FIELD TRIP GUIDEBOOK FOR THE WESTERN VERMILION DISTRICT, NORTHEASTERN MINNESOTA

PREPARED FOR THE 25TH ANNUAL MEETING OF
THE INSTITUTE ON LAKE SUPERIOR GEOLOGY
AND THE GEOLOGICAL SOCIETY OF AMERICA,
NORTH-CENTRAL SECTION
DULUTH, MINNESOTA, 1979

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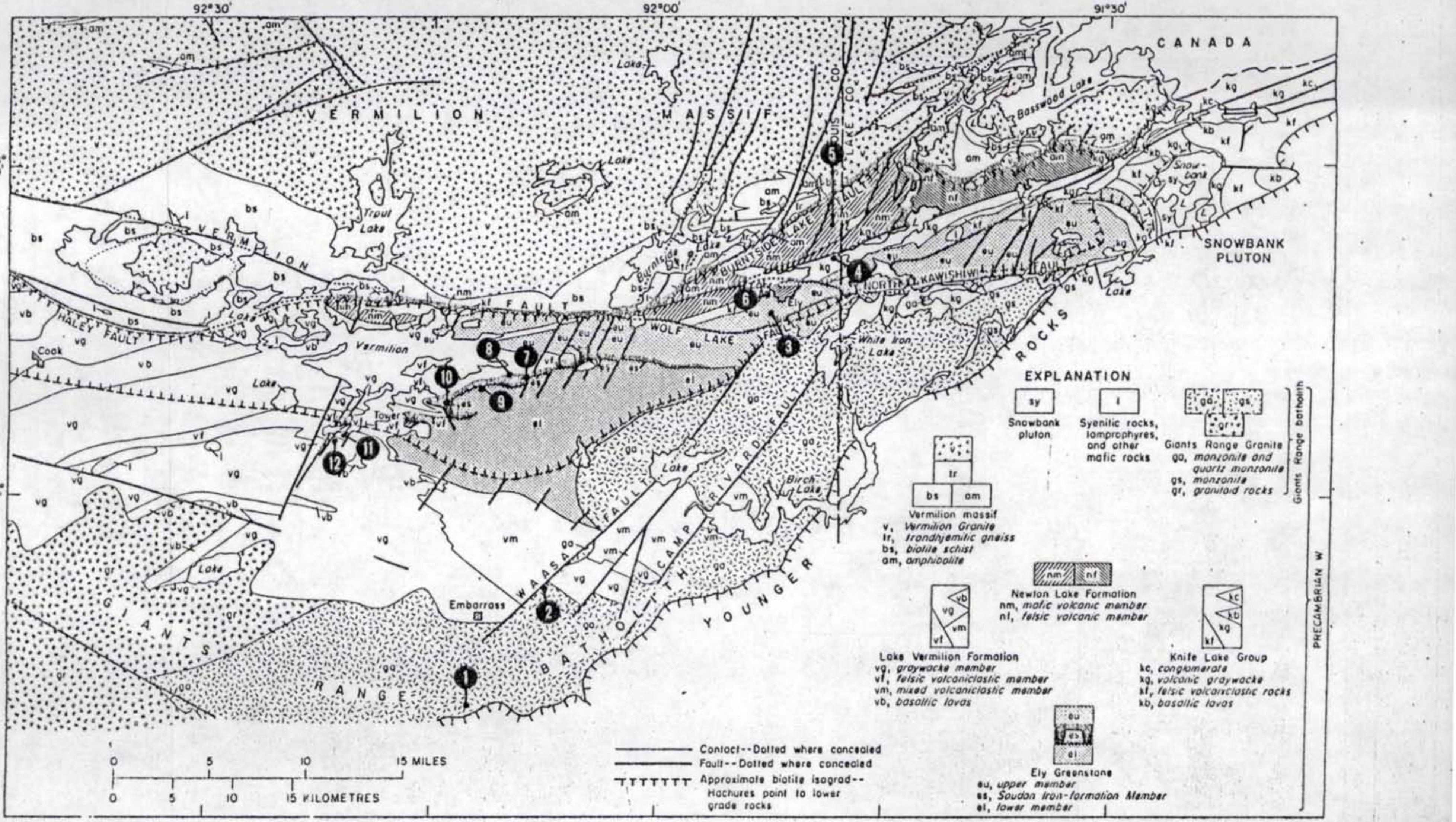
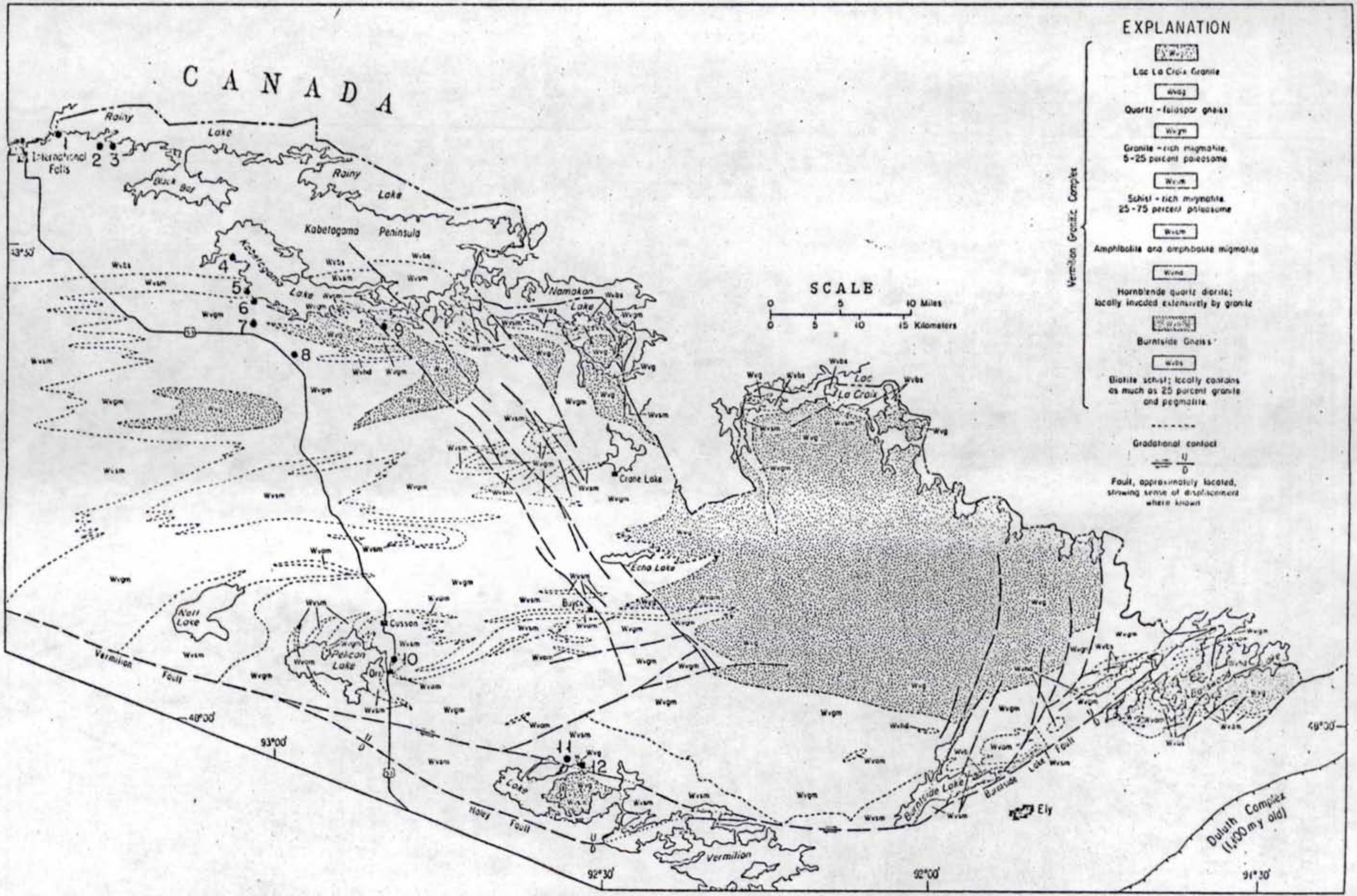


Geologic map of the Vermilion district showing locations of stops on Day 2 roadlog.



Geologic map of the Vermilian Granitic Complex
showing locations of stops on <u>Day 1</u> road log.

MINNESOTA GEOLOGICAL SURVEY
UNIVERSITY OF MINNESOTA
Matt Walton, Director

FIELD TRIP GUIDEBOOK FOR

THE WESTERN VERMILION DISTRICT, NORTHEASTERN MINNESOTA

N.H. Balaban, Editor

D.L. Southwick and R.W. Ojakangas, Leaders

Special Papers

THE VERMILION GRANITIC COMPLEX, NORTHERN MINNESOTA
D.L. Southwick

STRUCTURAL STUDIES IN THE NORWEGIAN BAY BLOCK OF THE VERMILION GRANITIC COMPLEX, NORTHERN MINNESOTA
Robert L. Bauer

THE WESTERN VERMILION DISTRICT - A REVIEW
G.B. Morey

ARCHEAN SEDIMENTATION IN THE VERMILION DISTRICT
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THE VERMILION GRANITIC COMPLEX, NORTHERN MINNESOTA

by

D.L. Southwick
Minnesota Geological Survey
1633 Eustis Street
St. Paul, Minnesota 55108

INTRODUCTION

The Vermilion Granitic Complex consists of granitic and migmatitic rocks of Archean age (2,700 m.y.) that are the westward extension into Minnesota of the Quetico gneiss belt of Ontario (fig. 1). The complex is chiefly light grayish-pink biotite granite (following the rock classification of Streckeisen, 1973) that grades into migmatite with increasing content of schistose inclusions. The major grayish-pink granite and its genetically related granite-rich migmatite were named the Vermilion Granite by Grout (1923), who was the first to study the rocks in detail (Grout, 1923, 1925b, 1926). Because migmatites are so abundant within the area Grout mapped as granite, and because other rock types such as quartz diorite and trondhjemite are important locally, the term Vermilion Granite has been replaced formally by the more inclusive term Vermilion Granitic Complex (Southwick and Sims, in press). Where the grayish-pink biotite granite that is the dominant component of Grout's Vermilion Granite is homogeneous, it has been renamed the Lac La Croix Granite, and it is understood to be a subunit within the Vermilion Granitic Complex (Southwick and Sims, in press).

Two broad categories of migmatite have been defined for the purpose of reconnaissance geologic mapping. Migmatite that contains an aggregate total of 5 to 25 percent inclusions is referred to as granite-rich; migmatite with more than 25 percent inclusions is termed schist-rich. In general the granite-rich migmatite contains a mixed population of schist, amphibolite, quartz diorite, and trondhjemite inclusions and has blocky or nebulitic structure. Schist-rich migmatite, on the other hand, contains a preponderance of biotite schist inclusions and tends to be layered. Other rock units in the Vermilion Granitic Complex that are older than the major granite, and are far less abundant, include quartz feldspar gneiss, quartz diorite and diorite, granodiorite and trondhjemite, amphibolite and amphibolite migmatite, older migmatite, biotite schist, and the Burntside Gneiss (Burntside Granite Gneiss of Grout, 1926). These lithologies are locally important constituents of the migmatitic zones around and within the granite. Relations among the various subunits of the Vermilion Granitic Complex are diagrammed in Figure 2.

The northern boundary of the complex is gradational and is arbitrarily placed where granitic rocks become sparse or absent from the flanking unnamed biotite schist of the Kabetogama Peninsula and its eastward extension into Canada (fig. 3). The southern boundary is defined mainly by high-angle faults, which provide a sharp break between granitic

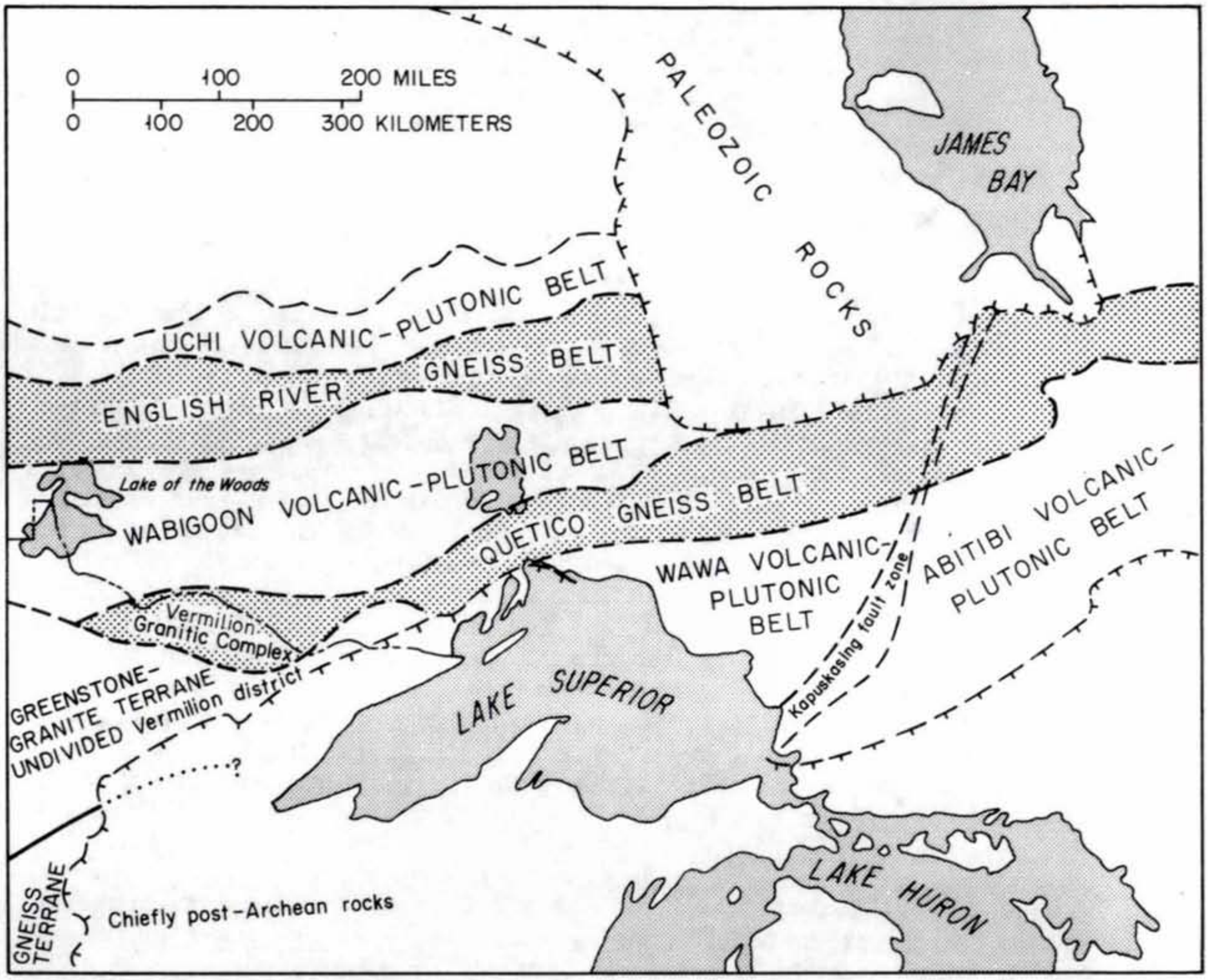


Figure 1. Map showing the location of the Vermilion Granitic Complex relative to the named petrogenetic belts of the Superior Province in Canada.

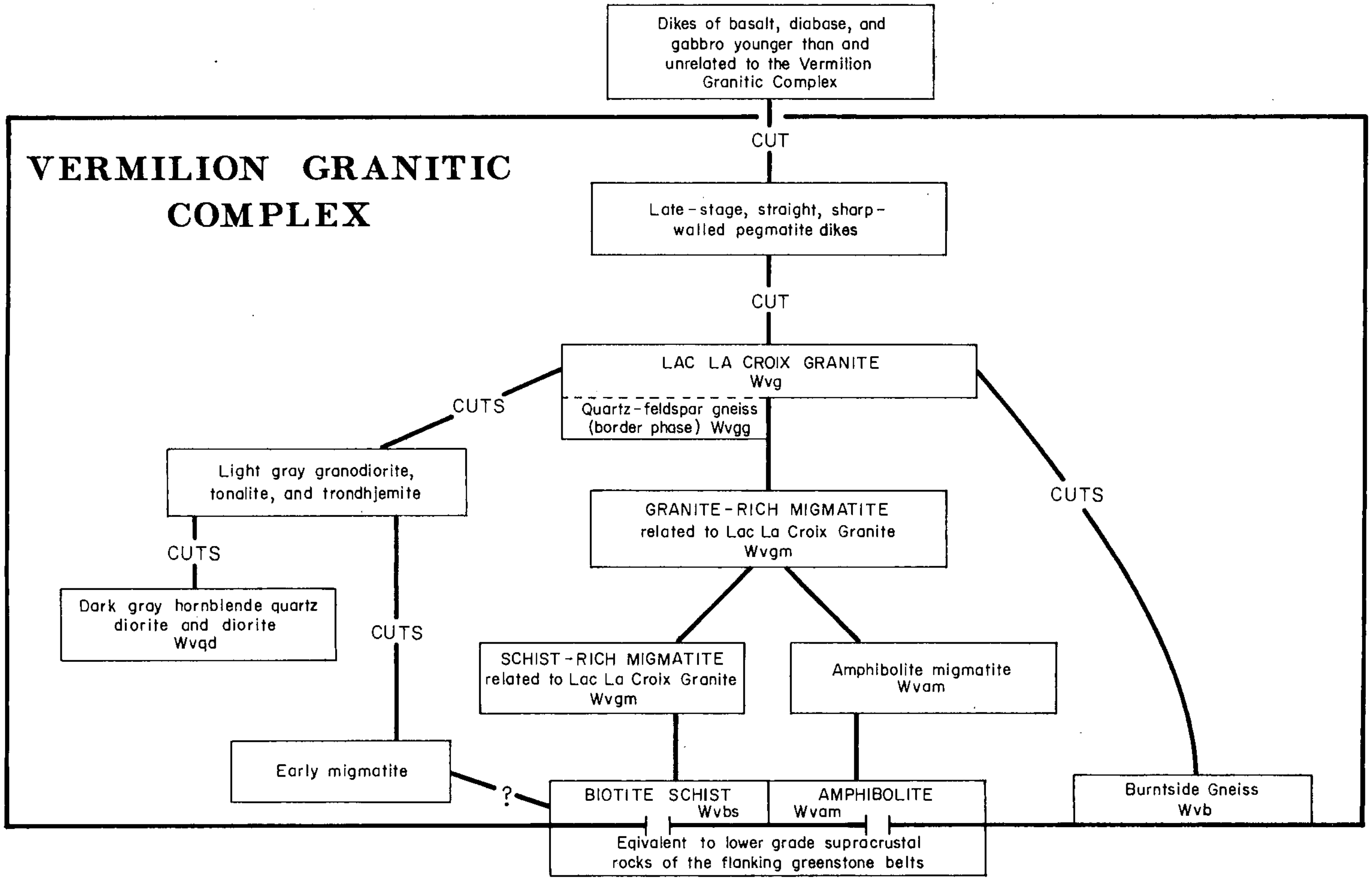


Figure 2. Schematic diagram of the interrelationships among lithologic subdivisions of the Vermilion Granitic Complex. Intrusive units are arranged with the youngest at the top of the diagram. Names spelled out in capital letters are the more abundant components of the complex.

