FIELD TRIP GUIDEBOOK FOR LOWER PRECAMBRIAN VOLCANIC-SEDIMENTARY ROCKS OF THE VERMILION DISTRICT, MINNESOTA

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LOWER PRECAMBRIAN VOLCANIC-SEDIMENTARY ROCKS OF THE VERMILION DISTRICT, NORTHEASTERN MINNESOTA

Leaders

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Special Paper

GEOLOGY OF THE WESTERN PART OF THE VERMILION METAVOLCANIC-METASEDIMENTARY BELT, NORTHEASTERN MINNESOTA,
P. K. Sims, J. C. Green, G. B. Morey and R. W. Ojakangas

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P.K.Sims, J.C. Green, G.B. Morey, and R.W. Ojakangas

INTRODUCTION

The Vermilion district is typical of the Lower Precambrian (Archean) greenstone-granite complexes of the Superior province in the Canadian Shield. It consists of a metavolcanic-metasedimentary sequence that is bordered on the north by the Vermilion batholith and on the south by the Giants Range batholith. Because of several excellent early studies, the sequence in the district has long been considered the classical section of the Early Precambrian in Minnesota and adjacent areas (Clements, 1903; Gruner, 1941; Grout and others, 1951; Goldich and others, 1961). Remapping of the western half of the district and surrounding areas during the past decade has provided new data on the stratigraphy, structure, and tectonic-igneous history of the region.

The metavolcanic-metasedimentary sequence in the district is complex and characterized by interfingering of lithologies and repetitions of rock types. The oldest known strata, metabasalt and related rocks (Ely Greenstone), are succeeded upward stratigraphically by felsic pyroclastic deposits and volcanogenic sandstones (Knife Lake Group and Lake Vermilion Formation). Locally, a significant iron-formation (Soudan) intervenes between the Ely and the Lake Vermilion formations. In the central part of the district, a second major mafic volcanic succession (Newton Lake Formation) conformably overlies at least part of the Knife Lake Group. Coeval hypabyssal porphyries of felsic-intermediate composition and metadiabase occur locally within the sequence, and lenses of serpentinized peridotite occur in the Newton Lake Formation.

The rocks in the district were deformed by two generations of folding and metamorphosed approximately synchronously with emplacement of the bordering granitic rocks about 2,700 m.y. ago, during the Algoman orogeny. Pervasive greenschist facies assemblages were developed except adjacent to intrusive bodies where metamorphism attained amphibolite grade. Faulting on a regional scale followed emplacement of the granitic rocks, and produced widespread cataclasis.

PREVIOUS INVESTIGATIONS

The general outline of the geology of the district was established at the turn of the century (Clements, 1903). The sequence was determined to consist mainly of an older mafic volcanic succession, named the Ely Greenstone, and a younger sedimentary succession, principally consisting of "Knife Lake slates". Coarse-grained deposits of various lithologies, named "Ogishke conglomerate", were considered to occur at the base of the sedimentary succession. At the eastern end of the district, the "Ogishke conglomerate" lies on the Saganaga Granite of Winchell (1888) and contains abundant clasts derived from it. It was interpreted as a basal conglomerate deposited unconformably on older deformed rocks.

Clements (1903, p. 437) considered the mafic lavas of the Ely Greenstone to be a part of a vast episode of mafic volcanism that extended throughout much of the Lake Superior region, and which was analogous to the later flood-basalts of the Keweenawan and the Tertiary. The Ely Greenstone was correlated (Van Hise and Clements, 1901) with similar greenstones in the Lake of the Woods and Rainy Lake areas, Ontario, Canada previously termed Keewatin by A. C. Lawson.

Subsequently, the stratigraphic framework established by Clements in the Vermilion district was extended to all older Precambrian terranes in northern Minnesota (Grout, 1926). All greenstones, especially pillowed basaltic flows, were called Keewatin, and the "Knife Lake slate" and associated "Ogishke conglomerate" were equated with the Seine series of the Rainy Lake area, described by Lawson (1913). Two unconformities were recognized, an older one following emplacement of Laurentian intrusive rocks, and a younger one following emplacement of Algoman intrusive rocks. In accord with the terminology used by A.C. Lawson in Ontario, Laurentian intrusive rocks were defined in Minnesota as being post-Keewatin (Ely Greenstone) and pre-Knife Lake, and Algoman intrusive rocks were defined as being younger than the Knife Lake. The Saganaga Granite of Winchell (1888) was considered the type Laurentian in Minnesota (Grout, 1929), and the granitic rocks of the Vermilion (Grout, 1925) and Giants Range batholiths and the Linden syenite of Grout (1926) were classed as Algoman.

Subsequent to the original work, knowledge of the geology of the Vermilion district and adjacent areas was refined, culminating in a review paper on the Precambrian of Minnesota (Grout and others, 1951). Notably, Gruner (1941) showed as a result of detailed mapping in the eastern part of the district that the Knife Lake series -- later changed to Group (Grout and others, 1951, table 3) -- was deposited in a tectonically unstable environment characterized by abundant felsic volcanism and that the so-called "Ogishke conglomerate" was not a basal clastic deposit of wide areal extent, as believed formerly, but instead was one of several coarse clastic deposits that were deposited intermittently within strata dominated by graywacke, slate, and tuff. Thus, the volcanic affinity of the Knife Lake Group was established. Grout and others (1951) retained the view, however, that all mafic flows in the older Precambrian sequence were time-stratigraphic equivalents of the Ely Greenstone, and that an unconformity separated the Ely Greenstone from younger Knife Lake rocks, at least in the eastern part of the district. In their three-fold division of the Precambrian rocks in Minnesota, Grout and others (1951, table 3) considered the unconformity that followed the so-called Laurentian orogeny to separate the Earlier Precambrian Era from the Medial Precambrian Era. The second major unconformity, developed after the Algoman orogeny, and which also involved the Knife Lake Group, was the basis for separating the Medial Precambrian Era from the Later Precambrian. The Animikie Group, which includes the Biwabik Iron-formation, was deposited on the younger erosion surface.

On the basis of K-Ar ages, principally on biotite, Goldich and others (1961, table 2) developed a time framework and revised the Minnesota classification, retaining a three-fold division. The rocks formerly assigned to the Earlier and Medial Precambrian Eras were grouped in the Early Precambrian. Significantly, they relegated the Laurentian orogeny to secondary importance because the available radiometric ages did not indicate that it represented a hiatus of significant duration. Later, Goldich (1968) assigned an age range of 2,400-2,750 m.y. to the one important igneous-tectonic event in the Early Precambrian, the Algoman orogeny.

Radiometric dating has not yet been successful in delineating more than one major period of plutonic igneous activity and metamorphism in northern Minnesota and adjacent areas in Ontario. For the Saganaga Lake area, Hanson and others (1971) obtained whole-rock isochron ages on the three principal rock types -- Northern Light Gneiss, the Saganaga Granite (referred to informally by them as the Saganaga tonalite, p. 1111), and the Icarus pluton -- of 2,740, 2,710, and 2,690 m.y., respectively, and concluded that these indicate a significant igneous-tectonic event at about 2,700 m.y. They prefer to call the event "Laurentian orogeny". The Giants Range Granite, which intrudes the metavolcanic-metasedimentary succession along the southern margin of the Vermilion district, has a Rb-Sr isochron age of 2,670 ± 65 m.y. (Prince and Hanson, 1971); and the Vermilion Granite, on the north side of the district, has a whole rock isochron age of 2,680 ± 95 m.y. (Peterman and Goldich, 1970). Inasmuch as the intrusive rocks of both the Giants Range and Vermilion batholiths were emplaced approximately synchronously with metamorphism and deformation of the supracrustal rocks of the Vermilion district, as discussed later, an age of approximately 2,700 m.y. can now be assigned to this orogenic event. The Linden pluton, which cuts the same succession of supracrustal rocks to the west of the district and is post-tectonic, has an age of about 2,700 m.y. (Prince and Hanson, 1971). This age, determined by Pb^{207}-Pb^{206} data on sphene and a Rb-Sr mineral-whole rock isochron, provides a minimum age for the time of regional deformation in the western part of the Vermilion district. To determine the total time span of the orogeny would require additional, precise geochronologic work on intrusive rocks known to have been emplaced early in the deformation. In the same way, the age of the Icarus pluton (2,690 m.y. ± 480 m.y.), which apparently is post-tectonic and similar lithologically to the Linden pluton (Hanson and others, 1971), provides a lower limit to the time of deformation in the eastern extremity of the district. Thus, within the limits of analytical error for the radiometric ages, igneous intrusion, metamorphism, and deformation took place virtually synchronously throughout the Vermilion district and probably also in adjacent areas. This orogenic period, herein called Algoman (ca. 2,700 m.y.), following the terminology of Goldich (1968), is approximately equivalent to the Kenoran orogeny (ca. 2,500 m.y.) of the Canadian Shield. The differences in ages probably are a result of the different techniques used in determining the time of orogeny.

PRESENT INVESTIGATION

The present investigation, carried out since 1962 as part of continuing studies of the Lower Precambrian rocks of northern Minnesota, has consisted of broad regional geologic mapping in the western half of the district and adjacent areas (Sims and others, 1968; Sims and others, 1970) and detailed mapping and study of critical areas (Gabbro Lake quadrangle, Green and others, 1966; and Green, 1970; Isaac Lake quadrangle, Griffin and Morey, 1969; Embarrass quadrangle, Griffin, 1969; Tower, Shagawa Lake, and Ely quadrangles, unpublished maps). Systematic geologic mapping has not been carried out in the eastern part of the district as a part of the present re-study; however, the excellent geologic map of Gruner (1941) in the type area of the Knife Lake Group remains a useful one, and S.S. Goldich, G.N. Hanson, and associates have examined critical areas in the Saganaga Lake - Northern Light Lake area as part of regional geochronologic studies.

Some conclusions resulting from the present investigations that differ substantially from earlier views are as follows:

(1) The metavolcanic-metasedimentary sequence in the district is a complex volcanic pile accumulation, deposited mainly in a sub-aqueous environment, which is analogous to those in other greenstone belts in the Canadian Shield (Goodwin, 1968; McGlynn, 1970).

(2) Mafic volcanism was repeated in time and, accordingly, pillowed basaltic lavas are not diagnostic of a unique time-stratigraphic unit (e.g. Ely Greenstone), as inferred previously (cf. Clements, 1903; Grout and others, 1951).

