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Part 2. Field Trip Guidebook

- Trip 1. North Shore Rhyolites, Minnesota**
- Trip 2. Penokean Structural Terranes
in East-Central Minnesota**
- Trip 3. Mellen Complex, Wisconsin**
- Trip 4. Archean Gold Occurrences and Their
Structural Settings**



35th Annual Meeting
May 3-6, 1989
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FIELD TRIP GUIDEBOOK
THIRTY-FIFTH ANNUAL MEETING
INSTITUTE ON LAKE SUPERIOR GEOLOGY
MAY 3-6, 1989
DULUTH, MINNESOTA

Trip 1: North Shore Rhyolites, Minnesota

Leader: J. C. Green
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Trip 2: Penokean Structural Terranes in East-Central Minnesota

Leader: T. B. Holst
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Cover: Anticline in the early Proterozoic Thomson Formation at
Thomson Dam, view from the east bank of the St. Louis River,
just south of the highway bridge, looking west.

Drawing by Wendell Wilson.

TABLE OF CONTENTS

FIELD TRIP 1

Large rhyolites of the Keweenawan North Shore Volcanic Group

J.C. Green.....A1 - A15

FIELD TRIP 2

Penokean structural terranes in east-central Minnesota

T.B. Holst.....B1 - B17

FIELD TRIP 3

Rock Types and relationships of the Mellen Igneous Complex

K.W. Klewin, J.F. Olmsted, and K.E. Seifert.....C1 - C15

FIELD TRIP 4

General geology and structure of Archean rocks of the Virginia

Horn Area, Northeastern Minnesota

J.L. Welsh, D.L. England, D.A. Groves, and

E. Levy.....D1 - D13

Archean gold occurrences and their structural settings:

western and central Vermilion district

D.L. Southwick, P.J. Hudleston, R.L. Bauer, and

W. Ulland.....D14 - D24

FIELD TRIP #1

LARGE RHYOLITES OF THE KEWEENAWAN NORTH SHORE VOLCANIC GROUP

Leader: John C. Green
Geology Department, University of Minnesota, Duluth

INTRODUCTION

The North Shore Volcanic Group (NSVG, Fig. 1), one of the products of the great Midcontinent Rift of North America (Wold and Hinze, 1982; Green, 1983; Van Schmus and Hinze, 1985), contains a wide variety of compositions of plateau lavas (BVSP, 1981; Green, 1982a). These range from the predominant olivine tholeiites through transitional basalts, basaltic andesites, andesites and ferroandesites to icelandites and rhyolites (Fig. 2). Felsic rocks (icelandites and rhyolites) are unusually abundant compared to other Keweenawan plateaus (e. g. Portage Lake Volcanics, Mamainse Point Volcanics, Osler Group, Michipicoten Island, etc.) and younger plateau provinces world-wide; they constitute about 10% of the southwest limb (the section from Duluth to Tofte) and about 25% of the northeast limb (Lutsen to Grand Portage), as measured by stratigraphic thickness along the lakeshore (Tables 1 & 2).

Airfall ash and pumice make up a very small percentage of these felsic units, but their rarity is probably exaggerated somewhat by their relative susceptibility to erosion and thus their lack of exposure. Small lava flows make up a small portion of the felsic rocks, but the great bulk consist of thick units, several of which can be traced for long distances.

It is well understood that magma viscosity depends principally on temperature and composition; felsic magmas are predictably many orders of magnitude more viscous than basaltic magmas at equivalent stages of crystallization. The most common perception and expectation for rhyolites is that they will erupt as either domes or thick, short (high aspect-ratio) flows, or as ash or pumice falls or pyroclastic flows, in which the viscous fluid has been blown apart by its rapidly vesiculating and expanding volatiles. Submarine and thinner subaerial ignimbrites are typically unwelded, whereas thicker subaerial units have a central welded zone (e. g. Ross and Smith, 1961; Fisher and Schmincke, 1984; Cas and Wright, 1987).

Table 3 (from Henry and others, 1988) summarizes the characteristics typical of pyroclastic flows as contrasted with lava flows and remobilized ash flows (rheoignimbrites).

