresh, clearly distinguishable hornblende granodiorite.

Although most of the batholithic granitic rocks are devoid of inclusions, some small areas contain many inclusions.

Mode of Intrusion. Several points bear on the intrusion of the batholith:

(1) The batholith is elongated parallel to the regional structure, conforms in some detail to the structure in the country rock, and is pervasively foliated parallel to its margins.

(2) The folding and boudinage of dikes, and the cutting of dikes and the body along the Waasa fault by the regional foliation, indicate intrusion prior to cessation of regional deformation. However, the dikes all retain their igneous textures.

(3) The granite is cut by large faults which appear to have been active previously during the regional deformation (see below). There is some evidence that the faults affected the granite before it was solidified, and that faults had some effect on the loci of emplacement. This implies a relatively shallow emplacement.

(4) Inclusions are generally scarce except at contacts, and metasomatism is not extensive.

This evidence indicates that the batholith is dominantly a late kinematic forceful intrusion that was emplaced at relatively shallow depths, and whose emplacement was largely controlled by pre-existing folds, faults, and regional foliation in the country rocks.

Petrography

Ely Greenstone

The Ely Greenstone consists of pillowed metabasalts, interbedded with fine-grained tuffaceous layers and discontinuous lenses of cherty iron-formation. Sedimentary rocks apparently predominate in the Isaac Lake quadrangle. The eastward increase in metamorphic grade from Tower toward Babbitt renders the greenstones progressively more schistose, and many rocks mapped as sedimentary may be schistose volcanic rocks.

Volcanic Rocks. The rocks of the Ely Greenstone in the northwest corner of the Issac Lake quadrangle are medium-grained metablastic hornblende-plagioclase gneisses. The plagioclase occurs either as narrow laths or equidimensional grains; compositions range from An_{55} to An_{65}. Hornblende is the dominant mineral and has the pleochroic formula Z = blue-green, X = tan, Y $\doteq$ dark green. Epidote occurs in prismatic grains in some samples but is apparently a retrograde mineral in others. Diopside locally coexists with hornblende and plagioclase. Sphene and pyrite are common accessory minerals.

Sedimentary Rocks. The sedimentary rocks of the Ely Greenstone are distinguished from the flows by having a poorly- to moderately-developed compositional layering on the scale of millimeters to centimeters, detrital quartz grains, and generally more calcic compositions. Compositional layering in the sedimentary rocks of Zone 1 typically results from variations in hornblende content, but in some rocks at the west end of the area quartz-plagioclase-biotite-hornblende-epidote and quartz-plagioclase-hornblende-epidote-calcite assemblages are interlayered. In the sedimentary rocks of Zone 2, compositional layering is much more pronounced. Layers of plagioclase, diopside, and epidote alternate with hornblende and/or hornblende-plagioclase layers on all scales. The more calcic layers commonly have boudinage structure. Foliations and lineations are typically better-developed in the sedimentary than in the interbedded volcanic rocks.

The high-grade sedimentary rocks of the Ely Greenstone in Zone 2 are thinly (1 mm to 2 cm) laminated nematoblastic hornblende-plagioclase (-diopside) gneisses with interlayered plagioclase-diopside-epidote granulites having boudinage structures. The amphibolitic gneisses consist primarily of well-aligned prisms of dark blue-green hornblende. In some sections two generations of hornblende having mutually perpendicular orientations were found. Plagioclase (An_{60-65}) generally occurs in poorly twinned equidimensional grains, strongly altered to epidote and/or sericite. Quartz commonly occurs as small rounded grains. Diopside generally occurs as rounded to euhedral pale green grains. The fine layering of these rocks reflects variations in the proportions of plagioclase, diopside, and hornblende. Pyrite, magnetite and sphene are common accessory minerals; poikiloblastic garnet occurs rarely. Epidote is abundant, but only as a retrograde mineral replacing plagioclase, hornblende, and diopside.

The calcic layers consist dominantly of diopside, calcic plagioclase, and secondary epidote. These layers have been pulled apart into lensoid pods; the centers of the pods generally consist of diopside and coarse-grained epidote which decreases in grain size toward the edges, where the pod is surrounded by a jacket of calcic plagioclase. The outer margins of the pods commonly show interlayering of diopside-plagioclase and hornblendite layers. In many of these pods, plagioclase and diopside are replaced by large poikioloblastic masses of epidote; commonly the whole pod may consist of epidote that has inclusions of the original minerals. A section across a typical pod reveals the following sequence of layers:

(1) hornblende + plagioclase

(2) hornblende + plagioclase + diopside

(3) poikioblastic diopside enclosing plagioclase grains

(4) coarse poikiloblastic epidote, enclosing diopside grains – passes inward into granular epidote

(5) coarse granular diopside

(6) thin selvedge of altered plagioclase

(7) coarse poikiloblastic epidote enclosing diopside

(8) center of pod – very coarse-grained epidote enclosing diopside grains

(9) granular diopside

(10) thin selvedge of chloritized hornblende

(11) diopside and altered plagioclase, with small poikiloblastic epidote grains

(12) thin prehnite seam

(13) hornblende

(14) hornblende-diopside-plagioclase (An_{65}). Plagioclase locally is altered to epidote.

In these pods the epidote is apparently secondary; it is typically poikiloblastic, replaces the calcic plagioclase, and tends to be concentrated along certain foliation planes. The first step in its development appears to be the replacement of plagioclase in diopside-plagioclase pods by microgranular epidote. This microgranular alteration product recrystallizes to prismatic epidote, which rapidly enlarges to poikiloblastic masses. At least locally, the epidote replaces diopside and hornblende as well as plagioclase. The association of prehnite and chlorite with the epidote also supports a retrograde origin for the epidote, although some chlorite is clearly later than the epidote.

Most of the boudins studied here are of the "chocolate-bar" type, necked in two nearly perpendicular directions. Field relations suggest two noncontemporaneous tensional episodes. The relations of the epidote to the overall structure of the pods suggests that water may have been introduced along foliation planes during or after the second of these episodes.

Iron-formation

Iron-formation is not exposed within Isaac Lake quadrangle. A sample from the southwest corner of the Eagles Nest quadrangle, just north of Isaac Lake quadrangle, is a poorly banded, very lean magnetite iron-formation. Quartz occurs in large flattened grains having sutured boundaries and undulatory extinction. Magnetite forms large anhedral to subhedral grains; it is replaced by pyrite and minor chalcopyrite. The mafic silicates are concentrated in layers consisting entirely of coarse-grained colorless monoclinic amphibole and large chloritized grains of monoclinic pyroxene. Calcite is locally present as late fracture-fillings.

Meta-Sedimentary and Meta-Volcanic Rocks

Gneisses of Zone 2. The gneisses of Zone 2 (no relict textures, no migmatization) include both a group of layered gneisses and the fine-grained biotitic Argo gneiss. The layered gneisses consist of hornblende-plagioclase and quartz-feldspar-biotite-hornblende gneisses, interlayered on all scales. These gneisses have granoblastic to nematoblastic textures, and display no textural features which could be interpreted with certainty as relics from sedimentary or volcanic parent rocks.

The gneisses of Zone 2 in the Isaac Lake quadrangle are folded only locally. The interlayered felsic and amphiobolitic gneisses are in general less quartz-rich than their counterparts to the west.

The felsic gneisses are well-foliated and poorly-lineated quartz-plagioclase (-microcline)-biotite-hornblende gneisses. Many have even-grained granoblastic textures, but others contain large rounded to irregular quartz grains, which may be flattened in the plane of foliation.

Interlayering of biotitic and amphibolitic, or mafic and felsic, rocks on scales from 5 to 15 mm is common. In some rocks layering is due to alternation of microcline-rich and microcline-poor compositions; in such cases the microcline is commonly poikiloblastic and appears to have been introduced.

Strong sericitization of plagioclase accompanies in thin mylonitic seams either parallel to or oblique to the foliation. K-feldspar may show pronounced replacement textures along the shear zones, locally becoming poikiloblastic.

Generally quartz forms rounded to elongate grains flattened parallel to the foliation, but locally it occurs as smaller grains that coalesce to form large irregular to subpoikilitic masses. Rare large (1-2mm) mono-crystalline grains suggest volcanic relics; such large grains may be broken down into granular aggregates having sutured grain boundaries. Undulatory extinction is very common; locally the strain has induced in quartz a 2V of more than 5°.

Plagioclase compositions range from An_{27} to An_{35}; albite twins are ubiquitous. Sodic rims are common. Grains are generally granoblastic, but may become subhedral with continuing recrystallization; such subhedral grains may contain quartz and biotite inclusions. Sericitization is locally extreme.

Microcline locally is present as abundant equidimensional grains and as interstitial patches. In some specimens the microcline is concentrated in bands and appears to have replaced plagioclase. Replacement textures along grain boundaries and myrmekitic replacement of plagioclase are common.

Biotite is ubiquitous but varies widely in abundance. Pleochroism is straw yellow to dark brown or reddish brown. Pleochroic haloes are rare. Feathery masses of greenish secondary biotite locally replace the larger flakes of brown primary biotite. Most biotite is altered to pennine and in some cases is contorted and develops pods of K-feldspar or epidote.

Hornblende varies widely in abundance. It generally forms anhedral to subhedral prisms which are poorly to moderately aligned. The pleochroic scheme is Z = blue-green, X = light brown to tan, Y = green to dark green. Alteration products include chlorite and epidote, especially near shear zones. Pale green diopside occurs rarely as trains of rounded grains intergrown with quartz, hornblende, and microcline.

Sulfides occur in euhedral to rounded grains, altered to limonite and rimmed by epidote. Oxides are locally abundant as rounded grains but are generally absent. Apatite is typically present as scattered small rounded grains but may be locally abundant. Sphene is less common than apatite and occurs mainly as small droplike grains, some of which induce pleochroic haloes in hornblende. Allanite may form orange-red cores in epidote grains.

The amphibolitic gneisses of Zone 2 in the Isaac Lake quadrangle consist of hornblende and calcic plagioclase with variable amounts of quartz, biotite, and diopside. Compositional and/or textural layering on scales from 1/4 - 1 1/2 in. is common. Locally mafic and felsic layers alternate, but generally the variation involves the proportions of diopside, hornblende, and plagioclase. Some samples contain large rounded quartz grains which may be relict volcaniclastic detritus.

Hornblende is generally well aligned, but the development of foliation varies from sample to sample. Locally there appear to be two perpendicular lineations of the hornblende within the foliation, but no relations were established. Shear planes at an angle to the layering are common. Rarely there are narrow bands, without visible displacement and at an angle to bedding, in which plagioclase is "freshened" and hornblende is bleached.

Quartz is generally absent or minor. It is mostly unstrained, though larger grains may be flattened either parallel to the foliation or to shear planes oblique to bedding. In finer-grained or less mafic layers quartz may comprise as much as half of the felsic constituents. Rare, large monocrystalline grains suggest relict volcaniclastic debris.

Plagioclase (An_{45}) makes up nearly 50 percent of most amphibolitic gneisses. It is typically altered either to sericite or to microgranular epidote. Albite twinning is present in all unaltered samples. Individual grains are generally granoblastic but tend toward subhedral outlines. Some plagioclase, commonly poorly-twinned, forms rims surrounding pods of diopside. No zoning was noted. No microcline was found within the amphibolites.

Biotite locally replaces hornblende or occurs in thin layers. Nearly all the biotite is altered to chlorite, lensoidal pods of K-feldspar or prehnite, and large grains of epidote.

Diopside occurs locally as large to small rounded pale green grains associated with plagioclase and hornblende, or only with plagioclase. It also occurs as poikiloblastic subhedral grains in large monomineralic pods jacketed by plagioclase. No replacement of hornblende by diopside was noted.

Hornblende occurs in medium to coarse anhedral to subhedral prisms. In most specimens it defines a good lineation but a moderate to poor foliation. The pleochroic scheme is Z = blue-green, X = straw yellow to light brown, Y = dark green to olive green. Inclusions of sphene and apatite are common. The hornblende is replaced in some rocks by chlorite or by large vermicular masses of epidote. Next to the epidote, hornblende is altered to a high-birefringence amphibole, probably cummingtonite, which is optically continuous with the hornblende. The masses of epidote are locally poikiloblastic, enclosing several hornblende and/or diopside grains. Epidote also occurs as a microgranular alteration product of calcic plagioclase; locally this dusty epidote recrystallizes to large clear poikilitic grains with diopside inclusions in former diopside-plagioclase layers.

Oxide grains occur only in one sample; they are replaced by sulfides, which are nearly ubiquitous. Apatite is common in medium-sized rounded grains. Sphene is common, and is locally abundant as small rounded grains. Prehnite occurs as radiate prisms replacing plagioclase, forming pods in altered biotite, and filling shears. Calcite occurs as shear fillings – K-feldspar-epidote-prehnite-calcite – and as irregular pods and patches within altered areas.

The rocks of the Argo gneiss were metamorphosed predominantly under conditions of Zone 2 as defined above. They generally show good layering, but retain no relict textures, and they are not migmatized. Locally, in the southeastern part of the mapped area, they are swirled about and show signs of anatexis and plastic deformation, typical of Zone 3.

The quartzose gneisses which make up most of the Argo gneiss are fine- to medium-grained quartz-plagioclase-biotite (-hornblende) gneisses having well-developed granoblastic textures. The abundant biotite generally defines a good foliation, and quartz and plagioclase may be flattened in the plane of the biotite foliation. Some quartzose gneisses show rough lamination of hornblende-rich and biotite-rich layers, or thin layers of hornblende, but the majority are not layered on the scale of a thin section. Thin hornblende-plagioclase-biotite layers (2-12 in.) occur locally within the quartzose gneisses.

Modal analyses of four quartzose gneisses from the Argo gneisse are given in Table 2. Quartz is abundant and generally occurs in small to medium-sized (0.1 mm) granoblastic grains. Locally, and especially near faults, the quartz grains become larger and irregular in outline. Undulatory extinction is ubiquitous, and is most pronounced in large grains.

