MINNESOTA GEOLOGICAL SURVEY

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STRATIGRAPHY OF THE LOWER PRECAMBRIAN ROCKS IN THE VERMILION DISTRICT, NORTHEASTERN MINNESOTA

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R. W. Ojakangas, and P. K. Sims

Report of Investigations 14

UNIVERSITY OF MINNESOTA

MINNEAPOLIS • 1970

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The study appearing in this publication was funded mainly by the State Legislature from the Natural Resources Account on the Recommendation of the Minnesota Resources Commission.

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STRATIGRAPHY OF THE LOWER PRECAMBRIAN ROCKS IN THE VERMILION DISTRICT, NORTHEASTERN MINNESOTA

by

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ABSTRACT

The system of stratigraphic nomenclature used previously for the Lower Precambrian rocks in the western part of the Vermilion district, northeastern Minnesota, is replaced by a formal nomenclature based on increased data gained from recent geologic mapping.

The resulting changes in stratigraphic nomenclature are the following:

1. Previously recognized lithostratigraphic units -- the Ely Greenstone, Soudan Iron-formation, and Knife Lake Group -- are redefined and restricted in usage.

2. The Lake Vermilion Formation is formally established for rocks exposed in the vicinity of Lake Vermilion that were previously considered part of the Knife Lake Group. Four informal lithologic members are recognized in the Lake Vermilion Formation. These include a metagraywacke-slate member, a feldspathic quartzite member, a volcaniclastic member, and a mixed metagraywacke-felsic conglomerate member. Each is characterized by dominant and distinctive lithologies and may contain several mappable rock units, such as iron-formation and pillowed metabasalt, that can be recognized and delineated on the ground, but whose geographic extent and/or stratigraphic relationships are not known completely.

3. A second unit -- the Newton Lake Formation, a metavolcanic formation -- also is formally recognized. It is inferred to stratigraphically overlie rocks assigned to the Knife Lake Group and to consist of two informal lithologic members, a dominantly mafic volcanic member and a dominantly felsic-intermediate volcanic member. The two members interfinger in the vicinity of the type locality at Newton Lake.

4. A variety of hypabyssal intrusive rocks are intimately associated with all the volcanic and sedimentary rocks in the Vermilion district. The hypabyssal rocks were emplaced over an interval of time as a consequence of the igneous cycle in the district. Accordingly the time term "Laurentian" should no longer be applied to these rocks in the Vermilion district.

5. The recognition that (1) mafic volcanism was not confined to a single period and (2) that a major unconformity separating an effusive volcanic episode ("Ely Greenstone" of the older literature) from a younger sedimentary series ("Knife Lake Group" of the older literature) is lacking raises serious doubts about the validity of regional correlations previously accepted in northern Minnesota. Accordingly, it seems necessary to abandon the terms "Keewatin" and "Coutchiching" as time-stratigraphic units for strata of Early Precambrian age in northern Minnesota.

INTRODUCTION

Rocks north of the Mesabi range in northern Minnesota are Early Precambrian, or in Canadian terminology, Archean in age. They consist mainly of belts of metavolcanic and metasedimentary rocks enclosed within larger areas of younger granitic rocks (pl. 1). The granitic rocks have been dated in the range of 2,400-2,750 million years, which brackets the Algoman orogeny (Goldich, 1968).

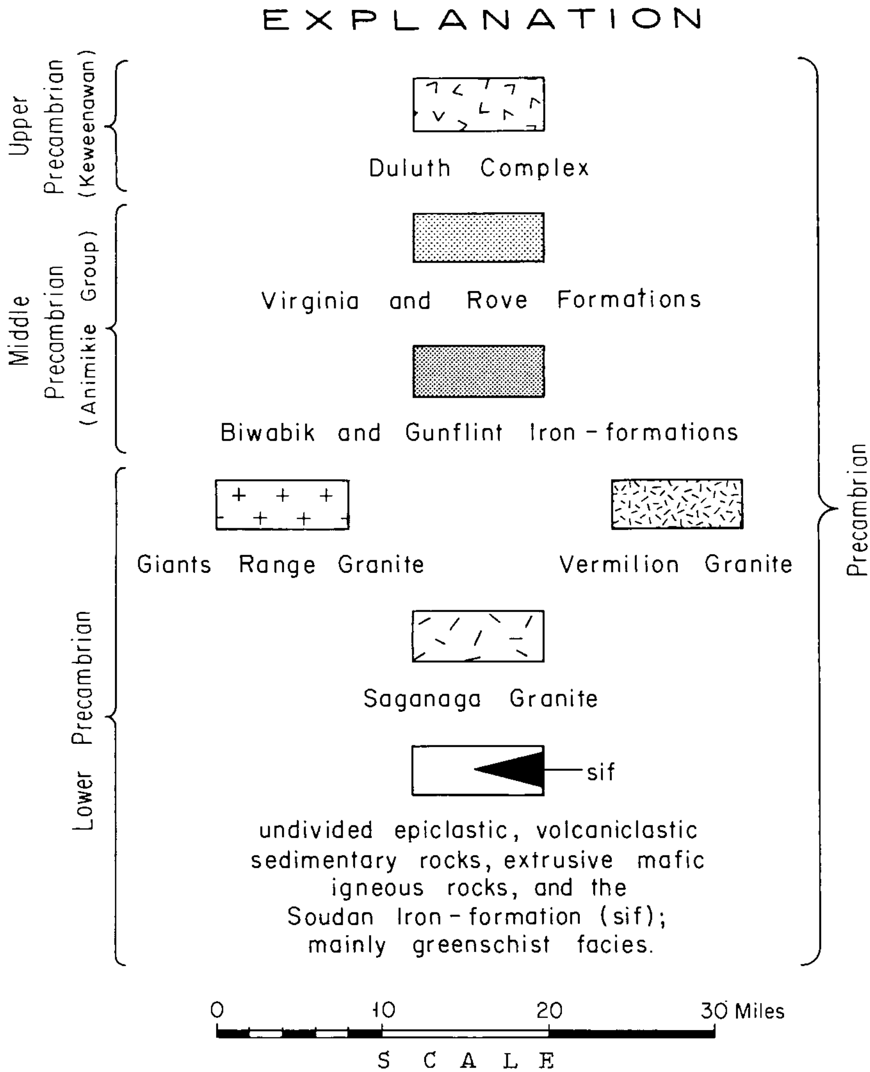
The most extensive exposures of the Lower Precambrian rocks are in the Vermilion district, where they form a volcanic-sedimentary belt 10 to 20 miles wide and more than 100 miles long that extends from the vicinity of Tower northeastward to the vicinity of Gunflint Lake and beyond into Ontario (pl. 1). Because of its economic importance as a major source of high-grade iron ores, the Vermilion district has been the focal point of studies of the older Precambrian rocks for nearly a century. Stratigraphic nomenclature established in the district during early studies has been retained, with minor revisions, to the present time and has been extended to similar lithic units in other parts of northern Minnesota (Grout and others, 1951; Goldich and others, 1961).