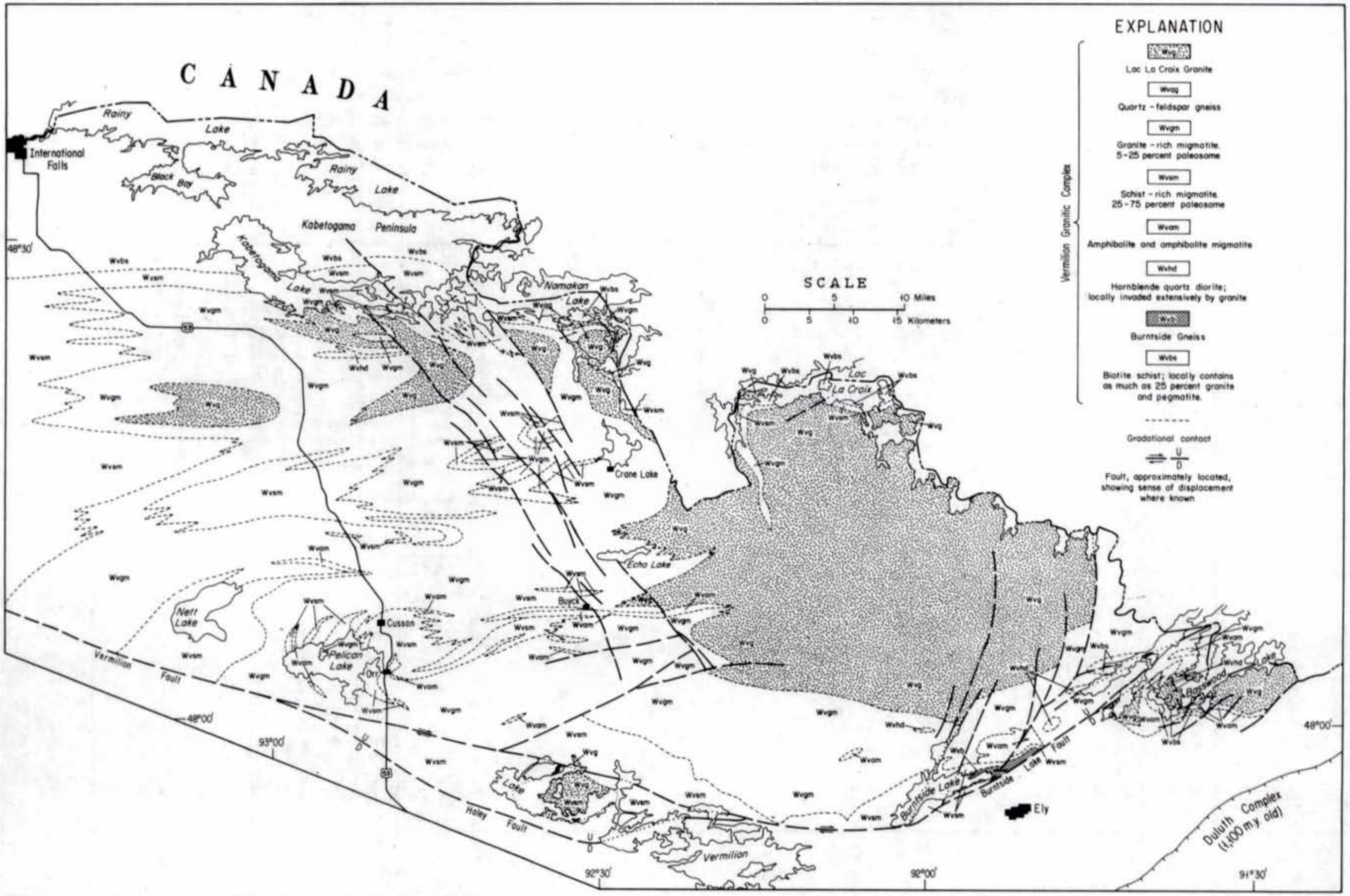


Figure 3. Generalized geologic map of the Vermilion Granitic Complex. The large-scale, east-trending major folds in the migmatite are clearly indicated by the map pattern between Pelican and Namakan Lakes. Map modified after Southwick and Sims (in press).

rocks and associated amphibolite-facies rocks of the complex and greenschist-facies volcanic and sedimentary rocks of the Vermilion district (Sims, 1976). The limits of the complex to the west and east are impossible to define precisely with present map data. West of International Falls the Precambrian bedrock is covered by thick glacial drift and existing bedrock mapping is sketchy. Southwick and Ojakangas (1973) tentatively concluded that the complex terminates to the west against the northwestward extension of the Vermilion fault. In Canada the complex merges into and is virtually equivalent to the Quetico belt, which continues eastward along strike for many kilometers.

INTERNAL STRUCTURE

The major structural features within the Vermilion Granitic Complex are summarized in Figure 3. The migmatitic western part displays large folds that are marked out by the orientation of schistosity in the paleosome. The folds trend essentially east-west, parallel to the axes of early isoclinal folds in older supracrustal rocks both north and south of the complex. Even where the folds in migmatite are mapped from scattered schistose inclusions in granite, the individual measurements of foliation and lineation are remarkably consistent. Small crinkle axes and lines of oriented hornblende and/or biotite plunge consistently east or west within a given major fold. Linear structures having plunges of similar magnitude and orientation occur in the folded, unmigmatized rocks in the Kabetogama Peninsula and the Vermilion District. The structural consistency of migmatite paleosomes in the western part of the Vermilion Granitic Complex, even in rocks that are chiefly granite, indicates that the granite fraction, whatever its origin, was emplaced in a manner that did not completely disrupt structural trends in pre-existing rocks.

Although the major folds in migmatite appear to be simple, small-scale folds of great geometrical complexity are common throughout the area. Complex folds are best developed in thinly layered schist-rich migmatite. The minor folds change rapidly in shape and symmetry over short distances, invariably exhibit abrupt pinching and swelling of the constituent layers, and typically can be interpreted in terms of multiple deformation. Areas of complex small-scale multiple folding also contain numerous ptygmatic folds in thin veins of quartz and quartz-feldspar pegmatite. Many of the ptygmatically folded veinlets have been boudinaged prior to folding, indicating that cross-layer flattening preceded buckling. It appears that early folds in metasedimentary rocks were first invaded by concordant and discordant masses of granite, and then were flattened and refolded later by stresses accompanying the diapiric rise of the main pluton of Lac La Croix Granite. Details of the structural geometry for an area northwest of Lake Vermilion have been worked out by Bauer (1978, this volume).

Fracturing of the complex occurred later than the folding and was more or less independent of the early fold system. The Vermilion fault (fig. 3) is the most important fracture in the area. Within 5 to 8 km of this fault and the subsidiary fault system related to it, the granitic rocks are pervasively sheared and recrystallized to a variety of cataclastic gneisses. Coarse microcline augen gneisses occurring in the cataclastic zone may indicate that shearing began along the Vermilion fault system while the rocks still possessed sufficient heat and chemical mobility to recrystallize coarse-grained feldspar. A second set of faults trends north-northwest across the central part of the complex. Pronounced topographic lineaments follow the documented faults and it may well be that other faults that cannot be demonstrated on the ground are responsible for the many other northwest-trending lineaments occurring throughout the area. Several northwest-trending fault zones are occupied by dikes of diabase or gabbro that have been dated at about 2,200 million years (Hanson and Malhotra, 1971).

SUCCESSION OF IGNEOUS EVENTS

Field relations indicate that at least two igneous events preceded the emplacement of the areally dominant Lac La Croix Granite and its cortege of related migmatites. The earliest igneous bodies are small, local, concordant plutons of dark-gray hornblende quartz diorite and hornblende diorite (probably lamprophyric, in part) that invaded supracrustal metavolcanic and metasedimentary rocks; both the intrusions and their wall rocks now are incorporated in belts of migmatite. Several of these small bodies have good igneous layering whereas others are essentially massive. Somewhat later the terrane was invaded by light-gray trondhjemite and biotite granodiorite. The total volume of trondhjemitic and related magma involved in this episode cannot be estimated accurately, but it clearly was greater than the preceding hornblende diorite and quartz diorite. Trondhjemite and granodiorite sills, stringers, and small, irregular plugs occur in the belts of schist-rich migmatite, where they comprise as much as 10 percent of the total rock mass at present levels of exposure. Emplacement of some of the trondhjemite and granodiorite was synorogenic, because stringers of them locally are folded with the enclosing schist and amphibolite and some of the trondhjemite masses are foliated. Emplacement of the major Lac La Croix Granite followed the gray trondhjemite and granodiorite, and in terms of sheer volume completely overwhelmed all earlier rocks. At the contacts the granite magma intimately invaded the schistose wall rocks as lensoid concordant tongues and crosscutting dikes. In addition, chemical components emanating from the magma replaced selected layers and locally whole volumes of wall rock with felsic minerals. The heat from the magma was sufficient to raise the grade of metamorphism in the schist belt north of the complex into the upper amphibolite facies within 3-4 km of the granite contact. All of these processes combined to produce a regional migmatite that is, in general, stromataform and paleosome-rich toward the external wall rock contacts and granite-rich toward the interior.

The Lac La Croix Granite and related migmatites are chiefly the result of igneous intrusion and not partial melting in place. This is indicated by the compositional homogeneity of the granite in migmatitic as well as massive parts of the complex, the sharp, crosscutting contacts of granite against other rocks, the low grade of regional metamorphism beyond a narrow contact zone around the complex, and the paucity of refractory mafic residue at the present level of exposure. The granitic magma may well have formed at lower crustal levels by partial melting of supracrustal rocks, but it moved as a discrete, well-homogenized body of melt to its present position. Geochemical evidence further supporting this view is presented below.

The coherent pattern of mappable folds in the western and central parts of the Vermilion Granitic Complex suggests that these migmatites formed near the roof the the Lac La Croix intrusion. Early folds in preexisting schists were split apart by invading tongues of granite and locally were replaced by chemically mobile constituents of the magma, but retained their identity. Some flattening and broad scale reorientation of the early fold system probably occurred as magma pushed its way into the older rocks, but the process was sufficiently slow and orderly to preserve the major fold geometry. The lack of inclusions in the eastern part of the complex and the consequent absence of decipherable pre-granite structure probably mean that the roof of the intrusion was well above the present erosion surface in that area.

MINERALOGY AND GEOCHEMISTRY

The earlier rocks of the trondhjemite-granodiorite suite are composed chiefly of plagioclase and quartz together with erratically variable small quantities of K-feldspar and biotite. Virtually all samples show some evidence of slight shearing and development of secondary sericite, chlorite, and clinozoisite. Samples near the Vermilion fault system (including the Burntside Gneiss) are strongly cataclastic (Sims and Mudrey, 1972). The Lac La Croix Granite and the granitic fraction of related migmatites are very consistent in mineralogy and composition, containing subequal quantities of plagioclase (An_{22}), perthitic microcline, and quartz together with 5 percent or less of biotite. These rocks also exhibit slight shearing and alteration over wide areas, and are extensively deformed near the major faults. Modes and major element chemical analyses are given in Tables 1 and 2.

Arth and Hanson (1975) have investigated the minor element geochemistry of the Vermilion Granitic Complex in the context of the whole greenstone-granite terrane of northeastern Minnesota. The trondhjemite, quartz diorite, and dacite of the region, including the Burntside Gneiss of the Vermilion Granitic Complex, are characterized by K/Rb ratios greater than 300, Sr^{87}/Sr^{86} ratios less than .701, Sr/Ba ratios greater than 1, light rare earth contents of 4 to 10 times chondrite, heavy rare earth contents of 1 to 2 times chondrite, and a weakly positive Eu anomaly. The Lac La Croix Granite is characterized by K/Rb ratios between 150 and 250, Sr^{87}/Sr^{86} ratios less than .701, Sr/Ba ratios near 0.3, light rare earth contents greater than 20 times chondrite, heavy rare earth content less than 5 times chondrite, and a negative Eu anomaly. Arth and Hanson (1972, 1975) concluded that the early trondhjemite and quartz diorite of the complex can be modeled geochemically by the melt fraction produced upon about 20 percent partial melting of eclogite or amphibolite at mantle depths, with a residue consisting chiefly of clinopyroxene and garnet. This phase of plutonic activity probably corresponded in time with the extrusion of chemically indistinguishable dacitic volcanic rocks in the volcano-sedimentary pile south of the Vermilion fault zone. The geochemical characteristics of the Lac La Croix Granite (termed the quartz monzonite of the Vermilion batholith by Arth and Hanson) are com-

Table 1. Modal composition of the early trondhjemite-granodiorite suite and the Lac La Croix Granite. Based on 14 analyses of 2100 points each for trondhjemite-granodiorite and 19 analyses for Lac La Croix Granite.

	TRONDHJEMITE-GRANODIORITE			LAC LA CROIX GRANITE		
	Mean	Standard Dev.	Extremes	Mean	Standard Dev.	Extremes
Quartz	24.7	5.47	9.8-32.3	28.3	6.7	20.7-36.4
Microcline [a]	9.4	8.23	0.6-26.9	32.4	5.7	22.9-52.1
Plagioclase [b]	56.0	8.50	40.3-65.9	33.3	4.9	21.5-39.0
Biotite	7.06	2.92	2.0-11.9	2.36	1.6	0.1-5.4
Muscovite	1.44	1.23	0.1-4.8	1.48	1.2	0.4-4.5
Chlorite	.22	.25	0.1-0.5	1.06	.8	0.1-2.3
Epidote and allanite	.51	.80	0.1-2.1	.21	.23	0.0-2.3
Myrmekite	tr	-	-	tr	-	-
Opaques	.10	-	0.1-0.5	.30	.22	0.1-0.7
Carbonate	.10	-	0.1-0.6	tr	-	-
Apatite	.10	-	0.1-0.6	tr	-	-
Zircon	tr	-	-	tr	-	-
Sphene	.20	-	0.1-1.8	tr	-	-
Tourmaline	tr	-		tr	-	-

NOTES:

a. The microcline of the Lac La Croix Granite is perthitic, containing about 17 percent exsolved albite.

b. The An content of plagioclase in the trondhjemite-granodiorite ranges from 20 to 30 mo/percent, and is very consistent at 22 mo/percent in the Lac La Croix Granite.

Table 2. Representative chemical analyses of the early trondhjemite-granodiorite suite and the Lac La Croix Granite. All analyses published elsewhere.

	TRONDHJEMITE-GRANODIORITE			LAC LA CROIX GRANITE			
	1.	2.	3.	4.	5.	6.	7.
SiO_2	67.70	68.25	65.70	74.0	71.73	72.06	73.8
Al_2O_3	15.86	16.94	17.27	13.8	14.76	16.00	14.6
Fe_2O_3	0.71	0.70	0.77	1.30	1.35	0.72	0.88
FeO	2.45	1.92	2.56	1.30	1.35	.072	0.88
MgO	1.02	0.75	1.42	0.30	0.62	0.97	0.20
CaO	3.79	2.92	3.39	0.87	1.18	0.86	1.40
Na_2O	4.91	5.52	5.05	3.85	3.58	4.56	4.40
K_2O	1.16	1.17	1.62	5.10	4.63	3.54	4.40
H_2O^+				0.25	0.64	0.39	-
H_2O^-	0.91	0.81	0.90	0.03	0.20	0.05	0.03
TiO_2	0.33	0.28	0.47	0.13	0.53	0.12	0.09
P_2O_5	0.17	0.10	0.17	0.03	0.14	0.09	0.03
MnO	0.03	0.04	0.06	0.02	0.03	0.06	0.13
CO_2	1.08	0.44	0.31	0.11	-	-	-
Other	-	-	-	-	0.28	0.36	-
TOTAL	100.12	99.84	99.69	100.2	100.25	100.24	99.8

1. Biotite trondhjemite (1.5 percent K-feldspar), Duluth, Winnipeg, and Pacific Railroad, 5 km (3.1 mi.) north of Ash Lake, Ash River SW quadrangle (Southwick and Sims, in press).

2. Biotite trondhjemite (0.6 percent K-feldspar), U.S. Forest Service Vermilion River road at Camp 40 Creek, Kabustasa Lake quadrangle (Southwick and Sims, in press).

3. Light gray biotite granodiorite (6.6 percent K-feldspar), U.S. highway 53 at Moose Lake Road, 1.6 km (1 mi.) north of Orr, Orr quadrangle (Southwick and Sims, in press).

4. Echo Trail mass, Echo Trail, just south of Little Indian Sioux River. (Arth and Hanson, 1975, p. 332, col. 26).

5. Grassy Bay mass, Sand Point Lake, (Grout, 1926, p. 48, col. 1).

6. Neosome of granite-rich migmatite, southeast of Pelican Lake, (Grout, 1926, p. 48, col. 2).

7. Neosome of granite-rich migmatite, U.S. highway 53, 2.6 km (1.6 mi.) west of St. Louis Co. road 122. (Arth and Hanson, 1975, p. 332, col. 25).

patible with those of melts produced by 20 to 50 percent partial melting of short-lived volcanogenic graywacke at deep crustal levels, with the residue consisting principally of plagioclase, amphibole, garnet, and pyroxene or biotite (Arth and Hanson, 1975, p. 354). Granular nodules within the Lac La Croix Granite that may be samples of the melt residue consist of about 61 percent hornblende, 15 percent clinopyroxene, 14 percent plagioclase, 3 percent quartz, and 3 percent biotite, with the remainder made up of sphene, epidote, K-feldspar, and Fe-Ti oxides. Geochemical investigation of these inclusions is under way.

Rye and Roy (1978) have investigated the distribution of Th, U, and K in rocks of the Vermilion Granitic Complex. They found that the radioelement content of the early trondhjemite-granodiorite suite is variable and generally low. The potassium content ranges from 1.6 to 3.9 percent, the thorium content from 2.7 to 12 ppm, the uranium content from 1.0 to 2.0 ppm, and the Th/U ratio from 2.1 to 8.1. The central part of the Lac La Croix granite, in contrast, is both richer in radioelements and more uniform in terms of their distribution. The potassium content is near 24 ppm and the uranium content near 2 ppm. These values increase westward toward the gradational contact with granite-rich migmatite, where the potassium content reaches 5.2 percent and the thorium content reaches 44 ppm. This area of the complex contains numerous pegmatites. The pegmatites and the elevated values of K and Th may have resulted from accumulation of volatiles beneath a migmatic cap over crystallizing Lac La Croix Granite.

The schist-rich migmatite west and south of the Lac La Croix Granite has highly variable radioelement compositions that fluctuate with the ratio of generally radioelement-poor schistose paleosome to more radiogenic granite. The paleosome has U, Th, and K values that overlap the concentration ranges for these elements in volcanogenic graywacke of the Knife Lake Group in the Vermilion greenstone belt. Therefore, if the migmatite formed by in-place partial melting of Knife Lake-like graywacke, an appropriate protolith from the standpoint of Rb-Sr systematics, the whole-rock thorium content for the migmatite should be no higher than that of the starting graywacke. The bulk thorium content of many migmatites, which is 2 or 3 times greater than that of the paleosome alone, indicates that the granitic component must have imported thorium from a source other than graywacke. The U-Th-K systematics clearly favor an injection origin for the migmatites. They do not rule out a partial fusion origin for the granitic melt at some other crustal level, but they argue against static, in-place partial melting of graywacke (Rye and Roy, 1978).

ORIGIN OF THE LAC LA CROIX GRANITE AND RELATED MIGMATITES

Conclusions developed from field mapping and structural studies (Southwick, 1972; Southwick and Ojakangas, 1973; Southwick and Sims, in press) and geochemical studies (Arth and Hanson, 1975; Rye and Roy, 1978) support the following self-consistent model for the origin of the major granite and migmatite in the Vermilion Granitic Complex.