Table 2 – Modes of Argo gneiss

Component	64-8a(1)	M12699	M12969a	M12972
Quartz	21.9	30.1	20.7	27.1
Plagioclase	51.8	58.6	53.5	46.0
K-feldspar	0.1	0.9	8.9	–
Biotite	25.5	9.5	8.1	26.2
Hornblende	–	0.3	8.3	–
Muscovite	–	–	–	–
Epidote	–	0.2	0.5	–
Opaque	0.7	0.2	–	0.2
Apatite	–	–	–	0.5
Sphene	–	0.2	–	–
Percent An in plagioclase	30	29	29	30

(1)Numbers refer to samples on file with the Minnesota Geological Survey.

Plagioclase occurs as equidimensional, straight-sided grains, compositions range from An_{25} to An_{44} and average about An_{30}. Most grains show zoning from calcic cores to sodic rims. No antiperthite was noted in the quartzose gneisses.

K-feldspar is rare in this unit; it is found as tiny interstitial patches of microcline, which appear to replace plagioclase and quartz along grain boundaries. One sample does contain abundant microcline in granoblastic grains showing no replacement textures.

Biotite is omnipresent as a primary metamorphic mineral in the quartzose gneisses. The color of X ranges from red-brown to very dark brown. Pleochroic haloes around allanite are abundant in about half of the samples and lacking in the rest. Epidote is associated with, and replaces, biotite; many epidote grains have allanite cores. Secondary biotite, lighter in color and having a fuzzy appearance, replaces hornblende as long poorly-defined flakes.

Hornblende is generally confined to certain layers or thin seams, but in some slides it occurs throughout the section. The pleochroic scheme is Z = blue-green, X = straw yellow to golden brown, Y = medium to dark green; absorption varies greatly. Most grains are anhedral to subhedral, and some have euhedral cross-sections. Partially to completely poikiloblastic grains occur locally. The hornblende grains generally are dimensionally aligned.

Sulfides are everywhere present as cubes or rounded grains, generally altered to hematite rims. Sulfides commonly coexist with rounded to irregular grains of oxides; locally the oxides rim and replace the sulfide. Apatite is commonly found in small rounded to euhedral grains. Sphene is less common, and generally in rounded or irregular grains.

Chlorite replaces biotite and hornblende. The chlorite is pleochroic from colorless to pale green and has a reddish or blue anomalous interference tint. Epidote also replaces hornblende, forming large vermicular masses completely surrounding, bleaching, and corroding hornblende grains.

Judged from two samples of thin, compositionally layered mafic layers, the hornblende is similar to that in the associated rocks. Plagioclase is strongly sericitized, and quartz is a minor phase; biotite is common as a replacement of hornblende, especially near the margins of beds. Pyrite, apatite, sphene and epidote are accessory minerals.

Gneisses of Zone 3. The gneisses of Zone 3 include both layered gneisses, which consist of interlayered quartzose and amphibolitic rocks, and coarse-grained biotitic gneisses, which can be traced as thick layers within the layered gneisses. Parts of the layered gneisses are intruded and migmatized by leucotrondhjemites which were metamorphosed to gneisses following their intrusion.

The modes of ten quartzose gneisses from Zone 3 are given in Table 3. The quartzose gneisses are well-foliated quartz-plagioclase (-microcline) -biotite (-hornblende) gneisses that show wide variations in texture and color index. In many specimens plagioclase forms equidimensional straight-sided grains, and quartz grains are rounded or ovoid and have smooth boundaries. However, most of these rocks have granoblastic plagioclase but more irregular quartz; in a few rocks the plagioclase is recrystallized locally to subhedral outlines, whereas quartz may be poikiloblastic. Plagioclase porphyroblasts that contain quartz inclusions are rare. Compositional layering is the only relict sedimentary feature recognized in the quartzose gneisses.

Quartz is ubiquitous and invariably shows undulatory extinction. Plagioclase ($An_{23} - An_{50}$) is the dominant mineral. Both albite and pericline twins are common. Antiperthite is present in 15 of 22 samples, but is rare in seven. Small blocky blebs of microcline are commonly concentrated in cores of antiperthite grains, but may form annular or irregular patterns. Several samples have patchy or stringy antiperthite textures which suggest replacement of plagioclase by microcline. Antiperthitic plagioclase is generally zoned about the concentrations of microcline blebs. Sericitization is locally heavy.

Microcline also occurs as small interstitial patches, replacing quartz and plagioclase along grain boundaries, and rarely as equidimensional grains. Where antiperthite is rare or absent, little or no interstitial microcline is found.

Biotite is ubiquitous but varies widely in abundance. The pleochroism is from straw yellow or golden brown to reddish brown or dark brown. Pleochroic haloes surround inclusions of allanite, which is commonly jacketed by retrograde epidote. Chlorite is a common alteration product. In several sections the biotite is broken down to lensoidal pods of K-feldspar, parallel to the folia and accompanied by trains of tiny oxide grains.

Hornblende is rare to abundant in several samples. In most cases the hornblende is anhedral and defines neither a good foliation nor a lineation. Larger grains are commonly filled with quartz and plagioclase inclusions.

Pleochroic scheme is Z = blue-green, X = light brown to golden brown, Y = green to very dark green; absorption varies widely. Not uncommonly, the hornblende is replaced by long narrow biotite flakes, which grew in part along the amphibole cleavages. Epidote locally replaces hornblende, and may be accompanied by intervening zones of cummingtonite.

Both oxides and sulfides occur as either rounded or cubic grains. The two may coexist or the oxides may replace the sulfide. Sphene is not common; it generally is associated with hornblende or forms rims on oxide grains. Apatite occurs commonly as small euhedra or as larger rounded grains.

The modes of eight amphibolitic gneisses from Zone 3 are given in Table 4. The amphibolitic gneisses consist essentially of hornblende and plagioclase, accompanied by variable amounts of quartz, biotite, and diopside. Although quite uniform in mineralogy, they show wide variation in grain size and texture.

The fine- to medium-grained amphibolites generally have well-developed granoblastic to nematoblastic textures. The long axes of the amphibole are aligned so as to define a foliation or lineation in some rocks, notably those with primary mineralogical layering. Ovoid to elongate grains of quartz are commonly aligned to define a foliation, but plagioclase is generally equidimensional or randomly oriented. Primary biotite, which is rare, is parallel to the foliation.

Coarser grained amphibolites typically have much more uneven granoblastic textures, with more equant hornblende, and commonly have neither foliation nor lineation. The hornblende is commonly poikiloblastic, and the plagioclase tends to be subhedral and to enclose numerous rounded quartz inclusions. This coarse-grained uneven-textured amphibolite is locally interlayered with finer-grained and more even-textured material of about the same composition. Gradiations between the two types have been noted in outcrop, both along and across the strike.

Interlayering of mafic and felsic materials on the scale of a few millimeters is common. The two examples of diopsidic amphibolite have interlayering of hornblende-diopside-plagioclase units and diopside-plagioclase units on the scale of 5 mm. One sample has rounded areas containing several large quartz grains grouped together; these might represent former quartz phenocrysts.

Quartz is rarely abundant and is rare in several specimens. The grain size is proportional to the abundance of quartz. The larger grains have undulatory extinction, whereas small grains are unstrained. Near shear zones larger quartz grains may be polycrystalline and have sutured internal boundaries.

Plagioclase in the fine- to medium-grained gneisses generally is equidimensional and straightsided, and has few inclusions. In coarse-grained gneisses the plagioclase tends to be subhedral and to enclose many small subrounded quartz inclusions. Plagioclase ranges in composition from An_{24} to An_{47} and generally is zoned. Large grains have a sodic center and are continuously zoned to more calcic outer parts; a sodic rim is then superposed on this core. The result is a calcic annulus, grading slowly to a sodic center and more sharply to a sodic rim. Smaller grains may have only the sodic rim and a relatively calcic center. In some specimens all plagioclase shows only sodic rims and calcic cores. In three samples small antiperthitic blocks of microcline occupy the sodic centers of large plagioclase grains.

In addition to the microcline within antiperthite, two samples contain interstitial microcline which replaces plagioclase along grain boundaries and surrounds quartz inclusions within plagioclase. Other samples are devoid of K-feldspar.

Table 3 – Modes of quartzose gneisses of Zone 3

Phase	64-5b	64-11a	M12577c	M12596c	M12622a	M12720	M12723a	M12723b	M12759b	M12963b
Quartz	37.0	19.5	8.9	25.8	21.5	24.7	28.5	24.3	24.4	30.2
Plagioclase	49.8	53.2	79.3	64.4	63.9	65.5	62.0	63.2	60.2	53.9
K-feldspar	3.2	1.6	3.8	0.9	0.5	0.2	2.9	1.0	–	3.7
Biotite	9.2	10.2	1.4	7.9	7.1	9.2	4.9	–	4.0	8.3
Hornblende	–	12.4	5.3	0.1	6.4	–	0.1	10.2	10.2	1.9
Epidote	0.6	2.3	1.3	0.8	0.6	–	0.6	0.5	–	1.4
Muscovite	–	–	–	–	–	–	0.3	–	–	–
Opaque	0.2	–	–	0.1	–	0.4	0.6	0.4	1.1	–
Apatite	–	–	–	–	–	–	0.1	–	0.1	0.1
Sphene	–	0.8	–	–	–	–	–	0.4	–	0.5
Percent An in plagioclase	35	27	20	27	26	28	35	28	50	12

Table 4 – Modes of amphibolitic gneisses

Phase	64-14a	M12549b	M12605	M12617b	M12694	M12718	M12759a	M12961
Quartz	1.0	7.2	4.1	8.2	5.2	2.9	2.6	8.4
Plagioclase	56.3	36.0	31.2	53.1	57.6	34.0	39.5	42.7
K-feldspar	0.2	–	–	–	–	0.1	–	–
Biotite	–	–	0.4	0.7	0.7	–	–	0.4
Hornblende	40.6	50.8	61.4	37.6	34.4	44.5	56.6	47.5
Epidote	1.5	–	–	0.1	0.1	0.8	–	–
Opaque	–	5.9	–	0.3	1.5	0.8	1.1	0.6
Apatite	0.3	0.1	0.1	–	0.5	0.1	0.2	0.4
Sphene	0.1	–	0.1	–	–	1.7	0.2	0.4
Diopside	–	–	–	–	–	15.1	–	–
Percent An in plagioclase	28	35	24	40	30	30	44	47

Biotite occurs rarely as a primary metamorphic mineral and more commonly as secondary flakes that cut hornblende. The occurrence of secondary biotite suggests that K_2O was introduced into the amphibolitic gneisses during the metamorphism; the subsequent alteration of most biotite further suggests that the introduction took place either during prograde or early retrograde metamorphism.

Locally diopside is common as rounded to euhedral grains and is pleochroic in shades of green. The diopside is replaced along cleavages by a brownish-yellow serpentine or chlorite. No disequilibrium with hornblende or plagioclase was noted.

Hornblende, which makes up 30 to 60 percent of the amphibolites, has the pleochroic formula: Z = blue-green, X = straw yellow to golden brown, Y = dark green. No brown hornblendes were found. Colors are generally so dark as to locally mask the interference tints. The grains range from anhedral to euhedral in cross section. Poikiloblastic hornblende containing rounded inclusions of quartz, plagioclase, apatite, and opaque minerals – sulfides as well as oxides – is common.

Hornblende is replaced by secondary biotite, as discussed above, and by vermicular masses of epidote. Adjacent to the epidote masses the hornblende is altered to a colorless high-birefringence amphibole (cummingtonite ?) in optical continuity with the host hornblende. The reaction may have been CaMgFe amphibole $\rightarrow$ MgFe amphibole + epidote. Locally the hornblende is replaced by a pale green chlorite.

Oxides are much more common than sulfides; in four of the eight thin sections in which sulfides were noted the sulfides have oxide rims. Sphene is locally abundant, and forms rims on oxide grains. Apatite is nearly ubiquitous as small rounded to euhedral grains, but also occurs in large rounded grains similar to those in the low-grade volcanic rocks. Allanite occurs locally as a common accessory mineral and forms cores of epidote grains. Retrograde minerals include chlorite, epidote, sericite, and prehnite. In some samples prehnite replaces plagioclase, and in others it fills thin shear zones and replaces plagioclase next to the shears.

The modes of seven coarse-grained biotitic gneisses are given in Table 5. Some coarse-grained biotitic gneisses have distinct granoblastic textures, but the quartz grains in most specimens tend to coalesce and are irregular or branching. Plagioclase occurs as coarse subhedral grains that have inclusions of quartz or smaller differently-oriented plagioclase grains. Some sections show trains of granoblastic plagioclase between very large lensoid quartz grains. Others vary from granoblastic to subgranitic in texture over the thin section, whereas still others have essentially a granitic texture with subhedral plagioclase and irregular interstitial quartz grains. No mineralogical layering or other primary features were noted. Compositions and textures vary widely along the strike of single layers.

Quartz generally forms large ovoid to very irregularly-shaped grains having very irregular borders and undulatory extinction. These large grains are commonly monocrystalline, but in some cases have apparently formed by the coalescence of several smaller grains of different orientations. Many are poikiloblastic and envelop plagioclase and biotite grains.

Granoblastic to subhedral plagioclase, ranging in composition from An_{23}-An_{28} and average An_{25}, is the major mineral in all specimens. Much of it is zoned and/or antiperthitic; twinning may be obliterated in such grains. The most common type of antiperthite contains small oblong blocks of microcline that are elongated parallel to the cleavage of the plagioclase. Nearly as common, however, is "patchy" antiperthite in which the microcline forms rounded to irregular patches which suggest replacement origin. Microcline also occurs locally in spindle-shaped rods, widening locally into patches, along the cleavage of the plagioclase.

Microcline other than that in antiperthite generally occurs as interstitial and intergranular patches and films, commonly poikiloblastic and visibly embaying and corroding the larger quartz and plagioclase grains. Myrmekite is locally developed between plagioclase and microcline. Microcline occurs as separate granoblastic grains in three sections, but even in these sections replacement of plagioclase and quartz by microcline was observed.

Biotite occurs in long, well-aligned grains, especially when more abundant, or in shorter, blocky flakes. Pleochroism is from straw yellow or golden brown to very dark brown or reddish brown. Biotite is commonly altered to chlorite – pale green pennine – and associated epidote, some grains of which contain allanite cores.