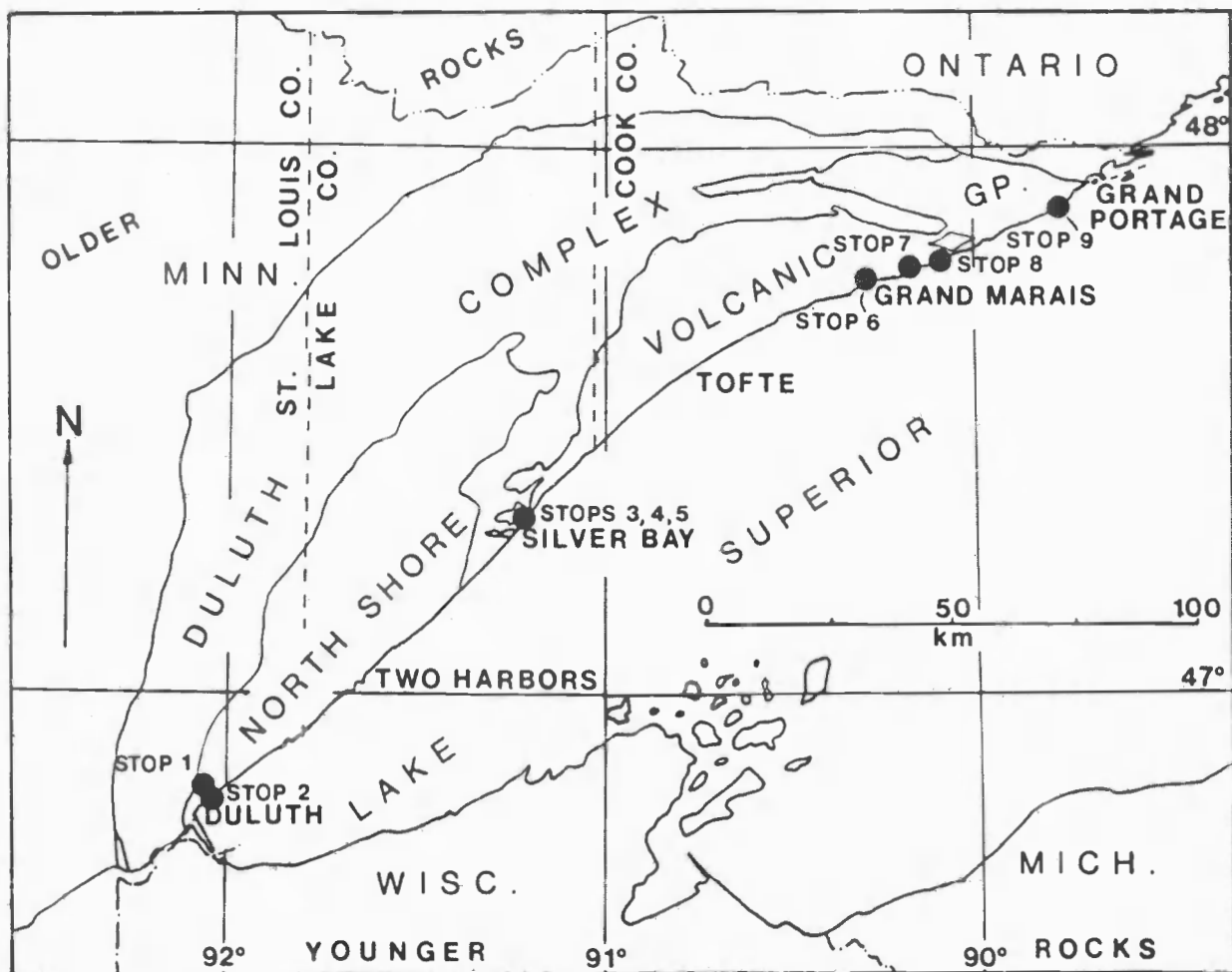


Fig. 1. Generalized geologic map of western Lake Superior area, showing the North Shore Volcanic Group (NSVG) and field trip stops.