1. Early magma of the trondhjemite-granodiorite suite was produced by partial melting of eclogite at mantle depths. The relatively minor representatives of this suite within the complex probably

are cogenetic with dacitic intrusions and flows that are preserved in the volcanic piles of the Vermilion and Rainy Lake greenstone belts. Detritus shed from the volcanic piles accumulated as thick sequences of graywacke, which were later subjected to burial and tectonism.

2. The major granitic magma represented by the Lac La Croix Granite and the granitic fraction of associated migmatite formed by partial melting of volcanogenic graywacke. The graywacke was eroded from volcanic source areas, buried, and partially melted within a time span of 50 m.y. or less, about 2,700 m.y. ago. About 20 to 50 percent of the graywacke melted, leaving a residue of plagioclase, amphibole, garnet, and pyroxene or biotite.

3. The granitic magma moved away from its source area and rose diapirically to higher levels, injecting its walls and carapace and perhaps shouldering them aside as it migrated upward. Most of the migmatitic rocks now exposed at the surface are the result of injection and metasomatism.

4. Though regional in extent, the intrusion of granite was sufficiently quiescent to preserve coherent early folds in the migmatitic roof and border zones. However, the emplacement of granite did flatten early folds and cause some refolding.

5. The western part of the complex is near the roof of the granite diapir. Volatile-rich fluids tended to accumulate beneath the capping migmatite, forming pegmatites and concentrating radioelements in the structurally highest parts of the granite-migmatite transition zone.

No direct evidence has yet been found of "old" (>2,700 m.y.) rocks within the Vermilion Granitic Complex. Available evidence suggests that this segment of continental crust was generated during a relatively brief span of time, and that crustal stability was achieved shortly after emplacement of the Lac La Croix Granite.

STRUCTURAL STUDIES IN THE NORWEGIAN BAY BLOCK OF THE VERMILION GRANITIC COMPLEX, NORTHERN MINNESOTA

by

Robert L. Bauer

Minnesota Geological Survey
1633 Eustis Street
St. Paul, Minnesota 55108

and

Macalester College
1600 Grand
St. Paul, Minnesota 55105

INTRODUCTION

The southern margin of the Vermilion Granitic complex contains a fault-bounded block (Norwegian Bay block) composed of biotite schists and a small quartz monzonite pluton known as the Wakemup Bay stock. The Norwegian Bay block is bounded on the south and southwest by the Haley fault and on the north by the Vermilion fault (see fig. 3 of Southwick, this volume). The Haley fault has a significant vertical slip component, and separates greenschist-facies metagraywackes and metavolcanic rocks of the Vermilion district on the south from biotite schists of the middle to upper amphibolite facies on the north. The Vermilion fault is a major strike-slip fault with a right lateral displacement of 16.8-19 km (Sims, 1976). It separates the schists that surround the stock from the granitic rocks and other biotite schists of the main position of the Vermilion Granitic Complex.

Four major rock types occur within the Norwegian Bay block. The oldest is a biotite schist which is locally aluminous and may contain porphyroblasts of fibrolitic sillimanite, staurolite, and garnet. No mappable stratigraphic units are present in the schist. The schist is cut by major and minor lamprophyre dikes and numerous granitic veins. The schists and lamprophyres are intruded by the quartz monzonite stock and all the units are cut by a pink granitic to pegmatitic phase.

Reconnaissance mapping by P.K. Sims revealed numerous minor folds and a prominent foliation parallel to the schist-stock contact. In response to this survey of the region three major objectives were considered for the present study:

1. To determine the relationship of the structural features in the schist to the emplacement of the Wakemup Bay stock.

2. To determine the sequence of deformation in the area.

3. To attempt to correlate major structural features and events in the area with structural features south of the Haley fault.

Three general conclusions can be drawn in this study:

1. The area has been subjected to four periods of folding.

2. The F_1, F_2 periods of folding pre-date the emplacement of the stock and F_3 is associated with emplacement of the stock.

3. F_1, F_2 and F_4 can be correlated with folding south of the Haley fault.

LEVEL OF EROSION ON THE STOCK

A major factor in determining structural relationships between the stock and the schist is the level of erosion into the stock exposed. Two pieces of evidence suggest that the surface exposures are very near the top of the stock. First is the presence of a flat-lying roof pendant of schist and lamprophyre near the center of the stock (fig. 3 of Southwick, this volume). The second is the presence of relatively flat-lying primary foliation in the stock's interior, and foliation along the southern and eastern margins of the stock dipping gently away from the stock (Dixon, 1975). However, the foliation along the northern margin of the stock dips more steeply away from the stock suggesting a north-south asymmetry.

STRUCTURAL ANALYSIS OF THE SCHISTS

Outcrops of schist are sparse along much of the southern margin of the stock as a result of burial beneath the Vermilion moraine. The availability of schist outcrops, as well as the different structural characteristics from area to area, leads to a subdivision of the region into two structural subareas:

1. The Vermilion Dam subarea to the east and southeast of the stock and north of the Haley fault.

2. The western subarea to the west and northwest of the stock.

The Vermilion Dam Subarea

The dominant foliation orientation (S_1) in the Vermilion Dam subarea strikes northeast and dips steeply to the southeast in the southern part of the area, but toward the stock contact to the northwest the strike of the foliation curves around the end of the stock and dips more gently away from the stock. S_1 is parallel to bedding (S_0) in the schist throughout most of the area. Exceptions to this parallelism occur in the hinge areas of rare minor F_1 folds where S_1 is axial planar to the folds. Most of the F_1 folds in the area are small, isoclinal, intrafolial folds; no major F_1 structures are evident from mapping of the area. The only facing criteria observed in the area are graded beds, and they are quite rare. Most sedimentary clasts have apparently been recrystallized and deformed by S_1 beyond recognition. The only area where graded beds occur indicates tops to the south, but there may be numerous reversals of tops as a result of undetected F_1 folding. Other minor structures associated with the F_1 folding and development of S_1 are deformed granitic and lamprophyric veins which are boudinaged parallel to S_1 and folded where they cut across S_1.

A second foliation (S_2) becomes progressively well developed in the southern part of the subarea as one approaches the Haley fault. The strike of S_2 makes an acute angle to the right of S_1 and S_2 dips more gently than S_1 to the south. The orientation of S_2 is quite consistent throughout most of the subarea except where it is deformed around the eastern end of the stock. S_2 is absent or only weakly developed around the end of the stock, but where present it maintains the same orientation with respect to S_1 as elsewhere in the subarea.

Numerous minor F_2 folds, invariably of S-symmetry, occur in the southern portion of the subarea but become more sparse toward the north. S_2 is axial planar to the F_2 folds, and L_2 lineations formed by S_1-S_2 intersections are coaxial with the F_2 folds. Both L_2 and F_2 plunge moderately to the southwest except for rare east- and northeast-plunging F_2 folds in the northern part of the subarea where S_1 and S_2 have been folded around the end of the stock. Fold interference patterns between F_1 and F_2 folds have not been observed; however, F_2 folding of boudinaged layers parallel to S_1 occurs locally throughout the area.

The folding of S_1 and S_2 around the end of the stock is F_3 in the deformation sequence, but no minor F_3 folds were observed in this subarea. The youngest folds in the area are small chevron folds and kink bands that deform the S_2 foliation and occur only where S_2 is well developed. These folds are F_4 in the regional sequence and do not appear to be related to any major structure in the area.

The major structure that is evident in the area is related to F_2. The S-symmetry of the F_2 folds and the S_1-S_2 foliation relationships indicate that this subarea is on the overturned north limb of a major southwest-plunging, F_2 antiform. Figure 1a illustrates the relationships of the S_2 foliation and minor F_2 fold symmetry to the major structure. The increased prominence of S_2 toward the Haley fault suggests that the axial trace of the major fold is being approached. Strong S_2 foliation in this area may have localized the faulting near the axial trace of the fold, and resulted in the relative downward faulting of the southern limb of the fold as illustrated schematically in Figure 1b. Structural analysis on the down-thrown side of the Haley fault by Hooper and Ojakangas (1971) indicated fold asymmetry and bedding-cleavage relationships consistent with this interpretation.

The Western Subarea

Structural relations in the western subarea are still being investigated, but certain major structural features in this area are readily apparent and can be correlated with structures in the Vermilion Dam subarea. S_1 and S_2 foliations and their associated minor structures are well developed in this subarea, but their distribution is more complicated by the F_3 folding of S_1 around the western end of the stock than is the case in the Vermilion Dam subarea.

A major, northerly-plunging F_2 antiform is evident in the area from reversals of minor F_2 fold symmetry and S_1-S_2 foliation relationships. A major lamprophyre dike occurs in this area and is folded into a large parasitic S-fold on the southeast limb of the major F_2 antiform. This lamprophyre is similar to and probably stratigraphically equivalent to the lamprophyre in the roof pendant and in the Vermilion Dam subarea (see fig. 3 of Southwick, this volume).

Refolding of the antiform by F_3 has resulted in a tightening of the limbs so that the fold is now approximately isoclinal with both limbs dipping to the west or northwest away from the stock. A strong divergent upward fanning of S_2 across the antiform may be the result of closing of its interlimb angle by the F_3 refolding. The axial orientation of minor F_2 folds and L_2 lineations varies considerably as a function of their location on the refolded limbs of the major F_2 structure.

The refolding around the western end of the stock forms an open F_3 antiform plunging to the west. Outcrops of the schist are not exposed on most of the southern limb of the structure, so complete definition of the orientation of the fold from foliation data is not possible. Several minor F_3 folds on the islands (not shown in fig. 3 of Southwick, this volume) just west of the stock constitute the major evidence for the orientation of the major F_3 fold; they are generally open to close warps of S_1 with nearly vertical east-west striking axial planes.

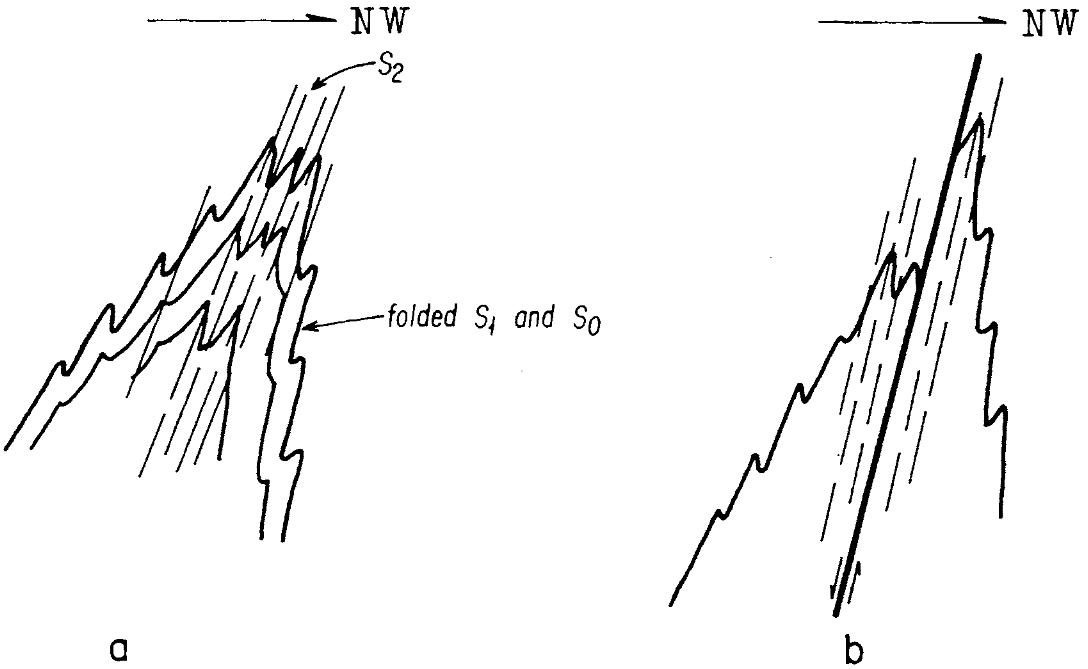


Figure 1. (a) Schematic cross section looking down the plunge of the inferred antiform in the Vermilion Dam subarea and in the schists south of the Haley fault.

(b) Schematic cross section illustrating the inferred faulting (Haley fault) near the axial plane of the antiform.

The relative age relationships among minor F_1, F_2 and F_3 structures are evident in a few places where both F_2 and F_3 have folded boudinaged layers in the schist parallel to S_1. In the areas where minor F_3 folds are common, some layers have developed folds in the necks of pinch and swell structures (S_1), as a result of F_3 deformation.

Further structural analysis in the western subarea is under way in hopes of better establishing the effects of the F_3 refolding on the F_2 minor structures. Incomplete analysis of the schists just north of the Vermilion fault suggests that F_1, F_2 and F_3 fold phases have also affected this area.

REVIEW OF CONCLUSIONS AND GEOMETRY OF DEFORMATION

Four major conclusions based on field mapping and the observations described above form the basis for evaluating the sequence of deformation of the Norwegian Bay block; these conclusions are:

1. The level of erosion on the stock is quite shallow so the surface exposure is very near the top of the stock.

2. The schist in the Vermilion Dam subarea forms the northern, over-turned limb of a major southwest-plunging antiform.

3. The southern limb of this F_2 structure has been downfaulted south of the Haley fault and is evident in the greenschist-facies rocks south of the fault.

4. The schist in the western subarea has been folded into a major F_2 antiform and then refolded by F_3 around the end of the stock.

On the basis of these conclusions, the following geometry and sequence of post-F_1 deformation is inferred for the Norwegian Bay block (fig. 2):

1. Formation of a major F_2 antiform plunging to the west.

2. Emplacement of the Wakemup Bay stock and synchronous F_3 refolding of the F_2 antiform over the top and western half of the stock. The variation in the position of the lamprophyre dike around and over the stock is one bit of stratigraphic evidence which supplements the structural data in this interpretation (fig. 2a).

3. Significant vertical displacement on the Haley fault, separating the north and south limbs of the F_2 antiform. The fault probably follows the area of well-developed S_2 foliation near the axial surface of the antiform around the southern margin of the stock (fig. 2b).

4. Strike-slip displacement on the Vermilion fault (fig. 2b).

5. F_4 folding may have been pre-, syn-, or post-faulting.

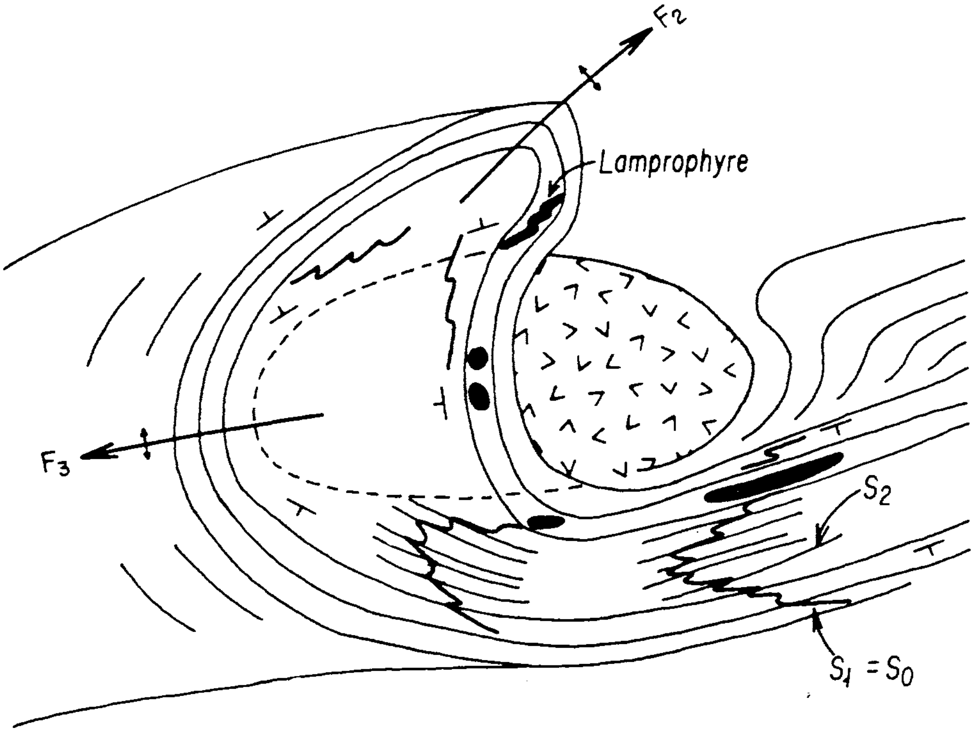


Figure 2. (a) Schematic illustration of the refolding (F_3) of the F_2 antiform over the top and western end of the stock.

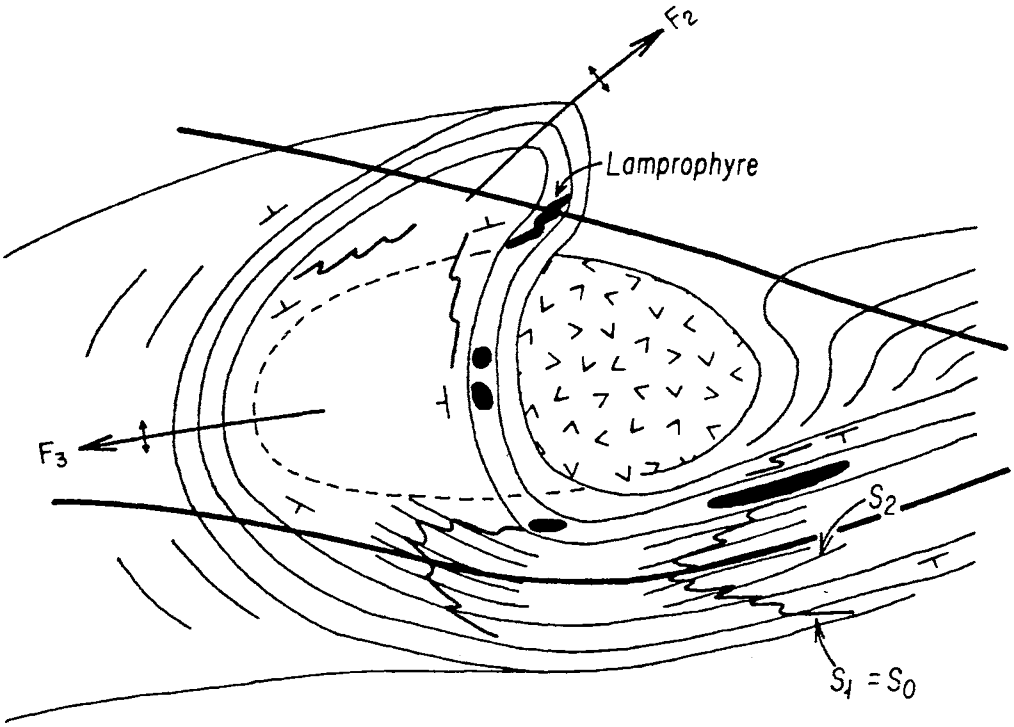


Figure 2. (b) Illustration of the positions of the Haley and Vermilion faults developed after F_3 folding.

THE WESTERN VERMILION DISTRICT--A REVIEW

G.B. Morey

Minnesota Geological Survey
1633 Eustis Street
St. Paul, Minnesota 55108

INTRODUCTION

The Vermilion district and adjacent areas in northeastern Minnesota (fig. 1) appear to form the western extension of the Wawa volcanic-plutonic belt of the Superior province of the Canadian Shield (see Southwick, fig. 1, this guidebook). The district consists of low-grade, steeply dipping subaqueous volcanic rocks, derivative sedimentary rocks, and intrusive granitic rocks that formed 2,750 to 2,700 m.y. ago (Goldich, 1972). This paper summarizes the results of geologic mapping and related studies (Green and others, 1966; Sims and Mudrey, 1978; Sims and others, 1968, 1970, 1972; Sims, 1972, 1973, 1976; Griffin and Morey, 1969; Hooper and Ojakanagas, 1971; Hudleston, 1976; Schulz, 1974, 1978) carried out in the western part of the Vermilion district during the past decade, mainly by the Minnesota Geological Survey. An essential temporal framework and insights into the petrogenesis of the major volcanic and igneous rock units were provided by geochronological studies (Goldich and others, 1961; Hanson, 1968; Peterman and others, 1972; Prince and Hanson, 1972; Goldich and others, 1972; Hanson and Goldich, 1972) and geochemical studies (Arth and Hanson, 1972, 1975; Jahn and others, 1974; Schulz, 1978) carried out over approximately the same period of time in a broad region in northern Minnesota.