Hornblende occurs as a minor constituent in some sections. It is generally in small to medium-sized anhedral grains. The pleochroic formula is Z = blue-green, X = tan, Y = green. In one section it is replaced by biotite.

Sulfides and oxides are rare. Apatite and sphene also are rare and do not occur together. Allanite occurs as large or small grains surrounded by thin rims of epidote with a narrow gradational zone between the two minerals. Plagioclase generally is weakly sericitized. Muscovite occurs in several slides as small ragged flakes along the edges of biotite grains or between quartz and plagioclase grains.

The leucotrondhjemitic gneisses of Zone 3 are poorly foliated medium-grained quartz-feldspar gneisses that have very low color indices and uneven textures. A few have granoblastic textures, despite their clearly intrusive relations in outcrop. The majority, however, have a hybird texture in which plagioclase is granoblastic to subhedral. Quartz is in large, very irregular grains, which range from ovoid pods with digitated borders, to larger multi-branched grains, to poikilitic or subpoikilitic patches of quartz having plagioclase inclusions. Invariably such large quartz grains are intensely strained. Some specimens contain large (1-1.5 cm) subhedral plagioclase porphyroblasts with quartz inclusions. These porphyroblasts are typical of the orthogneisses in the migmatized area in the east-central part of the Embarrass quadrangle. No relict igneous textures were recognized; where plagioclase is subhedral it appears to have attained that shape through metamorphic recrystallization. It seems likely that the original intrusive rocks were fine-grained. Some samples have a rough foliation due to flattening of quartz grains, and biotite may be aligned parallel to this foliation. Modes of eleven leucotrondhjemites are given in Table 6.

Plagioclase, which ranges in composition from An_{13} to An_{30} and averages about An_{20}, is the predominant mineral in most sections. Much of the plagioclase is zoned and antiperthitic; antiperthite is absent only in one section. Most is "blocky antiperthite," in which microcline forms sharp-edged oblong blocks 0.01-0.03 mm long, aligned parallel to the cleavages of the plagioclase. Such blocks vary in abundance and constitute as much as 30 percent of some plagioclase grains. In other cases the antiperthitic microcline forms irregular patches and stringers within the plagioclase.

Microcline also occurs in most samples as small irregular interstitial patches that replace quartz and plagioclase. Myrmekitic patches are common between

Table 5 – Modes of coarse-grained biotitic gneisses

Phase	M12537a	M12550	M12581	M12623a	M12712	M12957	M12962a
Quartz	21.5	47.9	24.7	41.5	34.9	37.6	33.7
Plagioclase	59.3	45.2	63.0	51.1	57.9	53.5	50.2
K-feldspar	0.5	2.1	4.6	2.8	5.1	1.4	11.2
Biotite	17.9	3.6	6.4	4.3	0.6	7.0	4.8
Hornblende	–	–	1.3	–	–	–	–
Muscovite	–	0.4	–	–	1.4	–	–
Epidote	–	0.9	–	0.4	–	0.5	–
Opaque	0.9	–	–	–	0.1	–	0.4
Percent An in plagioclase	17	25	22	24	26	20	22

Table 6 – Modes of leucotrondhjemitic orthogneisses

Phase	M12514c	M12548a	M12548c	M12579a	M12587	M12592b	M12607a	M12608	M12626b	M12655	M12965
Quartz	41.5	32.7	29.0	42.1	32.5	16.0	28.8	38.1	34.9	36.4	35.4
Plagioclase	57.1	60.7	66.0	51.2	64.6	72.3	67.8	55.7	62.5	59.0	60.0
K-feldspar	1.0	3.3	3.0	0.2	2.2	2.1	2.4	3.3	1.9	1.3	1.9
Biotite	–	3.1	1.2	4.3	0.5	3.4	0.9	2.9	0.3	3.0	0.8
Hornblende	–	–	–	–	–	4.3	0.1	–	–	0.3	–
Muscovite	tr	–	0.7	0.2	–	–	–	–	–	–	–
Epidote	0.4	0.2	0.1	0.4	0.2	0.4	–	–	0.4	–	1.7
Opaque	–	–	–	1.6	–	0.7	–	–	–	–	–
Apatite	–	–	–	–	–	0.5	–	–	–	–	–
Sphene	–	–	–	–	–	0.3	–	–	–	–	–
Percent An in plagioclase	27	20	16	29	16	30	24	9	20	16	27

microcline and plagioclase. In some cases the interstitial patches are large enough to contain numerous inclusions of rounded quartz, plagioclase and myrmekite.

Mafic minerals are scarce in the leucotrondhjemitic gneisses. Biotite occurs sporadically in most specimens, usually as blocky, poorly oriented, very dark brown flakes. Near the edges of dikes, trains of large biotite flakes may parallel either the foliation or the edge of the dike. Hornblende is a minor constituent in some samples, occurring in small anhedral grains, pleochroic in blue and green.

Rounded oxide grains occur in six samples, sulfides in three; in one case the oxide replaces the sulfide. Apatite is present as small grains in five samples, whereas sphene is present in only two.

Epidote is common in small, often vermicular grains replacing biotite; some epidote rims grains of pyrite and oxides. Sericitization of plagioclase is generally light. Muscovite occurs in small ragged flakes in several samples.

Giants Range Granite

Most of the batholith within the mapped area is composed of coarse-grained hornblende- or biotite-bearing granodiorites – Intermediate phase of Allison, 1925 – characterized by large tabular phenocrysts of microcline as long as one and one-half inches. These grains and some plagioclase phenocrysts commonly define a foliation. More mafic quartz diorites and monzonites, generally having well-developed foliations and lineations, commonly occur near the contact with the gneisses. The mafic phases are especially common north of Birch Lake and on Bear Island in Bear Island Lake, to the northeast of the Isaac Lake quadrangle. These phases appear to be gradational into the granodiorites. Smaller bodies of mafic granodiorites, diorites, and trondhjemites occur in the gneisses of Zone 2 in the quadrangle. Fine-grained biotite granodiorites occur as small rounded bodies in the porphyritic granodiorites, and as dikes intruding both the porphyritic granodiorites and the gneisses. The different occurrences are relatively uniform in composition and texture.

Porphyritic Granodiorite. Modes of two porphyritic granodiorites are given in Table 7. The porphyritic granodiorites have allotriomorphic-granular to hypidiomorphic-granular textures. Quartz is abundant as anhedral and interstitial grains; locally, it forms large ovoid pods and has undulatory extinction.

Table 7 – Modes of porphyritic granodiorites

Phase	M12530a	M12531a
Quartz	17.3	12.7
Plagioclase	62.4	61.8
K-feldspar	14.4	14.2
Biotite	–	–
Hornblende	–	9.8
Chlorite	5.4	tr
Muscovite	–	–
Epidote	0.2	1.1
Apatite	–	–
Sphene	–	–
Opaque	0.3	tr
Percent An in plagioclase	16	16

Plagioclase (oligoclase), the dominant mineral, is anhedral in some specimens and in others forms subhedral phenocrysts that have Carlsbad-albite twinning. Zoning is absent, though some grains have strongly sericitized cores suggesting some differences in composition.

Microcline is nearly as abundant as quartz; it occurs as large tabular grains, interstitial patches, and rare anhedral patches within plagioclase grains. Many of the large "phenocrysts" are in part porphyroblastic, and contain abundant inclusions of plagioclase and quartz, especially near their edges. Myrmekite is common where microcline is in contact with plagioclase, and inclusions of plagioclase in large microcline grains may be completely converted to myrmekitic intergrowths of plagioclase and quartz. The interstitial patches all replace quartz or plagioclase.

Hornblende, the most common mafic mineral, forms large euhedral grains that typically are dimensionally aligned. The pleochroic formula is Z = bluish green, X = light brown, Y = olive green. Pleochroic haloes are common. Hornblende and biotite are commonly altered to masses of chlorite and epidote.

Accessory minerals are apatite, sphene, oxides and muscovite. The first two are ubiquitous as euhedra and small rounded grains. Oxides occur in large rounded grains. Muscovite is an alteration product of plagioclase.

Mafic Phases. The mafic phases generally have hypidiomorphic-granular textures but a more pronounced foliation and/or lineation than the granodiorites. Modes of four mafic phases are given in Table 8. Quartz occurs in minor quantities, mostly as small rounded or interstitial grains. Plagioclase forms numerous large elongate subhedral unzoned phenocrysts (approx. An_{25}) having Carlsbad-albite twins; it also occurs as small equidimensional grains. Plagioclase is commonly replaced by microcline. Apparently the first step in the replacement is the development of a thin sodic rim (An_{3-5}) against the microcline; albite twinning is continuous through the rim. Subsequently the rim is converted to myrmekite and finally replaced by microcline. Some microcline forms anhedral patches within plagioclase, and these are surrounded by more sodic zones.

Table 8 – Modes of mafic phases of Giants Range batholith

Mineral	M12520b	M12675	M12722	M12885
Quartz	37.6	23.7	26.5	5.6
Plagioclase	55.5	60.0	57.8	58.3
K-feldspar	0.6	1.7	8.0	19.0
Biotite	4.5	–	2.2	5.4
Hornblende	–	2.6	4.7	8.8
Chlorite	–	9.8	–	–
Muscovite	1.4	–	–	–
Epidote	0.6	1.7	0.4	–
Apatite	–	0.1	0.4	0.5
Sphene	–	0.5	0.2	0.8
Opaque	–	0.1	–	0.8
Percent An in plagioclase	nd	10	12	17

M12520b – Foliated trondhjemitic dike cutting gneisses
M12675 – Small stock in gneisses of Zone 2
M12711 – Large sill in gneisses south of Waasa fault
M12885 – Mafic phase of batholith north of Birch Lake

In the batholithic rocks, microcline also forms large subhedral phenocrysts that have Carlsbad twinning. Each phenocryst has alternating bands of non-perthitic and coarsely perthitic microcline which parallel crystallographic planes and simulate zoning. The outer edges of the phenocrysts are irregular, as the microcline has overgrowths which replace adjacent grains of quartz and plagioclase. Microcline is much less abundant in many of the smaller mafic bodies within the gneisses and tends to be entirely interstitial.

Mafic minerals include both biotite and hornblende, which commonly are grouped in trains with smaller grains of oxides, apatite, and sphene. The biotite is reddish brown and altered to intergrowths of muscovite, chlorite, and epidote. The hornblende occurs in large subhedral to euhedral grains, which commonly are poikilitic. Pleochroism is: Z = bluish green, X = tan, Y = olive green. The hornblende is bleached (to cummingtonite?) where replaced by biotite along cleavage planes.

Biotite Granodiorite. The biotite granodiorites are typically fine-grained hypidiomorphic to allotrimorphic-granular rocks containing abundant quartz in large and small rounded to irregular grains. Modes of three samples are given in Table 9. Plagioclase (An_{23} – An_{26}) commonly forms square phenocrysts which may show oscillatory zoning; calcic cores are generally sericitized. Albite twins are common, but Carlsbad twins are rare. No antiperthite was noted, but plagioclase and quartz are commonly replaced by microcline. Microcline also forms large anhedral porphyroblasts in which the calcic cores of plagioclase grains occur as inclusions. Zones of myrmekite commonly form where microcline replaces plagioclase.

Biotite is the only mafic mineral and generally is altered to chlorite. Pleochroism is pale yellow to very dark brown, and pleochroic haloes are common around allanite. Muscovite may be common as anhedral to poikilitic flakes that grow parallel to cleavages of plagioclase, and as replacements of biotite and quartz. Minor constituents include apatite, sphene, small oxide grains, and epidote.

Table 9 – Modes of biotite granodiorites

Mineral	M12704	M12898	M12957b
Quartz	25.9	24.4	25.6
Plagioclase	48.5	55.7	45.1
K-feldspar	20.3	25.2	26.1
Biotite	4.0	1.5	8.1
Hornblende	–	–	–
Chlorite	–	1.7	–
Muscovite	1.2	1.8	4.1
Epidote	0.3	0.9	0.9
Apatite	–		–
Sphene	–	0.2	0.2
Opaque	–	0.2	0.2
Percent An in plagioclase	23	24	24

M12704 – Small intrusive body in porphyritic granodiorite on Birch Lake
M12898 – Dike in porphyritic granodiorite
M12957b – Dike in gneisses, parallel to NE shearing

Dike Rocks. The dike rocks, an extremely heterogeneous group, were not examined in detail. All of the phases of the batholithic rocks were observed as dikes cutting the gneisses and/or one another. In addition, several lithologies were observed only as dikes. Modes of four rock types observed only in dikes are given in Table 10. In general these dikes tend to be more quartzose and more potassic than any of the major phases of the batholith.

Table 10 – Modes of granitic dike rocks

Mineral	M12611	M12618b	M12623b	M12886
Quartz	27.2	28.0	32.6	31.0
Plagioclase	43.0	38.9	45.5	41.7
K-feldspar	26.5	32.5	17.8	26.6
Biotite	–	–	–	–
Hornblende	–	0.8	–	–
Chlorite	0.9	–	2.5	tr
Muscovite	0.1	–	1.2	0.7
Epidote	–	–	0.4	tr
Apatite	–	–	–	–
Sphene	–	–	–	–
Opaque	2.8	–	0.2	tr
Percent An in plagioclase	32	30	33	4

M12611 – "Pink granite" dike in porphyritic granodiorite
M12618b – Dikes in high-grade amphibolites (Ely?) on islands in Birch Lake
M12623b – "Pink granite" dike in gneisses
M12886 – Aplite dike parallel to NE shearing in porphyritic granodiorite

Metamorphic Petrology

Mineral Assemblages

The distinction between Zone 1 and Zones 2 and 3 is based primarily on the presence of relict clastic and volcanic textures in the rocks of Zone 1 and the absence of such features in the higher-grade rocks. The major difference in mineralogy between Zone 1 and Zones 2 and 3 is the absence of epidote and calcite from the equilibrium assemblages in the higher-grade rocks. Isopleths marking the disappearance of these two phases are essentially parallel, and lie close to the Zone 1 – Zone 2 boundary, northwest of Isaac Lake quadrangle (fig. 3).