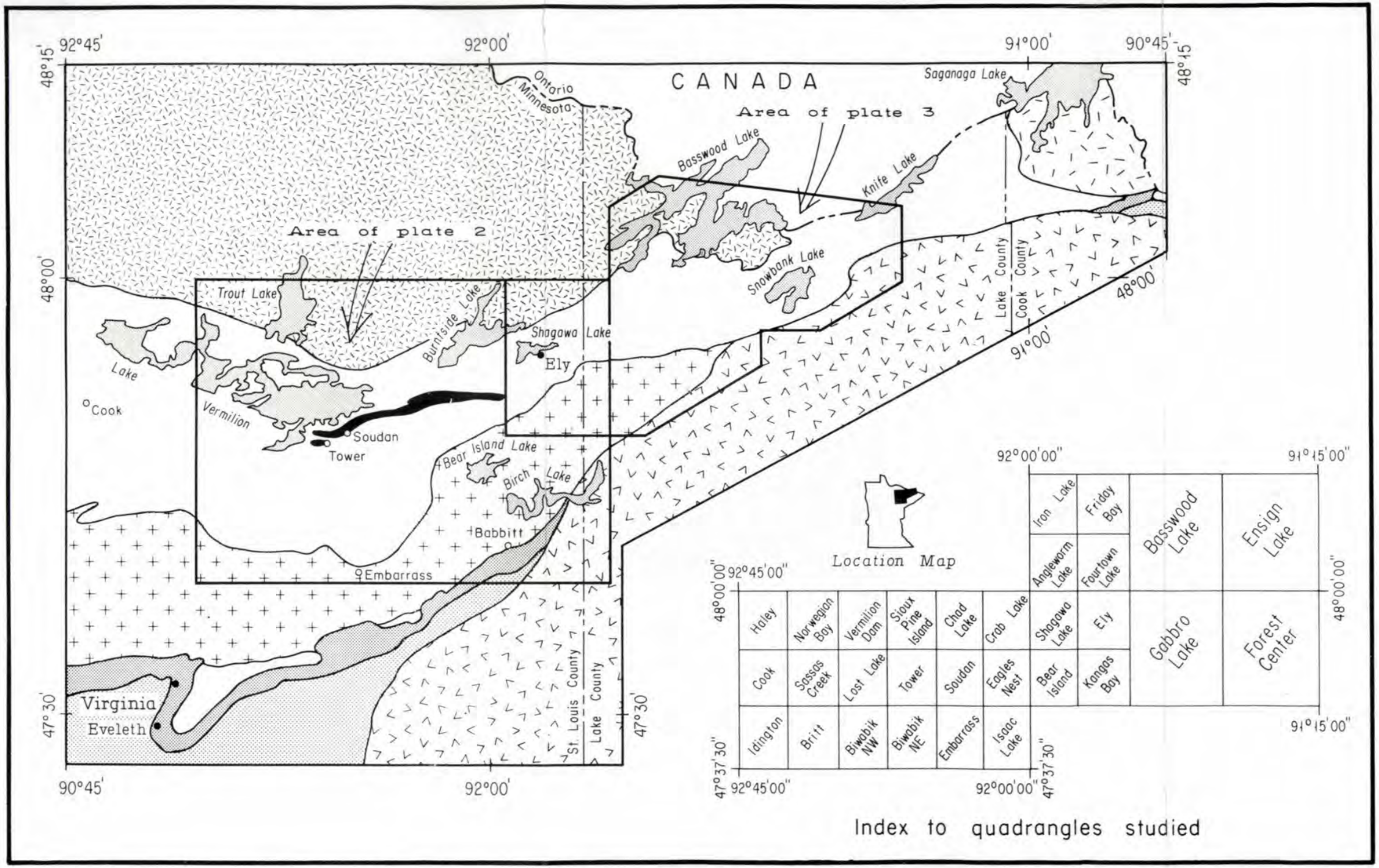
Geologic mapping in the Vermilion district and adjacent areas by the Minnesota Geological Survey since 1962 has indicated a need for modification of the earlier stratigraphic nomenclature. Previous reports have used the existing terminology with slight modification or have described rock units in terms of lithology, without formal designation. The present paper is written so that the problem can be reviewed in its entirety; additional geologic data pertinent to the nomenclature as redefined herein will be given in subsequent reports.

Our recent studies primarily have been in the west and west-central parts of the Vermilion district and adjacent areas (pl. 1). The area includes the type localities for two of the major stratigraphic units long recognized by the Minnesota Geological Survey -- the Ely Greenstone and the Soudan Iron-formation -- and includes large areas of a third unit, the Knife Lake Group. Our mapping included both regional reconnaissance (Sims and others, 1968) and detailed mapping of selected quadrangles (Tower, Ojakangas and Sims, 1970; Isaac Lake, Griffin and Morey, 1969; Embarrass, Griffin, 1969; and Gabbro Lake, Green and others, 1966). Gravity surveys (Ikola, 1968a, b; 1970) and the aeromagnetic map of northeastern Minnesota (Bath and others, 1965) aided in the geologic mapping.

Previous Stratigraphic Nomenclature

The stratigraphic nomenclature previously used in the Vermilion district was first defined by Van Hise and Clements (1901) and Clements (1903) and subsequently modified slightly by Grout (1926; 1933) and Gruner (1941) as a result of remapping of parts of the district. Additional discussions of the


EXPLANATION
Upper Precambrian (Keweenawan)
Duluth Complex
Middle Precambrian (Animikie Group)
Virginia and Rove Formations
Biwabik and Gunflint Iron-formations
Lower Precambrian
Giants Range Granite
Vermilion Granite
Saganaga Granite
sif
undivided epiclastic, volcaniclastic sedimentary rocks, extrusive mafic igneous rocks, and the Soudan Iron-formation (sif); mainly greenschist facies.
Precambrian
0
10
20
30 Miles
SCALE



GENERALIZED GEOLOGIC MAP OF THE VERMILION DISTRICT, MINNESOTA

stratigraphy have been given by Leith, Lund, and Leith (1935), Pettijohn (1937), Grout and others (1951), and Goldich and others (1961).

The stratigraphic succession determined by Clements (1903) consisted of, from oldest to youngest, a mafic volcanic unit, the Ely Greenstone; a local iron-formation, the Soudan; and a succession of dominantly clastic rocks, divided into a basal Ogishke Conglomerate, Agawa Iron-formation, and Knife Lake Slates, which include a large proportion of interbedded metagraywacke. Grout (1933) substituted Knife Lake Series for Knife Lake Slates and later (Grout and others, 1951) called the succession "Knife Lake Group". Gruner (1941), in an outstanding contribution to the geology of the eastern part of the Vermilion district, concluded that neither the Ogishke nor the Agawa are mappable units and that neither should have formational rank.

All earlier investigators accepted the contention that a profound unconformity, called "Epilaurentian" by Lawson (1913; 1930), separated the Ely Greenstone from overlying clastic strata. Evidence for the unconformity was found at the eastern end of the Vermilion district, where the Saganaga Granite (A. Winchell, 1888) cuts a body of greenstone -- assumed to be the Ely Greenstone -- and is overlain by clastic strata -- mapped as Knife Lake -- containing large boulders derived from the granite. The granite was assigned a Laurentian age -- post-Keewatin and pre-Knife Lake (Adams and others, 1905); the folding, uplift, and erosion associated with and subsequent to emplacement have been referred to as the "Laurentian orogeny" (*c.f.* Grout and others, 1951).

Gruner (1941) was the first to call attention to problems of defining the greenstone-clastic strata contact, although he retained the view that the Epilaurentian unconformity was of major regional significance (see Grout and others, 1951). He recognized the occurrence of several local conglomerates within the Ely Greenstone and for example, he stated (Gruner, 1941, p. 1585) "...one cannot be sure that this conglomerate -- which was mapped by Gruner as Knife Lake in his Gabimichigami Lake segment -- is not a pre-Saganaga fragmental phase of the greenstone." Further, he states (p. 1593) that "...small areas of conglomerate in greenstone cannot be shown separately on such a small scale...," and (p. 1594) "...it may be inferred ... that the Saganaga Granite was still unexposed when the conglomerate was laid down."

An additional problematic area where the greenstone-clastic strata contact cannot be easily defined is described by Grout and others (1951, p. 1030-31) who state that "one series of exposures north of Gunflint Lake...on the Canadian side...are greenstones which appear to be Keewatin, but others are black slates of uncertain relation to the greenstones -- they resemble Knife Lake Slates. The problem is that both the greenstone and the slate are intruded by acidic porphyry dikes such as might be apophyses from the Saganaga granite." They leave the problem unresolved, asking, "...Is there here a slate older than the Knife Lake group, or an acidic intrusive younger than the Saganaga Mass?"

The stratigraphic sequence and structural history of the Vermilion district as interpreted by Clements (1903) and accepted with some modification by later workers, necessarily depended on lithic similarity for correlation. For example, it has been common practice to refer all pillowed metabasalts to the Ely Greenstone and banded cherty iron-formations closely associated with the metabasalts to the Soudan (see Grout and others, 1951). In the same way, lithic similarity has been the basis for correlating units over the whole of northern Minnesota (see Grout and others, 1951), although long-range correlations commonly have been made cautiously. The practice of correlating rocks of similar lithology and similar order of arrangement over long distances has led to several still unresolved controversies, such as the Coutchiching problem (see Grout and others, 1951; Goldich and others, 1961). Failure to recognize the possible repetition of major rock types has resulted in the unjustifiable use of rock-stratigraphic names -- such as Keewatin, Ontarian, and Timiskamian -- as time-stratigraphic terms over broad regions. Until reliable and precise radiometric ages can be obtained to aid correlation, stratigraphic terminology in the Lower Precambrian rocks should be used in a restricted and locally defined sense.

Radiometric dating has not yet been successful in delineating more than one major igneous and metamorphic event in the Early Precambrian of northern Minnesota. In the Saganaga Lake area, for example, radiometric ages (Goldich and others, 1961; Anderson, 1965) fail to discriminate a Laurentian event from an Algoman event. Goldich and others (p. 52) suggest for the Saganaga Lake area that the mineral ages of rocks formed during a Laurentian event were reset by a "...pervasive low-grade metamorphism associated with the Algoman orogeny..." Possibly, however, the emplacement of the Saganaga Granite (pl. 1.) is simply one stage in a series of intrusive events that accompanied the Algoman orogeny as now defined (Goldich, 1968).

Structural Setting

The west and west-central parts of the Vermilion district (pl. 2) are bounded on the north by the Vermilion batholith and on the south by the Giants Range batholith, both of which are Algoman in age (Goldich, 1968). The rocks of the Vermilion batholith are separated from the district proper by a major fault, named the Vermilion fault (Sims and others, 1968). The fault also marks an abrupt transition in metamorphic grade from amphibolite-facies rocks associated with the granite to the north to dominantly greenschist-facies rocks to the south. On the south side of the district, the granitic rocks of the Giants Range batholith generally form irregular intrusive contacts with the older metavolcanic and metasedimentary rocks which exhibit a higher metamorphic grade nearer the batholith (Griffin, 1967). However, this contact also has been faulted at its eastern end.