As yet no attempt has been made to relate the tectonic-igneous history of the western part to that of the eastern part of the district as described by Gruner (1941). However, substantial modern data on the eastern part in reports by Goldich and others (1972), McLimans (1972), Hanson (1972), and Weiblen and others (1972) can provide additional insights into the stratigraphic sucession of the district as a whole.

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, consisting principally 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.

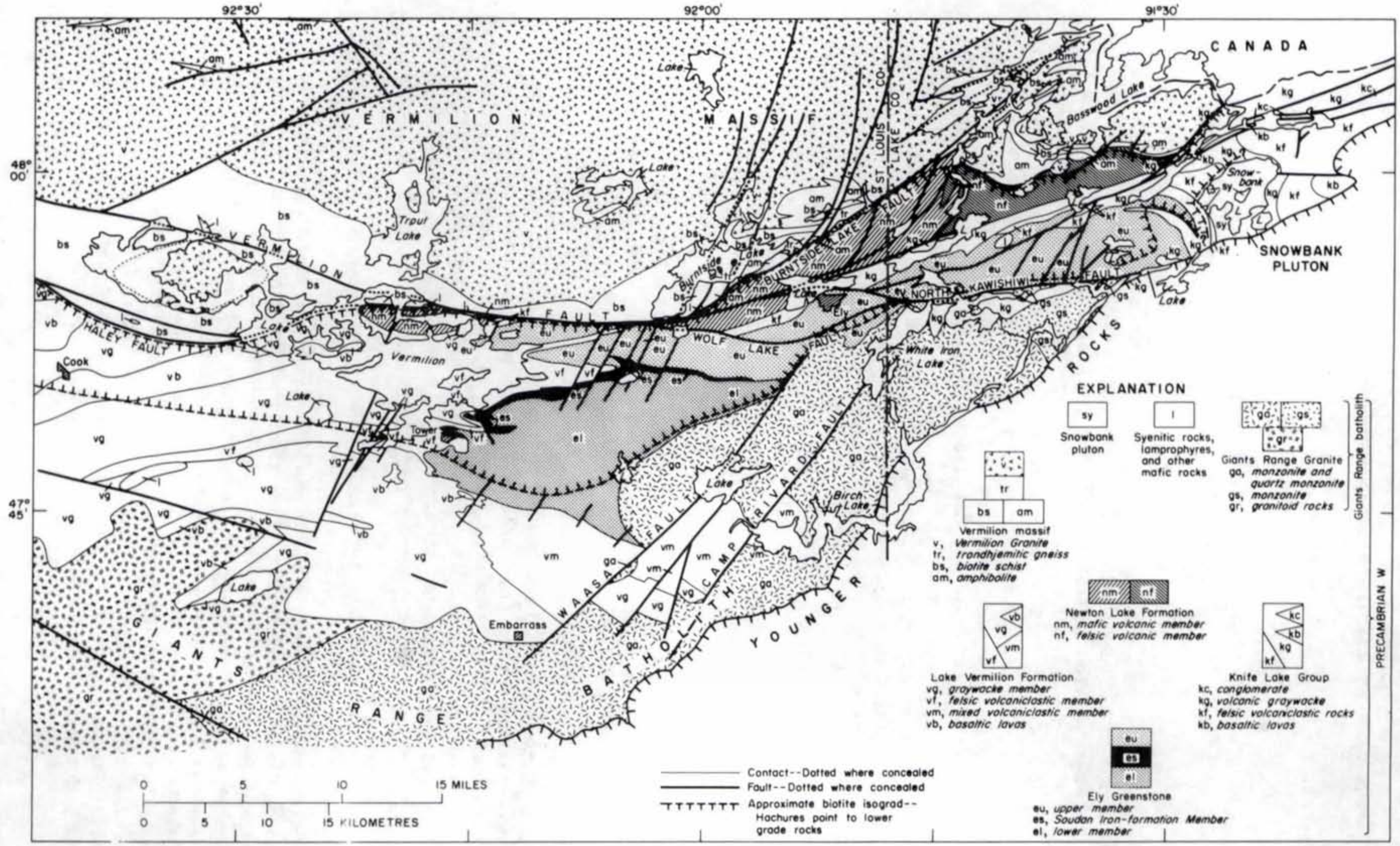


Figure 1. Geologic map of western part of Vermilion district and adjacent areas, northeastern Minnesota (Sims, 1973).

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 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 that were 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 by Grout (1926). All greenstones, especially pillowed basaltic flows, were called Keewatin, and the "Knife Lake slate" and associated "Ogishke conglomerate" were equated with Lawson's (1913a) "Seine Series" of the Rainy Lake area. 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 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, 1925b) 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, tbl. 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 rather 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--the Epi-Laurentian 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) considered the Epi-Laurentian unconformity to separate the Earlier Precambrian Era from the Medial Precambrian Era. The second major unconformity, developed after the Algoman orogeny, which also involved the Knife Lake Group, was the basis for separating the Medial Precambrian Era from the Later Precambrian Era. The Animikie Group, which includes the Biwabik Iron Formation, was deposited on the younger erosional surface.

On the basis of K-Ar ages, principally on biotite, Goldich and others (1961, tbl. 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 and its associated unconformity 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.

GENERAL GEOLOGY

The Vermilion district is a nearly linear belt of low-grade metavolcanic and metasedimentary rocks 10 to 30 kilometers wide and more than 160 kilometers long that extends from the vicinity of Tower on the south shore of Lake Vermilion (fig. 1) northeastward to the International boundary in the vicinity of Saganaga Lake. Metavolcanic rocks are dominant in the central part of the district (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 pyroclastic rocks. In general all of the supracrustal rocks have been complexly folded and metamorphosed by the diapiric rise of granitic bodies of batholithic dimensions (Sims, 1976); the supracrustal rocks now constitute a generally northward-facing sequence, with progressively younger strata from south to north.

The supracrustal rocks in the district are bounded on the north by the Vermilion granite-migmatite massif of Southwick (1972), now named the Vermilion Granitic Complex (Southwick and Sims, in press), on the south by rocks of the Giants Range batholith, and on the east by the Saganaga batholith. The younger Duluth Complex, Keweenawan (ca 1.1 m.y.) in age, transects the Giants Range batholith and the southern part of the supracrustal sequence in the eastern part of the district.

A major, longitudinal fault system--the Vermilion fault of Sims and others (1968)--generally but not everywhere separates the Vermilion Granitic Complex and its associated amphibolite-facies schist, amphibolite, and migmatite from greenschist-facies rocks of the Vermilion district proper. East of Ely, another major longitudinal fault, the North Kawishiwi fault, separates the Giants Range batholith and associated amphibolite-facies rocks from lower grade supracrustal rocks to the north; south of Ely, the transverse Waasa and Camp Rivard faults locally separate the two contrasting metamorphic rock assemblages. Elsewhere however, rocks of the Giants Range batholith have normal intrusive relationships in the older strata, with the development of amphibolite-facies assemblages adjacent to the contact.

The supracrustal sequence between the Giants Range batholith on the south and the Vermilion Granitic Complex on the north is broken into several blocks or segments by numerous high-angle faults, many of which are longitudinal. Because of uncertainties as to the direction and amount of displacement on many of these faults and because of the presence of complex folding, detailed stratigraphic correlations are generally lacking in the district.

SUPRACRUSTAL ROCKS

The supracrustal rocks throughout the Vermilion district are characterized by interfingering and repetitive rock types (Green, 1970; Morey and others, 1970; Sims and Morey, 1972; Sims, 1976). The strata in the western part of the district, however, have been assigned to four formal lithostratigraphic units (Morey and others, 1970; Sims, 1976). The oldest is the Ely Greenstone, composed mainly of mafic pillowed to massive flows and iron-formation. The Ely Greenstone is overlain stratigraphically in the central part of the district by the Knife Lake Group and in the western part by the Lake Vermilion Formation. Both the Knife Lake Group and the Lake Vermilion Formation are composed of felsic volcaniclastic rocks, graywacke, mudstone, and lesser amounts of mafic and felsic extrusive and hypabyssal rocks. The youngest unit is the Newton Lake Formation which conformably overlies the Knife Lake Group in the central part of the district and the Lake Vermilion Formation in the western part.

Ely Greenstone

Van Hise and Clements (1901, p. 402) named the Ely Greenstone from exposures around the town of Ely where a variety of green-colored extrusive, intrusive and fragmental rocks occur. Although Clements (1903) and many subsequent workers applied the name to all major bodies of greenstone in the Vermilion district, recent mapping has led to the restriction of the name Ely Greenstone to only those mafic metavolcanic and associated rocks continuous with the rocks exposed in the town of Ely (Morey and others, 1970).

Although stratigraphic relationships appear to be complicated, the Ely Greenstone is subdivided into three members with the laterally persistent Soudan Iron-formation Member separating lower and upper volcanic members. The lower member consists dominantly of pillowed and massive mafic flows and lesser amounts of intercalated sedimentary rocks. A distinctive feature of many of the pillowed flows is their generally amygdaloidal nature, whereas the massive flows have a micro-diabasic texture and few amygdules. Field relations suggest that the massive flow units grade into amygdaloidal pillow basalt, and may, therefore, represent the interior parts of single flows.

The majority of the flows appear to be basaltic, but flows of andesitic composition have been recognized at several places (Schulz, 1978). These rocks are gray to dark gray in color, fine grained, and some are pillowed and amygdaloidal. Generally lobate pillows are variable in size and have thick whitish rinds; vesicles are concentrated near the pillow margins and are filled with quartz which tends to stand in relief on weathered outcrops. Other andesitic flows are porphyritic; they have a very fine-grained matrix of quartz and feldspar.

Associated sedimentary rocks range from thin-bedded tuff to fine- to coarse-grained conglomerate and breccia composed of basaltic clasts. Beds of banded iron-formation also are common in the member.

The Soudan Iron-formation Member forms the thickest and longest banded iron-formation in the Vermilion district. It extends for a distance of about 25 kilometers eastward from Tower (fig. 1), and consists of several types of ferruginous chert that are interbedded with fine-grained carbonaceous and sericitic tuff and lesser agglomerate and basalt.

The upper member of the Ely Greenstone lies stratigraphically above the Soudan Iron-formation Member and interfingers to the east or is in fault contact with strata assigned to the Knife Lake Group (Morey and others, 1970). In the area of Lake Vermilion, the upper member interfingers with clastic strata assigned to the Lake Vermilion Formation. Additionally, thin beds of clastic rocks and iron-formation also are present in its upper part at several places. These field relationships clearly indicate that the upper member was, at least in part, contemporaneous with the clastic sedimentation of the Lake Vermilion Formation and the Knife Lake Group.

The majority of the rocks that comprise the upper member are of basaltic composition. The remaining fraction includes felsic volcanic rocks, chert and banded iron-formation, and clastic rocks. The basalts consist of pillowed lavas along with contemporaneous diabasic rocks showing both concordant and disconcordant relations.

Lake Vermilion Formation

In the extreme western part of the district, near Lake Vermilion, (fig. 1), the Lake Vermilion Formation overlies the Ely Greenstone. 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.

On the basis of the dominant lithology, the Lake Vermilion Formation is divided into three informal members (fig. 1). Agglomerate and associated tuff of the felsic volcaniclastic member conformably overlie the Soudan Iron-formation Member or where it is absent, the lower Ely member. The agglomerate is a light-gray, massive rock of dacitic composition; rounded clasts of dense felsite or quartz porphyry ranging in diameter from several centimeters to several tens of centimeters occur in a fine-to medium-grained crystal-lithic tuff matrix. Minor amounts of exotic rock fragments, mainly chert or banded iron-formation, also occur in the unit. The upper part of the felsic volcaniclastic member that is exposed on several islands in Lake Vermilion consists dominantly of massive crystal-lithic tuff with interbedded agglomerate.

The so-called mixed volcaniclastic member occupies an area of about 78 square kilometers on the south limb of the fold at Tower. Its stratigraphic relationships with the felsic volcaniclastic member are unknown, but to the northwest, it interfingers with the graywacke member and is stratigraphically overlain by it. The mixed volcaniclastic member consists of interlayered felsic to mafic volcaniclastic rocks, felsite flows, several types of conglomerate and agglomerate, and metagraywacke (Griffin, 1969; Griffin and Morey, 1969).

The graywacke member, which is the most extensive unit in the Lake Vermilion Formation, directly overlies the upper Ely member south of Tower and the felsic volcaniclastic member of the Lake Vermilion Formation west of Tower. It consists mainly of thin- to medium-bedded graywacke; the beds commonly are graded and contain other sedimentary structures indicative of turbidite deposition (Ojakangas, 1972a). A chloritic facies occurs on the shores of Lake Vermilion and adjacent areas, whereas a biotitic variety is dominant elsewhere. The graywacke member also is typified in places by intercalated units of pillowed and massive metabasalt.

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. 1). In the Ely area, the Knife Lake consists dominantly of a distinctive light-gray tuff of generally dacitic composition, whereas between Fall Lake and Snowbank Lake it consists mainly of graywacke with lesser felsic volcaniclastic rocks. In the central part of the district (Green, 1970), the belt of Knife Lake strata is no more than 750 meters wide; farther east in its type area, the Knife Lake is estimated to be about 4,500 meters thick (Gruner, 1941). In the type area, volcaniclastic rocks of generally dacitic composition including both tuff and agglomerate are abundant, as are a variety of conglomerates. The dominant rock is graywacke, which is mainly of volcanogenic origin (Ojakangas, 1972a).

Newton Lake Formation

The Newton Lake Formation was originally mapped as Ely Greenstone by Clements (1903) and was later mapped as the "unnamed formation" in the Gabbro Lake quadrangle (Green and others, 1966). Green (1970) later showed that the rocks of the "unnamed formation" overlie the Ely Greenstone and are in apparent depositional contact with the Knife Lake Group in this area. The name Newton Lake Formation was formally given to these younger volcanic rocks by Morey and others (1970), who divided it into two informal members that intertongue in the vicinity of Newton Lake--a mafic volcanic member occurring west of Newton Lake and a felsic-intermediate volcanic member to the east (fig. 1). A similar change, from dominantly mafic volcanic rocks to dominantly felsic volcanic rocks, possibly also occurs at the western end of the formation (Sims and Mudrey 1978). Large bodies of siliceous marble, first described by Green (1970), occur in the area of intertonguing between the mafic and felsic members in both areas.

The felsic member consists dominantly of fragmental breccia, scoriaceous breccia, tuff-breccia and tuff along with lesser amounts of volcanic arkosic wacke and volcanic graywacke (Green, 1970). Pillowed and flow-banded dacite lavas, interstratified with the tuff-breccia, are locally abundant and some of the flows are amygdaloidal. Siliceous marble occurs locally in the felsic member as layers as much as 150 meters thick and at least 1.6 km long; in general they are composed of fine-grained, recrystallized cherty limestone and recrystallized calcareous chert. Additionally, several conglomeratic zones having pebbles, cobbles, or granules of chert in a limey matrix are present locally.

The mafic member consists dominantly of pillowed to massive flows of basaltic composition. Felsic volcaniclastic units, iron-formation and siliceous marble are present locally and in places form an appreciable part of the member. These units commonly are lenticular, although a few felsic tuff units of andesitic composition have been traced laterally for a kilometer or more.

A coarse paraconglomerate also was found interbedded with basalt and tuff at one locality. This unit is characterized by rounded pebbles, cobbles, and boulders of quartz-rich tonalite with lesser amounts of fine-grained basalt and medium-grained diabase. The mafic clasts generally are much smaller and more angular than the tonalitic clasts. The matrix is structureless and consists dominantly of actinolite, with lesser amounts of chlorite, quartz, and plagioclase. The source for the plutonic clasts is unknown, but similar clasts from a conglomeratic unit in the Ely Greenstone have yielded ages similar to the greenstones themselves (2.69 b.y., Jahn and Murthy, 1975), suggesting derivation from intrusions contemporaneous with volcanism as opposed to an older granitic basement.

The mafic member also is characterized by numerous tabular bodies of mafic to ultramafic composition that have varying proportions of peridotite, pyroxenite, two-pyroxene gabbro and quartz gabbro. Massive bodies consisting entirely of gabbro or quartz gabbro also are present (Schulz, 1974; Green and Schulz, 1977).

INTRUSIVE ROCKS

Five distinct episodes of intrusive activity are recognized in the Vermilion district and adjacent areas. In order of inferred age, from oldest to youngest, these are: (1) synvolcanic rocks, including metadiabase and hypabyssal porphyries having a wide range in composition; (2) syntectonic granitic rocks of the Saganaga and Giants Range batholiths; (3) late- or post-tectonic syenitic rocks and related lamprophyres; (4) post-tectonic quartz monzonitic rocks of the Giants Range batholith and alkalic plutons such as the Linden pluton to the west of Tower; and (5) diabasic dikes of Middle Precambrian age and basalt dikes of Late Precambrian age. Only the synvolcanic and batholithic rocks are discussed here.

Synvolcanic Hypabyssal Rocks

Three varieties of synvolcanic hypabyssal intrusive rocks have been recognized in the volcanic-sedimentary sequence. These include: (1) diabasic dikes and sills in the Ely Greenstone and Newton Lake Formation; (2) differentiated mafic-ultramafic sills in the mafic volcanic member of the Newton Lake Formation; and (3) dikes, sills, and stocks of quartz-plagioclase or plagioclase-hornblende porphyry that occur locally, particularly in the Ely Greenstone. Most of these rocks are too small to be shown at the scale of the map in Figure 1, but can be distinguished readily on larger scale maps (Green and others, 1966; Sims and others, 1968).

Metadiabase is closely associated with basaltic lavas regardless of stratigraphic position. Generally the diabasic rocks occur as tabular bodies that are more or less conformable to the mafic lavas, but some contacts are strongly crosscutting. They are distinguished from mafic flow units by being distinctly coarser grained and by having a diabasic texture.

Differentiated mafic-ultramafic bodies in the Newton Lake Formation are generally conformable with enclosing flows, and are characterized by varying proportions of peridotite, pyroxenite, two-pyroxene gabbro and quartz gabbro. Many show features typical of layered intrusions including phase and cryptic layering, weak rhythmic layering, and well developed cumulus textures (Schulz, 1974). Other sill-like bodies consist entirely of gabbro or quartz gabbro, but generally all, regardless of composition, have complex chilled margins characterized by elongate, sometimes branching amphibole pseudomorphs after clinopyroxene. These pseudomorphic grains generally lie perpendicular to the contact and become longer and broader into the sills, forming a texture similar to the spinifex of peridotitic komatiites (Pyke and others, 1973). Similar textures also have been called pyroxene spinifex (Arndt, 1976). Compositionally the chilled margins are high in MgO and low in Al_2O_3, characteristics observed in some of the flows in the Newton Lake Formation. This compositional equivalence and the close spatial association of the sills and flows implies that they were comagmatically derived (Schulz, 1974) from a basaltic komatiite source (Green, 1974; Green and Schulz, 1977; Schulz, 1978).