Gneisses of Zones 2 and 3. Disequilibrium textures – zoned and antiperthitic plagioclase, myrmekite, and replacement of plagioclase by microcline – are widespread in the higher-grade gneisses. Therefore, mineral assemblages cannot be rigorously determined. For instance, it is often difficult to determine whether any of the microcline in a rock was ever in equilibrium with the plagioclase. The following list contains associations of non-retrograde minerals; no statement is made concerning their approach to mutual equilibrium. The relation to lithologic types is shown in Table 11.

Table 11 – Lithologic distribution of mineral associations in gneisses from Zones 2 and 3

Assemblage	Amphib. Gneiss	Leucocr. Gneiss	Argo Gneiss	Cr. -gr. Leucocr. Gneiss	Trondhjem. Gneiss	Total
1	–	1	5	–	–	6
2	12	–	1	–	–	13
3	–	2	4	—	–	6
4	3	–	–	–	–	3
5	–	–	–	–	1	1
6	–	7	2	9	6	24
7	3	1	–	–	–	4
8	2	12	3	3	5	25
Totals	20	23	15	12	12	82

Quartz-plagioclase-bearing assemblages:

(1) Biotite

(2) Hornblende

(3) Biotite-hornblende

(4) Hornblende-diopside

(5) K-feldspar

(6) K-feldspar-biotite

(7) K-feldspar-hornblende

(8) K-feldspar-biotite-hornbelende

The small number of assemblages in Zones 2 and 3 is partially due to the instability of epidote and calcite under higher-grade conditions.

Mineral assemblages of the Ely Greenstone in Zone 2 are listed below, and their lithologic distribution is given in Table 12.

(1) Hornblende-plagioclase

(2) Hornblende-plagioclase-diopside

(3) Hornblende-plagioclase-quartz

(4) Hornblende-plagioclase-diopside-quartz

As shown in Table 12, only one rock definitely recognized as volcanic in origin was collected from the Ely Greenstone within Zone 2. Some schistose rocks mapped as Ely sedimentary rocks might actually be volcanic rocks. The limited range of compositions within the rocks sampled, and the instability of epidote, combine to reduce the number of observed assemblages from 13 in Zone 1 to four in Zone 2. No outcrops of undoubted Ely Greenstone were found in Zone 3.

Table 12 – Lithologic distribution of mineral assemblages in Ely Greenstone samples

Assemblage	Volcanic	Sediment	Total
1	1	1	2
2	–	4	4
3	–	1	1
4	–	3	3
Totals	1	9	10

Retrograde Metamorphism

The rocks of Zones 1 and 2 show the series of retrograde reactions common to medium-grade metamorphic rocks. Plagioclase is commonly altered to sericite and/or fine-grained epidote. Biotite is typically chloritized without changes in morphology, and hornblende also is chloritized locally. In a few rocks, chloritized biotite contains pods of prehnite between the folia. More generally, and especially in contorted biotite flakes, the pods consist entirely of low-Na (0.3-0.7 percent Ab) untwinned K-feldspar, rimmed in some cases by opaque granules. Wones and Eugster (1965) point out that this reaction might attend a rise in f_{O_2} at low temperatures.

As noted above, many of the leucotrondhjemite orthogneisses and leucocratic paragneisses in Zone 3 contain antiperthitic plagioclase. The relations between zoning and K-feldspar suggest that the antiperthites are replacement features formed during late-metamorphic alkali-infiltration metasomatism (Griffin, 1967b).

The retrograde history of the gneisses of Zone 3 is complicated by the effects of the metasomatism which produced the antiperthites. K_2O has been introduced into some amphibolites, altering hornblende to biotite and epidote along cleavage planes and shears. This metasomatic effect is most prevalent in the more schistose amphibolites.

In the biotitic gneisses, biotite flakes commonly show embayments filled with low-Ab K-feldspar and rimmed with opaque granules. The opaque mineral is finely divided and has not been identified directly. However, the presence of unoxidized magnetite grains in some sections, and the local rimming of pyrite by magnetite, suggests that the oxide resulting from the breakdown of biotite is magnetite, rather than hematite. Textural evidence of this biotite breakdown reaction has been observed in all antiperthite-bearing sections of biotite gneiss; but is rare or absent in many sections which lack antiperthite. This correlation suggests that a rise in f_{O_2} accompanied introduction of the K-Na-bearing fluid which effected the formation of antiperthites. Wones and Eugster (1965) give experimental T-f_{O_2} curves for this reaction. The Fe/Mg ratio of the biotite in sample M12537A is 0.67; assuming the opaque mineral is magnetite, the minimum T for this reaction at P = 2,070 bars is 520 degrees C.

In some high-grade amphibolites the hornblende is partially replaced by vermicular epidote; the epidote is separated from the hornblende by a narrow zone of cummingtonite. In addition to the reactions which may be linked to the metasomatic activity, the following generalized reactions have been observed: (1) chloritization of biotite, (2) breakdown of hornblende to chlorite and sphene, and (3) replacement of plagioclase by sericite and/or epidote.

Metamorphic Facies

Fyfe and Turner (1966) define a metamorphic facies as "a set of metamorphic mineral assemblages repeatedly associated with one another in space and time, such that there is a constant and therefore predictable correspondence between the mineralogy of each rock and its bulk chemical composition."

Within the conditions of medium-grade regional metamorphism, Fyfe and Turner (1966, p. 361) recognize two facies, the albite-epidote-amphibolite and the amphibolite (formerly almandine-amphibolite) facies. They note that plagioclase within the diagnostic basic assemblage of the amphibolite facies is more calcic than An_{20}, and is commonly accompanied by epidote. The granulite facies is defined by the appearance of two-pyroxene assemblages in metabasaltic rocks (Fyfe, Turner and Verhoogan, 1958, p. 232).

The Ely Greenstone amphibolites of Zone 1 contain plagioclase more calcic than An_{25}, accompanied by hornblende and epidote. In Zone 2, epidote disappears from the equilibrium assemblage, but no two-pyroxene assemblages were found. The rocks of the Ely Greenstone in the mapped area thus lie entirely within the amphibolite facies of Fyfe and Turner (1966).

Biotite, hornblende and plagioclase are the principal minerals of meta-sedimentary and meta-volcanic rocks in all three metamorphic zones; each of these minerals displays a wide range of solid solution. Changes in pressure, temperature, and bulk composition therefore tend to be reflected as variations in composition and relative abundances of these phases, rather than in the formation of new minerals. For this reason it has been impossible to map Barrovian-type mineral isograds within this area, despite the textural evidence for a regional metamorphic gradient.

Structural Geology

The Isaac Lake quadrangle includes part of a large inverted anticline, cored by greenstone, whose axis trends roughly in a northwestly direction (fig. 2). Minor folds on this structure are isoclinal or tightly apressed. Two major transcurrent faults and numerous faults with smaller displacements offset the eastern end of the major structure in the Isaac Lake quadrangle. The rocks strike northwest and dip steeply to the northeast over most of the area, but between the two major faults dips are generally to the southwest. Shallowly-plunging lineations parallel the axis of the major structure over most of the area, but steeply-plunging lineations perpendicular to this axis are well-developed in the northwestern part of the quadrangle. Statistical and petrographic analysis of foliations and lineations indicates two episodes of folding along mutually perpendicular axes.

Fabric Elements

Foliations have been measured at most outcrops of Lower Precambrian rocks. In the meta-sedimentary and meta-volcanic rocks of Zone 1, nearly all foliations are defined by parallelism of biotite flakes and also represent the attitude of primary bedding. In the higher-grade gneisses, the mineral foliations, as defined by parallel orientation of biotite, tabular plagioclase and flattened quartz grains, are everywhere parallel to lithologic layering. This layering is believed to be relict sedimentary bedding. In rocks of the Ely Greenstone the foliation locally was observed to be parallel to sedimentary layering and to elongation of pillows. In most foliated greenstones, however, no primary structures were available for comparison.

The following types of lineations were observed, in order of decreasing abundance within the quadrangle: hornblende alignment, axes of minor folds or crenulations, boudinage structures, biotite smears, corrugations, and bedding-cleavage intersections. In addition, the elongation of pressure shadows surrounding megacrysts was observed in thin section. Most outcrops display only one direction of lineation, and if two or more types of lineation are present, all of the types are generally parallel. In the northwestern part of the quadrangle, however, many outcrops display two mutually perpendicular lineations. The most common pairs contain perpendicular boudinage structure and hornblende alignment, or a hornblende alignment crossed by small crenulations.

Statistical Analysis of Macroscopic Fabric Elements

For purposes of statistical analysis the area was divided into three subareas, as shown in Figure 4. Subarea II extends into the Embarrass quadrangle and includes some data from that quadrangle. Subarea III includes data from

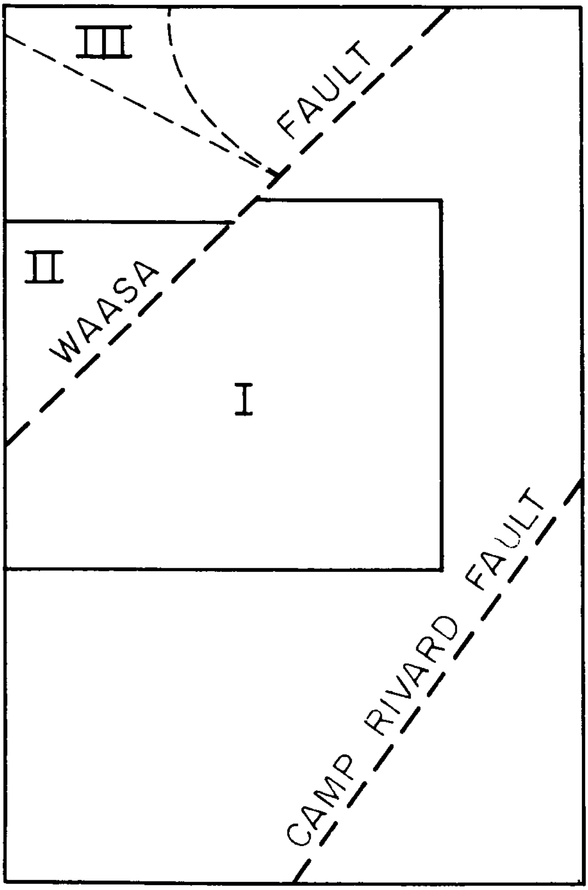
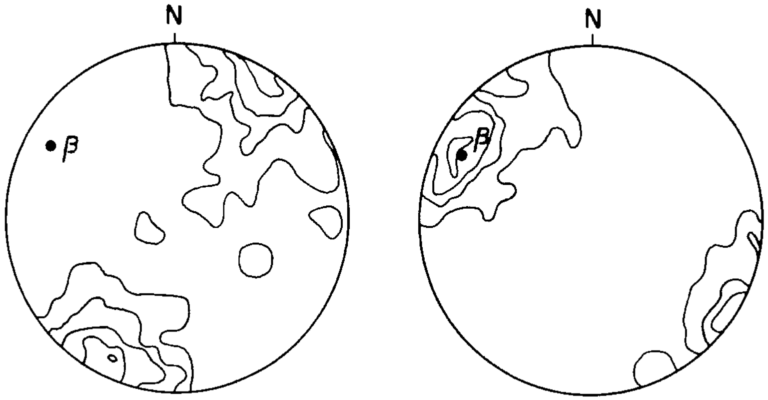


Figure 4. Area of the Isaac Lake quadrangle showing subareas used in statistical analysis of fabric elements.

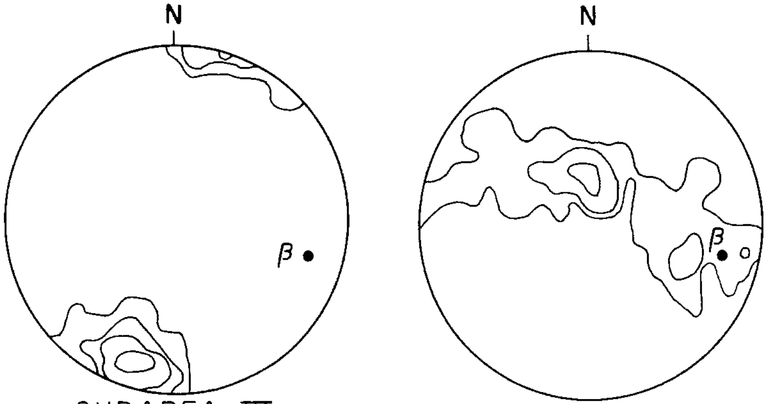
contiguous areas in the Eagles Nest and Soudan quadrangles. The lineations and poles to foliations were plotted on equal-area nets; each of the subareas is internally homogeneous with respect to these fabric elements. Subareas I and II may be grouped into a larger subarea, which displays homogeneous but more complicated patterns (fig. 5).

An S-pole plot for subareas I and II shows monoclinic symmetry and a weakly developed girdle. There is a suggestion of two girdles, or a broad scatter about one girdle, indicating that the folds are non-cylindrical. The lineation diagram contains a maximum corresponding roughly to the girdle pole β. As this direction roughly parallels the trend of the major fold, these lineations are correlated with the major fold axis B.



SUBAREA I & II
214 S-POLES
Contours 1/4, 2, 5, 10, 15%

SUBAREA I & II
100 LINEATIONS
Contours 1/2, 4, 8, 20%



SUBAREA III
91 S-POLES
Contours 1/2, 4, 12, 30%

SUBAREA III
68 LINEATIONS
Contours 1/2, 5, 15%

Figure 5. Equal-area diagrams of foliation and lineation in subareas I-II and III.

The S-pole diagram for subarea III displays a maximum corresponding roughly to that in subarea I. The lineations, however, appear to define two maxima and a great-circle girdle. This pattern is partly the result of combining two genetically different types of lineation. The maximum at 65°, N. 5° E. represents mostly mineral lineations in the greenstones and some gneissic rocks near the contact. The smaller maximum at 40°, S. 70° E. includes crenulations in the greenstone and mineral lineations in most gneissic rocks; much of the girdle to the west side of the diagram also is due to mineral lineations in gneissic rocks. The large maximum lies in the symmetry plane of the S-pole diagram, suggesting that it represents an A lineation. Petrographic evidence, such as pressure shadows, shows that this lineation parallels a direction of transport. The smaller maximum lies at about 90° from this direction and corresponds to the maximum in subarea I – II; it probably represents the axis of folding, B.