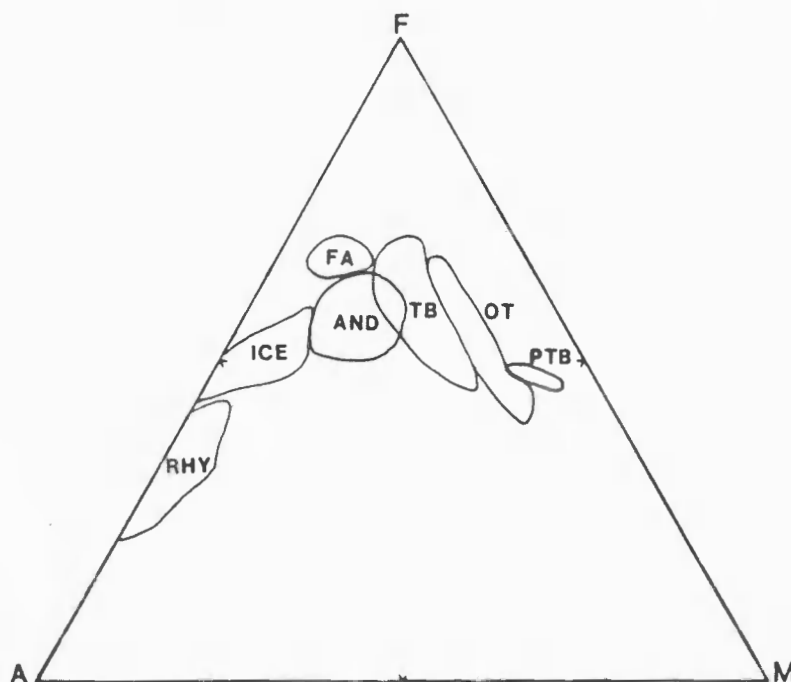


Fig. 2. Alkalies-Iron-Silica diagram for the NSVG showing fields of rhyolites (RHY), icelandites (ICE), andesites (AND), ferroandesites (FA), transitional basalts (TB), olivine tholeiites (OT), and augite-porphyrritic transitional basalts (PTB).

Table 1. Generalized volcanic stratigraphy of the southwest limb (Duluth to Tofte), NSVG. From Green, 1979.

Approx. thickness (m)	Lithostratigraphic unit	Lithic character
Top	Middle Keweenawan	
1200	Schroeder basalts	amygdaloidal ophitic olivine tholeiites
>90	Manitou trachybasalt flow (more of the Schroeder basalts)	red-brown granular trachybasalt to basalt
>170	Belmore Bay lavas	mostly quartz tholeiites, other basalts
>90	Palisade rhyolite flow	gray to pink, porphyritic rhyolite
>200	Baptism River lavas	mixed lavas, mostly basalts, one felsite
	Beaver Bay intrusive complex	
1000	Gooseberry River basalts	mixed basalts, one felsite
	Lafayette Bluff, Silver Creek Cliff intrusions	
315	Two Harbors fine-grained basalts	"melaphyres," some quartz tholeiites
550	Larsmont ophitic basalts	amygdaloidal ophitic olivine tholeiites
	Stony Point-Knife Island diabase intrusion	
1500	Sucker River basalts	mixed basalts, mostly ophitic
1350	Lakewood basalts	mixed basalts and andesites, some felsites
	Lester River diabase sill	
1100	Lakeside lavas	mixed basalts, andesites, felsites
	Endion diabase sill	
785	Leif Ericson Park lavas	mixed basalts, andesites
	Duluth Complex	
	Lower Keweenawan	
370	Ely's Peak basalts	porphyritic, diabasic, and ophitic basalts
8720	Total	
Base	Nopeming Sandstone	quartz sandstone
	----- Angular unconformity -----	
	Middle Precambrian	
	Thomson Formation	slate and graywacke

Table 2. Generalized volcanic stratigraphy of the northeast limb (Lutsen to Grand Portage), NSVG. From Green, 1979.

Approx. thickness (m)	Lithostratigraphic unit	Lithic character
Top	Middle Keweenawan	
310	Lutsen basalts	Olivine basalts, olivine tholeiites
50	Terrace Point basalt flow	Thomsonite-bearing ophitic basalt
95	Good Harbor Bay andesites	Brown, porphyritic andesite, trachyandesite
110	Breakwater trachybasalt flow or sill	Brown, columnar, granular trachybasalt
155	Grand Marais felsites	Pink, red, gray porphyritic rhyolite and felsite
185	Croftville basalts and andesites	Various fine-grained basalts and basaltic andesites
310	Devil Track felsites	Aphyric and porphyritic rhyolite flows
120-275	Red Cliff basalts	Amygdaloidal, ophitic olivine basalts
400	Kimball Creek felsites	Pink to tan, porphyritic felsites, icelandites
550	Marr Island lavas	Mixed tholeiitic basalt, andesites, felsites
310	Naniboujou basalts	Granular-diabasic basalts
1070	Brule River rhyolites	Pink to gray porphyritic rhyolite
	Hovland diabase complex	
	Lower Keweenawan	
1225 (est.)	Hovland lavas	Mixed porphyritic basalt, trachybasalt, andesite, rhyolite
	Reservation River diabase complex (Middle Keweenawan)	
610	Red Rock rhyolite flow	Red, porphyritic rhyolite
80	Deronda Bay andesite flow	Gray-brown, aphyric andesite
1380	Grand Portage basalts	Mixed tholeiitic basalts; porphyritic basalts locally at base
7220	Total flows	
Base	----- Disconformity -----	
	Puckwunge Formation	Cross-bedded quartz sandstone
	----- Disconformity -----	
	Middle Precambrian	
	Rove Formation	Shale and graywacke