Andesite, dacite, and rhyodacite porphyries 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 meters across to larger irregularly shaped stocks approximately a hundred meters wide.

All of the synvolcanic hypabyssal rocks have been metamorphosed to the same extent as the enclosing supracrustal rocks.

Batholithic Rocks

Several types of plutonic rocks intrude the volcanic-sedimentary sequence in the western part of the Vermilion district. The oldest recognized are the syntectonic rocks of granitoid composition that constitute the western part of the Giants Range batholith. Younger post-tectonic rocks of generally granodioritic to monzonitic to quartz monzonitic composition consititute the eastern part of the Giants Range batholith, and also occur as small, isolated plutons scattered along the length of the belt of supracrustal rocks.

The syntectonic granitoid rocks occur as a number of discrete plutons that range in composition from granite to tonalite (Sims and Viswanathan, 1972). Generally these rocks have steep foliations and contacts that are conformable to the internal structure of adjacent supracrustal rocks. In contrast, the post-tectonic rocks in the eastern part of the batholith appear to be gradational and do not show clear intrusive relations to one another (Green, 1970); they truncate the regional structure and have steep primary foliations and lineations that are discordant to the regional structure (Green, 1970; Sims, 1976).

In addition to the major batholithic units, post-tectonic rocks of generally syenitic composition form several small plutons that are widely scattered along the length of the belt of supracrustal rocks. Some are compositionally and structurally similar to the eastern part of the Giants Range batholith, whereas other bodies have different compositions and seem to be highly differentiated. Associated with the syenitic plutons are several types of lamprophyres that are interpreted as being cogenetic with them (Sims, 1976).

METAMORPHISM

All of the supracrustal rocks in the western part of the Vermilion district have been metamorphosed, generally to at least the greenschist facies. Quartzofeldspathic rocks contain chlorite, muscovite, albite, quartz, and epidote, whereas the mafic rocks contain chlorite, calcite, tremolite or actinolite, epidote and quartz. However, incomplete recrystallization is widespread as shown by well-preserved bedding features and primary textures. In addition, zoned plagioclase crystals and relict hornblende grains are widespread in the felsic volcanogenic and volcaniclastic rocks as are relict augite and labradorite in the mafic rocks.

In general the metamorphic grade within the greenschist facies increases in intensity toward bounding granite masses or major faults, and those rocks adjacent to or within plutonic igneous bodies have been prograded to the amphibolite facies.

Amphibolite facies assemblages adjacent to the plutons vary in width and maximum grade attained, depending on the tectonic setting in which the plutons were emplaced. For example, syntectonic plutons have wide metamorphic aureoles that range in grade from the greenschist facies to the upper amphibolite facies. The metamorphic aureoles are characterized by the progressive loss of relict volcanic and clastic textures, by the progressive disruption of layering, and by a progressive increase in the degree of migmatization. In contrast, the post-tectonic plutons have narrow metamorphic aureoles characterized by a lack of primary textures except for layering. The maximum grade obtained is generally of the lower or middle amphibolite facies. Regardless, all of the metamorphic assemblages in the district appear to be similar to the Abukuma-type facies series of Miyashiro (1961), which is characteristic of regions with steep thermal gradients at low to moderate pressures.

Retrograde metamorphism of the supracrustal rocks is widespread as indicated by mineralogic transformations such as: (1) the alteration of biotite to chlorite and/or pumpelleyite; (2) alteration of plagioclase to epidote, and (3) sericitization of metamorphic plagioclase. Whether these mineralogic transformations represent reequilibration in response to declining temperature during later stages of the Algoman orogeny or whether they formed in response to some subsequent period of cataclasis or very low-grade metamorphism has not been established (e.g., Hanson and Malhotra, 1971).

STRUCTURE

The supracrustal rocks in the district are steeply inclined and complexly folded; subsequent faulting also has superposed a steep shingling effect on the original fold patterns.

Folds have been developed to different degrees in the district, largely in response to the physical characteristics of the original rock types. In general, steep isoclinal folds with short wavelengths are well developed only in the layered rocks. In contrast, the more massive mafic volcanic rocks yielded mainly by brittle fracture and now form steeply-dipping homoclines of wide regional extent (Sims, 1976). Although evidence for superposed folding is widespread, the pattern of multiple folding has been examined only in the Tower area (Hooper and Ojakangas, 1971; Sims, 1976). In this area geographic names have been assigned to the two generations of folds that have been identified; the Embarrass-Lake Vermilion generation and the Tower generation (Sims, 1972, 1976). Earlier these two generations were characterized by the notation F_1 and F_2 respectively (Hooper and Ojakangas, 1971).

The younger (F_2) folds of the Tower generation and a pervasive accompanying cleavage largely obscure the older (F_1) folds of the Embarrass-Lake Vermilion generation. However, detailed studies near Tower and in adjacent areas (Hooper and Ojakangas, 1971) indicate that older tight to isoclinal folds have west-northwest-trending axes, steeply inclined axial surfaces, and probably gentle or moderate plunges. Major fold axes, as determined by consistently facing or opposing tops of beds, are spaced from 300 to 500 meters apart. Aside from rarely observed small fold axes, lineations are absent. Locally the folds have a weak axial plane cleavage that is subparallel to bedding.

Folds of the Embarrass-Lake Vermilion generation near Embarrass occur in middle and upper amphibolite-grade metamorphic rocks and are represented by small tight folds that have long limbs (Griffin, 1967). These folds trend west-northwest and have planar, steeply inclined axial surfaces and gentle southeastward-plunging axes. A conspicuous lineation marked by elongate hornblende grains and aggregates of biotite is subparallel to the fold axes.

The younger F_2 folds of the Tower generation comprise most of the mappable folds in the western part of the Vermilion district. Most of these folds are strongly asymmetric and have steep axial planes that trend eastward. In most of the area the F_2 folds are dominantly Z-folds, whose northwest-trending limbs are two or more times longer than the southwest-trending limbs. Both upward-facing and downward-facing folds occur, and plunges are generally steep. The intersection of a pervasive 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 intersections.

In the Tower area, several nearly vertical structures--faults, joints, and kink bands--displace the cleavage of the F_2 folds, and are thought to represent a still younger event.

A close temporal relationship between F_1 folding of the Embarrass-Lake Vermilion generation and emplacement of syntectonic granitoid rocks has been demonstrated in the southern part of the district (Griffin and Morey, 1969) where metamorphic minerals were formed contemporaneously with folding. The younger F_2 folds of the Tower generation can be accounted for by the supracrustal rocks having been compressed between rising batholithic bodies (Hooper and Ojakangas, 1971). Therefore Sims (1976) suggested that all of the folding is attributable to compression caused by the relative upwelling and convergence of buoyant granitic bodies. However, Hudleston (1976) has suggested that some of the first generation folds in the Tower area may be related to depositional processes related to downslope slump movements of some of the well-layered rocks.

Three steep fault sets post-date the folding (Sims, 1976): (1) dip-slip faults which have dominantly vertical separation, (2) strike-slip faults longitudinal to the Vermilion district, which have right-lateral displacements, and (3) transverse (northwest-trending) left-lateral strike-slip faults. Crosscutting relations among the fault sets have not been observed, but Sims (1976) suggests that both sets of strike-slip faults formed approximately at the same time, after the main movement on the dip-slip faults.

GEOCHRONOLOGY

Radiometric dating has not yet delineated more than one major period of plutonic igneous activity and metamorphism in northern Minnesota. For the Saganaga Lake area, Goldich and others (1972) obtained whole-rock isochron ages on the three principal rock types--Northern Light Gneiss, the Saganaga Granite (referred to by them as the Saganaga Tonalite), 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. The Giants Range batholith has a Rb-Sr isochron age of 2,670 ± 65 m.y. (Prince and Hanson, 1972), and the supracrustal rocks themselves have Rb-Sr isochron ages of 2,650 ± 110 to 2,690 ± 180 m.y. (Jahn and Murthy, 1975). Inasmuch as the intrusive rocks of both the Giants Range batholith and Vermilion Granitic complex were emplaced approximately synchronously with metamorphism and deformation of the supracrustal rocks, 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. (Catanzaro and Hanson, 1971). This age, determined by Pb 207-Pb 206 data on sphene and by Rb-Sr isotopes, provides a minimum age for the time of regional deformation in the western part of the Vermilion district. In the same way, the age of the Icarus pluton (2,700 m.y.), which apparently also is post-tectonic and similar lithologically to the Linden pluton (Goldich and others, 1972), 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 activity, metamorphism, and deformation all took place virtually synchronously throughout the Vermilion district around 2,700 m.y. ago and within perhaps a time interval of about 50 m.y.

A further constraint on models for the geologic evolution of the Vermilion district is provided by the $^{87}Sr/^{86}Sr$ initial values obtained by the geochronologic studies. The initial values are all below 0.701 and precluded derivation of the supracrustal and batholithic rocks from a preexisting sialic crust that was significantly older than 2,700 m.y. (Jahn and Murthy, 1975).

PETROLOGIC AND GEOCHEMICAL STUDIES

Although much is now known regarding the structure and stratigraphy, little is known about the petrologic and geochemical nature of the rocks in the Vermilion district.

The clastic sedimentary rocks have been described by Ojakangas (1972a) and McLimans (1972), who have concluded that they were derived in large part from felsic-intermediate volcanic material--mostly dacitic in composition--and deposited by turbidity currents. Geochemical studies by Arth and Hanson (1975), Jahn and Murthy, (1975) and more recently by Morey and Schulz (1977) have confirmed the dacitic parentage of the graywacke in the western part of the Vermilion district.

The plutonic rocks also have received considerable attention in recent years (Arth and Hanson, 1972, 1975; Rye and Roy, 1978). In particular, Arth and Hanson (1975) suggest, on the basis of trace and rare-earth element data, that the synvolcanic dacitic rocks and the Saganaga Tonalite of the eastern Vermilion district were derived by the partial melting of eclogite or amphibolite at mantle depths. Similarly they suggest that the syntectonic rocks in the western part of the Giants Range batholith were derived by the partial melting of dacitically derived graywacke at crustal depths, whereas the post-tectonic syenitic rocks were derived by the partial melting at mantle depths of a mixture of quartz eclogite, undersaturated eclogite and peridotite.

Early studies of the mafic volcanic rocks of the Vermilion district were mostly of a general nature. Sims (1972) concluded that the Ely Greenstone generally had a tholeiitic affinity, whereas the Newton Lake Formation had a calc-alkaline affinity. However, Schulz (1978) has recently shown that the lower Ely member is similar to recent island-arc calc-alkaline rocks, whereas the upper Ely Member consists largely of tholeiitic basalts that have attributes similar to those of ocean-floor and island-arc tholeiites. The felsic member of the Newton Lake Formation consists of calc-alkaline andesite and dacite which are chemically similar to the lower Ely member; these two suites probably had similar origins. In contrast the mafic member of the Newton Lake Formation consists of two basalt types that appear to be petrologically unrelated. One group is compositionally similar to basaltic komatiites from Australia and Canada, whereas the other group shows similarities with the South African komatiites and the so-called high-iron tholeiite suite in Munro Township, Ontario. Although petrogenetic relationships between these two groups are not well understood, Schulz (1978) has clearly demonstrated that the Vermilion district developed through the coalescence of a number of petrologically distinct centers and that the calc-alkaline volcanism was more or less continuous, whereas the basaltic volcanism was more or less episodic in nature.

SUMMARY

The western part of the Vermilion district is characterized by overlapping volcanic piles of basalt and related synvolcanic intrusive bodies of calc-alkaline, tholeiitic and komatiitic affinity. Lenses of banded iron-formation occur in the dominantly mafic parts of the succession, and particularly in the upper parts. The mafic rocks give way rather abruptly upward and laterally to dacitic and rhyodacitic rocks of calc-alkaline affinity. These rocks in turn grade upward and laterally into dominantly volcanogenic graywacke-shale sequences derived from the felsic portions of the volcanic centers. Thus a major unconformity between older mafic volcanic rocks and younger sedimentary strata does not appear to exist in the western part of the district. A major unconformity does exist at the eastern end of district where the Saganaga Tonalite of Goldich and others (1972) intrudes mafic volcanic rocks, and underlies sedimentary rocks of the Knife Lake Group. This area was previously believed to be a classic example of the Laurentian orogeny, as originally defined by Lawson (1913a) at Rainy Lake. However because some of the mafic rocks intruded by the Saganaga batholith are the lateral equivalents of the Newton Lake Formation, it appears that the Knife Lake Group, as presently defined, is both older and younger than the Saganaga batholith. Thus the so-called Laurentian orogeny and its associated Epi-Laurentian unconformity appear to have little regional stratigraphic significance.

Because mafic lavas are repeated throughout the sequence, they are not diagnostic of a unique and widespread rock unit as previously inferred (Grout and others, 1951). Furthermore the presence of distinct magma types in mappable lithologic units implies that distinct batches of magma were generated and fractionated. This in turn implies that magma generation was not a steady-state process. The interlayering of lavas with sedimentary rocks of variable thickness is further evidence for discontinuous volcanic processes.

Quantitative trace-element models indicate that all of the volcanic and plutonic rocks--except for the granitoid rocks in the western part of the Giants Range batholith which formed from the partial melting of short-lived graywacke at crustal depths--probably were derived directly from the mantle by varying degrees of partial melting. Nonetheless because distinct magma types have been found interbedded with one another, it appears that several magma chambers of restricted size, rather than a single, large continuous magma chamber existed. Thus the volcanic history of the Vermilion district is similar to that of modern plate-tectonic settings. In fact, much of the available geochemical and petrological information is compatible with the origin of the supracrustal rocks in a manner analogous to the origin of rocks in a modern marginal-basin/island-arc setting. This has led some workers (e.g., Jahn and others, 1974) to suggest that the rocks of the Vermilion district formed by essentially modern-day plate tectonic processes. However, others including Arth and Hanson (1975) have pointed out that the available geochemical data are inadequate for making comparisons of rock types common to both terranes. Thus in the Vermilion district, as in most other greenstone belts, the philosophical approach to the problem of genesis ranges from the orthodox uniformitarian outlook to the view that modern-day plate tectonic processes have little relevance to the interpretation of the Archean.

Although the now-existing and widely disparate models of Archean crustal evolution for the Vermilion as well as other greenstone bolts must be viewed as having equal scientific respectability, it seems wise to define more precisely those specific and unique conditions that controlled the development of this greenstone belt, rather than to speculate on modern analogs for its tectonic development. Whether or not such an approach will lead to a more comprehensive understanding of the Vermilion district in the near future may be a matter of speculation, but it is certain that such an understanding will be achieved only by additional work of the kind and quality cited in this review. To that end it should be stated that much of our present understanding of the district is the direct result of the interests and efforts of P.K. Sims while he was Director of the Minnesota Geological Survey.

ARCHEAN SEDIMENTATION IN THE VERMILION DISTRICT

R.W. Ojakangas
University of Minnesota, Duluth

INTRODUCTION

Nearly all of the sedimentary rock units within the Vermilion district are volcanogenic in origin. Some are pyroclastic, others are volcaniclastic, and the vast majority are graywacke and slate which display numerous characteristics of turbidite sequences (Ojakangas, 1972a; 1972b). Most are only slightly metamorphosed, with original textures and sedimentary structures well preserved.

The Vermilion district can be divided into three parts--western, central and eastern. The central portion consists largely of two mafic volcanic units which contain volcanogenic sedimentary rocks, but these sedimentary rocks are minor and will not be discussed here. The western and eastern portions consist largely of sedimentary rocks of clastic composition.

Apparently two major explosive felsic volcanic edifices were constructed upon the mafic volcanic platform, one in the west and one in the east (fig. 1). Detritus from these two volcanic centers was carried down the submarine flanks of the edifices into the adjacent deeps by turbidity currents. The total sedimentary rock sequence in the eastern Vermilion district has long been known as the Knife Lake Group (see Gruner, 1941), and that in the western Vermilion district has been named the Lake Vermilion Formation by Morey and others (1970).

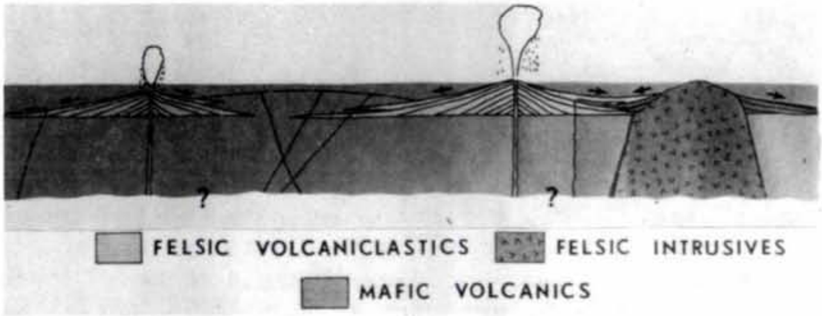


Figure 1. Generalized model for evolution of the volcanic-sedimentary rocks of the Vermilion district.

The five major rock units of the district are shown in Figure 2. Most beds are essentially vertical, and in general top northward. The Soudan Iron-formation Member is a key unit in that it provides a time marker in the pile; the presence of felsic rocks above it (Lake Vermilion Formation) along the western part of its extent and of mafic rocks above it (upper Ely Greenstone) along its eastern portion shows that felsic and mafic volcanism were contemporaneous.

There are sufficient differences in the sedimentary rocks of the two major sedimentary units, the Lake Vermilion Formation and the Knife Lake Group, to warrant separate descriptions.

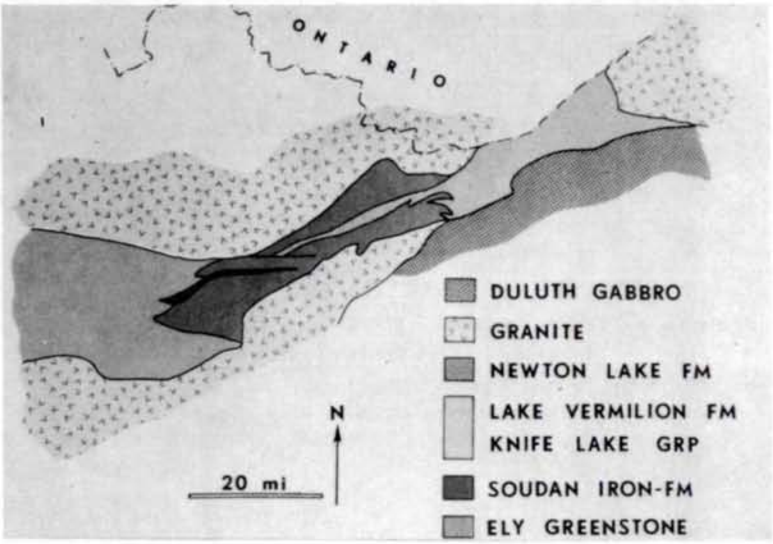


Figure 2. Simplified geologic map of the Vermilion district showing the five major rock units and adjacent batholiths. The Ely Greenstone and the Newton Lake Formation are predominantly mafic volcanic units, the Soudan Iron-formation Member is an exhalative precipitated unit, and the Lake Vermilion Formation and the Knife Lake Group primarily consist of volcanogenic-sedimentary rock units.

WESTERN VERMILION DISTRICT (LAKE VERMILION FORMATION)

Porphyritic dacitic dikes that probably were feeders to the felsic volcanic center (fig. 3) cut the Ely Greenstone and the Soudan Iron-formation Member. Dacitic agglomerates with clasts as large as one meter are present in the eastern part of Lake Vermilion near Tower-Soudan, and approximately locate the felsic center (fig. 4). Actual vents have not been observed; it is possible that water and swamp cover may be obscuring them, but it is far more likely that the actual vents were located at either a higher or lower level than the present surface which cuts the vertically dipping, northward-topping sedimentary sequence. The light-gray dacitic clasts in the agglomerate are very similar in lithology to the dacitic dikes in that they contain quartz and plagioclase phenocrysts; however, the matrix of the dacite in the clasts is finer grained, as expected, than in the hypabyssal dike rock. A scarcity of chilled margins on the clasts suggests that these rocks could be conglomeratic rather than agglomeratic in origin, but the rocks nevertheless indicate a location nearer to the volcanic center than any of the other sedimentary rocks.