Faults

Two major transcurrent faults that cut and displace the Lower Precambrian rock units strike northeastward across the quadrangle. The western-most one, the Waasa fault, cuts diagonally across Waasa Township and extends through the northern arm of Bear Island Lake. Just south of Embarrass it transects granite in a rail cut; the granite is sheared and silicified adjacent to the fault. The second one, the Camp Rivard fault, is parallel to the northwest shore of Birch Lake, and extends northeastward through Spruce and Blueberry Lakes. Where it transects the granite southwest of Babbitt, the granite is intensely sheared, but only relatively minor shearing has been found along its strike on the Giants Ridge. The locations of the two faults are marked on aeromagnetic maps (Bath and others, 1965) by parallel bands of steep magnetic gradients bounding a magnetic low. The Camp Rivard fault is the more strongly marked of the two, and clearly offsets a magnetic high north of Birch Lake.

Where they transect the gneisses, the faults are marked mainly by topographic depressions. Where they cut granite, however, they tend to form ridges as a result of intense silicification and mylonitization that accompanied the shearing. In NE 1/4 sec. 10 and SE 1/4 sec. 3, T. 60 N., R. 14 W., the Waasa fault is marked by a ridge of silicified granite which has been almost completely converted to red and green cherty mylonite cut by several generations of white quartz veins. Similar silicified mylonites form a ridge in NE 1/4 sec. 16, T. 60 N., R. 14 W., marking the Camp Rivard fault. These zones are rarely more than 50-100 feet wide, however, and the intense shearing appears to die out quickly away from the faults.

The faults appear to be essentially vertical and to have had primarily strike-slip movement, but no known means of estimating vertical displacement is available. The minimum displacement can be estimated by matching offset granite-gneiss contacts. On this basis, the Waasa fault has a sinistral offset of three and three-fourth miles and the Camp Rivard fault has an offset in the same sense of about two miles. However, contacts and fold axes within the gneisses appear to be offset more than the granite-gneiss contacts. The contact of the Argo gneiss with the layered gneisses is offset about four and one-half miles. Restoration of two miles offset along the Camp Rivard fault fails to match an anticlinal axis in the southern block with any mappable axis in the northern block. The restoration of three and three-fourth miles offset along the Waasa fault leaves southwest-dipping gneisses in the southern block along strike from northeast-dipping gneisses in the northern block. It would require a 40° rotation of the southern block to bring the two into conformity without further offset, and the northeastern part of the block does not seem to have been rotated. It seems likely that the two areas of opposing dips are on opposite sides of an anticlinal axis which has been displaced still further. Thus, total offset on the Waasa fault may be about four and one-half to five miles, part of which took place prior to intrusion of the Giants Range Granite. On the same basis, the Camp Rivard fault may have as much as three and one-half miles of offset, though the "extra" offset in this case may be taken up on several smaller subparallel faults.

There are other lines of evidence to suggest some pre-intrusion movement on the major faults.

(1) In the gneisses on Birch Lake there are several linear depressions parallel to the main faults that are accompanied by shearing and which do not extend into the granite nor offset the contact (Griffin, 1967a, p. 78).

(2) Several of the smaller faults parallel to the Waasa fault apparently have localized small intrusions of granite, which subsequently were sheared. It is not certain whether the Waasa fault itself localized the intrusion of the elongate granite body in the west-central part of the Isaac Lake quadrangle.

(3) Snowshoe Bay, a large linear depression in the gneisses on Birch Lake, extends into the granite as a shear zone but does not mark any significant offset of the contact. Along the shores of the bay the gneiss is intimately injected with granite, but the injection does not extend inland for more than 100 yards. The intrusion was apparently localized by a pre-existing zone of weakness (Griffin, 1967a, p. 79).

(4) Numerous granitic dikes are parallel to the strike of the faults, both in the gneisses and in the granite itself, and have been later sheared along their strike.

(5) Healed shears parallel to the Waasa fault in the coarse-grained biotitic gneiss in the east-central part of the Embarrass quadrangle suggest movement while the rocks were still relatively plastic, though this movement need not have been pre-intrusive.

Finally, the extensive and repeated silicification of the faults within the granite suggests that shearing occurred while abundant fluids were still available within the granite, possibly during and just after solidification.

Because of the absence of a detailed stratigraphy in the gneisses, no estimate can be made of the amount of offset parallel to or oblique to the strike of the gneisses.

Joints and Shears

Orientations of shears and possible joints, most of which have nearly vertical dips, are plotted in Figure 6. In subareas I and II (fig. 4) the maxima around N. 50° – 60° E. correspond to the orientation of the major transcurrent faults. The

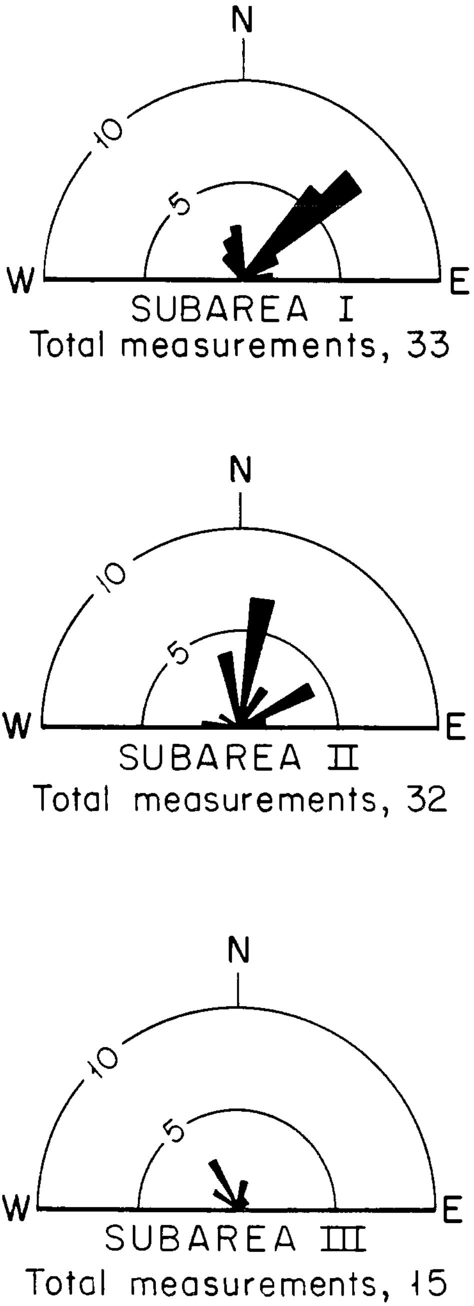


Figure 6. Orientation of joints and shear planes in subareas I and III.

smaller maxima around N. 20° – 30° W. in subareas I and II reflect the orientation of minor faults such as those that control the course of the Birch River Narrows. The pronounced maximum around N-S in subarea II appears to be associated with the axial plane of cross-folding which is prominent in the Embarrass and Soudan quadrangles. Orientations of dikes are plotted in Figure 7 for subareas I and II. Dike intrusion was apparently localized by shearing in subarea II, but the correlation is only approximate in subarea I.

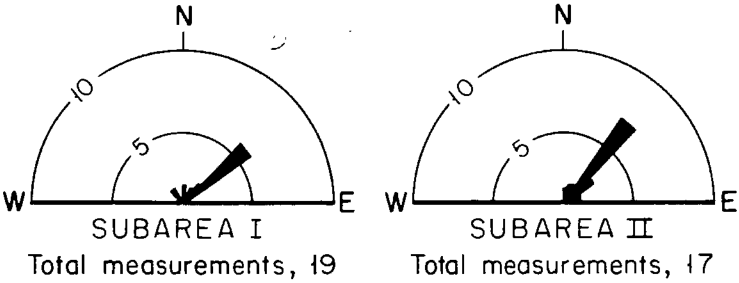


Figure 7. Orientation of granitic dikes in subareas I – II.

MIDDLE PRECAMBRIAN ROCKS

Stratigraphy

The Animikie Group comprises the entire Middle Precambrian in the Isaac Lake quadrangle. The stratigraphic position of this group has been discussed in detail by many previous workers, including Wolff (1917), Grout and Broderick (1919), Gruner (1924), Grout and others (1951), and Gundersen and Schwartz (1962); the reader is referred to these reports for general discussions of the group.

The Animikie Group consists of three conformable sedimentary formations; the Pokegama Quartzite, at the base; the Biwabik Iron-formation; and the Virginia Formation at the top. The lower two formations are well exposed in the quadrangle, but the Virginia is covered by Pleistocene deposits near the southern edge of the quadrangle and is known only through drilling information.

Middle Precambrian rocks were first mapped in detail in this part of the Mesabi district by Grout and Broderick (1919), shortly after an extensive forest fire. In the late 1950's, Gundersen and Schwartz (1962) examined many diamond drill cores and artificial exposures in Reserve Mining Company's open pit near Babbitt, immediately east of the Isaac Lake quadrangle. These earlier studies were very useful during this investigation.

Pokegama Quartzite

The basal part of the Pokegama Quartzite is well exposed in the Isaac Lake quadrangle. It lies unconformably on the Giants Range Granite, and fills minor irregularities cut onto the older granite surface, as indicated by the map pattern (pl. 1). Accordingly it is quite variable in thickness, ranging from near zero to approximately 30 feet. Small outliers of the formation also occur north of the main outcrop belt, indicating that it once had a greater areal distribution than that observed today.

The Pokegama is not a simple quartzite, but consists of a variety of rock types. The most common type is a fine- to medium-grained, massive, greenish-gray to pinkish-gray quartzite. Hand specimens show a relict "sandy" texture of quartz grains cemented by either quartz or calcite. Beds and laminae of dark green argillaceous siltstone are interlayered with the quartzite at several localities, and contain abundant chlorite as well as angular quartz grains that are arranged in thin sub-parallel lamellae. Thin beds of feldspathic graywacke also are present at several localities. In addition to quartz, this rock-type may contain as much as 30 percent sodic plagioclase ($An_0 - An_{20}$), but lacks rock fragments.

Where the Pokegama Quartzite is absent, the Biwabik Iron-formation locally is separated from the underlying granite by a green micaeous quartzose argillite layer about six inches thick. The lateral extent of this layer is not known. However, the granite beneath the argillite is unaltered, indicating that the argillite is not a residual soil.

The quartzite, which comprises more than three-fourths of the exposed formation, is characteristically structureless, but a few beds exhibit faint cross-bedding. Most of the cross-beds are small and of the planar type, and individual foreset beds are four to six inches long. Faint bedding plane structures that may be ripple marks also were observed at one locality.

The contact between the Pokegama Quartzite and the overlying Biwabik Iron-formation generally is sharp and readily recognizable in the field. It is an irregular, but conformable, sedimentary contact that separates a clastic sandstone from any overlying non-clastic algal chert unit. The lower part of the iron-formation has abundant subrounded clasts of quartz and chert "floating" in a chert matrix. Many of the clasts are fractured and filled with chert and cummingtonite, which is fine-grained, fibrous, and occurs as small rosettes that both enclose and replace the matrix. Rocks exhibiting these textural features would normally be assigned to the Pokegama Quartzite except that they also contain minor amounts of algal fragments and chert granules, features considered indicative of the iron-formation. Therefore there is no evidence in this area of any significant hiatus between the time the Pokegama Quartzite was deposited and deposition of the Biwabik Iron-formation.

Biwabik Iron-formation

The Biwabik Iron-formation can be subdivided on the basis of textures that are apparent in hand specimens into coarse-grained or "granular" (cherty) and fine-grained or "slaty" rocks. As noted by Gruner (1946) however, nearly all the mineral particles in the iron-formation have a very fine grain-size, and the coarse-grained appearance is given by the organization of particles into spherical or ellipsoidal bodies – called granules by Spurr (1894, p. 49). Some minerals tend to clump or cluster more than others, so the development of granules is in general related to the mineral composition. White (1954, p. 7) pointed out that iron-formation "... composed dominantly of chert with iron silicates or magnetite is apt to be granular, whereas rock that is made mostly of siderite and/or iron silicates is apt to be slaty."

Wolff (1917) subdivided the Biwabik Iron-formation into the Upper Slaty, Upper Cherty, Lower Slaty, and Lower Cherty Members on the basis of the ratio of "cherty" to "slaty" material present, and stated that the members are "... named from the predominant physical characteristic of the rock in them ..." Wolff's four-fold subdivision has generally been used since that time, although Grout and Broderick (1919) used a more comprehensive six-fold classification in the East Mesabi district. Fortunately, the two classification schemes are readily correlated (table 13).

Table 13 — Middle Precambrian nomenclature and generalized lithologic section.