(3) There is no evidence in the western part of the district for a major unconformity between the mafic volcanics (Ely Greenstone) and younger sedimentary strata, as interpreted by Clements (1903) and later workers. Specifically, the deposits of coarse-grained fragmental rocks at Stuntz Bay and vicinity, at the eastern end of Lake Vermilion, called "Ogishke conglomerate" by Clements (1903, p. 23), are agglomerate and tuff deposits which mark initial felsic pyroclastic discharge that followed mafic volcanism and deposition of the Soudan Iron-formation.

(4) The widespread porphyries in the volcanic succession are shallow intrusive (synvolcanic) equivalents of the extrusive rocks of the district, and are not related to a pre-Knife Lake (Laurentian) orogenic event (cf. Clements, 1903).

(5) Metamorphism and deformation in the western part of the district was complex, and followed deposition of the youngest clastic strata in that area, and was virtually synchronous with emplacement of the Giants Range and Vermilion batholiths; there is no evidence for tectonism prior to deposition of the clastic deposits.

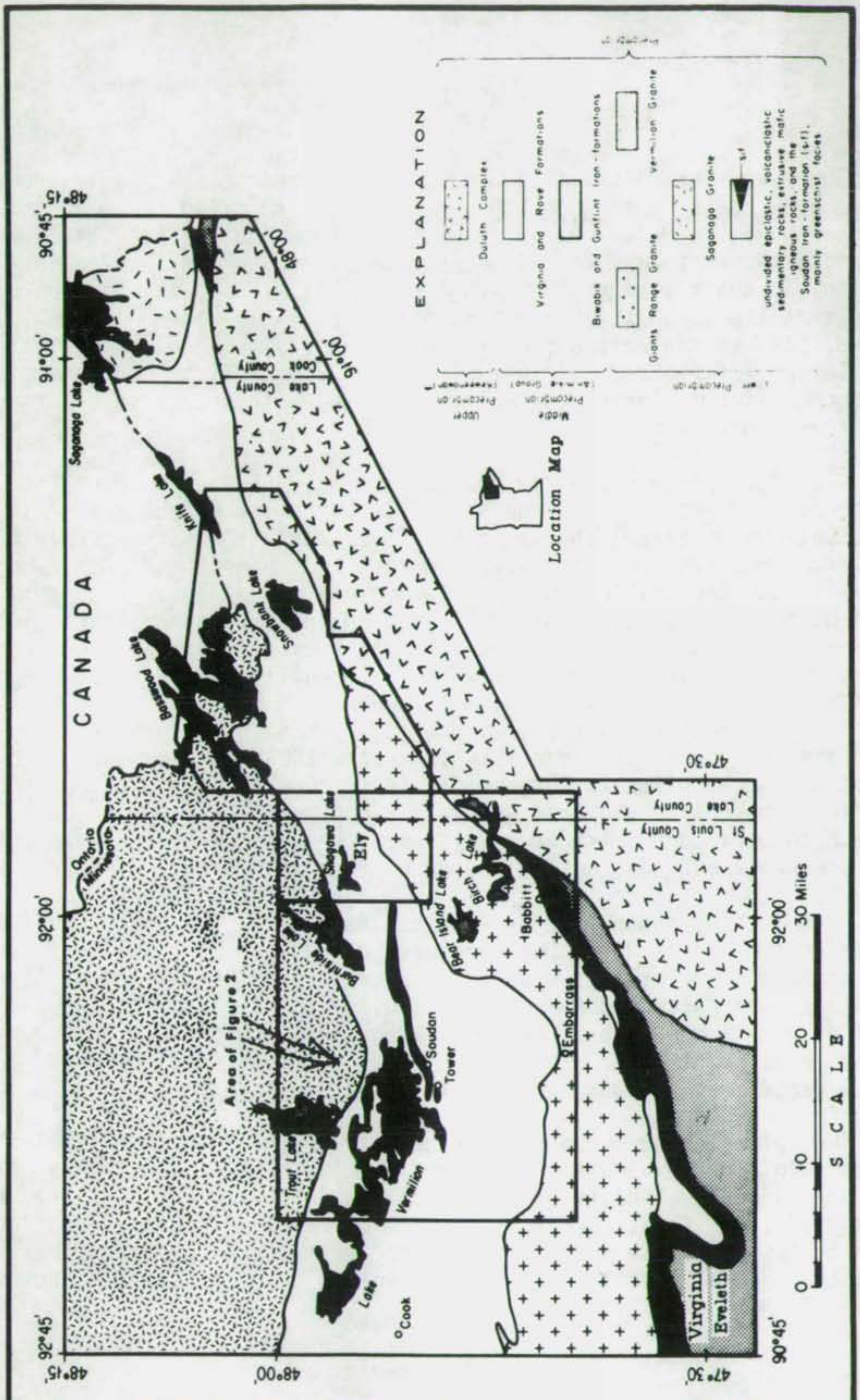


Figure 1. Generalized geologic map of the Vermilion district, Minnesota.

GENERAL GEOLOGY

The Vermilion district is a belt of low-grade metavolcanic and metasedimentary rocks 10 to 20 miles wide and more than 100 miles long that lies north of the Mesabi range and extends from the vicinity of Tower, on the south shore of Lake Vermilion, northeastward to the International boundary in the vicinity of Saganaga Lake (fig. 1). Metavolcanic rocks are dominant between Tower and Snowbank Lake; these rocks give way along strike, both to the east and west, to dominantly metasedimentary strata, with lesser interbedded volcanic flows and pyroclastics. In general, these rocks constitute a northward-facing sequence, with progressively younger beds from south to north.

The supracrustal rocks in the western half of the district (fig. 2) are bounded on the north by the Vermilion batholith and on the south by the Giants Range batholith. In the eastern part, the younger Duluth Complex, Keweenawan (ca. 1.1 m.y.) in age, transects the Giants Range batholith and the southern part of the volcanic-sedimentary sequence. Adjacent to the granitic plutons, the greenschist-facies volcanic-sedimentary rocks are prograded to amphibolite-facies assemblages and adjacent to the Duluth Complex they locally attain granulite-facies assemblages.

A major, longitudinal fault, previously named the Vermilion fault (Sims and others, 1968), generally separates the Vermilion batholith and associated amphibolite-facies schists from the lower grade of rocks of the district. Exceptions to this generality occur in the Basswood Lake area, where both mafic and felsic metavolcanic rocks of the Newton Lake Formation are prograded adjacent to bodies of Vermilion Granite (Green, 1970).

East of Ely, another major longitudinal fault, the North Kawishiwi, separates the Giants Range batholith and associated amphibolite-facies schists from lower grade supracrustal rocks to the north; and south of Ely, the transverse Waasa and Camp Rivard faults locally separate the two contrasting rock assemblages. Elsewhere, however, the granite has normal intrusive relationships to the older strata, with the development of amphibolite-facies assemblages adjacent to the contact.

The volcanic sedimentary sequence between the fringing batholiths is broken into several blocks or segments by high-angle faults, many of which are longitudinal. Because of uncertainties in the amount of displacement on many of these faults and the presence of complex folding, detailed correlations generally have not been made from one block to another. However, the general features of the stratigraphic succession are known.

STRATIGRAPHY

The metavolcanic and metasedimentary rocks of the western half of the Vermilion district are assigned to five formations. The stratigraphy has been described by Morey and others (1970) and by Green (1970). All the rocks in the sequence, including the synvolcanic hypabyssal intrusives, are metamorphosed at least to greenschist facies. However, the prefix "meta" is generally omitted throughout this paper for simplicity.

Ely Greenstone

Ely Greenstone, as redefined (Morey and others, 1970), is an elongate body of dominantly mafic volcanic rocks, on the average 2-4 miles wide, that extends from the vicinity of Tower eastward nearly to Snowbank Lake, a distance of about 40 miles (fig. 2). Snowbank Lake is 20 miles east of Ely. Pillowed or massive basaltic lava flows and intrusive diabase dominate the formation. Pillowed lavas and pyroclastic deposits of general andesitic composition, and lesser chert, banded iron-formation, and siliceous, carbonaceous siltstone (tuff?) comprise the remainder. Andesite and dacite porphyry are common hyabyssal intrusive rocks. Except for the iron-formation and siliceous tuff, the rocks contain moderate or abundant secondary chlorite and green amphibole, which impart a characteristic green color.

The base of the Ely Greenstone is cut out by granitic rocks of the Giants Range batholith from the vicinity of Bear Island Lake eastward to the vicinity of Ely. From there to the eastern termination of the formation, it is faulted off against metaclastic rocks and the Giants Range batholith (Green, 1970). The maximum exposed thickness of the Ely, estimated at about 15,000 feet, is in the area between Bear Island Lake and Ely; east of Ely, a minimum of 12,000 feet is exposed between the North Kawishiwi Fault and the lower-most strata of the Knife Lake Group. In both areas, the tops of separate flows are consistently to the north, as indicated by pillows.