Within the district proper, the strata are broken into several separate blocks by high-angle faults. The principal faults trend in a general easterly or northeasterly direction. Some of the east-trending faults appear to be branches from the major Vermilion fault. Because movements on many faults were in large part parallel to bedding surfaces, total displacements are not known. The northeast-trending faults are transverse structures, and lateral offsets of as much as four miles have been measured (Griffin and Morey, 1969).

All the rocks of the district, except for the youngest intrusive bodies, are folded; however, the trends of folds, the plunge of fold axes, and the extent of folding differ somewhat from one block to another. There is ample evidence in the sedimentary strata to indicate more than one period of folding. Much of the area, especially around Lake Vermilion, is typified by a lensoid form of the rock units and by the presence of large folds with nearly vertical axial planes and steep axial plunges (Sims and others, 1968). However, the lensoid shape of the original deposits together with steep folds of one generation does not satisfactorily explain the resultant cartographic pattern. Hooper and Ojakangas (in press) have shown that two major fold episodes can be demonstrated in the Lake Vermilion area. Early folding resulted in a set of tight isoclinal folds having near-vertical axial planes and gently plunging to horizontal axes that trend approximately in a west-northwesterly direction. The second set of folds consists of much more open structures with east-northeast-trending, steep-to-vertical axial planes, and with axes that, because of the steep foliation planes resulting from the first deformation, are steeply plunging. A third and minor period of deformation that has resulted in a number of faults, joints and kink bands also has been recognized around Lake Vermilion; however, these structures do not affect the cartographic distribution of rock types to any significant degree.

Of particular significance here is the extent to which the recurrence of lithologically similar rock types can be explained by the folding and faulting. Clements (1903) concluded that the rocks were complexly folded as a result of several periods of deformation, presumably during both the Laurentian and the Algoman orogenies, to account for "...an amazing irregularity in the distribution of the formations." However, he concluded that faulting was of little significance and interpreted the belts of greenstone as cores of eroded anticlines and the intervening clastic rocks as cores of synclines. Gruner's (1941) mapping in the eastern part of the district was the first to indicate the existence of several large, mainly longitudinal faults, which could account for many of the apparent complications in the map patterns of rock units. By careful mapping of features in the rocks indicative of the top directions of beds, he showed that folding was less prevalent than thought previously. Nevertheless, he interpreted all pillowed metabasalts to be Ely Greenstone and stated, "No ellipsoidal greenstone flows formed during Knife Lake time." (Gruner, 1941, p. 1639).

Geologic mapping done by us indicates that folding and faulting can account for some of the observed intercalations of lithic types, but that others are due to

EXPLANATION

North of Vermilion fault

Lower Precambrian

Giants Range Granite

Vermilion Granite

Biotite schist

Newton Lake Formation undivided

Amphibolite

vif — vmv — vgv — vgs — vq — vvm

Knife Lake Group (undivided)

Lake Vermilion Formation

vgs, metagraywacke member
vq, quartzite member
vgv, mixed metagraywacke - felsic conglomerate member
vvm, volcaniclastic member
vif, banded iron-formation
vmv, dominantly metabasalt and metadiabase

Saudan Iron-formation
dominantly jaspilite, jasper, and chert

eg — eif

Ely Greenstone

eg, dominantly metabasaltic and metaandesitic pillowed flows and intermediate composition pyroclastic deposits

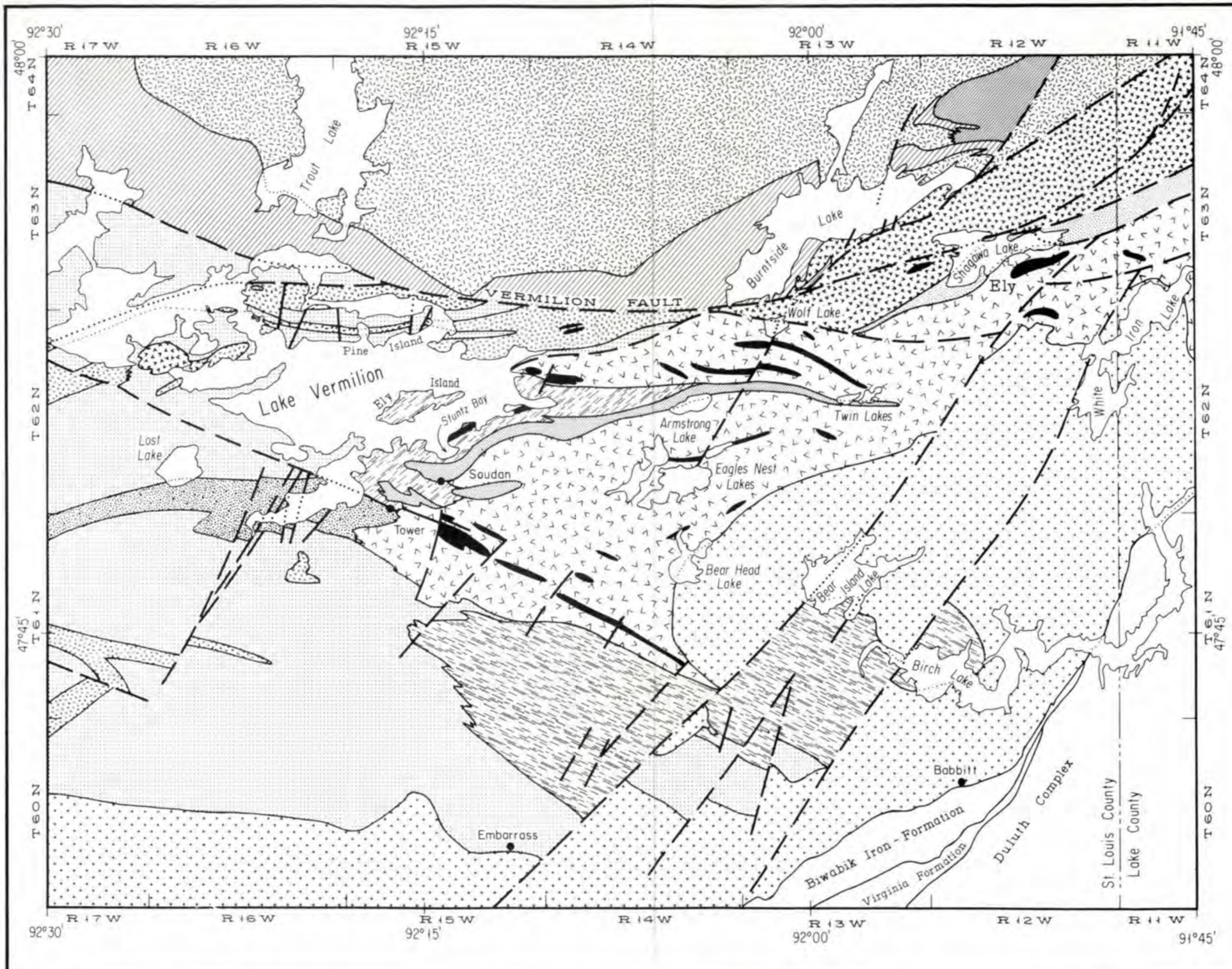
eif, banded Iron-formation

Contact, dotted where inferred

Fault, dotted where inferred

0 2 4 6 8 10 Miles

SCALE



GEOLOGY OF WESTERN PART OF VERMILION DISTRICT, MINNESOTA

the repetition of lithologically similar rocks in the stratigraphic succession, on both a large and a small scale. Recent mapping (Sims and others, 1968; Green, in press) clearly indicates that some of the repetitions of lithologies characteristic of the Ely Greenstone and the Knife Lake Group are the result of stratigraphic intertonguing rather than multiple folding.

Within the western and west-central parts of the district there is no evidence for a marked unconformity between pillowed metabasalts of the Ely Greenstone and overlying rocks. Younger strata including felsic agglomerates and other volcanigenic rocks immediately overlie and are virtually conformable to the older greenstone, and commonly grade into it. Conglomerates, although present, are local and not confined to the base of the younger clastic strata. Furthermore, the closely similar internal structures of the Ely Greenstone and younger clastic strata show that the rocks were deformed together, *i.e.,* there is no evidence for a deformational event (Laurentian) which affected only the Ely Greenstone.