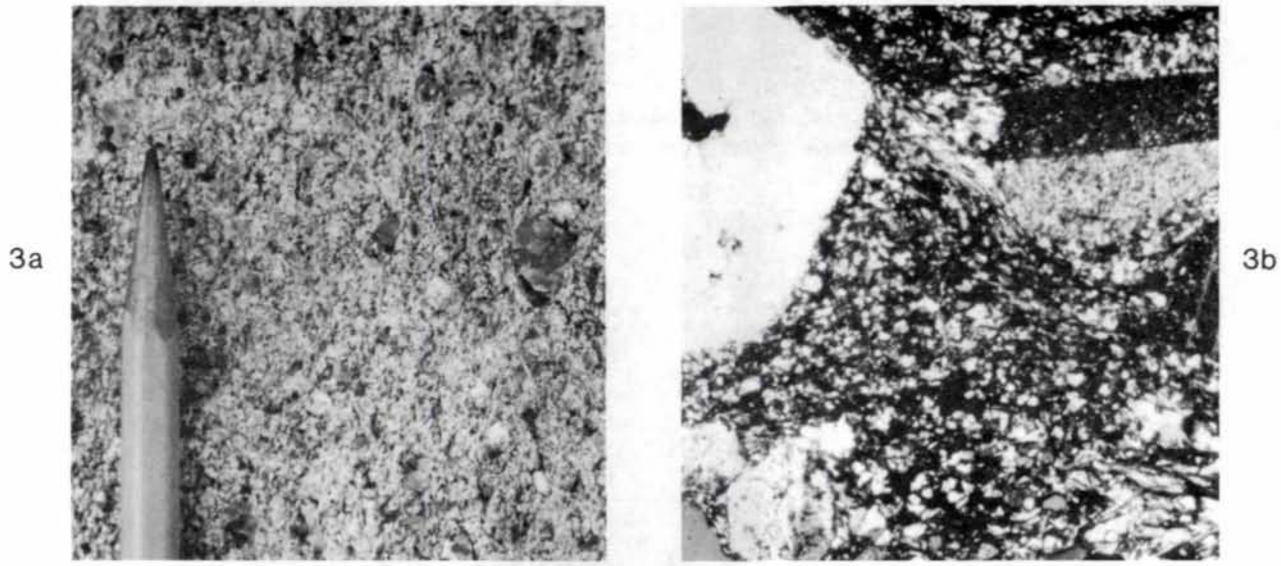


Figure 3. (a) Representative dacitic dike, western Vermilion district. Note the prominent quartz phenocrysts (gray).

(b) Photomicrograph of dacitic dike. Note volcanic quartz at left, plagioclase at right and finer volcanic groundmass. Field of view 2.5 mm across.

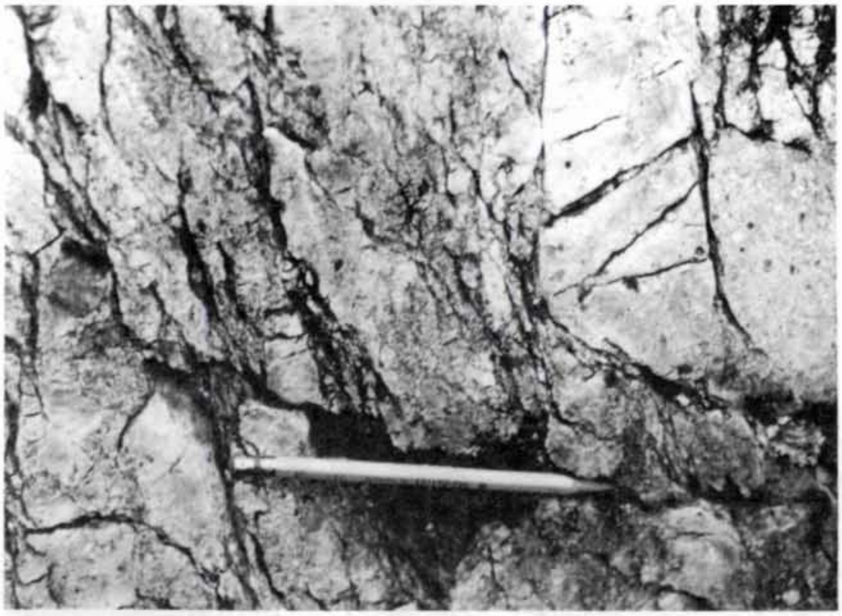
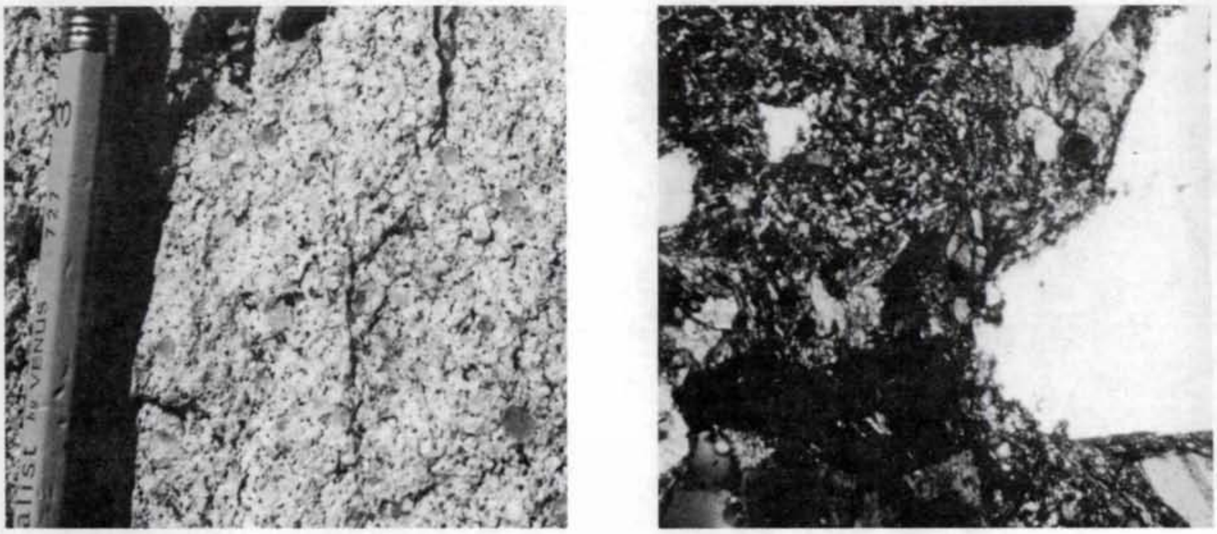


Figure 4. Dacitic agglomerate, western Vermilion district. Note quartz and plagioclase phenocrysts in finer groundmass of clast in upper right.

Interbedded with the agglomerate is dacitic ("quartz-eye") tuff (fig. 5). It contains the same components as the dike rock--volcanic quartz, plagioclase and fragments of the quartz-plagioclase groundmass. About 3 miles southwest of the probable volcanic center, and continuing for 25 miles to the west (see, e.g., Ojakangas and others, 1978), is a finer grained, better sorted reworked dacitic tuff which could also be called a volcanic sandstone (fig. 6). In outcrop it resembles a quartzite, but careful field and petrographic observation reveals that the same components as in the dacitic tuff--volcanic quartz, plagioclase and grains of volcanic groundmass--make up the rock.

5a

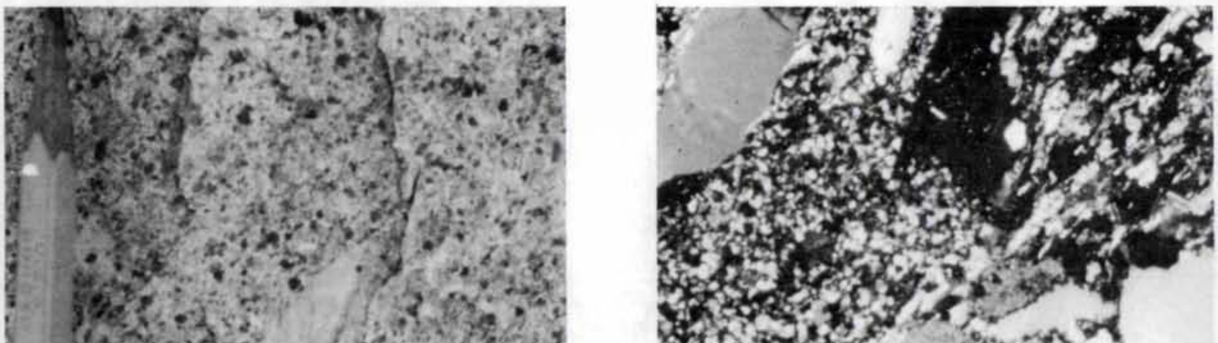


5b

Figure 5. (a) Dacitic tuff, western Vermilion district. Note large crystals of volcanic quartz and plagioclase.

(b) Photomicrograph of dacitic tuff. Note volcanic quartz at right, dacitic volcanic rock fragment at upper left, and smaller plagioclase grains at lower left. Field of view 2.5 mm across.

6a



6b

Figure 6. (a) Reworked dacitic tuff, western Vermilion district. Dark spots are volcanic quartz grains.

(b) Photomicrograph of reworked dacitic tuff. Note volcanic quartz grains at upper left, dacitic volcanic rock fragment at center, and large plagioclase grain at bottom center. Field of view 2.5 mm across.

The reworked dacitic tuff grades rather abruptly stratigraphically upward and laterally westward into a thick sequence of interbedded graywacke and slate (fig. 7). Grading, internal Bouma sequences, and loading signify deposition of the graywacke beds by turbidity currents. Again, the composition consists of volcanic quartz, plagioclase, and grains of dacitic volcanic groundmass. Some graywacke beds in the northern part of Lake Vermilion contain detrital hornblende as well.

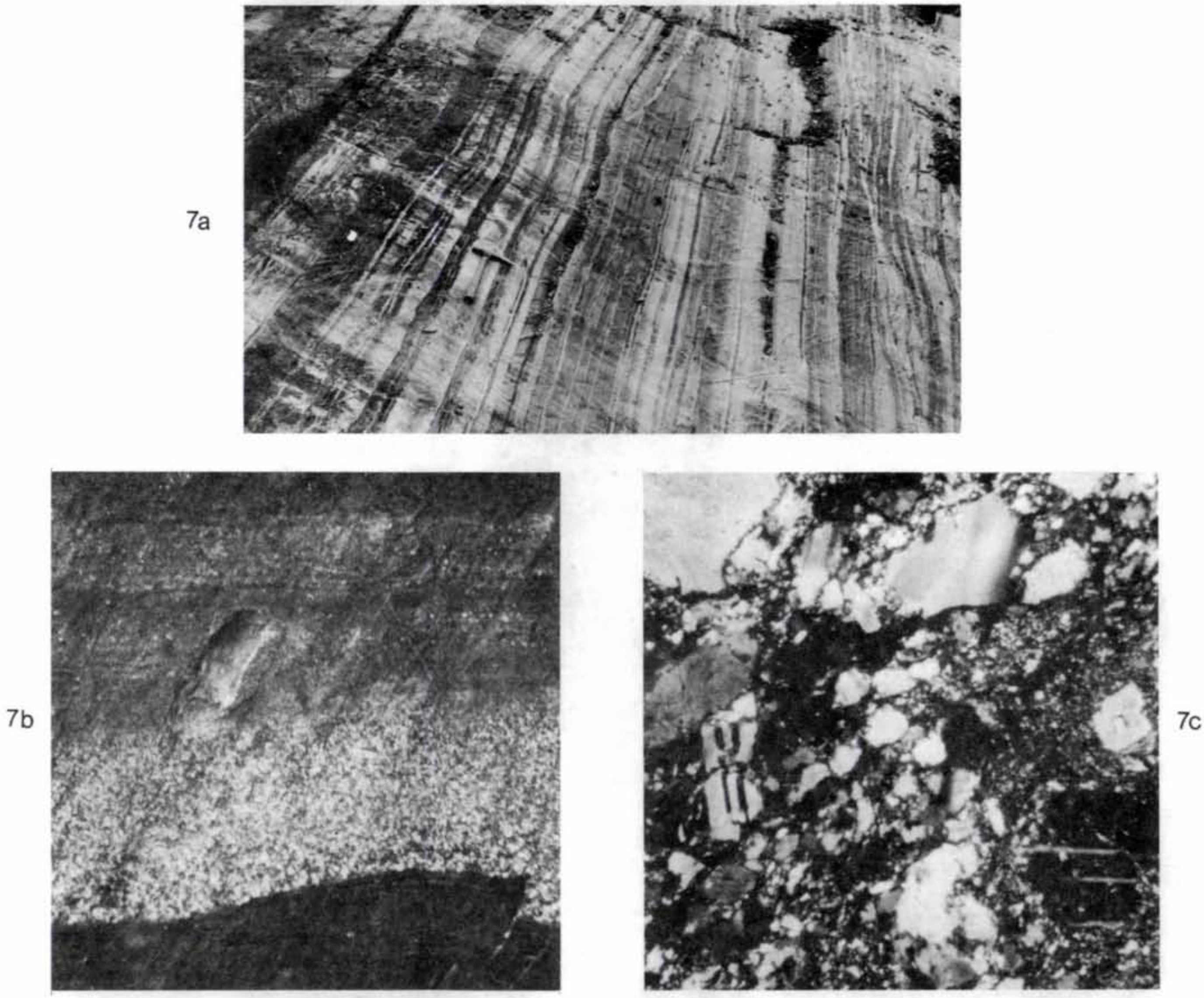


Figure 7. (a) Graded graywacke beds (white due to weathering), slate and siltstone beds (gray), western Vermilion district. Tops are to left.

(b) Graded graywacke bed (approximately 2 inches thick) in same section as 7(a). Top is up in photo.

(c) Photomicrograph of graywacke. Note large porphyritic dacite rock fragment at lower right, quartz in upper center, and numerous plagioclase grains. Field of view 2.5 mm across.

Therefore, it seems that the total sequence of sedimentary rocks which comprises the Lake Vermilion Formation is related to the felsic volcanic center. Certainly more than one vent was present at the volcanic center, for the total volume of dacitic detritus is enormous. In the Tower 7-1/2 minute quadrangle alone, 45 square miles are underlain by vertical sedimentary rocks of dacitic origin (Ojakangas and others, 1978) and about 150 total square miles are underlain by the graywackes and slates of the Lake Vermilion Formation in the western Vermilion district. Furthermore, 400 square miles of the higher grade biotite schist west and northwest of the Vermilion district proper may have originally been dacitic graywacke and slate (Ojakangas, 1972b).

EASTERN VERMILION DISTRICT (KNIFE LAKE GROUP)

Although the rocks of the Knife Lake Group are quite well exposed and quite variable, the lateral relationships of lithologies generally cannot be delineated as in the Lake Vermilion Formation because of numerous longitudinal faults with unknown horizontal displacements. The abundance of dacitic detritus again indicates the presence of a major explosive felsic center. However, very coarse volcaniclastics which would mark a center more precisely than "the vicinity of Knife Lake" have not been located.

Major volcaniclastic units of varying composition are present within the Knife Lake Group; pyroxene-andesite agglomerate and tuff, hornblende-andesite agglomerate and tuff (fig. 8), and dacitic tuff are all present.

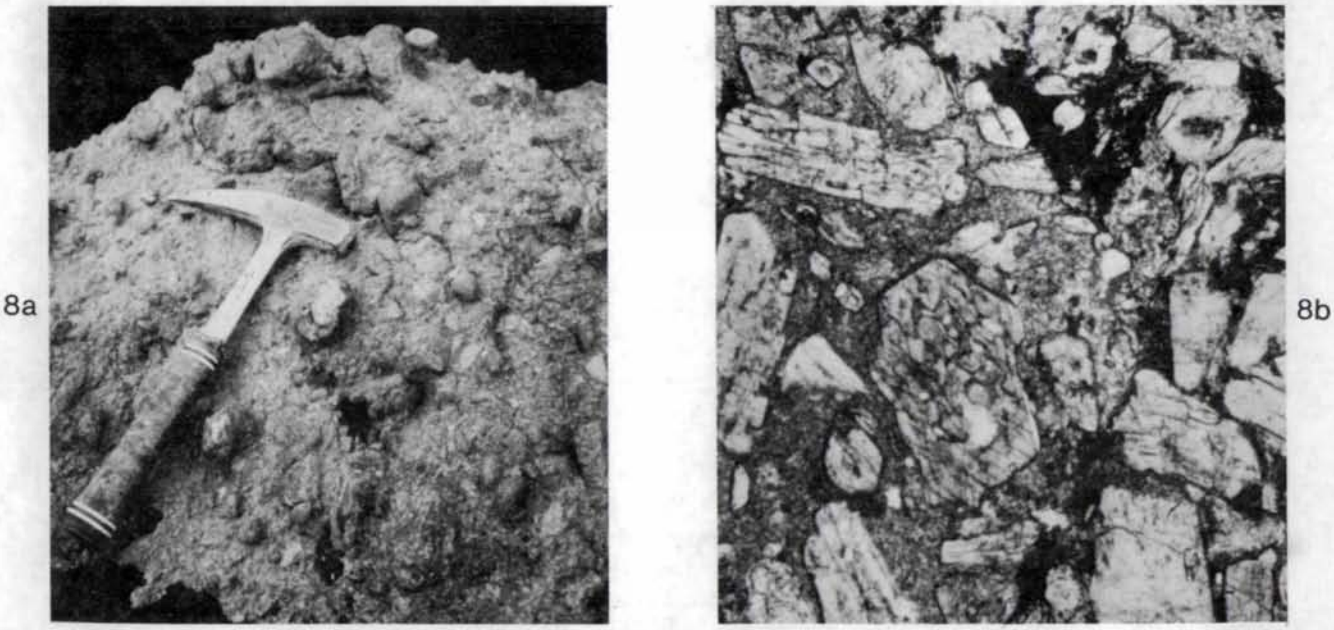


Figure 8. (a) Hornblende-andesite agglomerate, Kekekabic Lake, eastern Vermilion district.

(b) Photomicrograph of hornblende-andesite tuff, Kekekabic Lake. Well-formed crystals are hornblende crystals. Note large volcanic rock fragment at left. Field of view 2.5 mm across.

Thin beds of tuff also occur within graywacke-slate sequences (fig. 9). Two major andesite units, at least one of which appears to consist of subaerial flow units with columnar jointing, are present. Pillowed greenstones also occur at the base of and within the sequence.