				Wolff, 1917	Grout-Broderick, 1919	Gunderson, 1962	Bonnichsen, 1967	This paper	Approximate thickness	Columnar Section	Lithologic Description
PRECAMBRIAN	Middle	Animikie Group	Virginia Formation								Hornfels, quartzose, light gray, fine-grained, laminated. Unit observed only in drill core in Isaac Lake quadrangle.
			Biwabik Iron-formation	Upper Slaty	Aub$_6$ Aub$_5$	A B C D E F	us	bus	110'		Taconite, cherty and quartzose; mostly straight-to wavy-bedded or laminated, locally contains quartz-filled septaria structures at several horizons as well as pods of recrystallized chert and magnetite especially near base. Lower five feet is strongly convolute and passes indistinctly into underlying massive, cherty rocks. Upper 20 feet consists of calcite-marble, with minor amounts of fine-grained silicates; passes downward into laminated taconite and upward into Virginia Formation. This part of Upper Slaty Member observed only in drill core.
				Upper Cherty	Aub$_4$	G H I J	uc$_u$	buc 3	30'		Taconite, cherty; massive with magnetite granules and locally abundant silicate and magnetite layers, upper part of unit mottled with garnet, basal part of unit consists of jaspery to ferruginous chert containing conglomerate pebbles and algal structures.
						K L	uc$_m$	buc 2	100'		Taconite, cherty and quartzose; abundant magnetite granules near the bottom and magnetite granules and pebbles in the middle and top. Silicates, although present, are minor except near base while magnetite-silicate layers are abundant near top.
						M N O	uc$_l$	buc 1	40'		Taconite quartzose; silicate-rich with magnetite granules. Interbedded with wavy- and straight-layered magnetite. Magnetite becomes more abundant upward.
				Lower Slaty	Aub$_3$	P	ls	bls 2	60'		Amphibolite; massive to thin-bedded, abundant cummingtonite and metacrysts of olivine (?), minor lenses and pods of magnetite are more abundant near top.
					Aub$_2$	Q		bls 1	20'		Argillite, black, fine-grained, fissile, locally abundant silicates and traces of pyrite. Unit contains locally abundant pods of granular chert with magnetite.
				Lower Cherty	Aub$_1$	R S T U V	lc	blc	50'		Taconite, mostly cherty and massive with magnetite granules and locally abundant silicates interbedded with magnetite-silicate layers. Upper 10 feet is quartzose with magnetite granules, abundant cummingtonite and minor olivine (?). Basal five feet consists of a non-ferrugenous or jaspery chert with algal structures and locally abundant magnetite and granular chert pebbles.
			Pokegama Quartzite						0-30'		Quartzite; pink, fine-to medium-grained, massive to cross-bedded, interbedded with quartzose sandstone, shale, and feldspathic graywacke. If absent, the iron-formation rests directly on granite or a dark green argillite.
	Lower	Algoman	Giants Range Granite								

Gundersen (1960) subdivided the iron-formation into 22 sub-members on the basis of bedding characteristics and mineralogy. Although his classification was designed primarily for use with diamond-drill cores, most of the sub-members can be recognized in natural exposures. Most of the sub-members however, are too thin for areal geologic mapping at a scale of 1:24,000; therefore, the cartographic units summarized in Table 13 were used. The cartographic units used are based on a combination of Wolff's and Gundersen's classification criteria; the iron-formation is subdivided on the basis of bedding characteristics, texture, and gross mineralogy (fig. 8).

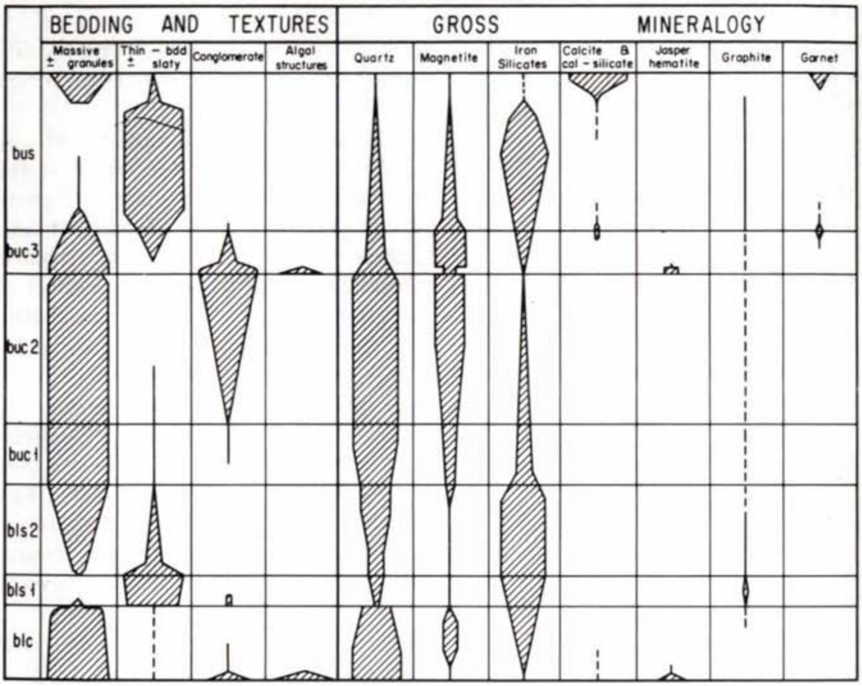


Figure 8. Bedding characteristics, textural features, and mineralogy of the Biwabik Iron-formation.

The Lower Cherty Member in the Isaac Lake quadrangle is thin – about 50 feet thick – and poorly exposed, and not susceptible therefore to division into the sub-members distinguished by Gundersen; instead it is more appropriately considered as a single unit, herein called blc. The bottom of the member is mostly a non-ferrugenous or jaspery algal chert that contains pebbles of the underlying quartzite and separate grains of detrital quartz. The top of the member is readily recognized by an abrupt change from a massive cherty taconite with granules containing disseminated magnetite and interbeds of silicate-rich taconite to a laminated rock that is black, silicate-rich, and magnetite-poor. Most of the member, where exposed, is quartzose and has moderate to locally abundant magnetite, especially in diffuse and disseminated granules and as thin irregularly diffuse layers. Near the base of the member silicates are sparse, but layers rich in silicates become more abundant upward and constitute a significant proportion of the rock near the top of the member.

The Lower Slaty Member can be subdivided into two cartographic units identical to Grout and Broderick's units A_{ub2} and A_{ub3} or Gundersen's units P and Q. The lower part, herein called unit bls_1, is known throughout the Mesabi range as the "intermediate slate." Within the Isaac Lake area it is very uniform in thickness, ranging from 17 to 20 feet. The "intermediate slate" typically is a black to dark grayish black, very fine-grained graphite-quartz-silicate rock that resembles slate; however, it lacks a true slaty cleavage. Although the unit appears to be massive in many places, it contains indistinct beds and laminae that are accentuated by weathering. Locally the unit contains small pods or fragments of granular taconite that contain scattered magnetite-rich granules. The largest pod observed was six inches thick and 18 inches long. Most of the silicate material is acicular cummingtonite, but trace amounts of fayalite are found. The fayalite has been altered to a dark reddish-brown material that locally imparts a mottled or patchy appearance to the unit.

The contact between the "intermediate slate" and the overlying unit, bls_2, is difficult to define in the field. It is more-or-less arbitrarily delineated at the stratigraphic interval where the rock becomes lighter gray in color and more massive in appearance. Characteristically, unit bls_2 is quartz-rich and contains abundant iron silicates but sparse magnetite, which occurs in thin irregular laminae that become thicker and more abundant upward. The upper contact of bls_2 is arbitrarily placed at the zone where irregular beds of magnetite interlayered with cherty taconite first appear; as defined, unit bls_2 is about 60 feet thick in the Isaac Lake area.

The Upper Cherty Member is divided into three cartographic units. The lowest unit, buc_1, is about 40 feet thick and consists of silicate-rich layers, similar to those present in unit bls_2, interbedded with chert-rich layers that characteristically contain magnetite in granules and in diffuse layers. The chert-magnetite beds become thicker and more abundant upward in the unit. Most beds are variable in thickness and pinch and swell in irregular lenses; however, there also is a gradual increase in the perfection of bedding upward in the unit.

The middle sub-division of the Upper Cherty Member, unit buc_2, is a magnetite-rich, irregularly-layered, conglomeratic unit about 100 feet thick. It contains sparse iron silicates, mainly near the bottom of the unit. Most of the conglomerate pebbles consist of magnetite and chert or magnetite, chert, and iron silicates. They are irregularly shaped, but most are flattened or disc-like and fairly well rounded. The matrix consists of granular chert, containing disseminated euhedra, granules, and irregular zones of massive magnetite. Many of the massive magnetite beds are irregularly folded and broken. This unit has the general appearance of a flat-pebble conglomerate. Near the top of the unit, planar beds of magnetite are both thicker and more abundant. This unit presently is being mined in the Isaac Lake area by Reserve Mining Company.

The base of the uppermost unit in the Upper Cherty Member, herein called unit buc_3, is marked by a thin, but persistent, algal-rich, iron-poor conglomeratic bed about three feet thick. The bed is very dense and compact, and accordingly it crops out at many localities and serves as an excellent marker bed. It varies from gray to red in color, the red parts being more jaspery than the gray parts. Numerous granules consisting mostly of chert and dusty hematite typify the bed; numerous small pebbles, composed of fine-grained magnetite and chert, as much as two inches in diameter also are present. Algal structures also typify the bed. Most of the algal structures were not found in place, but rather as angular fragments. The remainder of unit buc_3 consists of cherty taconite interbedded with thick irregular layers of magnetite and cummingtonite. The cherty beds contain varying amounts of magnetite in diffuse layers and in granules. The top of the unit is characterized by a massive chert- and magnetite-rich bed that locally contains andradite in pods or lenses and as disseminated crystals, some of which are more than three inches in diameter.

The transition between the Upper Cherty and the Upper Slaty Members is difficult to define in the Isaac Lake area. Gundersen assigned sub-member H, a wavy layered actinolite-magnetite-quartz unit, to the Upper Cherty and sub-member G, a massive quartz-magnetite-garnet unit, to the Upper Slaty. However, in the Isaac Lake area it is more appropriate to assign sub-member G to the Upper Cherty because it is more of a massive than a layered unit, and is in part characterized by beds of granular chert or quartz. The overlying unit, sub-member F, is well laminated and contains only small lenses or pods of recrystallized chert.

Several marker zones, useful in mapping, can be recognized within the Upper Slaty Member. A thin bed or series of beds characterized by the presence of quartz-filled septarian structures can be traced throughout the map area. These beds more-or-less separate overlying straight-bedded from underlying wavy-bedded rocks. Another zone, about six feet thick, consisting of highly contorted laminae that apparently are formed by penecontemporaneous slumping, also can be traced throughout the map area. Both of these marker zones characterize the lower part of the Upper Slaty Member.

In contrast to the thinly laminated, magnetite-rich rocks that comprise the lower 80 feet of the Upper Slaty Member, the upper 30 feet consists of a calcareous silicate-rich rock that in turn is overlain by about 10 feet of an impure carbonate rock now metamorphosed to skarn-like rock. The carbonate-rich unit is exposed only at two localities in the quadrangle, and therefore was not mapped as a separate unit.

Virginia Formation

The Virginia Formation conformably overlies the Biwabik Iron-formation, but is not exposed in the quadrangle. Its presence is known only through diamond drilling. Where studied in drill core, the formation is a vaguely laminated, grayish-black, fine-grained hornfels. Quartz and feldspar remain as remnants of the original framework grains, but the matrix now consists of recrystallized muscovite, chlorite, and biotite. Graphic (or carbonaceous material) is locally abundant in thin layers and laminae.

Petrography

Pokegama Quartzite

Most of the Pokegama Quartzite is a massive quartzose sandstone cemented by silica that contains, in addition, lesser amounts of feldspar, rock fragments, heavy minerals, and other interstitial material. However, both the matrix constituents and the cement vary in composition and relative abundance from bed to bed, and accordingly the formation locally contains silty, argillaceous, chloritic, or calcareous rocks.

For the most part, the formation consists of a quartz-rich rock with more than 95 percent detrital quartz. Pure quartzites are nearly white in color, but other varieties are various shades of gray, green, and pink, reflecting varying amounts and kinds of impurities. Simple and composite quartz grains having both straight and undulose extinction are mainly in the size range 0.05 to 0.5 mm., but a few grains exceed two mm. Commonly the quartz grains show tiny fluid inclusions arranged in straight lines through their interior and around their edges. Such inclusions are useful in ascertaining the original grain shape because almost all of the grains are now surrounded by irregular interlocking overgrowths of clear secondary quartz. Feldspar is generally present in quantities of less than three percent. It consists mostly of twinned plagioclase – albite and oligioclase – but includes minor amounts of orthoclase and microcline. Most grains are sericitized along cleavage planes, and alteration in more advanced stages has produced a mosaic of green weakly pleochroic chlorite, muscovite, and calcite. The matrix, which also consists of intergrown muscovite and chlorite (7 Å and 14 Å) has also replaced the quartz grains to varying degrees. Silica is the principal cement, but several beds also are cemented in part by calcite. Where both calcite and silica occur together, the carbonate is always later, and it replaces the original detrital grains, their overgrowths, and the matrix. Pyrite, magnetite, hematite or goethite, zircon, tourmaline, apatite, and hornblende are common accessory minerals.

The feldspathic quartzites differ from the quartzites only in containing from 10 to 15 percent feldspar. Feldspathic graywackes, on the other hand, differ markedly from the quartzites in that they consist of very fine- to fine-grained, randomly distributed quartz and plagioclase in a matrix of intergrown chlorite and muscovite which generally exceeds 25 percent of the rock volume.

The argillaceous siltstones are well indurated, thin-bedded to laminated, and contain scattered sand-size quartz grains. Texturally they differ from the feldspathic graywackes in being very fine-grained and in having quartz and plagioclase more or less concentrated in thin laminae rather than as randomly scattered grains.

Metamorphism of the Pokegama Quartzite by the Duluth Complex is reflected by the development of biotite and iron silicates such as cummingtonite, the replacement of clastic grains by matrix material, and the partial destruction of the sedimentary fabric.

Biwabik Iron-formation

The original mineralogy and texture of the Biwabik Iron-formation in the quadrangle has been modified extensively by metamorphism associated with the emplacement of the Duluth Complex. Gundersen and Schwartz (1962) have described the iron-formation in detail in the eastern part of the East Mesabi district, where metamorphism was most intense, and French (1968) has described the low and intermediate grades of metamorphism in the western part of the district. Inasmuch as the Isaac Lake Quadrangle is located approximately midway between the areas emphasized in these reports, the following description is provided.

Most of the Lower Cherty Member consists of chert that contains disseminated and diffuse layers of magnetite granules, thin irregular beds and laminae of magnetite, and minor to abundant amounts of iron silicates.

Granules typify the member above the basal conglomerate and increase rapidly both in size and abundance upward until they constitute a significant proportion of the rock. In many beds, the granules are widely dispersed in the matrix, but in others they are in closely packed layers. In some places, the granules are broken and angular, probably as the result of fracturing after consolidation, but in other places, where they are closely packed, the spherical shape of the granules is deformed so as to accommodate each other, suggesting that they were emplaced at their present site while still plastic. Chert, cummingtonite, blue-green hornblende, magnetite, and graphite (?) occur in all proportions in the granules. The granules near the bottom of the member consist almost entirely of chert and are outlined by rims of finely disseminated magnetite and/or graphite (?) whereas the granules immediately above the basal conglomerate are composed of various proportions of chert and magnetite. Cummingtonite and blue-green hornblende become abundant in the granules toward the top of the member, and near the top, the granules are composed almost entirely of these silicates and magnetite.