TABLE 3. CHARACTERISTICS COMMONLY USED TO DISCRIMINATE
RHYOLITE LAVAS FROM IGNIMBRITES
(FROM HENRY ET AL., 1988)

Common in conventional ignimbrites	Common in rhyolite lavas and in rheoignimbrites
Fiamme	Flow banding
Eutaxitic texture	Ramp structures
Abundant lithic fragments	Elongated vesicles
Nonwelded tops, bottoms, sides	Autobreccias
Gradual thinning at edges of units	Vitrophyres at or near tops
Wide areal extent of individual units	Lengths generally much <20 km.*
Low aspect ratio	High aspect ratio*
Glass shards in thin section	
Broken pheno's, different sizes	
Gas elutriation pipes	

*Unlike rhyolite lava flows, rheoignimbrites may have dimensions similar to those of other ignimbrites

Recently, many rhyolites have been described which show anomalous behavior according to these models. These may cover wide areas with low aspect ratios, indicating high mobility, yet do not show some of the common features of ash-flow tuffs. For some, high alkali content (peralkalinity) appears to have been a factor in lowering the viscosity (e. g. Price and others, 1986). For others, a high eruptive temperature and high rate of effusion appear to have been important contributors; an increase of 100 degrees C. will lower the viscosity about an order of magnitude (Ekren and others, 1984; Bonnicksen and Kauffman, 1987). A relatively low SiO₂ content seems to be common to many high-mobility flows. A survey of widespread lavas and lava-like units in southwest Idaho and trans-Pecos Texas (Bonnicksen and Kauffman, 1987 and Henry and others, 1988) shows volatile-free SiO₂ contents in the range 68 to 74%, whereas rheoignimbrites in the same areas have SiO₂ values of 72 to 77%. Many ash flows, made of hot, relatively low-viscosity froth particles, reconsolidate during and after emplacement to form a devolatilized, "reconstituted lava" that can flow en masse (a rheoignimbrite). This flowage, and any subsequent crystallization or devitrification, can obliterate primary pyroclastic textures. Thus the distinction between the end result of an explosive eruption and an effusive eruption can become greatly diminished. Bonnicksen and Kauffman (1987) and Bonnicksen and others (1988) have suggested some criteria by which they may be recognized, but they and others, notably Henry et al. (1988), have described widespread, low-aspect-ratio units whose origin is still unclear.

The felsic units in the NSVG show evidence of a wide variety of eruptive and emplacement styles, including large, problematical, low-aspect-ratio flows. This field trip will examine several units throughout the NSVG section and the physical evidence for their mode of emplacement. It is designed as a long one-day trip, starting at Duluth and nearly reaching Grand Portage before returning to Duluth. Descriptions of field trip stops in other lithologies of the North Shore (mainly the plateau basalts) can be found in Green, 1979 and 1987, and a discussion of the physical volcanology of the NSVG appears in Green, 1989. A regional (1:250,000) geologic map is also available (Green, 1982b).

Chemical analyses of these felsite units are presented in Table 4.

Table 4. Chemical analyses of felsic volcanic units at field trip stops, recalculated volatile-free.