Soudan Iron-formation

The Soudan Iron-formation, the thickest and longest banded iron-formation in the volcanic-sedimentary sequence, extends for a distance of about 16 miles eastward from Tower (fig. 2). In the Tower and Soudan area it is overlain directly by felsic volcaniclastic rocks of the Lake Vermilion Formation, whereas further eastward it is overlain directly by mafic volcanic rocks, which are assigned to the Ely Greenstone

The Soudan Iron-formation, as redefined (Morey and others, 1970), consists of several types of ferruginous cherts that are interbedded with fine-grained carbonaceous and sericitic tuffs and lesser agglomerate and basalt; all are intruded by diabase and by porphyries of general dacitic composition. The thickness of the formation has not been determined accurately because of complex folding, but probably is less than 1,000 feet. The several other banded iron-formations that occur locally

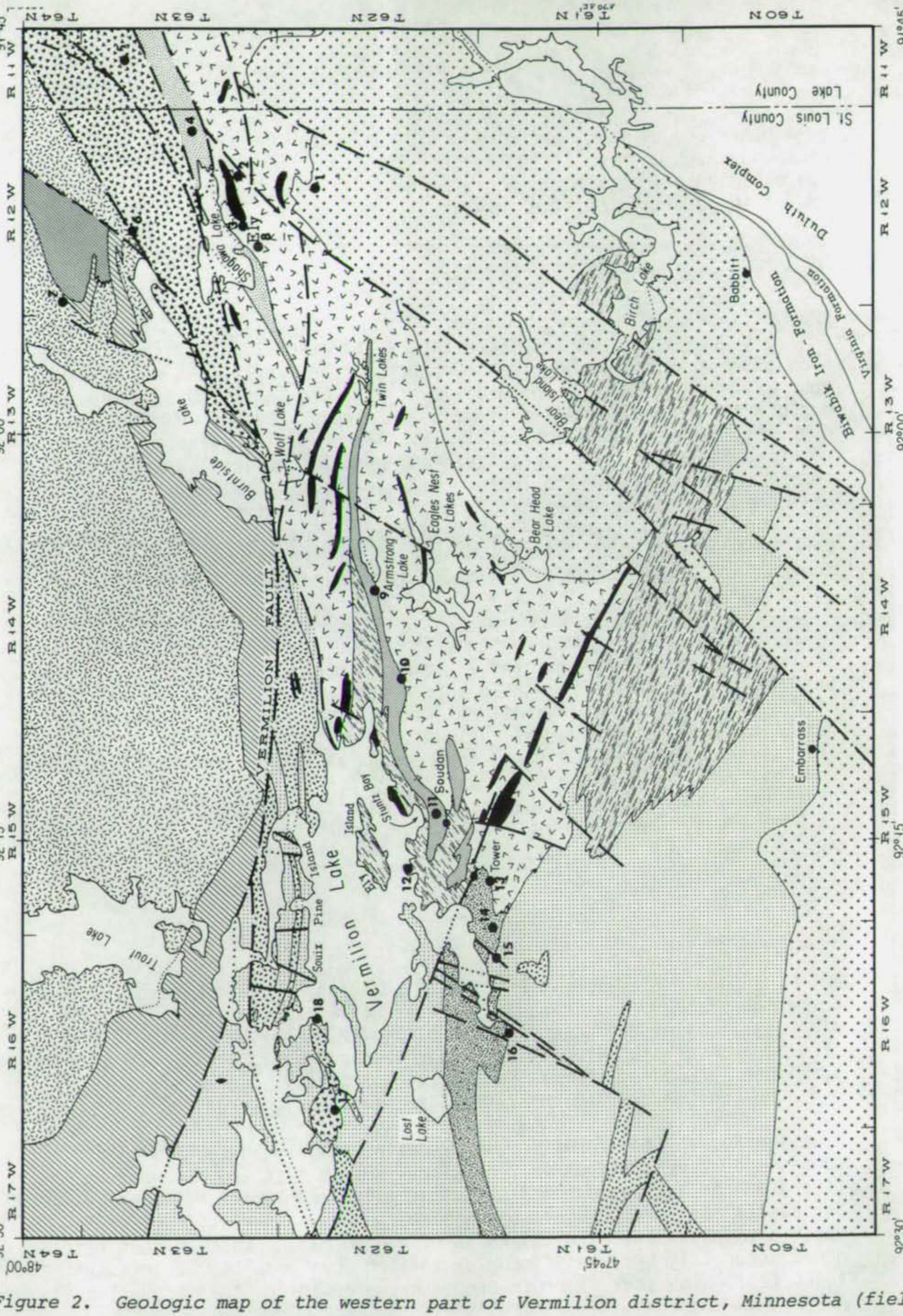
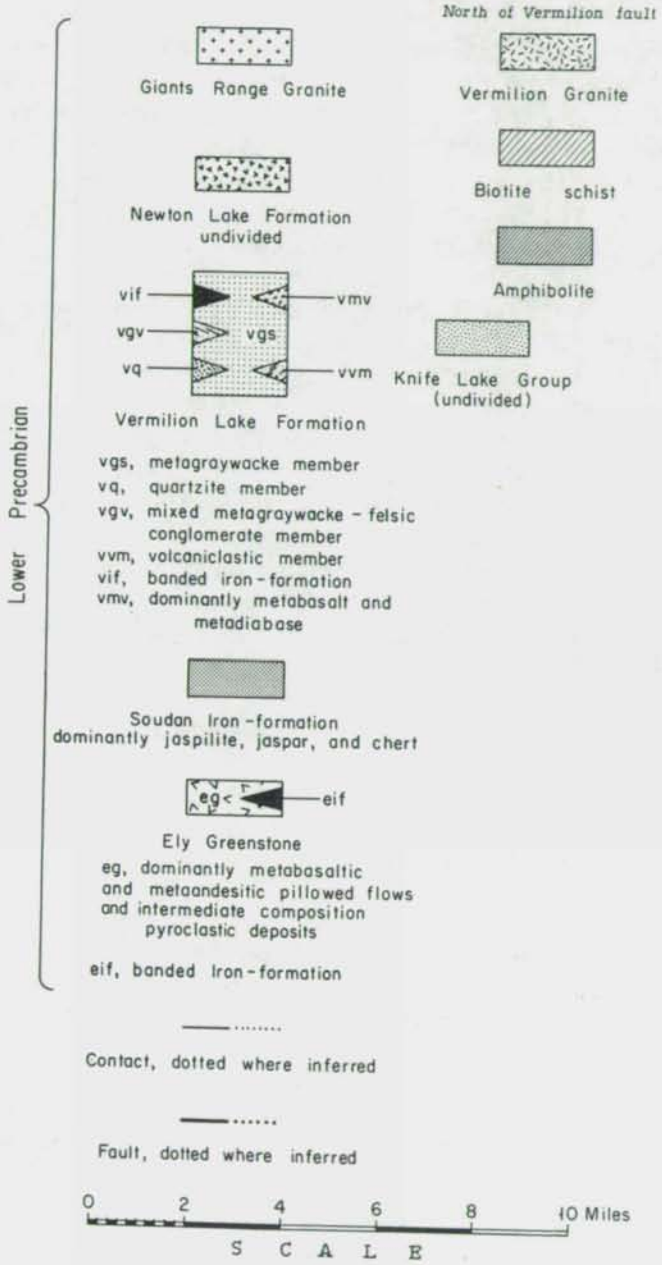


Figure 2. Geologic map of the western part of Vermilion district, Minnesota (field stops indicated by numbers).

EXPLANATION FOR FIGURE 2



in the Ely Greenstone and in younger units are not designated formally.

Lake Vermilion Formation

In the extreme western part of the district (fig. 2), the Lake Vermilion Formation overlies the Ely Greenstone and the Soudan Iron-formation. Previously (Grout and others, 1951; Goldich and others, 1961), these strata were assigned to the Knife Lake Group; they were reassigned (Morey and others, 1970) to the Lake Vermilion Formation because they are not demonstrably continuous with strata exposed in the type area of the Knife Lake. The Lake Vermilion Formation consists of sedimentary and pyroclastic rocks and lesser, thin basaltic flows. The basaltic rocks occur mainly within the graywacke member.

On the basis of the dominant lithology, the Lake Vermilion Formation was divided into four informal members (fig. 2). Agglomerate and associated tuff (volcaniclastic member) conformably overlie the Soudan Iron-formation, or where it is absent, the Ely Greenstone, in the Tower-Soudan area (fig. 2). The agglomerate is a light gray, massive rock of dacitic composition; rounded clasts of dense felsite or quartz porphyry ranging in diameter from about two inches to 24 inches occur in a fine- to medium-grained crystal-lithic tuff matrix. One to two percent of exotic rock fragments, mainly chert or banded iron-formation, occur in the rock. The upper part of the volcaniclastic member -- exposed on Ely Island and adjacent islands -- is composed dominantly of massive crystal-lithic tuff with interbedded agglomerate.

To the west of Tower, the feldspathic quartzite member abuts, and apparently stratigraphically overlies, the Ely Greenstone (fig. 2). It is older than the graywacke member, as indicated by abundant graded graywacke beds. The rock is light gray and massive, and consists mainly of angular grains of sodic plagioclase and volcanic rock fragments of dacitic composition; it has less than 10 percent matrix (Ojakangas, 1972). The term "feldspathic quartzite member", which was applied before petrographic studies were made, was an unfortunate designation for the rock, because quartz is sparse; a more suitable name would be "volcanic sandstone", for the rock probably is a reworked tuff.

The graywacke member, which is the most extensive unit in the Lake Vermilion Formation, directly overlies the Ely Greenstone south of Tower and directly overlies the feldspathic quartzite member of the Lake Vermilion Formation west of Tower. It consists mainly of thin-medium bedded graywacke; the beds commonly are graded. A chloritic facies occurs on the shores of Lake Vermilion and adjacent areas, whereas a biotitic variety is dominant elsewhere. Deposition by turbidity currents has been suggested on the basis of sedimentary structures (Ojakangas, 1972). The mixed graywacke-felsic conglomerate member occupies an area of about 30 square miles on the south limb of the fold at Tower. To the northwest, it interfingers with, and is stratigraphically overlain by, the graywacke member. It consists of a maximum of about 10,000 feet of felsic to mafic volcaniclastic rocks, felsite flows, several types of conglomerates and agglomerates, and metagraywacke (Griffin, 1969; Griffin and Morey, 1969).

It is difficult to determine the true thickness of the Lake Vermilion Formation and its constituent members because of complex folding and faulting and a lack of exposures. In the Tower quadrangle, the quartzite member is estimated to be 1,500-2,000 feet thick and the volcaniclastic member to be a maximum of about 4,000-5,000 feet thick. The metagraywacke-slate member probably is several thousands of feet thick.

Knife Lake Group

Graywacke, slate, tuff, and other volcaniclastic rocks of the Knife Lake Group directly overlie the Ely Greenstone from the vicinity of Ely, where the Knife Lake terminates against a fault, eastward to Snowbank Lake (fig. 2). In the Ely area, the Knife Lake consists dominantly of a distinctive light gray tuff of general dacitic composition, whereas between Fall Lake and Snowbank Lake it is composed mainly of graywacke with lesser felsic volcaniclastic rocks. In the central part of the district (Green, 1970), the belt of Knife Lake rocks is no more than 2,500 feet wide; locally, the rocks are in fault contact with the overlying and underlying mafic volcanic rocks. Farther eastward, in the type area, the Knife Lake is estimated to be about 15,000 feet thick (Gruner, 1941, p. 1624). In the type area, volcaniclastic rocks of general dacitic composition including both tuffs and agglomerates are abundant, as are a variety of conglomerates. The dominant rocks are graywackes, which are mainly of volcanogenic origin (Ojakangas, 1972).