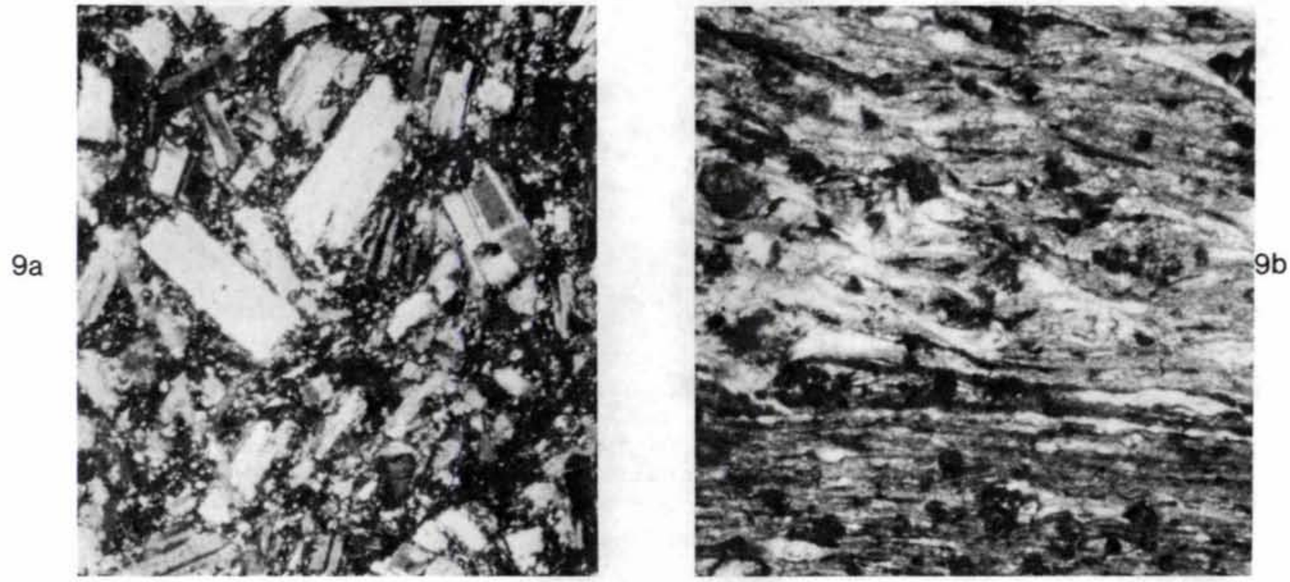


Figure 9. (a) Photomicrograph of plagioclase crystal tuff, eastern Vermilion district. Field of view is 2.5 mm across.

(b) Photomicrograph of possible vitric tuff. Note what may be ghosts of shards. Field of view about 1.25 mm across.

Graywacke and slate are the dominant lithologies in the Knife Lake Group. The graywacke is volcanogenic, but although similar in most respects to the dacitic graywacke of the Lake Vermilion Formation, the Knife Lake graywacke contains a mixture of different volcanic lithologies; rhyolite, dacite, andesite and basalt clasts are all present in varying amounts, with dacite dominant. Staining of thin section heels for K-feldspar is an aid in the identification of the volcanic lithologies. Figure 10 shows the variation in types of sand-sized volcanic grains in graywacke.

The Saganaga batholith at the east end of the district intruded into the volcanic-sedimentary pile and metamorphosed the older part of the pile. This high level pluton was rapidly unroofed, and shed detritus into younger portions of the pile while volcanism was continuing nearby. This distinctive plutonic tonalitic detritus is more visible in several conglomeratic units (fig. 11) in which it commonly makes up 5-12 percent of the pebbles, cobbles and boulders (McLimans, 1976). In two conglomeratic units, including a basal conglomerate which rests unconformably upon the Saganaga batholith, such clasts make up 50 to 100 percent of the total clasts. The conglomerate changes in texture basinward from the Saganaga batholith, over a distance of 10-12 kilometers, from massive and poorly sorted, to inverse and normally graded, to normally graded, to graded-stratified. In general, this fits the submarine fan model for resedimented conglomerate as described by Walker (1976).

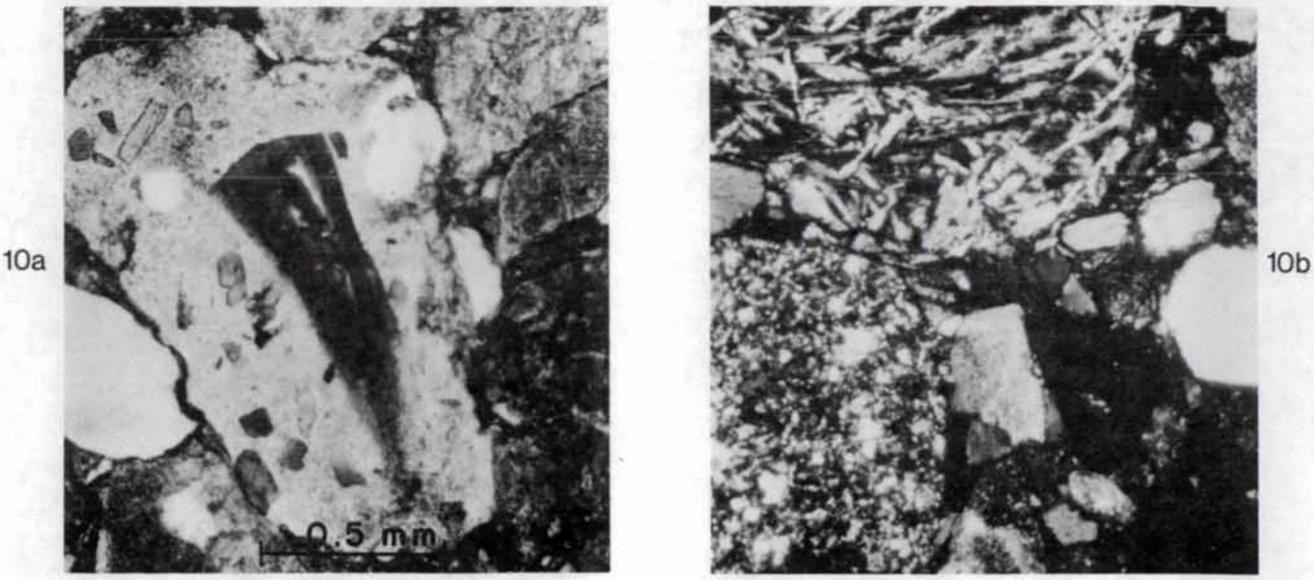


Figure 10. (a) Photomicrograph of volcanogenic graywacke, eastern Vermilion district. Basalt fragment at lower right, hornblende-quartz dacitic fragment at center, volcanic quartz at left center, and many small plagioclase crystals. Field of view 2.5 mm across.

(b) Photomicrograph of volcanogenic graywacke, eastern Vermilion district. Basalt fragment at top, dacite fragment at lower left, volcanic quartz at right, and many plagioclase crystals. Field of view 2.5 mm across.

Figure 11. Conglomerate, eastern Vermilion district. Pebbles of Saganaga tonalite at right and lower left, with large quartz "eyes." Other pebbles have a volcanic lithology.

Arkose consisting of tonalitic detritus is present above the tonalite-rich basal conglomerate. Massive (arkose?) beds as much as a few meters in thickness also occur interbedded with graywacke and slate in at least one structural segment; their origin has not yet been determined, but they may be grain-flow deposits.

Thus, although the sedimentary rocks of the Knife Lake Group are dominantly of mixed volcanogenic origin, a plutonic component was contributed by the Saganaga batholith. A generalized model for the concurrent volcanism, batholithic unroofing, and sedimentation which occurred near the Saganaga batholith is presented in Figure 12. Conglomerate was deposited in submarine channels. Graywacke was deposited by turbidity currents in interchannel areas of fans, in more distal portions of fans, and probably also at the base of the volcanic edifices even where fans were not present. Scatter in the few paleocurrent directions thus far measured in graywacke beds suggests derivation from various locations, perhaps from various volcanic islands, within the volcanic-sedimentary domain. Some sedimentary units are pyroclastic and some are reworked pyroclastic (volcaniclastic), but most are epiclastic, formed by the erosion of slightly older crystalline volcanic and lithified volcaniclastic rocks. Pelagic mud, probably consisting of fine volcanic ash and altered volcanic ash, was formed by steady fallout through the water column.

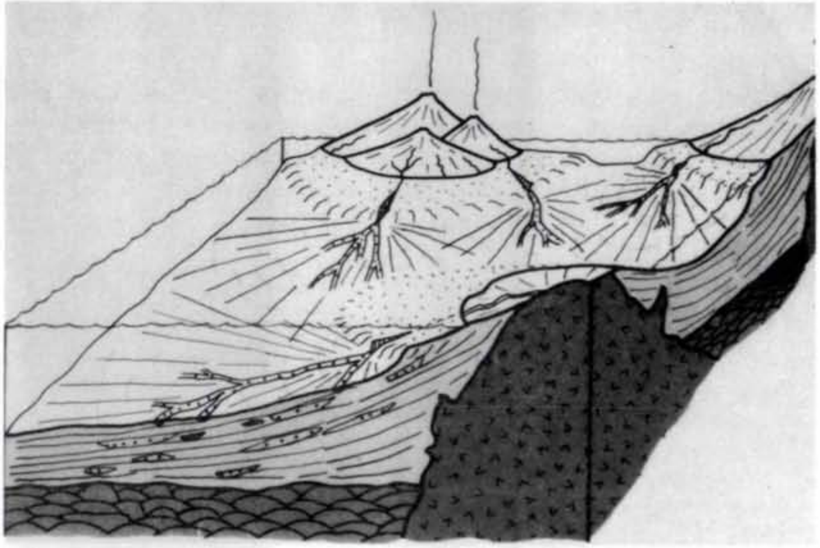


Figure 12. Generalized model showing erosion of volcanic islands (with batholiths) and deposition of detritus at bases of slopes by turbidity currents. Note channels on fans where conglomerates are localized. Note coeval erosion and volcanism.

SUMMARY

Generalized modes of some of the major sedimentary rock types of the Vermilion district are presented in Figure 13; they emphasize the general similarity of the composition of the Lake Vermilion Formation in the west and the Knife Lake group in the east.

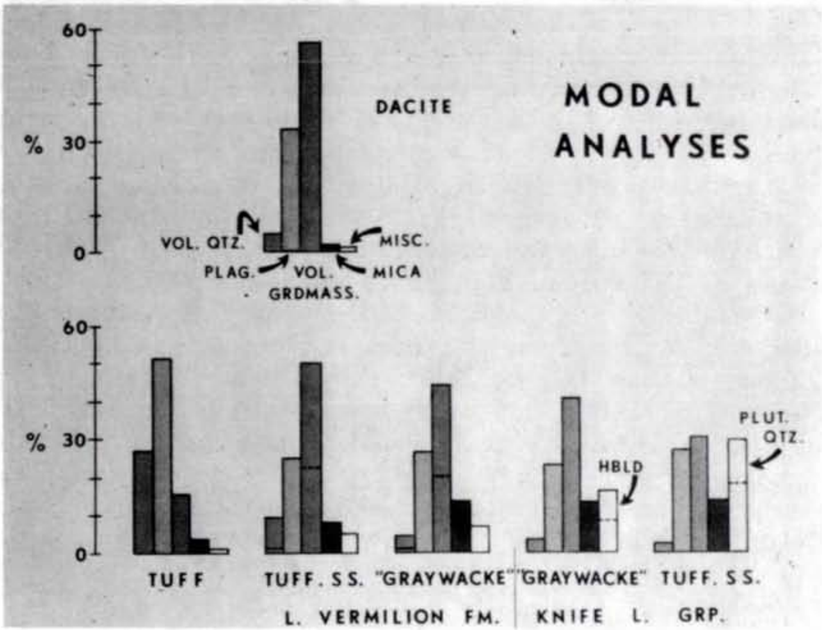


Figure 13. Modal analyses of representative dacite dike compared with averages of a few modes of each major lithology in western (Lake Vermilion Formation) and eastern (Knife Lake Group) Vermilion district. Tuffaceous sandstone of the Knife Lake Group is the "arkose" of the text.

DAY 1--RAINY LAKE GREENSTONE BELT AND VERMILION GRANITIC COMPLEX

D.L. Southwick, R.W. Ojakangas, and Robert L. Bauer

This road log starts at the intersection of U.S. Highway 53 and Minnesota Highway 11 near the center of International Falls, Minnesota (3rd Ave. and 4th St.) and terminates at Main Street and U.S. Highway 53 in Cook, Minnesota. The 11 stops on this segment of the field trip provide an opportunity to examine several of the major rock types and many of the structural attributes associated with the Minnesota extension of the Rainy Lake greenstone belt (Ojakangas, 1972c) and the Vermilion Granitic Complex of Southwick and Sims (in press). However not all of the stops can be visited in one day. Additional localities are included for those people who might want to examine the geology on subsequent visits.

Mileage	
0.0 [0.0]	Junction U.S. Highway 53 and Minnesota Highway 11. Proceed east on Highway 11.
1.4 [1.4]	Bridge.
1.2 [2.6]	Junction with Koochiching County Highway 20; turn left (north) to Ranier.
0.35 [2.95]	STOP 1. Metasedimentary rocks which Lawson (1913b) called the Coutchiching in the Rainy Lake area are present near both Fort Frances and International Falls. This exposure of metagraywacke (fine-grained biotite schist) is representative of the least metamorphosed parts of this unit. The best exposure has been a small knob just south of the municipal liquor establishment, but lichen growth in recent years has partially obscured the original sedimentary structures. The beds have an attitude of N. 45° E./80° NW. and display excellent grading with tops to the northwest. Lineations plunge to the north-northeast at 45-50°. Small-scale cross-bedding occurs locally in interbedded silty laminae and flame structures are visible in a few places. Although a few large detrital grains of quartz and plagioclase are present, these exposures consist dominantly of finely recrystallized plagioclase, with lesser amounts of quartz and biotite; garnet is rare. In general the rocks resemble coarser grained garnet- and staurolite-bearing biotite schists that crop out south of the greenstone belt. Return over same route.
0.35 [3.3]	Junction with Highway 11; turn left (east).

2.5 [5.8] Junction with Koochiching County Highways 20 and 109. Turn right (south) and follow highway 109.

0.6 [6.4] Sharp curve -- caution.

0.6 [7.0] STOP 2. This exposure of feldspathic quartzite is one of a number that form a discontinuous easterly-trending belt 16 km long and 0.8 km wide. The beds strike east-northeast, are nearly vertical, and plunge to the east at 3°-55°. Abundant cross-beds indicate that the unit tops to the south. The cross-bedding is partially obscured by shearing; it is best seen on the south side of the exposure about 30 m east of the road. The original clastic texture is commonly well preserved in spite of pervasive shearing. Quartz comprises 50 percent of the rock; other grains in the abundant sericitic matrix include felsic to intermediate volcanic rock fragments, plagioclase, felsic plutonic rock fragments, carbonate, pyrite and K-feldspar.

This rock type lies beneath about 180 m of coarse polymict conglomerate exposed on Neil Point, about 6.5 km to the east. The conglomeratic unit is characterized by granitic, volcanic and metasedimentary clasts within a clast-supported framework. Both the feldspathic quartzite and the conglomerate are equivalents of the Seine Conglomerate to the east-northeast in Canada in the same belt. Lawson (1913b) called these units Huronian and placed them at the core of a syncline. Grout (1925b) said they are located on the north flank of an anticline. Ojakangas (1972c) showed them to be part of a southward-facing fault block.

Continue south on Highway 109.

0.3 [7.3] Sharp turn to the left (east).

0.5 [7.8] Sharp turn to the left (north).

0.3 [8.1] Turn right and cross creek into the Fred Koch farm.

0.1 Parking area; proceed 75 m north to gate. Outcrops are 30 m east of gate in field. Additional outcrops visible some 100 m to the northeast. Obtain permission from owner before entering pasture.

STOP 3. Highly sheared, mafic metavolcanic rocks of the type displayed here occur in a narrow belt that strikes northeastward into Rainy Lake. At this particular locality, remnant thin beds are parallel to foliation and some possible remnants of highly elongated pillows may be present. The rocks consist mainly of chlorite-actinolite schist and actinolite schist, and exhibit evidence for several periods of deformation.

Return over same route toward International Falls.

2.5 [10.7]	Junction of Koochiching County Highway 109 with Minnesota 11. Turn left (west) and follow Highway 11.
2.4 [13.1]	Junction with Koochiching County Highway 20; continue straight ahead on Highway 11.
2.2 [15.3]	Junction with Koochiching County Highway 332 (truck by-pass around International Falls); turn left and follow Highway 332 south.
0.6 [15.9]	Stop sign; junction with 13th street; turn left (east) and follow Highway 332 south.
3.5 [19.4]	Junction with U.S. 53; turn left and follow U.S. 53 south.
5.7 [25.1]	Village of Ericsburg; continue south on U.S. 53.
5.8 [30.9]	Minnesota Department of Natural Resources fire tower on right (west); continue south on U.S. 53.
0.7 [31.6]	Railroad overpass.
1.6 [33.2]	Village of Ray; sharp corner at junction with Koochiching County Highway 217; continue east on U.S. 53.
7.1 [40.3]	"Gateway Store" and junction with St. Louis County Highway 122. Turn left (north) and follow Highway 122 toward Kabetogama Lake.
2.3 [42.6]	Junction with St. Louis County 123 (straight ahead): turn left (west) and stay on Highway 122.
3.3 [45.9]	"Y" in road at junction with St. Louis County Highway 902; continue straight ahead on Highway 902.
0.3 [46.2]	Paved road ends; continue on gravel road.
0.3 [46.5]	Highway 902 ends at junction with St. Louis County Highways 673 and 675; turn right and follow Highway 675 to Rocky Point Resort.
0.3 [46.8]	Follow driveway on left to Rocky Point Resort. Obtain permission from resort owners before examining outcrops.

0.1 STOP 4. Isoclinally folded biotite schist, locally with garnet and sillimanite, is cut by numerous layers of pegmatitic granite. The granitic layers tend to follow bedding and schistosity, but crosscutting relations are far from rare. The granitic layers have been flattened and folded in a deformational episode that followed the initial isoclinal folding of the host biotite schist. This outcrop is located in the broad transition zone between essentially granite-free biotite schist (to the north) and schist-rich migmatite of the Vermilion Granitic Complex (to the south).

Return over same route.

0.1 [47.0] Junction with Highway 675; turn right.

0.3 [47.3] Junction with Highway 902; turn left and follow Highway 902.

0.6 [47.9] Follow Highway 122 straight ahead.

3.3 [51.2] Stop sign; turn left and follow Highway 123.

0.2 [51.4] Turn left on gravel road to Tomahawk Resort.

0.1 [51.5] Tomahawk Resort; park and walk northwest along lakeshore to outcrops. Obtain permission from resort owners before crossing property.

STOP 5. Outcrops in and north of Tomahawk Resort are schist-rich migmatite of the Vermilion Granitic Complex. This outcrop is similar to the previous one except that the proportion of granite is greater, the granite layers are thicker, and less of the granite is pegmatitic. Schist-rich migmatite is defined as containing 25-75 percent schistose paleosome and possessing a distinct layered structure. It crops out extensively along the shores of Kabetogama and Namakan Lakes (to the east) and is transitional to more granite-rich phases of the Vermilion Granitic Complex that lie to the south.

Return over same route.

0.2 [51.7] Junction; turn right and follow Highway 123.

0.1 [51.8] Junction; follow highway 122 straight ahead.

0.1 [51.9] STOP 6. A large multiple dike of somewhat altered quartzose hornblende gabbro and diorite is exposed in these road cuts.

The chilled margin of the dike against migmatite of the Vermilion Granitic Complex can be seen a few meters into the woods at the south end of the outcrop. The central part of the dike is lighter in color and finer in grain size than the outer parts. It appears that a dike of hornblende gabbro was emplaced first, and then split more or less down the middle to admit a second batch of more dioritic magma. This dike is one of an extensive swarm that trends northwestward from this area to Kenora, Ontario, and beyond. Dikes from the swarm have been dated at 2,200 m.y. by Hanson and Malhotra (1971).

Continue straight ahead on Highway 122.