Another observation pertinent to reinterpretation of the stratigraphy of the district is that metamorphic grade is not an indicator of stratigraphic or time-stratigraphic units. Lithic types characteristic of both the Ely Greenstone and the Knife Lake Group, as defined by Clements (1903), are metamorphosed to different metamorphic grades from place to place. In the western part of the district, Griffin has described in detail the increase in metamorphic grade of both the Ely Greenstone and graywacke and related rocks (Knife Lake of Clements, 1903) from the vicinity of Tower southeastward toward the Giants Range batholith (Griffin and Morey, 1969); in the same way, there is an increase in grade of the same rocks northward toward the Vermilion batholith although the Vermilion fault somewhat complicates the relationship. In the west-central part of the district (Green and others, 1966), similar metamorphic gradients have been observed (Green, in press).

In summary, our mapping in the western and west-central parts of the district indicates that the entire succession constitutes a volcanic pile accumulation much like those described from the Canadian part of the Superior Province by Goodwin (1965, 1967, 1968). Mafic volcanism was followed by both felsic and mafic volcanism, accompanied by deposition of fragmental volcanic and epiclastic sediments and intrusions of intermediate and felsic hypabyssal rocks. Lateral gradations are rapid in and adjacent to the volcanic pile. Marginal to the centers of volcanism, layers of fragmental detritus with a predominance of volcanically-derived quartz, feldspar, and rock fragments were deposited and these strata intertongue laterally with the volcanic rocks.

Revised Stratigraphic Nomenclature

In revising the stratigraphic nomenclature in the Vermilion district we have retained existing terminology insofar as possible. In this report, we (1) redefine and/or restrict the use of the terms "Ely Greenstone", "Soudan Iron-formation", and "Knife Lake Group"; and (2) define two new formations, the "Lake Vermilion Formation" and the "Newton Lake Formation". Each of the new formations, as defined, consists of several informal members, each characterized by dominant and distinctive lithologies. Each member in turn consists of several mappable rock units that can be recognized and delineated on the ground, but whose geographic extent and/or stratigraphic relationships are not known completely.

ELY GREENSTONE

Van Hise and Clements (1901, p. 402) named the Ely Greenstone "...from the fact that under and adjacent to the town of Ely very large and typical exposures of the formation occur." At Ely, the formation is not uniform in that some rocks are extrusive, others intrusive, and still others fragmental; all rocks are altered and are various shades of green because of abundant secondary chlorite, epidote, and green amphibole. Subsequently, it was common practice to consider all green mafic metavolcanic rocks in the region Ely Greenstone regardless of stratigraphic position. We now propose to restrict the name "Ely" to that body of mafic metavolcanic and associated rocks that is continuous with the rocks exposed in the town of Ely. The Ely Greenstone is here defined as an elongate lenticular body that extends 22 miles from Tower, through Ely, to the vicinity of Moose Lake, 18 miles east of Ely (pl. 3). As such, it is 40 miles long and on the average 2 miles wide, but between Tower and Ely the outcrop width is as much as 6 miles, probably as a result of folding and faulting.

On the south limb of the large inverted anticline near Tower, the Ely Greenstone is stratigraphically overlain by strata we herein assign to a new unit, the Lake Vermilion Formation. At the fold nose, southwest of Tower (pl. 2), the Ely is apparently conformably overlain by the feldspathic quartzite member, and south of Tower it is conformably overlain by the metagraywacke-slate member. Southeastward the metagraywacke-slate member passes laterally into the mixed metagraywacke-felsic conglomerate member which also overlies the Ely Greenstone. The Giants Range batholith transects the Ely Greenstone in the vicinity of Bear Head Lake and cuts out the stratigraphically lower part of it. In the same way, it transects the Ely or is in fault contact with it eastward to the North Kawishiwi River (Green and others, 1966). Accordingly, the base of the Ely Greenstone is not exposed anywhere.

Relationships between the Ely Greenstone and younger strata are still more complex on the north limb of the inverted anticline at Tower (pl. 2). In the vicinity of Tower and Soudan, the Ely is overlain conformably by the Soudan Iron-formation. However, eastward from Armstrong Lake, pillowed metabasalt of the Ely overlies the Soudan Iron-formation and in turn is overlain by the metagraywacke member of the Lake Vermilion Formation (pl. 2). In the vicinity of Wolf Lake, the Ely Greenstone is in fault contact with the Newton Lake Formation. In the area extending from Ely eastward to Moose Lake, the Ely Greenstone is overlain conformably by or is in fault contact with slates, metagraywackes, and associated rocks of the Knife Lake Group; thin beds of clastic strata (conglomerate, graywacke) are interlayered with the upper part of the Ely Greenstone (Green and others, 1966). At its eastward termination, in the area between Moose Lake and Snowbank Lake (pl. 3), the Ely interfingers with or is faulted against the Knife Lake Group.

The field relations clearly indicate that the Ely Greenstone is not entirely older than other rocks; some clastic strata of the Lake Vermilion Formation and the Knife Lake Group were contemporaneously deposited with at least the upper part of the Ely Greenstone.

Rocks of basaltic composition comprise well over 90 percent of the Ely Greenstone. Intermediate-felsic volcanic rocks and hypabyssal intrusive rocks, banded iron-formation and chert, and metasedimentary rocks constitute the remainder. The basalt occurs dominantly as flows, most of which are pillowed and must have been extruded into water. Intrusive metadiabase is associated with the flows as both concordant and discordant bodies; probably the diabasic rocks are nearly contemporaneous and consanguineous with the metabasalts, and represent shallow intrusives or feeder bodies. Fragmental rocks of intermediate composition are widespread in the western part of the district, and range texturally from tuff-breccia to tuff. Beds and lenses of banded iron-formation and chert are scattered throughout the Ely. Several rock units can be traced along strike for distances of a few miles and can be distinguished separately on large-scale maps. Examples are given on the published map of the Gabbro Lake quadrangle (Green and others, 1966). For the most part the rocks in the formation are pervasively altered by retrograde processes to minerals characteristic of the greenschist facies (sodic plagioclase, quartz, actinolite, chlorite, epidote, calcite, sphene, leucoxene, and opaque oxides); locally, relict augite and calcic plagioclase as well as pseudomorphs of olivine are present. Adjacent to younger intrusive rocks of the Giants Range and Vermilion batholiths, the rocks have mineral assemblages characteristic of the amphibolite facies.

Because of the great predominance of metabasalt and metadiabase, members of the Ely Greenstone are not distinguished here.

The thickness of the Ely Greenstone is imperfectly known because of uncertainties in the structural details, and because the base of the unit is transected by granite. However, in the vicinity of Twin Lakes, southwest of Ely – where the succession does not appear to be duplicated by either folding or faulting – the Ely is estimated to be at least 20,000 feet thick. A minimum comparable thickness of 12,000 feet is estimated in the Gabbro Lake quadrangle (Green, in press).

The Soudan Iron-formation was named by Van Hise and Clements (1901, p. 1402) from exposures at Soudan Hill, near the town of Soudan. The type locality was the original site from which large amounts of high grade iron ore were shipped between 1884 and 1963. Clements (1903, p. 173) states, "The formation is most notably exposed...at Tower and Soudan...and forms prominent topographic features known as Tower, Lee, and Soudan Hills, and...Jasper Peak." These localities still contain excellent exposures of the formation.

Lenses and beds of banded iron-formation are common in the Vermilion district, particularly in the Ely Greenstone, and it generally has been presumed that they represent parts of a once continuous body. For example, Grout and others (1951, p. 1027) state that "...the remarkably complex folding partly explains the distribution of the Soudan Iron-formation..." Our mapping indicates, however, that the geographic distribution of banded iron-formations cannot be accounted for entirely by any combination of multiple deformation. Rather, the banded iron-formations are lenticular and occur at several stratigraphic positions. Most are in the Ely Greenstone, especially at or near its upper part, and others occur stratigraphically above the Ely in dominantly clastic strata.

Accordingly, we herein restrict the term "Soudan Iron-formation" to that body that is stratigraphically continuous with exposures at the type locality, and we propose that it be given formational rank. The Soudan, as redefined, can be traced from the type locality eastward to the vicinity of Twin Lakes, a distance of 16 miles. It appears to lens out within a short distance of Twin Lakes, and is not equivalent to the iron-formation mined in the Ely trough (Reid, 1956; Machamer, 1968).

The outcrop width of the Soudan Iron-formation, as defined herein, is as much as 3,000 feet on Soudan Hill and in the area near Four Mile Lake, east of Soudan. Because of folding within the unit, the true thickness of the formation is less, but could not be estimated.

Near Soudan, the Soudan Iron-formation, as redefined here, overlies the Ely Greenstone and is overlain by agglomerates, tuffs, and interbedded volcaniclastic rocks that are assigned to the Lake Vermilion Formation. However, east of Armstrong Lake, it is overlain by at least 7,000 feet of mafic metavolcanic rocks and lenses of iron-formation that are assigned to the Ely Greenstone. Although geologic relationships in the Armstrong Lake-Wolf Lake area are structurally complex, the Soudan Iron-formation defines an excellent marker horizon which indicates the contemporaneity of mafic volcanism – Ely Greenstone – with intermediate to felsic pyroclastic discharge and clastic deposition – Lake Vermilion Formation.