Newton Lake Formation

The Newton Lake Formation was mapped earlier (Clements, 1903) as Ely Greenstone, but has been renamed (Morey and others, 1970) because it is stratigraphically younger than at least part of the Knife Lake Group (fig. 2). Evidence for the younger age has been discussed by Green (1970), but consists mainly of northward-facing pillow tops at or near the base of the formation. The formation is truncated on the north by the Vermilion fault and along strike to the northeast by granitic rocks of the Vermilion batholith. At its western extremity, near Wolf Lake, the formation also is truncated by a fault.

The western part of the Newton Lake Formation is composed principally of mafic volcanics and the eastern part of felsic volcanics; accordingly, the unit is divided into a mafic volcanic member and a felsic volcanic member. The two members interfinger in the vicinity of Newton Lake. The mafic volcanic member consists dominantly of basaltic and andesitic lavas, some of which are pillowed, and fine-to-coarse-grained diabase and mafic tuff or tuff breccia. The felsic member consists dominantly of tuff breccia deposits and lesser proportions of flows. Detailed descriptions in the

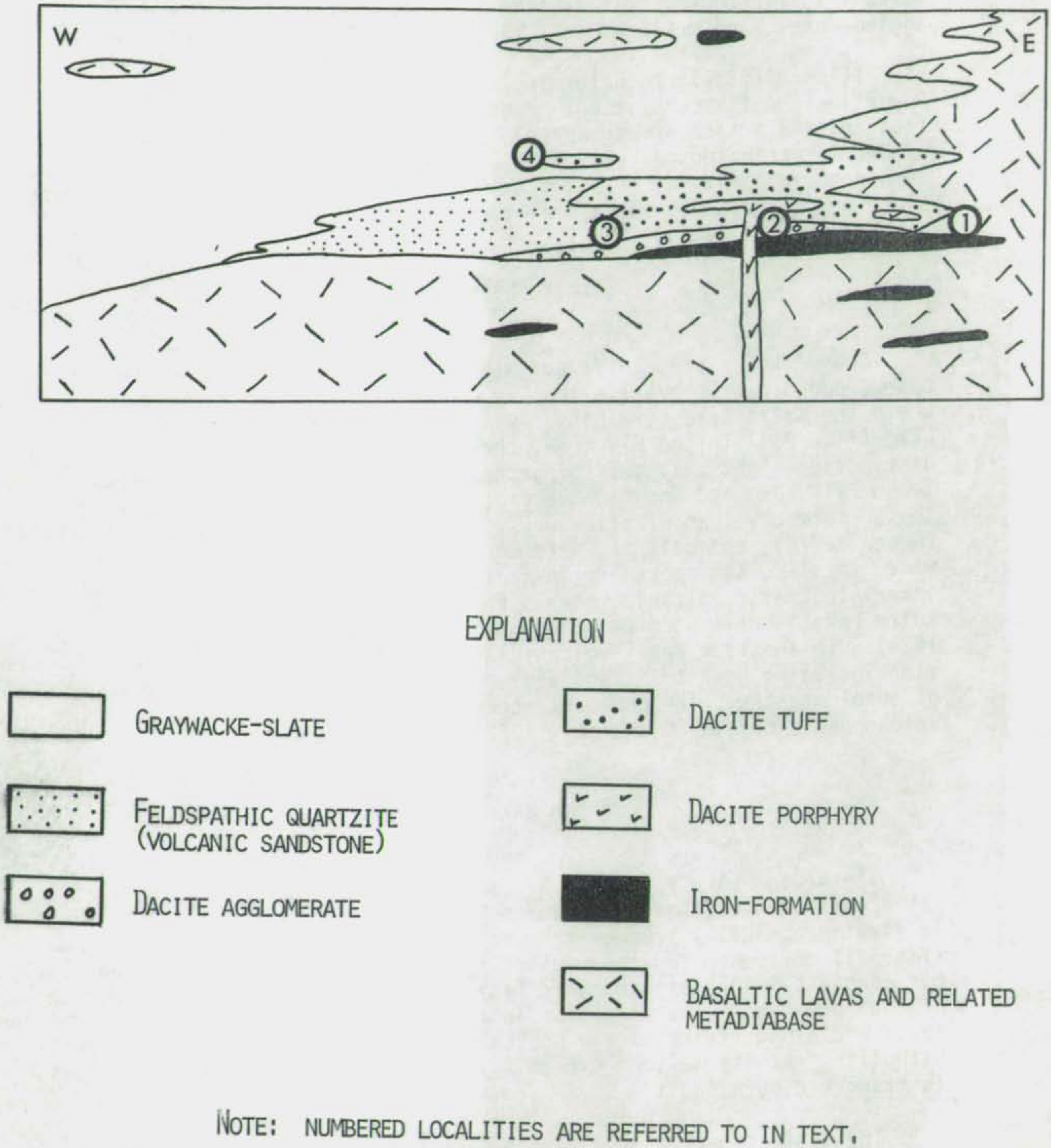


Figure 3. Schematic diagram showing inferred stratigraphic relations in the western part of the Vermilion district (not to scale; because of structural distortion, only an approximate geographic correspondence can be made with figure 2).

type area are given by Green (1970). Several small bodies of serpentinized peridotite, which are part of differentiated mafic-ultramafic bodies, are associated spatially with the basalt and diabase, and a few small lenses of siliceous marble and banded iron-formation occur in the formation. The marble is interbedded with tuffs in the upper, exposed part of the formation.

Stratigraphic Interpretation

An interpretation of the stratigraphic relationships in the western part of the district is presented graphically in figure 3. The diagram shows the inferred distribution of rock types prior to deformation; structure has been removed insofar as possible. Localities that are critical to interpretation of the stratigraphy are shown by numbered circles.

Mafic lava flows, and lesser diabase and pyroclastic deposits (Ely Greenstone) constitute the base of the seuqence. Iron-formation formed locally during accumulation of the flows, probably in local depressions on the surface. Probably, they formed directly from volcanic emanations, as proposed by Goodwin (1962) for similar deposits in Ontario, Canada.

The largest and most widespread of the iron-formations, formally named the Soudan, accumulated during a major interruption in mafic volcanism. This unit because of its remarkable persistence along strike, represents an important time-stratigraphic unit. To the east of Armstrong Lake (loc. 1, fig. 3), it is succeeded by about 7,000 feet (stratigraphically) of mafic and intermediate lavas and pyroclastic rocks and local lenses of banded iron-formation (Ely Greenstone). To the west, it is overlain directly by agglomerate and tuff (felsic volcaniclastic member of the Lake Vermilion Formation). Thus, the iron-formation serves to indicate the approximate contemporaneity of mafic (on the east) and felsic volcanism (on the west) in the succeeding strata. Inasmuch as there is no evidence for an unconformity between the iron-formation and the younger rocks, the time lapse between the cessation of iron-formation deposition and renewal of volcanic activity probably was small.

The agglomerate at locality 2 (fig. 3) is of interest because it was interpreted by Clements (1903) as conglomerate, and equated with the "Ogishke conglomerate". The rounded clasts in the rock were interpreted as fragments of felsic porphyry, which Clements presumed was intruded during a "pre-Knife Lake slate" orogenic event (later named Laurentian), and subsequently eroded and redeposited. Instead, the agglomerate marks the abrupt onset of felsic pyroclastic discharge; the exotic rock fragments -- iron-formation and greenstone -- most likely were ripped from the underlying strata during the explosive action.

Westward from Soudan, the agglomerate and tuff of the Lake Vermilion Formation grade transitionally, both laterally and vertically, into the feldspathic quartzite member (reworked tuff and agglomerate) of the Lake Vermilion Formation (loc. 3, fig. 3). Details of the gradational relations remain obscure because of sparse exposures, but the broad relationship is clear. In successive outcrops westward from Tower, agglomerate decreases proportionately to tuff and bedding becomes more prominent.

Deposition of graywacke-slate was partly contemporaneous with accumulation of felsic pyroclastic deposits. Ojakangas (1972) has concluded that vast quantities of volcaniclastic rocks are required to account for the volume of volcanogenic detritus in the graywacke. A likely source was the nearby dacitic tuffs and agglomerates in the upper part of the volcanic pile. Possibly, a substantial proportion of the total accumulation of these rocks was eroded, to yield the volcanogenic graywacke. If so, estimates of the abundances of felsic volcanic rocks in the volcanic pile accumulations based on present-day exposures may be substantially less than the original accumulations.

Locally, during accumulation of the graywackes, basaltic lavas were erupted onto the surfaces of deposition (loc. 4, fig. 3); some of these accumulations now constitute bodies several miles long and a few miles thick (see Sims and others, 1970).

INTRUSIVE ROCKS

Five distinct episodes of intrusive activity are recognized in the region. In order of inferred age, from oldest to youngest, these are:

(1) synvolcanic bodies, including metadiabase and hypabyssal porphyries having a wide range in composition,

(2) syntectonic granitic rocks of the Saganaga, Giants Range, and Vermilion batholiths,

(3) late- or post-tectonic syenitic rocks and related lamprophyres,

(4) post-tectonic alkalic Linden pluton to west of Tower and Icarus pluton to east of Saganaga Lake, and

(5) diabasic dikes of Middle Precambrian age and basaltic dikes of Late Precambrian age.

Only the synvolcanic bodies and the batholithic rocks are discussed herein.

Synvolcanic Hypabyssal Bodies

Several types of altered and metamorphosed intrusive rocks are spatially and temporally associated with the metavolcanic rocks. They range in composition from basalt to rhyodacite and include rather abundant andesite and dacite. Most bodies are dikes or small irregular plutons that are too small to show at the scale of the map in figure 2, but can be distinguished readily on larger scale maps (cf. Green and others, 1966; Sims and others, 1968).

Metadiabase is closely associated with the basaltic lavas; generally it is intercalated with and is more or less conformable to the mafic lavas, but some contacts are strongly cross-cutting. It is distinguished from the metabasalt by being distinctly coarser grained and in having a diabasic texture. Metadiabase is abundant in both the Ely Greenstone and the Newton Lake Formation, and constitutes about 25 percent by volume of the mafic rocks.

Andesite, dacite, and rhyodacite porphyries, which are metamorphosed to the same extent as the metadiabase, are widely distributed in the Ely Greenstone, and occur locally in the younger formations. The bodies vary from thin dikes and small irregular "plugs" a few tens of feet across to larger irregular plutons several hundreds of feet wide.