	A	B	C	D	E	F	G	H	I	J
SiO ₂	75.11	75.41	68.30	75.46	74.85	73.08	69.92	63.81	62.07	72.54
TiO ₂	.28	.22	.70	.24	.40	.40	.53	1.11	.99	.25
Al ₂ O ₃	12.45	11.99	12.76	11.10	11.62	11.76	12.52	12.24	15.09	12.02
Fe ₂ O ₃	1.58	.84	1.61	1.66	.92	3.13	4.09	8.34	2.79	2.51
FeO	1.25	3.04	5.79	2.95	3.33	.74	1.63	2.06	6.00	3.64
MnO	.03	.01	.09	.05	.04	.04	.10	.12	.18	.05
MgO	.06	.07	.27	.30	.60	.54	.51	1.43	.88	.21
CaO	.32	.30	1.95	.51	.88	.51	.51	2.26	3.67	.71
Na ₂ O	3.28	2.13	2.69	1.96	2.22	3.54	3.43	4.12	3.77	3.86
K ₂ O	5.59	5.92	5.68	5.72	5.09	5.50	5.37	4.23	4.04	4.15
P ₂ O ₅	.02	.01	.08	.04	.06	.04	.09	.28	.52	.05
ZrO ₂	.03	.06	.12	-	.08	-	-	-	-	-

- A. Stop 1: Tischer Creek rhyolite (ave. of two analyses).
- B. Stop 2: 42nd Ave E. ignimbrite (D-87).
- C. Stop 2: icelandite flow beneath B (D-91).
- D. Stop 3: Palisade rhyolite (F-201).
- E. Stop 5: Silver Beaver felsite (F-278).
- F. Stop 6: Devil Track rhyolite (ave. of three).
- G. Stop 7: Kimball Creek rhyolite (ave. of five).
- H. Stop 8: Rangeline icelandite (MI-2).
- I. Stop 9: Deronda Bay andesite/icelandite (MC-3b).
- J. Stop 9: Red Rock rhyolite (MC-7).

FIELD TRIP STOPS

STOP 1. Tischer Creek at Superior Street, Duluth.

Here the stream has eroded a gorge through the small-jointed Tischer Creek rhyolite, which is approximately 300 m thick. This unit contains many thin, discontinuous color bands or laminae that resemble well-flattened fiamme, and moderately abundant, small xenoliths; both suggest an ignimbrite rather than a lava. It also shows occasional open, quartz-lined or quartz-filled tension fractures that must have formed after welding. Devitrification has destroyed whatever microscopic shard or pumice textures were once present. The laminae (fiamme?) are generally parallel to the base of the unit, but locally show folding, indicating flow after deposition and welding. This flow is thus probably a "High-temperature" type according to Bonnicksen et al. (1988). The base of this unit is intruded (and probably melted) by the thick Endion diabase sill.

STOP 2. Lake Superior shore at foot of 42nd Avenue East, Duluth.

At this locality is the contact between two felsite units, an icelandite overlain by a rhyolite (Fig. 3). Where the trail reaches the shore there are abundant exposures of the lower part of a thick (about 60 m) rhyolitic ignimbrite, full of small (1-4 cm) slabs and chips of what were probably pumice, in a fine-grained, devitrified matrix now devoid of recognizable shards. Alteration at different stages, probably including that due to contemporaneous degassing and later burial metamorphism, has created distinct color contrasts between the fragments and matrix. Several xenoliths are present, including a few blobs (bombs) of chilled mafic lava. The pumice fragments are not obviously flattened parallel to the base of the flow, even though this is a fairly thick unit. This indicates that it was probably erupted at a relatively low temperature (Bonnichsen et al.'s Type L) and did not weld or even compact very much except at the very base. A very similar texture is found at the base of the large, Tertiary caldera-filling Gomez Tuff of trans-Pecos Texas (Price et al., 1986).

In the impassable cliff up the shore to the northeast this rock is directly overlain by another rhyolite with a distinctly different structure. Above a narrow transition zone of a few centimeters, it contains thin, discontinuous color bands and lamellae, rather like the Tischer Creek unit, but with a strong lineation of small wrinkles and open fold axes. These features suggest a high-temperature ash flow, resulting in thorough welding and bulk flow, after emplacement, in the direction of the lineations - a rheoignimbrite of Bonnichsen et al.'s Type H.

In the other direction (SW) along the beach, the basal 2 or 3 meters of the main unwelded ash flow is not exposed, but several loose blocks of laminated rock, found only in this vicinity, appear to be the strongly compacted and welded basal portion of this unit.