The Soudan Iron-formation at the type locality consists of several types of fine-grained ferruginous cherts with minor amounts of interbedded fine-grained clastic rocks and metabasalts. The clastic rocks are mainly siliceous sericitic phyllites and carbonaceous slates. Locally, these rocks are intruded by mafic dikes and felsic porphyries. For cartographic purposes, the contact between the Soudan and adjacent rocks is placed at the highest and lowest beds of iron-formation. It is recognized, however, that the iron-formation in the Soudan and Tower quadrangles is underlain (and locally overlain) by clastic rocks that resemble those present within the boundaries of the formation.

It should be noted that this redefinition of the Soudan appears to differ substantially from that of Klinger (1956). In detailed mapping of the Soudan mine area, on Soudan Hill, Klinger considered the clastic sedimentary rocks and mafic flows that are interbedded with the lenses of iron-formation as part of the Ely Greenstone. This accounts for his conclusions that the Soudan Iron-formation occurs within the upper part of the Ely. Schwartz (1956, p. 3) accepted this conclusion and suggested that the Soudan should be a member "within or near the top of the Ely Greenstone." We however, place the intimately-associated clastic rocks within the Soudan Iron-formation rather than in the Ely Greenstone because the clastic rocks – mainly sericitic and carbonaceous phyllites – that occur in the vicinity of the type locality have a mineralogy distinct from typical Ely Greenstone. However, eastward toward Twin Lakes, interbedded mafic flows within the unit called the Soudan Iron-formation become more abundant and the clastic rocks become thinner, less abundant, and ultimately disappear. Thus from Armstrong Lake eastward the rock unit we call the Soudan Iron-formation might be considered a member of the Ely Greenstone. However, because this unit is continuously mappable for a distance of 16 miles, regardless of boundaries, contact relationships, or associated rocks, we prefer to consider it as having formational status.

Three principal types of ferruginous chert occur in the Soudan Iron-formation. In decreasing order of abundance these are: (1) greenish-white chert, composed principally of quartz but containing minor amounts of chlorite and pyrite; (2) lean jasper, a rock composed of quartz and hematite, which has an iron content of less than 20 percent; and (3) jaspilite, a banded rock composed of quartz, jasper, and hematite, which contains somewhat more than 30 percent iron (Klinger, 1956). Commonly the cherts, regardless of type, form lenses or more rarely persistent layers interbedded with phyllites, or less rarely with metabasalts. At Soudan, individual iron-formation layers are as much as 100 feet thick (Klinger, 1956, p. 126). Locally the iron-formation, as at Soudan, has been brecciated and recemented by hematite or guartz. Within the breccia zones hematite locally engulfs the iron-formation, and subangular blocks of iron-formation remain in a matrix of hematite. The massive blue hematite, which has replaced iron-formation, was the source of the high-grade ores mined at Soudan (Gruner, 1926; Klinger, 1956), and has been considered hydrothermal in origin by nearly all investigators.

EXPLANATION

Upper Precambrian

Duluth Complex

Lower Precambrian

Giants Range Granite
undivided

Snowbank Lake Stock
undivided

Vermilion Granite
includes associated schists

Biotite schist

Amphibolite

nfv — nfi — nmi

Newton Lake Formation

nmi, mafic volcanic member
nfv, felsic - intermediate volcanic member dominantly felsic-intermediate pyroclastic rocks and lesser flows (nfi) of similar composition

kv — kms — kmb

Knife Lake Group

kms, dominantly metagraywacke and slate
kmb, dominantly metabasalt
kv, dominantly volcaniclastic rock of felsic to intermediate composition

eg — eif

Ely Greenstone

eg, dominantly metabasaltic and metaandesitic pillowed and intermediate composition pyroclastic deposits

eif, banded iron-formation

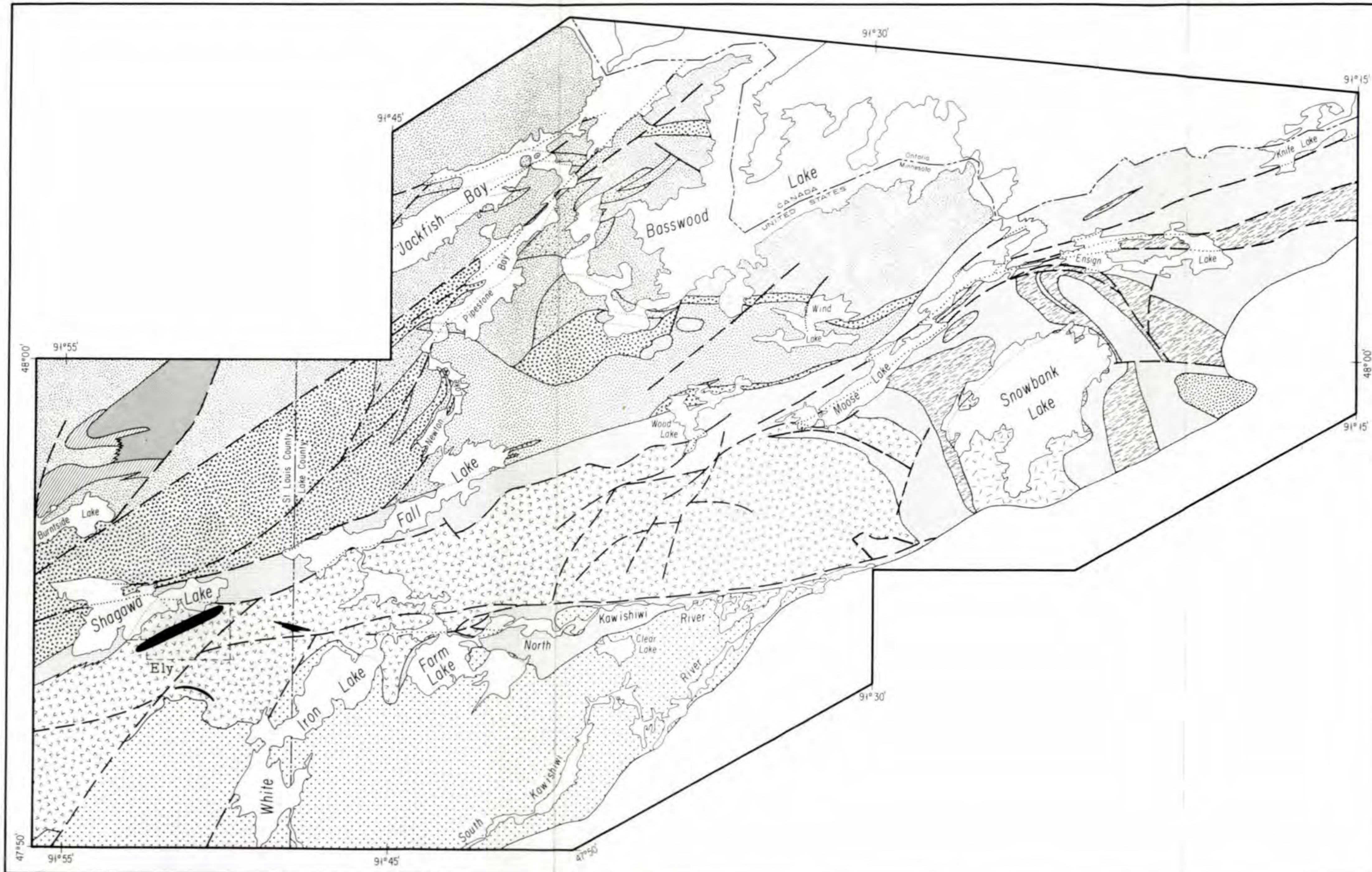
Precambrian

Contact, dotted where inferred

Fault, dotted where inferred

0 1 2 3 4 5 6 Miles

S C A L E



GEOLOGY OF CENTRAL PART OF VERMILION DISTRICT, MINNESOTA

KNIFE LAKE GROUP

The name Knife Lake Group (Knife Lake Series of Gruner, 1941) was first used by Grout in 1933 for rocks that are typically exposed around Knife Lake, near the International boundary, and which were previously called Knife Slates (Van Hise and Clements, 1901), or Knife Lake Slates (A. Winchell, 1888; Clements, 1903). The rocks were thought at that time to overlie what was called the Ogishke Conglomerate (A. Winchell, 1888), and to be interbedded with the Agawa Iron-formation. However, Gruner (1941, p. 1578) recognized: (1) that the Knife Lake Group consists of 10-20 mappable units that he called members; (2) that conglomerates similar to the "Ogishke Conglomerate" appear at several horizons; and (3) that Agawa-like beds are scattered throughout the Knife Lake Group. Therefore, he suggested that all names except Knife Lake Series be dropped, and his terminology has been followed in Minnesota with slight modification since that time.