The differentiated mafic-ultramafic bodies in the Newton Lake Formation probably are differentiated sills, which were intruded approximately synchronously with effusive mafic lavas. The largest known body, exposed near Little Long Lake, north of Ely, is about three miles long and 200 feet wide. It constitutes the basal part of a differentiated body about 600 feet (?) thick, and is overlain conformably (?) by a mafic pyroxene-rich gabbro which in turn is overlain by and gradational into a diabasic gabbro. The upper part of the mafic body is truncated by the Vermilion fault.

Vermilion and Giants Range Batholiths

The plutonic rocks of the Vermilion and Giants Range batholiths, which border the supracrustal rocks and partially engulf them, profoundly affected the volcanic-sedimentary sequence. Granitic rocks of the Giants Range batholith, on the south, irregularly intrude the sequence or are in fault contact with it, and near Bear Island Lake have cut out an unknown amount of the lower part of the Ely Greenstone (fig. 2). Further westward, they irregularly embay and transect the Lake Vermilion Formation; east of Ely, rocks of the batholith intrude metaclastic rocks assigned to the Knife Lake Group (Green, 1970) and both are faulted against the Ely Greenstone. The Vermilion batholith, on the north side of the district, transects the upper part of the supracrustal sequence. Except in the Basswood Lake area and in the Wakemup Bay area (fig. 2), it is separated from the supracrustal rocks by the Vermilion fault.

The Vermilion batholith, named by Grout (1925), underlies an area of more than 2,800 square miles in northern Minnesota and extends into Ontario for an undetermined distance. The most common granitic rock is a gray or pink, medium- to coarse-grained, generally equigranular biotite granite, which is called Vermilion Granite. The granite contains nearly equal amounts of quartz, plagioclase (An_{20}-An_{30}), and perthitic microcline, and has a few percent of red-brown biotite. Lesser intrusive rock types are biotite granodiorite, hornblende quartz diorite, and hornblende diorite. The Burntside granite gneiss of Grout (1926, p. 29), a biotite trondhjemite, is an early satellitic phase of the batholith in the Burntside Lake area. Belts of schist-rich migmatite are common within the boundaries of the batholith (D.L. Southwick, 1971, unpublished map of International Falls two-degree sheet), and consist of schist, amphibolite, and intermediate gradational rock types that are intercalated with variable quantities of granite and pegmatite.

The Giants Range batholith differs in gross form, internal structure, and composition from the Vermilion batholith. It trends northeastward, parallel to the regional structure and, as exposed, is more than 100 miles long and 5 to 25 miles wide. It is inferred from geophysical data to extend another 100 miles southwestward from its most westerly exposure (see Sims, 1970). The batholith is composite. The eastern part consists dominantly of either equigranular or porphyritic adamellite, monzonite, and granodiorite that contain hornblende as the dominant mafic mineral (Green and others, 1966; Green, 1970). Small bodies of hornblende tonalite and diorite are common, and several types of probable cognate dikes cut the main facies. The western, exposed part consists of several different granitoid bodies that range in composition from tonalite to granite (Sims and others, 1970). Granite is much more abundant than in the eastern part. Although the separate plutons vary widely in composition, the Giants Range batholith as a whole has a composition similar to the average Archean granitic rocks (granodiorite) of the Canadian Shield, as determined by Fahrig and Eade (1968, table 1, column 11).

METAMORPHISM

The supracrustal rocks within the district dominantly contain mineral assemblages characteristic of the greenschist facies (Turner, 1968). Adjacent to the Vermilion and Giants Range batholiths, the rocks are metamorphosed to the amphibolite facies.

Precise mapping of metamorphic zones is hindered by marked evidence of mineralogical disequilibrium, wide-spread retrograde reactions that locally have destroyed earlier metamorphic minerals, and the absence over much of the area of rocks having compositions suitable to yield diagnostic metamorphic mineral assemblages. Evidence of incomplete recrystallization is widespread in the greenschist-facies rocks, and is indicated by relict hornblende and zoned plagioclase in the metagraywackes and relict augite and labradorite in the mafic volcanic rocks. In the metagraywackes, the coarser framework grains -- feldspar, quartz, and volcanic rock fragments -- typically show little evidence of recrystallization.

Most of the district is underlain by rocks in the lower range (chlorite zone) of metamorphic grade in the greenschist facies. Assemblages have not been distinguished in detail, but quartzo-feldspathic rocks commonly contain chlorite, muscovite, albite, quartz, and epidote, and mafic rocks contain chlorite, tremolite/actinolite, epidote, albite, quartz, and calcite. The peridotites contain serpentine and, rarely talc and tremolite. Higher grade rocks in this facies (biotite zone) contain biotite in addition to the common phases listed above.

Definite amphibolite-facies rocks, as indicated by the presence of almandine, rare staurolite, and/or plagioclase having a composition An>20 in quartzo-feldspathic rocks and by hornblende-plagioclase (An>20) assemblages in mafic rocks, occur within and adjacent to the major batholiths. Evidence of retrograde reactions is widespread in the amphibolite-facies rocks. Plagioclase commonly is partly altered to sericite and/or epidote, biotite is typically chloritized without changes in morphology, and hornblende is partly chloritized. Details concerning the amphibolite-facies rocks are lacking except in the Embarrass area south of Tower (Griffin, Unpublished Ph.D. dissertation, University of Minnesota; Griffin and Morey, 1969).

The amphibolite-facies rocks form narrow aureoles around the batholithic masses in most of the region. For example, the width of the aureole adjacent to the Giants Range batholith in the vicinity of Bear Island Lake is about 2,000 feet. Comparable widths are found in the central part of the district adjacent to both major batholiths. In the southwestern part of the region (fig. 2), on the other hand, amphibolite-facies rocks extend outward from the Giants Range batholith for distances of as much as seven miles. Judged from gravity data, this area is underlain at relatively shallow depths by felsic igneous rocks, which can account for the higher metamorphic grade there.

STRUCTURE

The supracrustal rocks strike generally eastward, are steeply inclined, and are complexly deformed. Two generations of folding and a younger generation of deformation including both faulting and kinking have been recognized (Hooper and Ojakangas, 1971).

Although deformation was pervasive, primary structures remain in most of the greenschist-facies rocks. Graded bedding and other original features such as flame structures remain in much of the graywacke-slate, and pillow structures, amygdules, and variolites are largely preserved in the mafic lavas. At places, deformation was sufficiently intense to obscure or even obliterate bedding and other primary features. In the amphibolite-facies rocks, on the other hand, primary structures other than bedding rarely are recognizable because of a pervasive foliation and thorough recrystallization.

In the western part of the area the rocks are complexly folded as a result of two distinct episodes of deformation. The younger folds and a pervasive accompanying cleavage largely obscure the older folds, although the older folds were important in determining the distribution of the rocks. Detailed studies in the Tower quadrangle and adjacent areas (Hooper and Ojakangas, 1971) indicate that the bedded volcaniclastic strata, and to a lesser degree the metavolcanic rocks, first were folded on west-northwest-trending axes. These (F_1) folds were tight to isoclinal, had steep axial planes, and probably had gentle or moderate plunges. Major fold axes, as determined by consistently facing or opposing tops of beds, were spaced from 700 to 1,500 feet apart. The younger (F_2) folds, which comprise most of the mappable ones, are strongly asymmetric and have steep axial planes that trend eastward. In most of the area the (F_2) folds are dominantly Z-folds, and the northwest-trending limbs are two or more times longer than the southwest-trending limbs. Both upward-facing and downward-facing folds (Cummins and Schackleton, 1955) occur, and plunges are generally steep. The intersection of a pervasive, mild, axial plane cleavage with bedding is parallel to F_2 fold axes. In biotite- and higher-grade rocks, new minerals are aligned parallel to the cleavage-bedding intersection. In the Tower area, several nearly vertical structures -- faults, joints, and kink bands -- displace the cleavage of the F_2 deformation.

High-angle faults of two trends, longitudinal and transverse, break the metavolcanic-metasedimentary sequence into a number of blocks or segments and separate it in part from the marginal batholithic rocks.

The major longitudinal fault -- the Vermilion -- separates the supracrustal rocks of the district at most places from the Vermilion batholith. It is a long, curvilinear fracture with many subsidiary strands that has been traced northeastward to the Canadian boundary and is inferred on the basis of aeromagnetic and geologic data (Sims, 1970) to extend northwestward through the northwest corner of the state. Its inferred length exceeds 300 miles. The amount and direction of the horizontal component of movement is not known, but possibly is several miles. The vertical displacement is inferred to be on the order of a mile, to bring higher-temperature-facies rocks on the north against lower-temperature-facies rocks in the district.

Other longitudinal faults slice the northern part of the district into separate segments. The Wolf Lake fault -- a major structure -- cuts off the Knife Lake and Newton Lake Formations west of Ely (fig. 2); probably displacement on the fault was dominantly right lateral. The North Kawishiwi fault, in the central part of the district, largely separates the predominantly low-grade rocks in the inner part of the district from amphibolite-facies schists and gneisses and associated granitic rocks of the Giants Range batholith (Green, 1970). If the metaclastic rocks on the south side belong to the Knife Lake Group, as suggested by Green (1970), the fault has a stratigraphic throw of at least 12,000 feet.

The transverse faults trend northeastward or north-northeastward and have dominantly left lateral displacements. The principal faults of this set, the Waasa and Camp Rivard in the southeastern part of the map area (fig. 2), have measureable displacements of about 3-4 miles (Griffin and Morey, 1969) and cut and offset both the older metamorphic rocks and the granitic rocks of the Giants Range batholith. The metamorphic rocks are offset more than the granite-metamorphic rock contacts, indicating some pre-intrusion movement. Some post-granite movement also is indicated by shearing and brecciation in the granitic rocks. These faults may merge, beneath glaciofluvial cover, with the North Kawishiwi fault just southeast of Ely.

The major faults are expressed commonly as narrow, linear topographic depressions. Where exposed, they are seen to consist either of wide zones of crushed and altered rocks or of intensely silicified and altered rocks. Mylonite as much as a few hundred feet wide occurs at places along the faults; not uncommonly a brick red coloration characterizes fault zones within the granitic rocks.