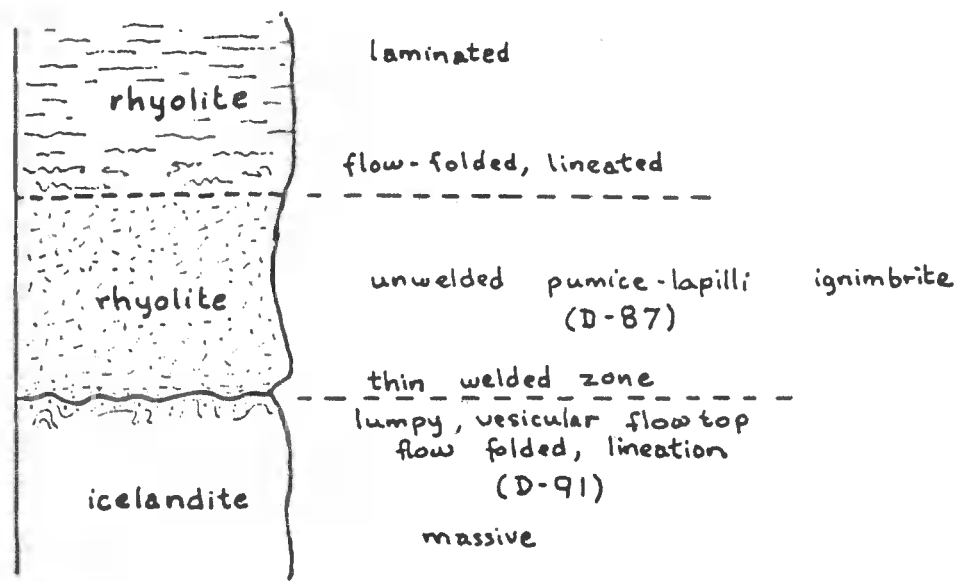


Fig. 3. Diagrammatic columnar section at field trip Stop 2, lakeshore at foot of 42nd Ave East, Duluth.

Just beyond this zone is the top of a 130-m thick porphyritic icelandite. It is highly vesicular to frothy but not pumiceous, and the top meter or two are penetrated by arkosic sandstone dikes that filled in open cracks in the flow top before eruption of the overlying ignimbrite. The vesicles (now largely calcite amygdules) are stretched to varying degrees, and large flowage folds are evident. This vesicularity dies out to the southwest as the rock becomes massive and granular. There is little brecciation. These textures and structures indicate that this unit was a large and fairly hot and rapidly emplaced lava flow.

None of these units can be traced inland for more than a few kilometers because of glacial drift cover and intersection by large mafic intrusions.

For more details on these Duluth units see Motamedi, 1984.

STOP 3. Palisade Head, Lake County (Figs 4,5).

This scenic promontory is made of a 90+ m thick massive, porphyritic rhyolite. The same unit forms the prominent Shovel Point to the northeast (stratigraphically lower flows are exposed in the Baptism River basin in between), and it can be traced from East Beaver Bay (to the southwest) at least 23 km along strike to the northeast. See also Miller, 1987 and 1988 and Miller et al., 1987 for detailed local geology.

Throughout most of its extent the Palisade rhyolite closely resembles this exposure at Palisade Head: massive, with no evidence of pyroclastic texture, only rare xenoliths, and with only rare broken phenocrysts. Under the microscope it shows fine-grained, poikilitic quartz pseudomorphic after tridymite, implying crystallization well above 870 degrees C. At the base, the only exposure (in the southwest end of this hill) shows flow laminations, locally much folded on a small scale, in the lowest 1 to 3 meters. Elsewhere, larger folds in laminations occur farther above the base. At the top, the only exposure is vesicular (amygdaloidal) but not pumiceous or brecciated. These characteristics suggest an origin as a large, unusually mobile, hot lava flow. However, one outcrop in the interior shows small, discontinuous bands or streaks that suggest relict fiamme, and another (next stop) contains abundant discontinuous streaks suggesting strongly flattened fiamme. The unit may be a high-temperature rheoignimbrite.

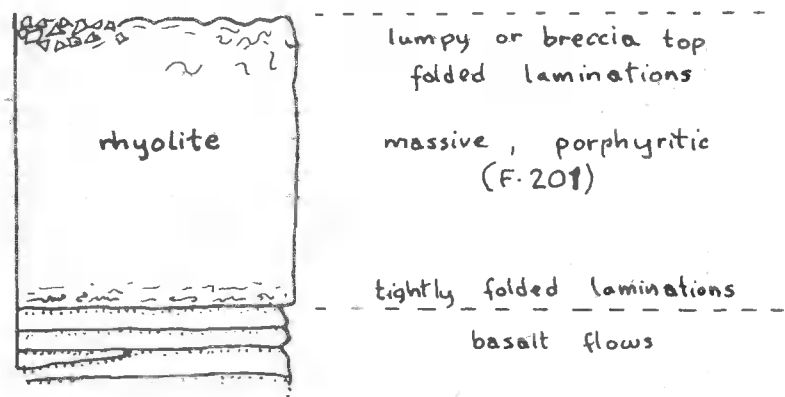


Fig. 4. Diagrammatic columnar section of Palisade rhyolite, field trip Stops 3 and 4.