Inasmuch as very little work has been done in the area mapped by Gruner subsequent to his work, we do not propose to modify the existing terminology used in the eastern part of the district. However, because the name Knife Lake has been applied indiscriminately to similar-appearing rocks as much as 150 miles away from the type locality, the Minnesota Geological Survey now restricts usage of the term to those rocks that can be demonstrated to be continuous with exposures in the type locality.

The Knife Lake Group, as restricted herein, cannot be traced into the Lake Vermilion area. Between Moose Lake and the vicinity of Shagawa Lake, it overlies the Ely Greenstone and in turn is overlain by the Newton Lake Formation. The contact between the Knife Lake and the underlying and overlying formations is in part depositional and in part faulted. About three miles west of Shagawa Lake, the Knife Lake is less than 1,000 feet thick and terminates against a fault. Eastward from Moose Lake, the Knife Lake increases rapidly in thickness and becomes more diverse in lithology, as described by Gruner (1941). Some of these rock types are similar to the felsic-intermediate member of the Newton Lake Formation. The total thickness of the Knife Lake in the type area is estimated by Gruner to be between 11,500 and 21,000 feet (Grout and others, 1951, p. 1033).

In the Gabbro Lake and Ely quadrangles, the Knife Lake Group consists mainly of gray to green slates, phyllites and graywackes that contain graded beds. In the Gabbro Lake quadrangle, felsic to intermediate volcaniclastic rocks also are abundant, especially near the base of the group, and volcanic conglomerate typically overlies the Ely Greenstone where the contact is not faulted. A few conglomerate lenses, metabasalt flows, chloritic phyllites, and thin iron-formation beds also are present. Along the North Kawishiwi River, metaconglomerate and metagraywacke of amphibolite facies is tentatively assigned to the Knife Lake Group (Green, in press).

LAKE VERMILION FORMATION

Inasmuch as strata of the Knife Lake Group cannot be traced from their type locality into the Lake Vermilion area, a new unit, the Lake Vermilion Formation, is defined herein to include the epiclastic and volcaniclastic rocks and their metamorphic derivatives that are well exposed from the vicinity of Lake Vermilion southeastward to the Babbitt-Embarrass area (pl. 2). Previously, these strata were assigned to the Knife Lake Group (Grout, 1933). The formation is exposed along the shores and islands of Lake Vermilion and also in road cuts and on low hills in that area. Because the formation crops out over a wide area and is estimated to be several thousand feet thick, it is not practical to designate a single type section. Also, the rocks are complexly folded, faulted, and incompletely exposed, and correlation of small stratigraphic or mappable units between areas is somewhat tenuous.

The Lake Vermilion Formation can be divided into four informal members: (1) a feldspathic quartzite member; (2) a metagraywacke-slate member; (3) a volcaniclastic member and; (4) a mixed metagraywacke-felsic conglomerate member. Specific type localities and stratigraphic interrelationships are described for each member in the sections that follow.

Feldspathic Quartzite Member

The informal feldspathic quartzite member of the Lake Vermilion Formation is composed of interbedded feldspathic quartzite and minor amounts of conglomerate. The quartzite weathers to a nearly white color that contrasts sharply with adjacent gray or green metagraywacke units. It is structureless to very poorly bedded and is composed mainly of angular grains of quartz, sodic plagioclase and felsic volcanic rock fragments. Some of the quartz grains are as much as 4 mm in diameter and distinctly bluish in color. Epidote and carbonate are common minor components; small amphibole crystals are rare; muscovite is the principal mica, and biotite and chlorite are less common.

An excellent exposure of the quartzite is located two miles west of Tower along State Highway 169-1, and this is designated the type locality of the member. The conglomeratic facies can be seen in the farmyard just north of the highway 169 bridge over West Two Rivers (one mile west of Tower), on the west bank of Two Rivers south of the bridge, and in a large iron-stained roadcut just west of Tower on State Highway 169-1.

The quartzite member abuts and overlies the Ely Greenstone west of Tower and extends west for at least eleven miles. The member is gradational into and stratigraphically older than the metagraywacke member. The transition from quartzite to metagraywacke is fairly abrupt, being marked by thin alternating beds of quartzite and metagraywacke across a width of a few tens of feet. The minimum thickness of the feldspathic quartzite member is estimated at 1,500 feet.

Metagraywacke-Slate Member

The informal metagraywacke-slate member is areally the most extensive member of the Lake Vermilion Formation. This member is the major rock unit in the western part of the Vermilion district, and extends even further westward at least to longitude 93° 00′ W. Pillow lava tops in the Ely Greenstone and graded beds in the metagraywackes indicate that on the north limb of the inverted anticline at Tower, the unit is younger than the Ely Greenstone and the quartzite member of the Lake Vermilion Formation; on the south limb, the member passes laterally into and overlies the mixed volcaniclastic-graywacke member. Near the Giants Range batholith contact in the Babbitt-Embarrass area, this unit has been metamorphosed to a dominantly quartzose gneiss with lesser amounts of hornblende- and biotite-rich gneiss, which Griffin (*in* Griffin and Morey, 1969) has called the Argo Gneiss.

As defined, the metagraywacke-slate member is composed of interbedded metagraywacke and slate and subordinate amounts of conglomerate, mafic volcanic and volcaniclastic rocks, iron-formation, and metadiabase. Two varieties of graywacke and two varieties of slates can be distinguished. Gray to black biotitic metagraywackes and slates have a wide geographic distribution, whereas greenish-gray chloritic metagraywackes and slates are restricted to the vicinity of Lake Vermilion. The differences in color may be the result of differing degrees of metamorphism or of a slightly different chemical composition. Nevertheless, the two differently colored units are mappable entities that can be easily recognized in the field.

The most biotitic metagraywacke-slate unit in this member consists dominantly of alternating beds of gray (black in fresh specimens), commonly graded metagraywacke and dark-gray to black slates. Individual beds commonly are 3 to 12 inches thick, but range in thickness from less than one inch to more than 10 feet. The metagraywackes are poorly sorted rocks containing angular grains of quartz and sodic plagioclase as much as 2 mm in diameter scattered in a matrix dominantly composed of the same minerals. Also present as large grains are fragments of felsic volcanic rocks, some with phenocrysts of quartz and plagioclase. Biotite is common, and epidote, chlorite, pyrite, and carbonate minerals are present in lesser amounts. In some specimens, hornblende occurs as grains which are generally metamorphic but which may be in part detrital in origin.

Excellent exposures of the biotitic metagraywackes and slates can be observed along State Highway 169-1 west of Tower, and in the outcrops immediately northwest of the bridge (County Highway 77) over the Pike River (in SW ¼, sec. 3, T. 61 N., R. 16 W.); the latter exposures are here designated the type locality.

Lenticular conglomerate zones, a maximum of a few tens of feet thick, are interbedded locally with the metagraywackes and slates north of Tower and

Soudan. The conglomerates contain clasts as much as 3 inches in diameter of plagioclase porphyry, chert, quartz, black slate, iron-formation, and white quartzite. The matrix is composed of sand-size quartz, plagioclase, biotite, epidote, chlorite, and carbonate minerals. Locally, as in the Embarrass (Griffin, 1969) and Soudan quadrangles (Griffin, 1967), conglomeratic units are sufficiently thick to form extensive mappable units.

The chloritic metagraywacke-slate unit also commonly consists of graded beds of graywacke and slate that range in thickness from one inch to about 12 feet. Almost without exception the slates have an excellent cleavage. Metabasalt layers are locally present in the unit, as are subordinate amounts of banded iron-formation and black carbonaceous (?) slate. The chloritic metagraywackes differ from the biotitic metagraywackes in having a distinctly greenish hue, in weathering to a rougher surface, and in containing dominant chlorite and minor greenish sericite rather than biotite and amphibole.

The green color of the unit results mainly from chlorite, which generally is abundant, and to a lesser extent from fine-grained greenish-white sericite. Some samples contain sparse chlorite; epidote-group minerals seem to comprise much of the matrix in these specimens. The chloritic metagraywackes in general are poorly sorted; angular quartz and plagioclase grains as much as 2 mm in diameter are conspicuous, and felsic volcanic rock fragments are abundant. The matrix is a finer-grained mixture of mica, quartz, plagioclase, and volcanic rock fragments. Both detrital and metamorphic hornblende grains are present locally. Carbonate minerals and pyrite are ubiquitous. Excellent exposures of the chloritic metagraywacke unit are present on the Isle of Pines (secs. 3 and 10, T. 62 N., R. 16 W.); this area is designated the type locality of this unit.

Layers or lenses of pillowed metabasalt and associated rare mafic volcaniclastic rocks occur locally within the metagraywacke member. These bodies, which are lithologically similar to flows that characterize the Ely Greenstone, are stratigraphically well above the top of the Ely Greenstone. Individual metabasalt layers typically are as much as several hundred feet thick, and can be traced along strike for several miles. Other bodies are irregular in outline and much smaller in size. The metabasalt and associated rocks are altered, generally fine-grained, and contain chlorite, sodic plagioclase, epidote, carbonate and, locally, iron sulfides. Exposures of the metabasalt can be seen at Arrowhead Point (secs. 3, 4, and 9, T. 62 N., R. 16 W.) at the end of St. Louis County Road 77.