1.6 [53.5] STOP 7. Roadside outcrop of granite-rich migmatite of the Vermilion Granitic Complex. This outcrop is dominantly granite with vague, extensively assimilated inclusions. Regionally the inclusions make up about 5 to 25 percent of the total rock and vary somewhat in degree of assimilation; this outcrop is atypical in its higher than normal inclusion content and the modal uniformity of the inclusions. Many inclusions throughout the area were biotite schist originally, and others were trondhjemite, tonalite, or granodiorite. Where assimilation has been extensive, as in this outcrop, it is virtually impossible to identify the protolith of the inclusions.

Continue straight ahead on Highway 122.

0.7 [54.2] "Gateway Store" at junction with U.S. 53. Turn left (east) and follow U.S. 53 south.

2.9 [57.1] Junction with St. Louis County Highway 765 (Ash River Trail); turn left (east).

0.8 [57.9] STOP 8. Granite-rich migmatite, consisting of 5 to 10 percent inclusions in modally uniform, faintly gneissic granite, crops out just north of the Ash River Trail. Numerous indefinitely bounded lenses and layers of pegmatite occur here, and are typical of granite-rich migmatite in the Vermilion Granitic Complex.

Continue on Highway 765.

4.5 [62.4] Sharp turn to the left (north); continue on Highway 765.

0.6 [63.0] Paved road starts.

3.4 [66.4] Ash Trail Lodge. Park and walk along indistinct trail (starting by north side of green cabin) to top of hill at base of microwave-radio-relay. Obtain permission from cabin owners if cabin is occupied.

STOP 9. This large knob of Lac La Croix Granite (Vermilion Granite of Grout, 1923) is part of a crescent-shaped body that occupies the hinge area of a large, east-plunging fold. It contains no more than 5 percent inclusions, several of which are well displayed near the microwave tower, and also has pegmatitic lenses. This is about as homogeneous as the Lac La Croix Granite gets in the northwest part of the Vermilion Granitic Complex. Almost perfectly uniform granite crops out some 50 km to the southeast, well beyond the itinerary of this field trip. The hilly vista to the southeast is typical of terrain underlain by the Vermilion Granitic Complex.

Return over same route.

9.3 [75.7] Junction with U.S. 53. turn left (south) and follow U.S. 53 (to Virginia).

22.0 [97.7] Village of Cusson.

3.0 [100.7] Junction with St. Louis County Highway 677 (Moose Lake Road). Turn left onto Highway 677 and park.

STOP 10. WATCH OUT FOR TRAFFIC! TRUCKS TRAVEL AT HIGH SPEED AROUND THIS CURVE! This is a complex exposure that summarizes the relations among several rock types in the Vermilion Granitic Complex. The oldest rocks are compact, dark-gray biotite-quartz-plagioclase granofels and schist that are approximately time-equivalent to better foliated schists farther north. These metasedimentary rocks are intruded by somewhat gneissic gray quartz diorite, which in turn is cut by pinkish-gray granite and associated pegmatite. The pink granite is equivalent to the granite and granitic migmatite seen at Stops 7, 8 and 9. Trondhjemite, quartz diorite, and granodiorite older than the pink granite occur sporadically throughout the complex, but form such small, highly segmented bodies within migmatitic belts that they cannot be portrayed separately on regional-scale maps.

Return to U.S. 53, turn left and continue south.

1.1 [101.8] City of Orr; 30-mile zone; continue south on U.S. 53.

0.5 [102.3] End 30-mile zone; continue south on U.S. 53.

8.4 [110.7] Junction with Minnesota Highway 73 (to Chisholm); continue south on U.S. 53.

6.2 [116.9] Junction with Minnesota Highway 1; turn left (east) and follow Highway 1.

1.1 Stop sign at railroad tracks; continue straight ahead.

[118.0]

0.5 [118.5] Stop sign; turn left and follow St. Louis County Highway 24 north.

0.6 [119.1] "Y" intersection; follow Highway 24 (paved road) to the right (east).

1.9 [121.0] Junction with St. Louis County Highway 78; follow Highway 24 straight ahead (east).

6.9 [127.9] Paved road ends; follow gravel road (Highway 24) east.

6.7 [134.6] Unmarked logging road to the right (south).

STOP 11. Biotite-hornblende schist on south flank of Vermilion Granitic Complex. The biotite-hornblende schist in this area has undergone three periods of folding, and minor folds from all three phases are evident at this stop. The F_1 folds are tight to isoclinal with axial traces parallel to the dominant foliation (S_1) in the schist. This outcrop is on the northwest limb of a major northerly-plunging F_2 antiform, and several minor F_2 folds with Z symmetry and a weak axial plane foliation are present here. The major F_2 structure has been broadly folded by F_3 into an open westward-plunging antiform. Minor F_3 folds in this area have Z symmetry and commonly have sheared short limbs, but no axial plane foliation.

Continue east on Highway 24.

0.3 [134.9] Turn right at "Life of Riley Resort" sign.

0.5 [135.4] "Y" intersection; continue left to Life of Riley Resort.

0.4 [135.8] Life of Riley Resort. Obtain permission of resort owners before examining outcrops.

STOP 12: Outcrops of metalamprophyre may be found along peninsula on the west side of the resort complex. This is one of the few readily accessible exposures of lamprophyre in the Vermilion Granitic Complex. It has been metamorphosed to amphibolite-facies grade and contains assemblages of hornblende, plagioclase, and microcline; various combinations and proportions of quartz, epidote, and biotite also may be present. The hornblende rarely contains cores of clinopyroxene. The lamprophyre is commonly schistose parallel to the dominant foliation (S_1) in the biotite-hornblende schist at Stop 11.

Return over same route.

0.9 [136.7]	Junction; turn left and follow Highway 24 west.
16.5 [153.2]	Junction with Highway 1; continue straight ahead on Highway 24 toward Cook.
0.4 [153.6]	City of Cook; turn right and cross railroad tracks.
0.3 [153.9]	Turn left and follow Main Street.
0.2 [154.1]	Stop sign is at intersection with U.S. highway 53.

End of Day 1.

DAY 2 -- VERMILION GREENSTONE BELT

D.L. Southwick and R.W. Ojakangas

This road log starts at Holiday Inn in Eveleth, Minnesota and ends at the junction of highways 1 and 169 about four miles southwest of Tower, Minnesota. The 12 stops on this segment of the field trip provide an opportunity to examine rock types and structural attributes associated with the western part of the Vermilion greenstone belt, an Archean terrane that comprises the southern part of the exposed Superior province of the Canadian Shield.

Mileage	
0.0 [0.0]	Intersection of Holiday Inn driveway and frontage road; turn right onto frontage road and proceed south.
0.3 [0.3]	Stop sign; turn left (east) and right (south) onto U.S. Highway 53.
0.1 [0.4]	Follow right lane exit to Minnesota Highway 37 to Eveleth and Gilbert.
0.4 [0.8]	Stop sign; turn left (east) and follow Highway 37 to Gilbert.
1.9 [2.7]	Junction with St. Louis County Highway 97 to Sparta; continue east on Highway 37.
0.6 [3.3]	Gilbert city limits; 30-mile zone; continue east on Highway 37.
1.2 [4.5]	Junction with Minnesota Highway 135 and Highway 37; continue east on Highway 135 to Biwabik.
0.1 [4.6]	End 30-mile zone.
2.7 [7.3]	Junction with St. Louis County Highway 20 to McKinley; continue east on Highway 135.
4.1 [11.4]	Biwabik city limits; start 30-mile zone; continue east on Highway 135.
0.2 [11.6]	Stop-and-go lights; continue east on Highway 135.
0.3 [11.9]	Stop-and-go lights; continue east on Highway 135.
0.1 [12.0]	End 30-mile zone; continue east on Highway 135.
3.6 [15.6]	Aurora city limits; start 40-mile zone.

0.1 [15.7] Junction; turn left (north) and follow Highway 135 to Tower.

5.2 [20.9] Outcrop on left (north) side on Highway 135.

STOP 1. Giants Range batholith: The Giants Range batholith in this area consists dominantly of coarse-grained, hornblende- or biotite-bearing granodiorite characterized by pink or red, oblong, euhedral grains of microcline and elongate prisms of hornblende. Regional geologic relationships suggest that this phase of the batholith is post-tectonic in age and that it truncates the regional structure in adjacent metasedimentary and metavolcanic rocks. The rocks at this locality exhibit a steep primary foliation that is discordant to the regional structure, but concordant with the structure in adjacent wall rocks that crop out nearby. The Archean rocks are overlain immediately to the south by strata of the Animikie Group of Proterozoic age.

Continue east on Highway 135.

3.1 [24.0] Embarrass River.

2.5 [26.5] Junction with St. Louis County Highway 21; turn ~~left~~ right (east) and follow Highway 21 to Babbitt.

2.4 [28.9] Embarrass city limits; start 30-mile zone; continue on Highway 21.

1.2 [30.1] End 30-mile zone.

3.9 [34.0] STOP 2. Coarse-grained, amphibolitic and biotitic gneisses intruded and locally migmatitized by medium-grained orthogneiss of leucotrondjemitic composition. The amphibolitic and biotitic gneisses are foliated parallel to lithologic layering and are characterized by extensive boudinage and local small-scale folds; long directions of the boudins and the axial traces of the small-scale folds parallel the dominant foliation. The leucotrondhjemite commonly occurs as tabular bodies several centimeters to several meters thick that cut the layering at an oblique angle. If followed far enough, the sill-like bodies branch and swell into pod-like masses.

The leucotrondhjemite lacks relict igneous textures and is foliated parallel to layering in the paleosome, but regional relationships indicate a magmatic origin. Many of the sill-like bodies are folded, a fact implying that the leucotrondhjemite was intruded early in the tectonic history of the greenstone belt and prior to emplacement of the granodioritic rocks seen at Stop 1.

Continue east on Highway 21.

6.1 [40.1] Junction with St. Louis County Highway 698; continue east on Highway 21.

2.6 [42.7] Junction with St. Louis County Highway 70 to Babbitt (straight ahead); turn left (north) and follow Highway 21 toward Ely.

13.2 [55.9] Junction; turn left (west) into Harry Homer Lumber Company driveway. Obtain permission at office before examining outcrop.

STOP 3. Pillowed metabasalt of the ~~Lower~~ upper member of the Ely Greenstone is beautifully displayed in a glacially polished outcrop in the lumberyard. The pillows have been flattened tectonically but are exceptionally well preserved.

Return to Highway 21 and continue north to Ely.

1.3 [57.2] Ely city limits; 30-mile zone; continue north on Highway 21 (Central Ave).

0.9 [58.1] Junction with Minnesota Highways 169 and 1 (Sheridan Street); turn right (east) and follow Highways 169 and 1 through Ely.

1.1 [59.2] Junction with Minnesota Highway 1 to Isabella and Illgen City; continue east on Highway 169 to Winton.

0.6 [59.8] Voyageur Vistor Center on right; continue east on Highway 169.

0.3 [60.1] Junction with St. Louis County Highway 88; continue east on Highway 169.

0.8 [60.9] Junction with Section 30 Road; continue east on Highway 169.

0.85 [61.75] Shagawa River.

.05 [61.8] Village of Winton; junction with St. Louis County Highway 177.

0.3 [62.1] Water tower on left. Proceed past water tower, turn left on next street, go 1 block to end of street, turn left; go past water tower to fork in road near tower; follow right fork and park; walk to outcrops near base of tower.

STOP 4. This is one of the readily accessible, large exposures of strata assigned to the Knife Lake Group. The exposure consists of phyllitic metasedimentary rocks that are representative of one rock type within a highly variable unit. It can be seen here that shearing is pervasive, bedding is indistinct, and late-stage kink banding is common. Foliation trends to the northeast.

Return to fork, turn left, and follow gravel road to the southwest.

0.4 [62.5] Railroad tracks; turn right before crossing tracks.

2.8 [65.3] Intersection with private road on right.

STOP 5. These low-lying exposures of serpentinized peridotite within the mafic member of the Newton Lake Formation are part of a northeast-trending, 330-meter-thick and several-kilometer long differentiated sill that is dominantly composed of diabasic gabbro. Where they may be observed in their entirety, the sills of this type typically grade upward from serpentinized peridotite to pyroxenite to coarse-grained hypersthene gabbro to diabasic gabbro to quartz gabbro.

At this locality serpentinized peridotite is exposed within 60 meters of the intersection on the northwest side of the main gravel road, whereas the first outcrops on the private road are hypersthene gabbro. Succeeding outcrops along the private road are diabasic gabbro and quartz-bearing diabasic gabbro. Pillowed lavas also assigned to the mafic member of the Newton Lake Formation are exposed about 280 meters down the private road on both sides of a sharp bend on the crest of a small hill.

Return over same route.

2.8 [68.1] Intersection at railroad tracks; turn right (southwest) and follow gravel road.

1.0 [69.1] Junction with St. Louis County Highway 88. Turn left (south).

1.2 [70.3] Junction with Minnesota Highways 169 and 1; turn right (west) and return to Ely.

2.0 [72.3] Junction with St. Louis County Highway 21; continue straight ahead.

0.4 [72.7] Ely city limits; end 30-mile zone.

0.2 [72.9] STOP 6. Pillowed metabasalt that is typical of the ~~lower~~ upper member of the Ely Greenstone is exposed in the roadcut on the north side of the highway. The pillows have smoothly rounded tops, nearly flat bases, and are somewhat drawn out in vertical dimension. The chilled rinds are as much as several centimeters thick. The pillow structures strike approximately north-northeast, dip steeply south, and face southeast; the long dimension of the pillows is subparallel to the intersection of cleavage and bedding and plunges steeply to the northeast.

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

Continue west on Highways 169 and 1.

11.2 [84.1] Junction with St. Louis County Highway 408 (Mud Creek Road); continue west on Highways 169 and 1.

3.3 [87.4] Turn right (north) onto abandoned road and park.

STOP 7. The Soudan Iron-formation Member of the Ely Greenstone and a crosscutting dike of dacite porphyry are exposed at this locality. The iron-formation consists of thin to thick beds of black, red, and white chert, intercalated with black argillaceous beds having abundant pyrite-rich stringers and pods. Hence, both the oxide and sulfide facies of the iron-formation are represented here. Mafic volcanic rocks associated with the iron-formation are exposed in roadcuts to the east, and both they and the iron-formation are cut by a dacite porphyry dike. There are numerous such dikes and sills in this area; they apparently were feeders for the felsic pyroclastic rocks and flows of the Lake Vermilion Formation, which overlies the Ely Greenstone.

Continue west along abandoned road.

0.6 [88.0] Narrow driveway to the right (north).

STOP 8. Cherty, oxide facies iron-formation, felsic tuff, felsite porphyry, felsic tuff breccia, pillowed greenstone, and mixed mafic and felsic breccia all are exposed on a hill located approximately 300 feet north of the intersection of the abandoned road and driveway. The beds strike east-west, dip vertically, and become younger to the north. The 15-meter-thick layer of felsic rock at the top of the hill is chiefly intrusive porphyry. North of it is a 20-meter-thick layer of iron-formation that is overlain by pillowed greenstone. Tuffaceous rocks crop out down the steep slope to the north. Complex stratigraphy involving both felsic and mafic volcanic rocks together with ferruginous chert is typical of the Soudan Iron-formation Member in this area.

Continue west along abandoned road.

1.1 [89.1] Turn left (east) onto dirt track into woods.

0.1 [89.2] Large open area.

STOP 9. Although the greater part of the Ely Greenstone in the Tower-Soudan area is massive amygdaloidal basalt, important quantities of tuff, volcanogenic breccia, and cherty iron-formation occur locally. The outcrops in this clearing illustrate some of these lithologies. Massive, medium- to coarse-grained metadiabase crops out at the utility pole and along the low ridge to the east. It is probably a sill. The outcrop in the northwest corner of the clearing is well-cleaved mafic tuff and tuff breccia. The same rock is in contact with a thin unit of cherty iron-formation in exposures behind the old foundations at the east edge of the clearing. Massive amygdaloidal basalt crops out just south of the tuff and iron-formation, and is exposed in the highway cuts. South of the highway there are scattered outcrops of massive metabasalt, pillowed metabasalt, and pillow breccia.

Follow dirt road straight ahead (south).

0.2 [89.4]	Junction with Highways 169 and 1; turn right (west) and follow Highways 169 and 1 to Soudan.
2.2 [91.6]	Soudan city limits; 30-mile zone.
0.1 [91.7]	Turn right (northwest) into Soudan.
0.5 [92.2]	Street ends; turn right (north) and go up the hill toward the headframe at Tower-Soudan State Park.
0.2 [92.4]	Junction; Tower Soudan State Park headframe and other facilities straight ahead; turn right (north) and follow gravel road toward Stuntz Bay on Lake Vermilion.
0.05 [92.45]	Crest of Soudan Hill.

STOP 10. Soudan Iron-formation of the type locality is exposed on right (east) side of road. (No hammering, please!). This classical exposure of iron-formation is characterized by numerous folds of at least two generations. Most of the more obvious folds are a result of regional deformation. They plunge east at steep angles. An earlier set of folds, which can be seen in places, may be the result of an earlier period of regional deformation, but may be the result of soft-sediment deformation. Joints and faults related to a third deformation cross the folds.

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 the Tower-Soudan State Park.

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 2.25 million tons. The high cost of mining and the preference of blast furnace operators for taconite pellets rather than for high-grade lump ore caused it to close.

Return over same route.

0.4 [92.85] Street ends; turn right (west).

0.4 [93.25] Junction; turn left (south).

0.3 [93.55] Junction with Minnesota Highways 169 and 1; turn right (west) toward Tower.

1.0 [94.55] Tower city limits; 30-mile zone.

0.7 [95.25] Junction with Minnesota Highway 135 to Aurora; continue west on Highways 169 and 1 toward Virginia and Cook.

0.1 [95.35] End 30-mile zone; continue west on Highways 169 and 1.

1.7 [97.05] STOP 11. This large roadcut of very light gray, medium-grained volcanic sandstone was originally mapped as the feldspathic quartzite member of the Lake Vermilion Formation. The field term, "feldspathic quartzite," was unfortunate, for subsequent studies have shown that this rock type is a slightly reworked dacitic tuff. Note the quartz "eyes" that are smaller than those in the dacite tuff and dacite porphyry seen at Stops 7 and 8. Although the rock is generally structureless, faint bedding and lamination are visible on the outcrop, and some sericitic phyllite (originally fine-grained tuff?) beds are present. At the east end of the south cut, felsic volcanic rock fragments as much as a few centimeters in diameter are present.

The 6-meter-thick dike of diabasic gabbro at the west end of the south cut has a minimum age of 1,570 m.y., and similar dikes a few kilometers away have apparent ages of 1,520 m.y. and 1,685 m.y. (Hanson and Malhotra, 1971). The dike has narrow chilled borders and contains some inclusions of volcanic sandstone.

Continue west on Highways 169 and 1.

0.6 [97.65] STOP 12. Highly folded biotite-bearing metagraywacke and slate of the metagraywacke-slate member of the Lake Vermilion Formation. (No hammering, please!) Note the excellent graded bedding. Some geologists have speculated that much of the folding resulted from penecontemporaneous soft-sediment deformation as indicated by small clastic dikes cutting the beds. However, the major deformation can be 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.

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

(D) Folding is similar in trend and style to that observed in the Soudan Iron-formation Member at Stop 10, which also is on a major fold axis.

(E) Trends of the numerous fold axes fit the regional structural pattern as defined by Hooper and Ojakangas, (1971). A third deformation is marked by faults, joints, and kink bands that cut transversely across the folds.

Continue west on Highways 169 and 1.

1.8 [99.45] Junction with St. Louis County Highway 77; continue straight ahead on Highways 169 and 1.

0.1 [99.55] Junction with Highway 1 to Cook; follow Highway 169 toward Virginia.

End of Day 2.

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