Magnetite first appears near the top of the basal conglomerate, where it occurs either as disseminated euhedral-shaped grains or as skeletal grains scattered throughout the matrix and in the granules. Magnetite also is present in thin to thick, irregular beds near the middle of the member. These beds consist of more or less interconnected aggregates of interlocking magnetite crystals of various sizes. In many places the aggregate grains are so closely packed that they appear to form continuous layers.

Chert is the most abundant single mineral constituent in the matrix near the base of the member. The fact that boundaries between individual chert "grains" are always sharp and regular implies that much if not all of the chert has been recrystallized from a finer grained parent material. The basal part of the member contains, in addition to chert, a few scattered acicular grains of cummingtonite, but iron silicates become more abundant until near the top of the member where they comprise almost entire beds. In these silicate-rich beds, cummingtonite and blue-green hornblende tend to cluster into rosettes and patches that merge into one another leaving what appears to be isolated remnants of chert. In the same beds, large tabular plates of pale yellow to tan cummingtonite and blue-green hornblende poikilitically enclose granules composed of chert, magnetite, and fibrous cummingtonite. The individual plates are not aligned in any particular way and tend to merge with one another to produce an interlocking mosaic texture.

Minor amounts of graphite (or carbonaceous material) occur in wavy and irregular laminae scattered throughout the member.

The "intermediate slate," unit bls_1, is very fine-grained, and generally lacks granule structures and magnetite. It is difficult to identify any minerals in thin section because of the fine grain-size and because of the presence of abundant quantities of black graphitic (or carbonaceous) material that obscures other minerals. In general, however, the unit is characterized in thin section by a felt-like mosaic of iron silicates with "ghosts" of what might have been metacrysts of hornblende and/or fayalite. X-ray analyses indicate that cummingtonite and hornblende now are the most abundant minerals, but quartz and chlorite (14 Å) also are present. The metacrysts are now almost completely replaced by needles of fibrous cummingtonite. A faint layering in the rock is imparted by thin laminae composed of what appears to be fine silt-size detrital quartz and/or concentrations of graphitic material.

Pods or fragments of cherty taconite that occur within unit bls_1 are composed of chert and chert-magnetite granules "floating" in a recrystallized chert-cummingtonite matrix. The granules are outlined by finely disseminated magnetite and/or graphite. These pods are very similar both in mineralogy and texture to rocks in the Lower Cherty Member and may have been derived from the underlying member.

The upper part of the Lower Slaty Member, unit bls_2, characteristically contains very fine- to fine-grained, acicular to prismatic cummingtonite and quartz, but only minor amounts of magnetite. Blue-green hornblende is associated with some of the cummingtonite. Small remnants of fayalite and tabular cummingtonite, which poikilitically enclose quartz and magnetite, also are present. Most of the poikiloblasts are less than 0.5 mm. in diameter and are best seen on slabed surfaces or in thin sections. They are abundant enough locally to impart a mottled appearance to some beds. Fibrous cummingtonite has replaced much of the fayalite.

The matrix, though rich in iron silicates, is cherty in many places. Relict granule structures are abundant and are composed mostly of chert and cummingtonite. Most of the chert-silicate granules have been reconstituted during metamorphism through the recrystallization and merging of smaller granules into large "granule-shaped" clusters of silicates. Many of the granules have been fractured and healed with small irregular veinlets of chert and cummingtonite.

The lowermost part of the Upper Cherty Member, unit buc_1, is mineralogically similar to unit bls_2 except that it contains cherty beds with abundant magnetite-bearing granules, scattered magnetite-bearing pebbles, and irregular laminae of magnetite that become more abundant upward in the unit.

Many cherty beds are almost completely composed of closely-packed and interlocking chert-silicate-magnetite granules. The granules in some beds are replaced by fine-grained, fibrous cummingtonite and blue-green hornblende so that the original texture is now almost completely destroyed.

Magnetite is present as finely disseminated grains enclosed within a matrix of fine-grained chert, and fibrous cummingtonite. Fine-grained closely packed magnetite euhedra also occurs in thin, wavy, laminated beds two to four inches thick, and to a lesser extent in pebbles that are concentrated in thin irregular zones.

The matrix in the silicate-rich beds varies greatly in proportion from bed to bed. In general, however, fine-grained acicular cummingtonite is most abundant and there are only a few scattered remnants of fayalite like those observed in unit bus_2. Much of the fayalite is now partly altered to fibrous cummingtonite that is enclosed in plates of tabular cummingtonite and blue-green hornblende.

The middle part of the Upper Cherty Member, unit bus_2, is similar to unit buc_1 except that it has better layering and contains lesser amounts of iron silicates and more conglomeratic zones composed of magnetite-rich clasts. The layering is imparted by beds containing various proportions of recrystallized chert and iron silicates. Some beds are almost completely composed of recrystallized chert with only traces of fibrous cummingtonite, but others, especially near the base of the unit, contain abundant fine-grained, fibrous, and acicular cummingtonite. In the cummingtonite-rich beds, small poikiloblasts of hedenbergite and hornblende enclose magnetite and quartz. Most of the hedenbergite is partially replaced by blue-green hornblende, which in turn is replaced by fibrous cummingtonite. Hypersthene, present in one sample studied, also is partly replaced by fibrous cummingtonite. In the same sample, large pods of intergrown calcite and diopside, which enclose magnetite, in part are replaced by acicular actinolite.

Magnetite occurs as disseminated grains throughout the chert-silicate matrix, as thin laminae of recrystallized interlocking, subhedral grains, and as constituent parts of granules. A wide variety of relict magnetite-chert granules can be found in all stages of progressive destruction and replacement by fine-grained fibrous cummingtonite. Recrystallization is so complete locally that the cummingtonite appears to merge into a continuous mosaic that superficially appears to be structureless. Veinlets of calcite and actinolite are intimately associated with the massive silicate layers as are a few grains of apatite and plagioclase.

Most of unit buc$_3$ consists of strata composed of fine-grained magnetite and chert, interlayered with beds containing actinolite, hornblende, and chert. The chert-magnetite beds consist of recrystallized chert and granule structures now consisting of magnetite, chert, and trace amounts of cummingtonite and actinolite. Other beds are composed almost entirely of intergrown tabular cummintonite and blue-green hornblende with metacrysts of hedenbergite partially replaced by cummingtonite.

The top of the Upper Cherty Member in the Isaac Lake area is characterized by small to large irregular lenses and pods of andradite and actinolite which are enclosed within a granule-bearing cherty taconite that contains many thin, irregular magnetite-rich beds; yellowish-green to yellowish-brown actinolite poikilitically encloses much of the magnetite. Medium- to coarse-grained, brownish-red andradite is the most distinctive mineral in this part of the member. It is developed within pegmatoid pods and is associated commonly with a complex mineral assemblage consisting of quartz, calcite, diopside, hedenbergite, actinolite, epidote, and clinozoisite. The garnet, which is euhedral, is isotropic to slightly anisotropic, and contains inclusions of magnetite, chlorite, and cummingtonite. The enclosing rock consists of a matrix of fine-grained recrystallized chert that has irregular patches of cummingtonite and blue-green hornblende and scattered randomly oriented neddles of yellowish-green actinolite. Patches of calcite, idocrase, and chlorite (14 Å) replace and enclose some of the quartz and magnetite and in turn are replaced partly by cummingtonite and actinolite.

Most of the Upper Slaty Member exposed in the quadrangle is a laminated to thin-bedded chert-silicate rock that only locally contains abundant magnetite. The laminae are expressed through differences in the relative proportions of the mineral constituents. Most laminae consist of either cummingtonite with minor amounts of magnetite and chert, or chert and magnetite with variable amounts of cummingtonite. The silicates in the silicate-rich layers are arranged in patches of radiating neddle-like grains. The patches appear to replace recrystallized chert by merging into one another, to produce a more-or-less continuous mosaic of silicates with irregular "islands" of chert. Magnetite occurs in these layers as disseminated grains and as discrete euhedra in diffuse laminae and irregular pods, commonly in association with actinolite. Moderate amounts of hedenbergite, generally associated with calcite and traces of diopside, are associated with the silicate-rich layers near the uppermost exposed part of the member. Part of the hedenbergite is replaced by cummingtonite and blue-green hornblende.

Incipient granule structures are abundant in the chert-rich beds of the Upper Slaty Member. Most of the granules consist of recrystallized chert outlined by finely disseminated, discrete anhedra of magnetite. Many of the granules are also rimmed by fibrous cummingtonite and intergrown blue-green hornblende, further accentuating their structure. Near the silicate-rich laminae, silicates associated with the granules merge imperceptibly into the silicates of the silicate-rich layers.

The chert pods near the base of the Upper Slaty Member are texturally and mineralogically similar to the chert-rich laminae. They are composed of recrystallized chert-magnetite granules with minor to locally abundant amounts of fibrous cummingtonite and blue-green hornblende. Detrital plagioclase (An_9), graphite (?), and colorless euhedral almandite that has black opaque inclusions and rims also were identified in several samples.

The uppermost calc-silicate part of the iron-formation is not well exposed in the quadrangle, but has been described by Gundersen and Schwartz (1962, p. 65-68) from the adjacent area to the east.

Virginia Formation

Several thin sections of the Virginia Formation from a diamond drill hole in the SE 1/4 SW 1/4 sec. 33, T. 60 N., R. 13 W. were studied, and are thought to be representative of its character within the quadrangle. All samples contain chlorite, muscovite, and some biotite, and reflect the metamorphism by the Duluth Complex. Angular detrital quartz grains and a few sericitized plagioclase fragments are still visible. The fine-grained matrix is cloudy and consists of recrystallized quartz, muscovite, and chlorite, interlayered with laminae of biotite, muscovite, plagioclase, and quartz. The concentration of biotite into specific laminae probably reflects initial sedimentary layering; the mineralogy is controlled by the original bulk composition. The laminae are not foliated, but characteristically have a decussate fabric indicating recrystallization under thermal rather than stress conditions. Pyrrhotite occurs extensively as small and large blebs. In addition, minor amounts of cordierite (?) most of which has been altered to chlorite or sericite, are present.

Metamorphic Petrology

It is obvious from the preceding petrographic descriptions that the Animikie Group has been metamorphosed by the Duluth Complex. However, because the lateral extent of these rocks is limited to about two and one-half miles in the quadrangle, it is not possible to observe any mineralogic changes along strike that reflect differences in metamorphic intensity. Therefore it is necessary to use the present mineral assemblages to deduce both metamorphic grade and original composition.

Mineral Assemblages

The metamorphic mineral assemblages observed in the Animikie Group in the Isaac Lake quadrangle are listed below. The list does not indicate the relative amounts of the phases, which may result from differences in either the bulk composition of the original rock or the metamorphic environment. The assemblages are arranged roughly according to rock type.

I. Pokegama Quartzite

1. Muscovite-chlorite-albite-quartz
2. Muscovite-chlorite-quartz
3. Muscovite-biotite-albite-quartz
4. Muscovite-biotite-chlorite-plagioclase-quartz

II. Biwabik Iron-formation

1. Cherty rocks, or rocks with abundant quartz.
   All assemblages also may contain magnetite.

   a. Quartz
   b. Cummingtonite
   c. Quartz-commingtonite
   d. Quartz-hornblende (iron-rich)
   e. Cummingtonite-hornblende (iron-rich)
   f. Cummingtonite-hypersthene
   g. Cummingtonite-hypersthene-quartz
   h. Cummingtonite-hornblende (iron-rich)-garnet
   i. Calcite
   j. Calcite-cummingtonite-hedenbergite
   k. Calcite-cummingtonite-hornblende (iron-rich)
   l. Cummingtonite-hedenbergite
   m. Cummingtonite-actinolite
   n. Cummingtonite-hornblende (iron-rich)-actinolite

2. Slaty rocks, or rocks with minor amounts of quartz.
   All assemblages also may contain magnetite.

   a. Cummingtonite-hornblende (iron-rich)
   b. Cummingtonite-hypersthene
   c. Cummingtonite-fayalite
   d. Cummingtonite-hypersthene-quartz
   e. Cummingtonite-hypersthene-fayalite
   f. Cummingtonite-fayalite-biotite
   g. Cummingtonite-hedenbergite
   h. Hornblende (iron-rich)-garnet

3. Calcareous rocks. Assemblages also may contain quartz and magnetite.

   a. Calcite
   b. Calcite-diopside
   c. Calcite-epidote
   d. Calcite-garnet
   e. Calcite-epidote-chlorite
   f. Calcite-diopside-garnet

III. Virginia Formation

1. Muscovite-chlorite-albite-quartz
2. Muscovite-chlorite-quartz
3. Muscovite-biotite-albite-quartz
4. Muscovite-biotite-chlorite-plagioclase-quartz
5. Cordierite-biotite-muscovite-plagioclase-quartz

Each phase of a particular assemblage listed above is in contact with all other phases in that assemblage, and it is possible that each assemblage, given the proper bulk composition and proper pressure-temperature conditions, had the opportunity to approach chemical equilibrium. The above assemblages also comply with Gibb's Phase Rule, but this in itself is not sufficient evidence to demonstrate attainment of chemical equilibrium. The application of the Phase

Rule to complex natural systems is generally ambiguous because of the difficulty in defining components. This is particularly true for the iron-formation which contains minerals that have a wide range of solid solution compositions. The above assemblages also are topologically compatible when plotted on appropriate phase diagrams. However, a knowledge of the compositions of the phases of each assemblage would be necessary to establish the detailed topology of the diagrams and prove or disprove the compatibility of the actual observed assemblages. Unfortunately, this type of information has not been obtained for this region. However, French (1968) has demonstrated the compatibility of many of these assemblages, especially in rocks in the lower grades of metamorphism.

Petrogenesis

From the foregoing discussion, it appears likely that many of the mineral assemblages listed above probably attained at least partial chemical equilibrium. However, some of the phases show petrographic textures indicating sequential age relations with respect to other phases of the assemblage. It is clear from these textures that there has been both prograde and retrograde adjustment by the various phases. Thus, although the mineral assemblages are repeatedly associated with one another to produce a predictable correspondence in the mineralogy of each sample, the probability is very great that complete chemical equilibrium has not been attained in all of the assemblages.