Lenses of banded iron-formation, generally only a few tens of feet thick, and several tens to hundreds of feet long, are interbedded in the member, especially in association with the chloritic metagraywacke and slate. They are composed dominantly of jasper and are similar in all essential respects to the Soudan Iron-formation. Easily accessible exposures of iron-formation in the member can be found in several test pits in NE ¼ SW ¼ SE ¼ sec. 36, T. 63 N., R. 15 W., just south of County Road 480 (the Mud Creek Road).

The minimum thickness of the metagraywacke-slate member is 3,000 feet, based on an area having consistent top directions. However, the total thickness may be three times as much; folding severely complicates the estimate.

Volcaniclastic Member

The informal volcaniclastic member of the Lake Vermilion Formation is a heterogeneous unit that consists dominantly of metamorphosed felsic volcaniclastic and epiclastic strata, associated conglomerates, and banded iron-formation. For cartographic purposes, some hypabyssal intrusives are included in this member, especially where the presence of a pervasive schistosity makes them difficult to distinguish from the clastic rocks. The member is restricted to the eastern part of Lake Vermilion (Tower and Soudan quadrangles) and adjacent areas to the east (Soudan quadrangle). Good exposures occur on Ely Island and the adjacent mainland, especially in sections 13, 14, 15, 16, 21, 22, 23, 24, T. 62 N., R. 15 W., and sections 18, 19, T. 62 N., R. 14 W.; this area is designated as the type locality. The member is closely associated, and in part interbedded with, the metagraywacke-slate member.

The dominant component of the member is felsic volcaniclastic material, which probably has been reworked to some extent, and quartz-plagioclase (dacite) porphyries, which are nearly indistinguishable in the field from the volcaniclastics because of similar lithologies and a pervasive schistosity that partly obscures primary features in both rocks. A common rock type is a white to light-green inequigranular, massive to poorly bedded quartz-plagioclase metatuff. It consists of sand- or granule-size grains of quartz, sodic plagioclase, and felsic rock fragments in a recrystallized finer-grained matrix of these components plus muscovite and chlorite. Prominent scattered quartz grains are 4 to 10 mm in diameter. Because of the difficulty in distinguishing this metatuff from porphyry in the field in the eastern part of the Tower quadrangle (Ojakangas and Sims, in prep.), the two types were mapped as a single unit. Closely associated and interbedded with the metatuff, as on Ely Island, are fine to coarse tuff-breccias and agglomerates – probably including some conglomerates – composed predominantly of dacite pebbles and boulders with a few pebbles of jasper, gray and black chert, greenstone, and sericitic phyllite.

The banded iron-formations that locally occur as interbeds in the member are similar to the Soudan Iron-formation. Iron-formations have been mapped in the area between Mattson Bay and Cable Bay, on Pine Island and near Rice Bay.

Units within the member apparently are characteristically lenticular, and accordingly it is difficult to distinguish the degree to which the rocks are folded. Furthermore, much of the area is covered by the lake. We tentatively estimate that the maximum thickness of the unit is at least 5,000 feet.

Mixed Metagraywacke-Felsic Conglomerate Member

The informal mixed metagraywacke-felsic conglomerate member occupies an area of approximately 30 square miles on the south limb of the inverted anticline south of Tower. To the northwest, it interfingers with and is overlain by the metagraywacke member. The metamorphic grade of these rocks increases toward the southeast; in the Babbitt-Embarrass area the member dominantly is a gneiss with interlayered thick beds of medium- to coarse-grained mafic (amphibolitic) and felsic (quartz-plagioclase-biotite-hornblende) rocks. Closer to the Giants Range batholith, the gneisses are intruded and locally migmatized by leucotrondhjemite orthogneisses.

In the northwestern part of its outcrop area where the metamorphic grade is low, this member resembles in many ways the volcaniclastic member. However, because we cannot demonstrate a correlation of these strata at this time, we prefer to consider them separate distinguishable and mappable units.

The mixed metagraywacke-felsic conglomerate member is a heterogeneous unit approximately 10,000 feet thick that consists dominantly of felsic to mafic volcaniclastic rocks, extrusive flows dominantly of felsic composition, a variety of conglomeratic rocks, and metagraywackes.

The metagraywackes are lithologically like those described in the metagraywacke-slate member, being dark to medium gray when fresh and light gray when weathered. They range from coarse grits having obviously clastic textures to fine-grained homogeneous feldspathic quartzite. Graded beds are common on all scales. Some thin graded beds of mafic composition are present; these rocks may be mafic metatuffs.

Griffin (1967) mapped two lenses of conglomerate as continuous units, though each contains minor amounts of metagraywacke and slate. One lens, as much as 3,000 feet thick, lies near the base of the member and consists almost entirely of coarse angular debris derived from extrusive volcanic rocks. The other conglomeratic unit is approximately 700 feet thick and lies some distance above the base of the member and consists in part of metabasalt, sedimentary rock debris, and rare granite pebbles. No evidence was found of a continuous basal conglomerate shown on earlier maps (Clements, 1903; Grout, 1926).

Lenses of conglomerate too small to be mapped are scattered throughout the member. Many of these consist almost entirely of angular pebbles of slate and fine-grained graywacke and are probably intraformational. Others contain clasts of greenstone and chert as well as sedimentary derivatives.

Agglomerates and breccias of andesitic composition are intimately associated with the conglomerates in this member, as are a number of siliceous flows having a quartz latitic to rhyodacitic composition. Most of these rocks are light- to dark-gray and have large phenocrysts of quartz and plagioclase and pseudomorphs of hornblende after clinopyroxene set in a fine-grained groundmass. Keratophyres also are present and are generally more mafic than the siliceous volcanic rocks; ordinarily they contain abundant plagioclase phenocrysts and minor hornblende. Mafic volcanic rocks containing small quartz amygdules also are present in this area. They differ from typical Ely Greenstone rocks – which they resemble in outcrops – in having abundant biotite.

Although many of the igneous rocks associated with this member appear to be hypabyssal rather than extrusive, others exhibit a complex interlensing with the conglomerates containing up to cobble-size clasts of petrographically similar rocks. This implies that many of the igneous rocks underwent erosion soon after emplacement as subaerial extrusives. Thus all conglomerates in this member are local in extent and are intimately related to localized source areas of extrusive rocks. Many of the rocks thought to be extrusive are finer-grained and contain fewer phenocrysts than their hypabyssal counterparts. For these reasons these igneous rocks are considered an integral part of the Lake Vermilion Formation.

NEWTON LAKE FORMATION

The name "Newton Lake Formation" is given to a belt of dominantly metavolcanic rocks that was mapped (Green and others, 1966) in the Gabbro Lake quadrangle as the "unnamed formation." The rocks, originally mapped by Clements (1903) as Ely Greenstone, crop out as a belt two to three miles wide that is north and northwest of the narrow belt of Knife Lake Group metasedimentary rocks that lies stratigraphically above the Ely Greenstone between Ely and Moose Lake.

The formation consists of two informal members, a mafic metavolcanic member and a felsic-intermediate metavolcanic member. Felsic-intermediate volcanic rocks, which are in substantial part pyroclastics, are uncommon in the western part of the belt but increase northeastward and are dominant in the northeastern part. In the vicinity of Newton Lake, here designated the type locality, the two major types of metavolcanics intertongue.

One of us (Green and others, 1966) originally mapped the contact between the "unnamed formation" and the Knife Lake Group as an inferred fault. He has since ascertained from top-sense determinations in pillowed flows, especially in the area between Wood and Wind Lakes, that the contact is mainly depositional and that the rocks in the Newton Lake Formation are stratigraphically above those of the Knife Lake Group. This interpretation is supported by dominantly north-facing pillow tops in the unit in the Wolf Lake area (Crab Lake quadrangle) and in areas to the east near Shagawa Lake, although bands of south-facing tops indicate some major isoclinal folds in the unit.

The formation is bounded on the northwest along most of its length by the Vermilion fault, which separates the dominantly greenschist-facies rocks of the unit from amphibolite-facies rocks and granite of the Vermilion batholith to the northeast. The formation can be traced northeastward to Basswood Lake, where it is irregularly truncated by granitic rocks of the Vermilion batholith, and southwestward to the vicinity of Wolf Lake, where it is truncated by an east-trending fault. It is probable that the belt of dominantly mafic metavolcanic rocks that extends from Birch Lake, on the International boundary, northeastward to and along the north shore of Saganaga Lake (Gruner, 1941, pl. 1; Pye and Fenwick, 1965; Harris, 1968) is a continuation of the Newton Lake Formation.