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ROAD LOG AND STOP DESCRIPTIONS

R.W. Ojakangas

This field trip starts a few miles south of Ely and ends a few miles west of Tower, and is designed as a two-day trip. Typical outcrops of all formations in the district are included, but most stops will examine the Lake Vermilion Formation. The rocks that will be seen on this trip are tightly folded and steeply plunging; therefore, we will be looking at a cross-section (but a structurally complicated one) of a volcanic-sedimentary pile. All the rocks in the area are metamorphosed, but for simplicity the prefix "meta" will generally be omitted.

FIRST DAY

The field trip starts at the roadcuts 2.6 miles south of Ely on State Hwy. 1.

STOP 1: Giants Range Batholith: -- The most abundant rock type within the batholith in this area is medium-grained, porphyritic hornblende-biotite adamellite with pink K-feldspar phenocrysts and sparse quartz (the "Farm Lake Facies" of Green, 1970). Hornblende and K-spar are commonly aligned in flow structure. Monzonitic, granodioritic, and dioritic phases also occur; all rock types are cut locally by shear zones.

NOTE: The intrusive contact of the Giants Range Granite into the Ely Greenstone is located along Hwy. 1, 1.1 miles north of STOP 1. The Ely Greenstone exposed under the powerline, a few hundred feet northeast of the contact, consists of dacitic to andesitic pillowed lavas, which are an uncommon variety of lava within the Ely Greenstone. Pillow shapes indicate that tops face north, as is the case for most of the formation in this area. The volcanic rocks are cut by aplitic dikes related to the Giants Range batholith.

NOTE: Stops 2 through 5 are in successively younger stratigraphic units.

From STOP 1 drive north on State Hwy. 1 to Ely, turn west on Hwy. 169-1, then turn right on 13th Ave. E. (by the A&W) for 1 block, left on Camp St. for 1 block, right on 12th Ave. E. for 2 blocks, right on Washington St. for 1 block, left on the next street (unnamed) for 1 block, and left on the next street, which is "Main Street" (but unmarked here), for half a block to exposure adjacent to street.

STOP 2: Ely Greenstone (No hammering, please!) -- This is a loose block of Ely Greenstone which probably has been transported to this locality from outcrops a few hundred feet to the north by glaciers. However, it is an excellent 3-dimensional example of relatively undeformed pillows of metabasalt. (At many greenstone exposures, the pillows have been tectonically elongated and are visible only on two-dimenstional glacially striated outcrops.) Pillowed lavas within a few hundred feet to the north of this loose block show that tops are to the north.

From STOP 2, continue west on "Main St." to 11th St., turn left on 11th St. for 1 block, then right on Washington St. and follow through town to Camp St., then turn right on Camp St. for 1 block, right on Pioneer, cross railroad tracks, and proceed about another block to large open pit on right.

STOP 3: Iron-formation: -- (Unnamed unit at or near top of Ely Greenstone). This large pit exposes a doubly plunging, faulted syncline called the Ely trough: pillows top north just north of the pit rim and top south just south of the pit rim. Two head frames of the Pioneer mine can be seen to the east. The pit is mainly the result of collapse of surficial materials into underground workings, some of which extend to a depth of 1,600 feet. The ore was massive crystalline hematite, brecciated and cemented by a later generation of crystalline hematite; silica in the iron-formation was replaced by the hematite (Machamer, 1968). The mines in the Ely trough produced about 88 million tons of the total of 104 million tones produced from the Vermilion district between 1888 and 1967, when the Pioneer mine -- the last operating mine -- ceased operations. The Pioneer mine still has reserves estimated at 6 million tons.

Turn around and return to Hwy. 169-1 (1st stop sign about 2 blocks from railroad tracks) and turn left (east). Proceed through Ely to village of Winton, about 2-1/2 miles east of Ely. After crossing bridge and entering village turn left on St. Louis Co. Hwy. 117. Proceed past water tower on left and turn left on next street, go 1 block to end of street and turn left, pass water tower to fork in road near tower, take right fork and park. Walk to outcrops near base of tower.

STOP 4: Knife Lake Group: -- This is one of the readily accessible, large exposures of Knife Lake rocks, and consists of phyllitic metasedimentary rocks that are representative of one rock type within the highly variable unit. It can be seen here that shearing is pervasive, bedding is indistinct, and late-stage kink-banding is common. Foliation trends NE-SW and lineation is very steep (80-90°) to SW.

Drive west from Winton water tower on gravel road about 0.5 mile to railroad tracks. Turn right at railroad without crossing tracks. Drive 2.8 miles on a gravel road heading north and northeast and park at intersection with private road on right. Exposures are located along first 900 feet of private road (NW1/4, SE1/4, Sec. 7).

STOP 5: Newton Lake Formation: -- Low-lying exposures of serpentinized peridotite are located within 200 feet of the intersection on northwest side of main gravel road. These are part of a northeast-trending, 1,000-foot-thick and several-mile-long differentiated sill that is dominantly composed of diabasic gabbro. Many such bodies have been mapped in the Newton Lake Formation area by J.C. Green (oral communication, 1972;

Minnesota Geological Survey open-file map of Ely quadrangle). Where well exposed, the sills typically grade upward from serpentinized peridotite to pyroxenite to coarse-grained hypersthene gabbro to diabasic gabbro to diabasic gabbro with interstitial quartz.

The first outcrops on the private road are hypersthene gabbro. Succeeding outcrops are diabasic gabbro and quartz-bearing diabasic gabbro. Pillowed lavas (the country rock in which the sill was intruded) are located about 900 feet down the private road on both sides of a sharp bend in the road on the crest of a small hill.

Return to intersection at railroad tracks and turn right (SW) on gravel road. Proceed on gravel road for about 1 mile to intersection with paved road (Co. Hwy. 88). Turn right and proceed 1.4 miles to intersection with Echo Trail. (Note high greenstone ridge north of the intersection.) Turn right and drive 2.6 miles on the Echo Trail to White's Shig-Wauk Lodge on Little Long Lake.

Continue west on Echo Trail for about 0.7 miles to intersection with Moat's resort road (Co. Hwy. 752).

STOP 6: Vermilion Fault: -- The resort road (Co. Hwy. 752) has been built in and along the topographic depression marking the location of the Vermilion Fault. Note the 50-foot-high ridges on either side, typical of its expression in this region. The fault here is characterized by mylonitized metasedimentary (?) rocks, and in places is visible as a highly silicified shear zone as much as 200 feet wide. The fault trends northeasterly, and probably extends into Canada. Geophysical and geological evidence suggests that it can be traced west-northwestward from the Vermilion district nearly to North Dakota.

The Vermilion Fault is one of the major known faults in northern Minnesota. It separates lower grade (greenschist-facies) metamorphic rocks to the south (Newton Lake Formation) from higher grade (amphibolite-facies) rocks and the Vermilion Granite to the north.

Proceed northward along the Echo Trail for 3.6 miles and stop on the right side of road on pulloff adjacent to Everett Lake sign.

STOP 7: High-grade metamorphic rocks and Vermilion Granite: -- Roadcuts here consist of pink Vermilion Granite and amphibolitic inclusions of country rock. Excellent roadcuts are present on the next hill, 0.2 miles farther north on the Echo Trail. Rocks here consist of amphibolite and biotite schist layers in pink Vermilion Granite, but a few miles to the north, the Vermilion Granite is homogeneous and lacks inclusions.

NOTE: The remainder of the stops on this trip (with the exception of STOP 17) are in successively younger stratigraphic units.

Drive southward on Echo Trail to intersection with Co. Hwy. 88 on north side of Shagawa Lake (distance: about 8 miles). Turn left at intersection and proceed to intersection with Hwy. 169-1 (about 2-1/2 miles). Turn right and drive through Ely on Hwy 169-1. About 0.25 miles west of Ely are high roadcuts.

STOP 8: Ely Greenstone: -- Pillowed metabasalt that is typical of mafic lavas of the Ely Greenstone is exposed in roadcut on north side of highway. The pillow structures have smoothly rounded tops, nearly flat bases, and are somewhat drawn out in vertical dimension. The chilled rinds are as much as an inch thick. The pillow structures strike approximately N. 20° E., dip 80° SE., and face southeastward. The long dimension of the pillows is subparallel to the intersection of cleavage and bedding and plunges steeply northeastward. The exposures are on the northwest limb of the same tight syncline mentioned at STOP 3, the axis of which passes through the Ely trough.

On the south side of highway, fine-to-medium-grained metadiabase is exposed in roadcut and on hill to south. The metadiabase intrudes and crosscuts the pillowed metabasalt. A contact can be seen in the southern part of the crest of the hill.

NOTE: Piles of crushed greenstone (a tuff in Newton Lake Formation) about 2 miles west of STOP 8, on north (right) side of road, are remnants of an unsuccessful experiment (early 1930's) in which crushed greenstone was used for the making of roofing granules.

NOTE: Numerous outcrops between Ely and Soudan (22 miles to the west) consist of Ely Greenstone and Soudan Iron-formation.

From STOP 8, proceed westward on Hwy. 169-1 to point 0.8 miles west of Mud Creek Road (distance: 12.2 miles west of STOP 8). Turn into large gravel pit on right (north) side of road. Near center of pit is rock outcrop several feet high; similar exposures are present in woods to the east of this outcrop.

STOP 9 (optional): Ely Greenstone and Soudan Iron-formation cut by a dacite porphyry dike: -- Pillowed lavas and jaspillite, striking NW and dipping 65° NE are cut at low angle by a 15-foot dacite porphyry dike (nearly a sill). Refer to STOP 10 for a description of dacite porphyry.

Proceed 2.6 miles west on Hwy. 169 to large roadcuts on crest of hill. Just beyond cut on right, pull off to right on old highway.