It has been known for many years that the Biwabik Iron-formation where not metamorphosed by the Duluth Complex consists of a mixture of iron silicates, iron carbonates, quartz, hematite, and magnetite (Gruner, 1946; White, 1954). French (1968) has suggested that several zones reflecting increasing metamorphism can be delineated in the East Mesabi district. He recognized four zones, which are from west to east: (1) unaltered taconite consisting of quartz, iron oxides, iron carbonates, chamosite, greenalite, minnesotaite, and stilpnomelane; (2) transitional taconite, consisting of the same minerals with extensive replacement by quartz and ankerite, (3) moderately metamorphosed taconite, characterized by the formation of grunerite (cummingtonite) and by the disappearance of layered silicates and carbonates; and (4) highly metamorphosed taconite characterized by increased hardness and grain-size, and by the formation of iron-bearing pyroxenes. Zone 1 is roughly equivalent to the chlorite-biotite facies, and Zone 4 is equivalent to the sillimanite facies of regional metamorphism (James, 1954, p. 1475). French concluded that the matamorphism was essentially isochemical with the exception of the loss of CO_2 and H_2O. Both monomineralic and polymineralic beds of silicates are present in the iron-formation. Thus it seems probable that the original bulk composition of each laminae controlled the formation of each mineral assemblage now observed. Carbonates and layered silicates such as greenalite, stilpnomelane, and minnesotaite could have reacted isochemically, with increasing temperature, to form cummingtonite and hornblende; the only chemical changes associated with these reactions would be the loss of CO_2 and H_2O and the addition of SiO_2. It also may be possible that the layered silicates alone were converted to cummingtonite. Both minnesotaite and stilpnomelene contain more SiO_2 than is necessary for amphiboles, and the addition of only small quantities of SiO_2 would be necessary in the conversion of greenalite to cummingtonite. These minerals could have then decomposed with increasing temperature to form anhydrous phases such as the pyroxenes. These reactions would involve a net los of H_2O and SiO_2. All of the minerals formed in these ways would be found in association with quartz. It is also possible that some of the pyroxenes or fayalite that occurs in monomineralic layers could have formed directly from the carbonates rather than having formed from an intermediate amphibole. For example, when a temperature at which siderite decomposed, was attained, fayalite could have formed with a loss of CO_2 while SiO_2 moved to the reaciton site. Only enough SiO_2 would have moved to form the fayalite, and quartz would not be present. Other minerals such as hypersthene, hedenbergite, and diopside also could have formed in a similar way by the breakdown of impure siderite, ankerite, dolomite, or a mixture of the various carbonates. Thus it is possible that thermal metamorphism under essentially isochemical conditions produced the various mineral assemblages in response to the original bulk composition and the temperature, a conclusion first proposed by Grant (1889) and well documented by French (1968).

Most of the retrograde effects in the iron-formation involved the formation of hydrous phases from anhydrous phases, such as an amphibole from a pyroxene. If some of the water lost from the original minerals during prograde metamorphism was retained in the rock, it obviously would still be available to react again with the anhydrous minerals during the period of falling temperatures. Thus the retrograde minerals observed today probably reflect the fact that water was retained in the system during prograde metamorphism. If the iron-formation cooled over a long period of time, there would be ample opportunity for these retrograde reactions to take place.

Temperatures attained by the Animikie Group during metamorphism are difficult to estimate. Diopside occurs in some of the carbonate-rich rocks near the top of the iron-formation in the Isaac Lake area. In addition, wollastonite has been reported from the same unit at the east end of East Mesabi district (Gundersen and Schwartz, 1962, p. 100). The presence of these minerals may be used to estimate possible temperatures attained by these rocks during metamorphism. James and Clayton (1962, p. 227) have estimated that if the temperature of the gabbro magma, when emplaced, was about 1,100° C., the temperature a few hundred meters below the gabbro must have exceeded 600° C. They also estimated that if the gabbro was 10 km. thick, a temperature about 500° C. would have remained for at least two million years, a length of time sufficient for extensive chemical readjustment to occur. If the gabbro is assumed to have been 10 km. thick, P_{CO_2} in the carbonate-rich units was probably on the order of 500 to 1,000 bars (French, 1968); at this pressure, the temperature at which wollastonite, quartz, and calcite (plus CO_2) would co-exist would be around 600° C. (Greenwood, 1962, 82-85; Harker and Tuttle, 1956). Non-calcereous rocks in the Virginia Formation containing cordierite, biotite, muscovite, and quartz also indicate a temperature in the range of 500° to 700° C. at P_{H_2O} around 1,000 bars (Winkler, 1957). Therefore it is likely that the rocks in the Animikie Group reached a minimum temperature of around 600° C. adjacent to the gabbro contact. Temperatures of this order of magnitude are further indicated by the work of Perry and Bonnichsen (1966, p. 528) who suggested on the basis of oxygen-isotope fractionation in magnetite-quartz pairs that the maximum temperature attained by the iron-formation at the east end of the East Mesabi district was around 700° to 750° C.

The mineral zoning described by French (1968) indicates that the temperature progressively decreased in a westward direction generally away from the present location of the gabbro contact. French (1968), concluded that grunerite (cummingtonite) formed at "... temperatures not in excess of 400°

C.; it is probable that temperatures of 300 to 400° C. were attained . . ." during its development.

It is apparent from the foregoing discussion that Animikie rocks in the Isaac Lake quadrangle attained a minimum temperature of between 400 and 600° C. This conclusion is further supported by the experimental work of Yoder (1952) which indicates that diopside, present in the carbonate-rich upper part of the iron-formation in the Isaac Lake quadrangle forms at temperatures of around 500-600° C. in the pressure range P_{H_2O} equals 1,000 to 3,000 bars.

Structural Geology

The structure of the Animikie Group is relatively simple. The beds dip 5°-15° SE., and accordingly, most of the irregularities shown in the contacts on the map (pl. 1) result from topographic valleys that cross the beds. In detail, however, the structure is somewhat more complicated because of the presence of small amplitude folds that are 100 to several hundred feet across and whose axes trend north-northwest and plunge south-southeast at low angles. The presence of these small-scale folds is inferred from many closely-spaced strike and dip determinations. The folds are most apparent along the northern edge of the outcrop belt, in the lower part of the Biwabik Iron-formation. Structural closure on each fold seems to decrease upward; near the top of the iron-formation the structures are no longer apparent. Grout and Broderick (1919, p. 10) suggested that some structures in the Lower Cherty Member are ". . . probably due to irregularities of the floor on which the beds were deposited . . .", but it seems more likely that the structures mapped in this quadrangle are tectonic rather than depositional in origin.

Faults that cut the Animikie Group were not noted in the mapped area and, if present, probably have small displacements and local significance.

UPPER PRECAMBRIAN ROCKS (?)

Keweenawan (?)

A diabasic gabbro dike, about 10 feet thick, exposed in the NE 1/4 NW 1/4 sec. 32, T. 60 N., R. 13 W., is the only rock known to be younger than the Animikie Group in the Isaac Lake quadrangle. The dike appears to be nearly vertical in outcrop, trends north-northwest, and where exposed cuts the Lower Cherty and Lower Slaty Members. The same dike has been encountered along its south-southeast projection in several drill holes in the Upper Cherty Member. In hand specimen the dike is a dark gray, fine-grained, diabasic gabbro, consisting of well-developed euhedra of plagioclase and interstitial anhedra of pyroxene. Although it appears fresh in hand specimen, it is seen to be altered in thin section. The interstitial pyroxene, which originally was augite, is in part recrystallized and in part replaced by pale green hornblende, pale brown to green biotite, and colorless to pale green chlorite. The plagioclase, which compositionally is labradorite, is corroded and resorbed along edges and corners and partly altered by sericite. Magnetite occurs as original anhedral grains filling interstitial spaces and as rod-like blebs associated with the pyroxene.

Grout and Broderick (1919, p. 8) concluded on the basis of texture and alteration that this and other similar dikes in the East Mesabi district were metamorphosed at the same time as the Animikie Group. The dikes therefore, are younger than the Animikie Group and older than the Duluth Complex. They are tentatively assigned to the Middle Keweenawan because of a similarity in chemical composition to the other gabbroic rocks of that period.

REFERENCES

Allison, I. A., 1925, The Giants Range batholith of Minnesota: Jour. Geol., v. 33, p. 488-508.

Bath, G. D., Schwartz, G. M., and Gilbert, F. P., 1965, Aeromagnetic and geologic map of northeastern Minnesota: U.S.G.S. Geophysical Investigations Map GP-472.

Clements, J. M., 1903, The Vermillion iron-bearing district of Minnesota: U.S.G.S. Monograph 45, 463 p.

Dietrict, R. V., 1960, Banded gneisses: Jour. Petrol., v. 1, p. 99-120.

Elftman, A. H., 1898, The geology of the Keweenawan area in northeastern Minnesota: Am. Geol., v. 21, p. 90-109.

French, Bevan, M., 1968, Progressive contact metamorphism of the Biwabik Iron-formation, Mesabi range, Minnesota: Minn. Geol. Survey Bull. 45, 103 p.

Fyfe, W. S., and Turner, F. J., 1966, Reappraisal of the metamorphic facies concept: Contr. Mineral. and Petrol., v. 12, p. 354-364.

Fyfe, W. S., Turner, F. J., and Verhoogan, J., 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. Amer. Memoir 73, 259 p.

Goldich, S. S., Nier, A. O., Baadsgaard, Halfdan, Hoffman, J. H., and Kreger, H.W., The Precambrian geology and geochronology of Minnesota: Minn. Geol. Survey Bull. 41, 193 p.

Grant, U. S., 1898, Sketch of the geology of the eastern end of the Mesabi iron range in Minnesota: Minn. Univ. Eng. Year Book, v. 6, p. 49-62.

Greenwood, H. J., 1962, Metamorphic reactions involving two volatile components: Annual report of the Director of the Geophysical Laboratory, Carnegie Institute of Washington, p. 82-85.

Griffin, W. L., 1967a, Geology of the Babbitt-Embarrass area, St. Louis County, Minnesota: Ph.D. Thesis (unpubl.) Univ. of Minnesota.

Griffin, W. L., 1967b, Replacement antiperthites in gneisses of the Babbitt-Embarrass area, NE Minnesota (MS).

Grout, F. F., 1926, The geology and magnetite deposits of northern St. Louis County, Minnesota: Minn. Geol. Survey Bull. 21, 220 p.

Grout, F. F., and Broderick, T. M., 1919, The magnetite deposits of the eastern Mesabi range, Minnesota: Minn. Geol. Survey Bull. 17, 58 p.

Grout, F. F., Gruner, J. W., Schwartz, G. M., and Thiel, G. A., 1951, Precambrian stratigraphy of Minnesota: Geol. Soc. America Bull., v. 62, p. 1017-1078.

Gruner, J. W., 1924, Contributions to the geology of the Mesabi range, with special reference to the magnetites of the iron-bearing formation west of the Mesabi: Minn. Geol. Survey Bull. 19, 71 p.

Gruner, J. W., 1946, The mineralogy and geology of the taconites and iron ores of the Mesabi range, Minnesota: Office of the Commissioner of The Iron Range Resources and Rehabilitation, St. Paul, Minnesota, 127 p.

Gundersen, J. N., 1960, Stratigraphy of the eastern Mesabi district, Minnesota: Econ. Geol. v. 55, p. 1004-1029.

Gundersen, J. N., and Schwartz, G. M., 1962, The geology of the metamorphosed Biwabik Iron-formation, Eastern Mesabi district: Minn. Geol. Survey Bull. 43, 139 p.

Harker, R. J. and Tuttle, O. F., 1956, Experimental data on the P_{CO_2} – T curve for the reaction – calcite + quartz + carbon dioxide: Am. Jour. Sci., v. 254, p. 239-256.

James, H. L., 1955, Zones of regional metamorphism in the Precambrian of northern Minnesota: Geol. Soc. America Bull., v. 66, p. 1455-1488.

James, H. L., and Clayton, R. N., 1962, Oxygen isotope fractionation in metamorphosed iron formations of the Lake Superior region and in other iron-rich rocks: *in* Petrologic Studies: a volume in Honor of A. I. Buddington, A. E. J. Engel, H. L. James, and B. F. Leonard, eds., Geol. Soc. America, p. 217-239.

Lieth, C. K., 1903, The Mesabi iron-bearing district of Minnesota: U.S.G.S. Monograph 42, 316 p.

Perry, E. C., Jr., and Bonnichsen, Bill, 1966, Quartz and magnetite: Oxygen-18-Oxygen-16 Fractionation in metamorphosed Biwabik Iron-formation: Science, v. 153, p. 525.

Spurr, J. E., 1894, The iron-bearing rocks of the Mesabi range in Minnesota: Minn. Geol. Survey Bull. 10, 268 p.

White, D. A., 1954, Stratigraphy and structure of the Mesabi Range, Minnesota: Minn. Geol. Survey Bull. 38, 92 p.

Winchell, N. H., 1901, Glacial lakes of Minneosta: Geol. Soc. America Bull., v. 12, p. 109-128

Winkler, H. G. F., 1957, Experimentelle Gesteinmetamorphase: Geochim. et Cosmocchim. Acta., v. 13, p. 42-69.

Wright, H. E., Jr., 1956, Land forms and glacial history of northeastern Minnesota: *in* Geol. Soc. America Guidebook Series, Field Trip 1, Precambrian of northeastern Minnesota, G. M. Schwartz, ed., p. 11-19.

Wright, H. E., Jr. and Ruhe, R. V., 1965, Glaciation of Minnesota and Iowa: *in* the Quaternary of the United States, H. E. Wright, Jr. and D. G. Freys, eds. Princeton University Press, Princeton, N. J., p. 29-41.

Wolff, J. F., 1917, Recent geologic developments on the Mesabi iron range, Minnesota: Am. Inst. Min. Met. Eng. Trans., v. 56, p. 142-169.

Wones, D. R., and Eugster, H. P., 1965, Stability of biotite: experiment, theory and applications: Amer. Mineral., v. 50, p. 1228-1272.

Yoder, H. S., 1952, The $MgO-Al_2O_3-SiO_2-H_2O$ system and the related metamorphic facies, Bowen Volume: Am. Jour. Sci., p. 569-627.