The Newton Lake Formation grossly resembles the Ely Greenstone, but differs from it in several significant ways: (1) the Newton Lake Formation contains a much greater proportion of felsic-intermediate volcanics east of Newton Lake than does the Ely; (2) it contains several small lenses of impure siliceous marble and several small bodies of metaperidotite, both of which are totally lacking in the Ely; and (3) banded iron-formation and porphyries are common in the Ely Greenstone but rare in the Newton Lake Formation.

Relationships and descriptions of this formation are elaborated in another report (Green, in press).

Mafic Volcanic Member

The informal mafic volcanic member, which resembles Ely Greenstone in gross appearance, comprises the southwestern part of the formation and is characteristically developed in the area north and northeast of Shagawa Lake. It consists dominantly of pillowed and massive metabasalt and metaandesite flows and fine- to medium-grained metadiabase. Several small bodies of black, partially serpentinized metaperidotite are associated with the metadiabase and metabasalt.

In the vicinity of Newton Lake, the mafic member interfingers with the felsic-intermediate member, and to the northeast it occurs as interbeds in dominantly felsic-intermediate volcanics. Locally, as northwest of Newton Lake, conglomerates – containing granitic cobbles – and other clastic detritus occur in this member.

The rocks of the formation have been altered to varying degrees to the greenschist facies except adjacent to granitic rocks of the Vermilion batholith where the metamorphic grade is higher. Characteristic minerals are albite, quartz, chlorite, calcite, epidote, sericite, sphene, and opaque iron oxides.

At least 4,500 feet of mafic volcanic rocks are present in this member, but because of the structural complications a maximum thickness is not estimated.

Felsic-intermediate Volcanic Member

The felsic-intermediate volcanic member, as here defined, comprises the major part of the Newton Lake Formation from the vicinity of Newton Lake eastward (Green and others, 1966). It consists dominantly of felsic-intermediate pyroclastic deposits (tuff, breccia, and agglomerate) and lesser flows of similar compositions, some of which are pillowed. All the volcanic rocks are rich in soda and poor in potassium; compositionally they are andesites and dacites. Epiclastic deposits are scattered irregularly through the member and include volcanically-derived arkose and graywacke. A lens of recrystallized limy chert and cherty limestone about 1,000 feet thick and at least a mile long, lies within this member at the outlet of Fall Lake.

These rocks have also been altered to the greenschist facies, and contain albite, quartz, chlorite, calcite, epidote, actinolite, sericite, sphene, opaque iron oxides, apatite, ankerite, pyrite, and zircon.

Several thousand feet of volcanic rocks are present in this member, but a more precise estimate cannot be made.

HYPABYSSAL INTRUSIVE ROCKS

A variety of intrusive rocks that were emplaced at shallow depths are associated spatially with the volcanic and sedimentary rocks in the Vermilion district. Aside from diabase, which is relatively fresh and unaltered and undoubtedly much younger than the volcanism and sedimentation (post-Algoman), the intrusive bodies are believed to be cogenetic with the volcanism and thus in effect an integral part of the stratigraphy.

The most widespread and abundant hypabyssal intrusive rock is metadiabase, which is closely associated spatially with metamorphosed mafic flows throughout both the Ely Greenstone and the Newton Lake Formation. Because of the resemblance of this rock to massive mafic flows, distinguishing between the two is sometimes difficult; however its common grain size and lack of volcanic structures such as pillows generally make recognition possible. In general, metadiabase is more abundant in the Newton Lake Formation than in the Ely Greenstone.

Other hypabyssal rock types closely associated with the bedded rocks are porphyries that range in composition from andesite to rhyodacite. These are widely scattered throughout the Ely Greenstone, particularly in the upper part, and occur sporadically in the Knife Lake Group (Green and others, 1966). Except for rare andesite porphyry, porphyries are absent in the Newton Lake Formation. As mentioned above, felsic porphyries also are common in the volcaniclastic member of the Lake Vermilion Formation.

To judge from available data, the porphyries were intruded over an interval of time that spanned deposition of at least the upper part of the Ely Greenstone and a part of both the Knife Lake Group and the Newton Lake Formation. Evidence that porphyry emplacement began before the close of Ely time is present in the eastern part of the Gabbro Lake quadrangle (Green and others, 1966); here dacite porphyry that intrudes metabasaltic greenstone is found as cobbles in greenstone conglomerate that stratigraphically is immediately above the intruded greenstone, and is overlain by more greenstone. This indicates unroofing and erosion of the porphyry virtually contemporaneously with mafic volcanism. The dacite porphyry may actually have been extruded onto the surface in this area.

The presence of small bodies of both andesite-dacite porphyry and rhyodacite-dacite porphyry in Knife Lake rocks overlying the Ely Greenstone in the Moose Lake area indicates a continuance or renewal of porphyry emplacement during Knife Lake time. In the same general area, but further west, there is a linear body of lithologically different andesite-dacite porphyry in the Newton Lake Formation, which extends the duration of porphyry emplacement into Newton Lake time. In the Tower-Soudan area at the western end of the district, the major period of porphyry emplacement is believed to have been post-Soudan Iron-formation, for quartz-plagioclase (dacite ?) porphyry cuts Ely Greenstone, the Soudan Iron-formation and rocks that belong to the volcaniclastic member of the Lake Vermilion Formation. It is not known definitely in this area whether porphyry emplacement occurred over a short or a long period of time.

In general, there is some evidence for a gross spatial relationship between porphyries of a particular composition and volcanic rocks, suggesting that they are cogenetic. This relationship is most evident in the Tower-Soudan area, where dacite porphyries are clustered within and adjacent to felsic pyroclastics (the volcaniclastic member of the Lake Vermilion Formation). Reconnaissance mapping indicates that quartz-feldspar porphyry bodies gradually decrease in abundance eastward from the east end of Lake Vermilion, and are rare in the Ely quadrangle.

The observation made during our mapping that dikes and irregular bodies of porphyry cut strata younger than the Soudan Iron-formation and the Ely Greenstone is contrary to earlier conclusions by Clements (1903) and Gruner (1941). Because cobbles of porphyry are common in rocks considered by Clements to be basal Knife Lake conglomerates in the Tower-Soudan area (Lake Vermilion Formation of this report), he assigned the porphyries to a Laurentian (pre-Knife Lake -- post-Ely) age. Our re-interpretation of these rocks in the Tower-Soudan area as agglomerates rather than conglomerates places the age of their formation in Lake Vermilion time. Gruner (1941, p. 1489) agreed on a Laurentian age, but noted that porphyry emplacement was not entirely post-Ely, for he reported porphyry boulders "caught up in younger greenstone flows" in the Ely Greenstone. This observation accords with ours that porphyries were not emplaced during a single, short episode, but instead over an interval of time. It seems certain that the emplacement of porphyries was a consequence of the igneous cycle in the volcanic piles, and was not related to a tectonic or metamorphic event in the district. Accordingly, the time term "Laurentian" should no longer be applied to these rocks in the Vermilion district.

DISCUSSION

The recognition that (1) mafic volcanism was not confined to a single period and, (2) that a major unconformity separating an effusive volcanic episode (Ely Greenstone) from a younger sedimentary series (Knife Lake) does not exist in the main part of the Vermilion district, raises serious doubts about the validity of regional correlations previously accepted for northern Minnesota. Experience in the district clearly indicates that lithologic similarity in itself is not a valid basis for correlation; accordingly, no longer is it appropriate to use rock-stratigraphic terms in the Vermilion district as time-stratigraphic units for all of northern Minnesota, except where such usage can be justified by means of accurate geologic mapping or precise radiometric dating. Until the means are available for making regional correlations, it is preferable to establish a separate stratigraphic nomenclature for each isolated district. The rock-stratigraphic terms should be used in a time-stratigraphic sense only when necessary to place local events in their proper sequence. Accordingly, it seems necessary to abandon the terms Keewatin and Coutchiching as time-stratigraphic units for the strata of Early Precambrian age in northern Minnesota. Recognizing the problem of a time classification for the Precambrian succession, Goldich (1968) previously abandoned the terms Ontarian and Timiskamian, which he (Goldich and others, 1961, p. 5) had introduced earlier as time-stratigraphic units within the Early Precambrian.

Also, evidence for a Laurentian orogeny (Goldich, 1968, table 1) is lacking except in the Saganaga Lake area (Goldich and others, 1968), and even this evidence may be questioned (*see* Bass, 1961); usage of this term in Minnesota should be abandoned or at least restricted to this local area. Data supporting a metamorphic event as a part of the Laurentian is not compelling even in the Saganaga Lake area, (see pl. 1) and it seems preferable at present to apply the term Laurentian to the emplacement and subsequent uplift of the Saganaga Granite (Grout, 1936; Goldich and others, 1961).

Despite recent moderately detailed geologic mapping and extensive radiometric dating of rocks of Early Precambrian age in northern Minnesota and adjacent areas in Ontario, a statement made more than 30 years ago by Pettijohn (1937, p. 155) still holds true: "The early pre-Cambrian, or 'basement complex,' however, is still a *terra incognita* and is the frontier of stratigraphic and historical geology."

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