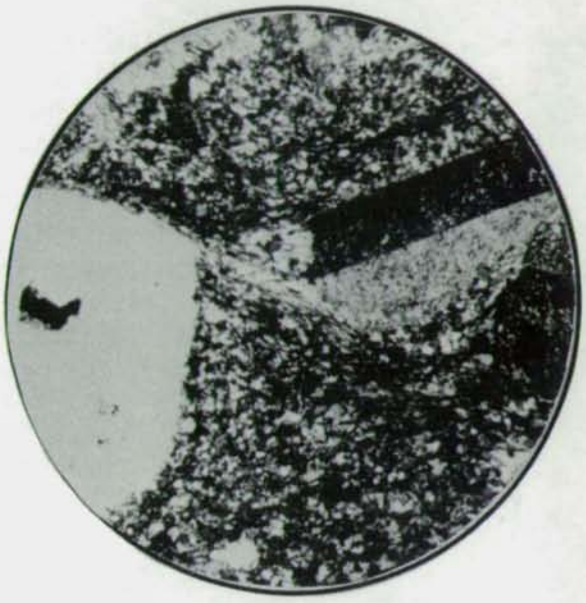
STOP 10: Soudan Iron-formation and cross-cutting dacite porphyry dike: -- Dike is exposed on both sides of highway. The iron-formation is composed of interlayered black, red, and white chert, hematite and magnetite layers, and black argillaceous layers that contain abundant stringers and pods of pyrite. Hence, both oxide and sulfide facies of the iron-formation are represented. The iron-formation is deformed into drag folds that plunge 50-60° NE. The beds trend N. 85° W. and dip steeply N. Ely Greenstone is exposed in roadcuts to the east.

The dacite porphyry is one of numerous dikes and sills that cut the

Ely Greenstone and the Soudan Iron-formation in the western Vermilion district (G.B. Morey, Soudan 7.5' quadrangle, unpublished reconnaissance map: Minn. Geol. Survey). Apparently they were feeders for the dacitic tuffaceous sandstones, tuffs, agglomerates, sills, and flows of the Lake Vermilion Formation, which overlies the Soudan Iron-formation.

Generalized Mode of Dacite Porphyry

33-38%	Plagioclase (oligoclase)
0-12.5%	Volcanic quartz
50-63%	Fine-grained matrix
Tr-3.5%	Other



0.5 mm

Photomicrograph of representative dacite porphyry
(Volcanic quartz at left, plagioclase at right, groundmass top and bottom, scattered muscovite and chlorite.)

END OF FIRST DAY

SECOND DAY

Outcrop just west of Stuntz Bay road at crest of Soudan Hill, 1,000 feet west of the Soudan mine at the north edge of the village of Soudan.

STOP 11: Soudan Iron-formation (No hammering, please!): -- This is a classical exposure of folded Soudan Iron-formation, comprised of alternating bands of steely-gray hematite, white to pink chert, and red jasper. Note that each band of hematite and chert consists of numerous laminae on the order of 1 mm thick.

The numerous folds visible on the outcrop have in the past been interpreted as soft-sediment deformation. However, recent studies (Hooper and Ojakangas, 1971) have shown that folding is the result of two regional deformations. Joints and faults related to a third deformation cross the folds.

Most of the more obvious folds are a result of the second deformation (F_2) and plunge E at steep angles. However, evidence of an earlier set of folds (F_1) is provided by structures such as those shown in the following illustrations.

View of folded Soudan Iron-formation at STOP 11.
Hammer is oriented approximately east-west.

F_1 fold in Soudan Iron-formation modified by F_2 deformation. Trace of F_1 axial plane shown by short dashes and trace of F_2 axial plane shown by long dashes.

"Eye structure" (interference pattern) in Soudan Iron-formation. Result of erosion of an undulating (with respect to horizontal) F_1 axial plane. Undulation caused by crossing of F_1 axis by F_2 axis.

The nearby Soudan mine was opened in 1884 and operated continuously until 1962, when it was deeded to the state by the U. S. Steel Corp. for the development of Tower-Soudan State Park. Tourists can put on hard hats and descend to the 26th level, nearly a half mile down, and ride an electric train to the most recent workings. The Soudan was the first iron mine in Minnesota and shipped 16 million tons of high grade ore containing 63-66 percent iron. Initial operations were open-pit. The mine was not closed because of exhaustion of the ore; known reserves total 2-1/4 million tons. The high cost of mining and the preference of blast furnaces for taconite pellets rather than for high grade lump ore caused it to close. (Ore shipments from the Vermilion district, now inactive, totaled 104 million tons.)

Drive back into village of Soudan and turn right (west) on first crossing street. At northwest corner of village, opposite store, take the road toward Tower-Soudan State Park and McKinley Park. Pass the State Park turnoff and continue to McKinley Park (about 1-1/2 miles). Upon entering the McKinley Park clearing, take first small private road to right. Drive about 0.8 miles to end of main gravel road, which is on large peninsula east of McKinley Bay.

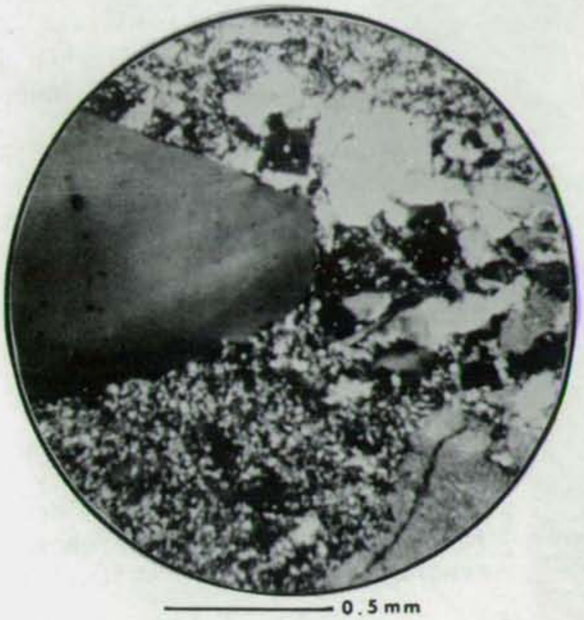
STOP 12: Lake Vermilion Formation, Volcaniclastic Member: -- White dacitic tuffs, white dacitic agglomerates, black carboniferous slates, and chloritic graywackes, all of the volcaniclastic member, are interbedded in this area. Thin beds of iron-formation also occur here.

As the best exposures of the dacitic agglomerate are accessible only by boat, we will see only some large locally derived glacial erratics of this rock type. All clasts, with the exception of very minor gray or black chert and very rare greenstone, are dacite porphyry. Note that the groundmass of the clasts is much finer grained than in dacite porphyry dikes at STOPS 9 and 10, but that the quartz and feldspar phenocrysts resemble those in the porphyry dikes.

The dacitic tuff ("quartz eye tuff") is very difficult, and sometimes impossible, to distinguish in the field from dacite flows; both rock types are massive and sheared. Generally, studies of thin sections are necessary to resolve the question, but the shearing makes microscopic interpretation difficult. It is of some comfort to know that Clements (1903) and numerous other workers had similar difficulties.

Generalized Mode of Dacite Tuff

47-58%	Plagioclase
13-42%	Volcanic quartz
8-24%	Volcanic rock fragments (dacitic)
3-5%	Other



Photomicrograph of representative dacitic tuff.
(Volcanic quartz at left, plagioclase at lower right, volcanic rock fragments at top and bottom, small quartz and plagioclase grains upper middle.)

Return to Soudan and continue west on Hwy. 169 to village of Tower. Drive 0.35 miles west of Tower on Hwy. 169 to large roadcuts on both sides of road.

STOP 13: Lake Vermilion Formation, Volcaniclastic Member: -- Limonite-stained dacitic agglomerate of the volcaniclastic member. Bedding (indistinct) and volcanic clasts are best observed on the glaciated surface at the western end of the south roadcut. Note strong development of F_2 lineation (streaking and elongate clasts), which plunges about 60° E.

The limonite has resulted from oxidation of disseminated pyrite and pyrrhotite. Larger blebs of sulfide, as much as several inches long, appear to have replaced dark felsic-intermediate volcanic rock fragments in the agglomerate. Most clasts are light-colored dacitic volcanic rocks; minor amounts of darker volcanic rock fragments suggest that the agglomerate may be in part an epiclastic deposit. The matrix is very similar to the dacite tuff.

NOTE: South of the highway for the next 0.75 miles is the folded western extremity of the Ely Greenstone. The fold nose, located south of the bridge over West Two Rivers, closes to the west, but the fold plunges about 55° E. This is, therefore, a downward-facing fold (see text). Some small folds at STOP 15 have the same structure.

Roadcuts north and south of Hwy. 169, about 1.5 miles west of STOP 13 and 1.85 miles west of Tower.

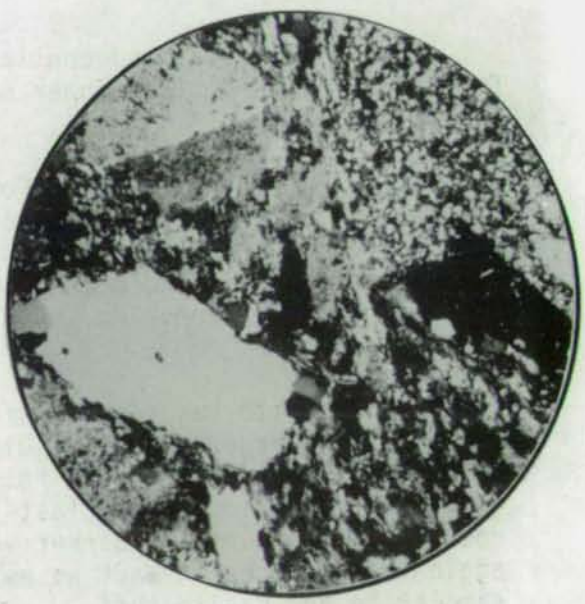
STOP 14: Lake Vermilion Formation, Feldspathic quartzite Member: -- Large roadcuts of very light gray, medium-grained volcanic sandstone, probably reworked tuff. Note the quartz "eyes", smaller than in the dacite tuff and dacite porphyry. Although generally massive, faint bedding and lamination are visible on the outcrop, and some sericitic phyllite (originally fine-grained tuff?) bands are present. At the east end of the south cut, felsic volcanic rock fragments as much as a few inches in diameter are present.

The volcanic sandstone forms a long narrow, east-west-trending map unit, which is intermittently exposed for a distance of 18 miles to the west. The field term, "feldspathic quartzite", was an unfortunate name, for further studies have shown that this rock type resulted from slight reworking of dacitic tuff similar to the tuff observed at STOP 12.

The 20-foot-thick dike of diabasic gabbro at the west end of the outcrop is the youngest rock in the area. It has a minimum K-Ar age of 1,570 m.y., and similar dikes a few miles away have ages of 1,520 and 1,685 m.y. (Hanson and Malhotra, 1971). The dike has narrow chilled borders, and contains some inclusions of the volcanic sandstone.

Generalized Mode of the Volcanic Sandstone

20-30%	Plagioclase
8-12%	Quartz (some definitely volcanic)
15-30%	Volcanic rock fragments, dacitic
25-30%	Fine recrystallized quartz and plagioclase (probably was dacitic volcanic rock fragments prior to recrystallization)
5-10%	Micaceous matrix



Photomicrograph of reworked tuff
(Volcanic quartz at left, plagioclase at top; volcanic rock fragment, with plagioclase phenocryst, at right; recrystallized quartz and plagioclase, muscovite, and epidote at bottom.)

Long roadcut south of Hwy. 169 on curve nearly opposite Pike Bay Drive, about 0.7 miles west of STOP 14 and 2.5 miles west of Tower.

STOP 15: Lake Vermilion Formation, Metagraywacke-slate Member (No hammering, please!): -- Highly folded biotitic metagraywacke and slate. Note the excellent graded bedding. Some geologists have speculated that much of the deformation is penecontemporaneous soft-sediment deformation, as evidenced by small clastic dikes cutting the beds. However, the major deformation is interpreted as tectonic, for the following reasons:

(A) These structures in graywacke-slates are unique to this small area.

(B) Well-preserved sedimentary structures nearby are not chaotic (see Ojakangas, 1972).

(C) This exposure is located near a major F_2 fold axis.

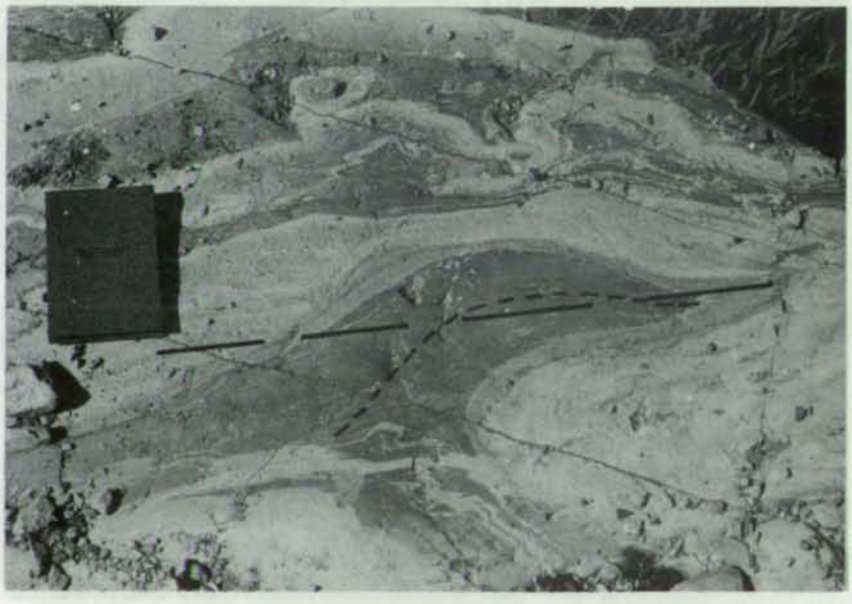
(D) Folding is similar in trend and style to that observed in the Soudan Iron-formation at STOP 11, which is also on a major fold axis.

(E) Trends of the numerous fold axes fit the regional structural pattern (Hooper and Ojakangas, 1971).

The complex folding is the result of two deformations, as described in the text accompanying this guide and illustrated below. A third deformation is marked by faults, joints, and kink bands that cut transversely across the folds.

"Eye structure" (interference pattern) in graywacke-slate. This is the result of the erosion of an undulating (with respect to horizontal) F_1 axial plane. Undulation caused by crossing of F_1 axis by F_2 axis.

F_1 fold in graywacke-slate, crossed by cleavage of second deformation. Cleavage (S_2) of the second deformation is shown by long dashes and trace of F_1 axial plane is shown by short dashes. (Photo by P.R. Hooper).



F_1 fold in graywacke-slate, modified by F_2. Cleavage (S_2) of the second deformation is shown by long dashes and trace of F_1 axial plane is shown by short dashes. (Photo by P.R. Hooper).

Generalized Mode of Graywacke

10-20%	Plagioclase
2-5%	Quartz(probably in origin, but now cataclasized)
15-25%	Volcanic rock fragments, dacitic
30-50%	Fine recrystallized quartz and plagioclase (probably was dacitic volcanic rock fragments prior to recrystallization)
10-15%	Micaceous matrix (mostly biotite)

Photomicrograph of biotitic metagraywacke (Volcanic rock fragment at center, quartz at center left, several plagioclase grains, scattered biotite.)

Exposure northwest of bridge across Pike River on St. Louis Co. Hwy. 77, 0.55 miles north of Hwy. 169-1. (Junction of Co. 77 and Hwy. 169-1 is 2.4 miles west of Tower)

STOP 16: Lake Vermilion Formation, Metagraywacke-Slate Member (No hammering, please!): -- Excellent exposure of biotitic metagraywacke and slate. Note the excellent graded bedding; 64 percent of the 201 graywacke beds in this exposure are graded and nine percent of the 100 siltstone beds are graded (Ojakangas, 1972). Here, the beds are thin, but graywacke beds in the area are as much as 12 feet thick.

North-trending kink bands were formed during the latest (F_3) deformation. Small scale faults are common. A north-northeast-trending fault having about 1,000 feet of left-lateral displacement forms the south side of the river channel at this locality, and extends for some distance to the north and south.

NOTE: About 3 miles north of STOP 16, Co. Hwy. 77 climbs onto the Vermilion moraine and follows the crest of the moraine nearby to STOP 17. Lake Vermilion is confined on its southern side by the moraine, which probably marks the southern extent of the last advance of the Rainy lobe into northern Minnesota. North of this moraine in northern Minnesota, outcrops are relatively abundant; to the south, thick drift is generally present.

Continue north on Co. Hwy. 77 for 6.7 miles to outcrops on left side of road opposite Daisy Bay of Lake Vermilion.

STOP 17 (optional): Pluton of massive, gray to pink hornblende-bearing adamellite and syenodiorite about 2 miles long (in an east-west direction) and as much as three-fourths of a mile wide. The pluton is concordant on a gross scale. It has prograded the metabasalt and meta-graywacke country rocks; some inclusions of country rock are visible here. This rock is an example of strongly foliated hornblende-bearing syenitic intrusives which occur as small bodies within the low-grade rocks of the Vermilion district. In this exposure, adamellite is the dominant rock type. One modal analysis gave 19% quartz, 38% plagioclase (An_{10}), 24% K-feldspar, 13% hornblende, and minor muscovite, epidote, chlorite, cal-cite, sphene, and iron oxides.

NOTE: For the next 2.7 miles along Co. Hwy. 77 there are exposures of greenstones (both massive and pillowed) which occur within the metagray-wacke-slate member of the Lake Vermilion Formation and hence are younger than the Ely Greenstone.

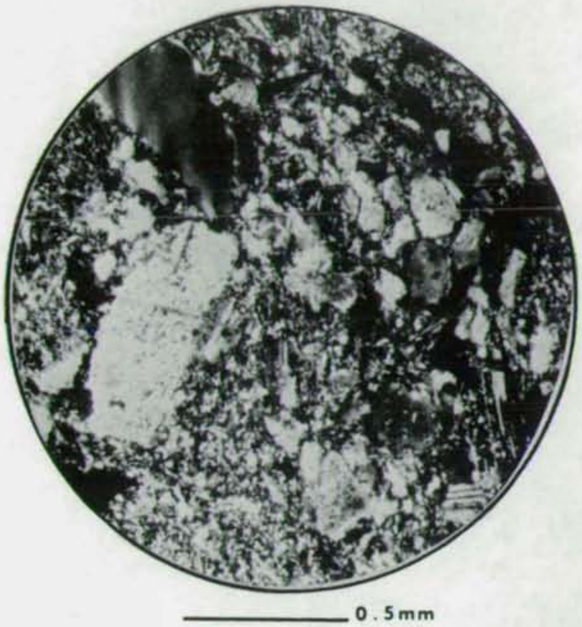
2.7 miles northeast of STOP 17 (10.0 miles from Junction of State Hwy. 169-1 and Co. Hwy. 77 and 9.4 miles from STOP 16) turn right on gravel road leading to Gruben's Resort. Drive 0.35 miles to Gruben's Resort on Arrowhead Point. Good exposures are present in front of resort store and just across wooden bridge leading to Isle of Pines.

STOP 18 (optional): Lake Vermilion Formation, Metagraywacke-Slate Member: -- Exposures of chloritic graywackes and slates. Both east and west of this locality, pillowed lavas are interbedded with the graywacke-slate.

This locality is near the axis of the Arrowhead Point fold, which is an F_2 east-northeast-trending anticline whose axis plunges steeply W., although the beds at the fold nose are younger to the east. Note excellent cleavage-bedding relationships.

Generalized Mode of
Chloritic Metagraywacke

40-50% Plagioclase
2-6% Quartz (volcanic)
20-25% Volcanic rock fragments, dacitic
15-20% Micaceous matrix (chloritic)



Photomicrograph of chloritic metagraywacke (Volcanic rock fragment, with large plagioclase phenocryst, at left; quartz at upper right, scattered plagioclase, hornblende and chlorite grains.)

NOTE: Return via Co. Hwy. 77 to State Hwy. 169 (10.35 miles) and turn right (west) towards Virginia. Continue on Hwy. 169 to junction with State Hwy. 53. Turn left on Hwy. 53-169.

NOTE: Between the Co. Hwy. 77-Hwy. 169 intersection and the Giants Range, about 18 miles to the south, Hwy. 169 crosses two moraines of the Rainy lobe and intervening swamp and lake deposits of Glacial Lake Norwood, which was about 5 miles wide and 30 miles long.

Roadcuts between and on both sides of two lanes of State Hwy. 53-169 on "Confusion Hill," the Laurentian (continental) Divide, about 3 miles north of Virginia and about 23 miles west of Tower.

STOP 19 (optional): Giants Range Granite: -- This exposure illustrates the complexity of rock types at the south edge of the Giants Range batholith. A gray granite gneiss containing amphibolite inclusions is cut by diorite; minor pink granites cut the above rocks.

At the top of the exposure, between the two lanes of the highway, are amphibolitic remnants of thinly bedded sediments (tuffaceous?), mafic lapilli tuffs (?), and massive basalt flows (?).