Fig. 5. View to the southwest of Palisade Head from the top of Shovel Point (both made of columnar-jointed Palisade rhyolite). Lower cliffs in middle distance at right (at Baptism River mouth) are made of the Silver Beaver felsite (Stop 5), stratigraphically beneath the Palisade rhyolite.

STOP 4. Road cuts in Palisade rhyolite, Minn. Highway 1, Illgen City.
Here part of the upper portion of this unit is exposed, showing in contrast to typical outcrops, a breccia made of diversely oriented blocks. Each block is itself flow-laminated. The laminations appear discontinuous and may be strongly flattened fiamme. Clearly the breccia was formed after cooling across the ductile-brittle transition, during late-stage movement of the flow.

STOP 5. Silver-Beaver felsite at the Baptism River (Fig. 6).
(Park at Rest Area at Tettegouche State Park headquarters).

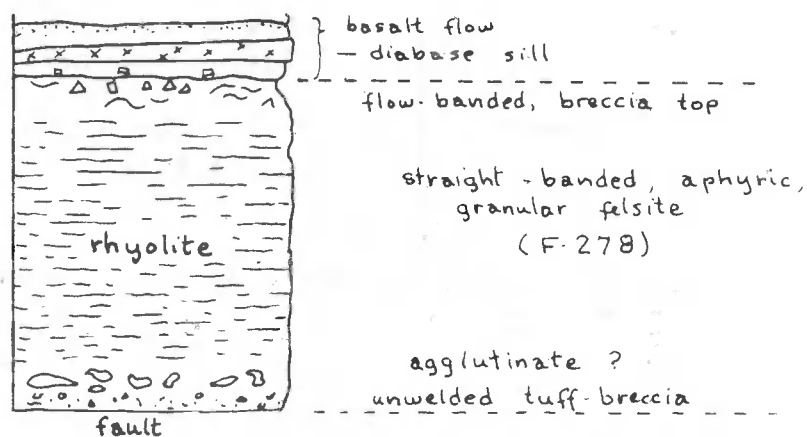


Fig. 6. Diagrammatic section of Silver Beaver felsite, Stops 5a and 5b, Baptism River.

A. Walk across Baptism River on foot bridge, then left through woods on an unofficial trail to a high outcrop overlooking the river mouth at the lakeshore. Here is fairly typical, banded, fine-grained, weakly porphyritic to aphyric felsite, dipping steeply to the east toward the lake. Across the river the unit is a tuff-breccia at water level. Follow along the top of the shore cliff to the south to the first beach-cove. Here the basal portion is exposed, overlying a pale, chalky-clayey zone that may be either altered airfall ash or fault gouge. The basal 3 to 5 m is an irregularly fractured, unwelded tuff-breccia or lapilli-tuff containing fragments of various once-glassy felsite textural types which include pumice, spherulites, perlitic cracks, etc., considerably altered to kaolinite and quartz. This zone is overlain by what appears to be agglutinate, containing faint blobby areas (Fig. 7) and grading up into more typical, weakly flow-banded, uniform, finely crystalline felsite.

Across the beach to the west is a very discordant, steeply SE-dipping contact where a laminated basaltic andesite overlies the rubbly, sand-matrix top of another flow. A fault separates these rocks from the felsite.

Return to highway.



Fig. 7. Deformed agglutinate (?) blobs in lower part of the Silver Beaver felsite, lakeshore southwest of Williams Creek, Silver Bay area.

B. After crossing back to the north side of the river, go west across the highway and up the trail (via stairs) along the top of the bank to a long flight of wooden steps leading down to the river again. The outcrops here are near the stratigraphic middle of the Silver Beaver felsite. Faulting has dropped it down relative to its exposures at the river mouth, but it still dips east. The uniform, typically planar lamination is characteristic, as is the fine-grained (rather than dense-aphanitic), aphyric texture. In thin section quartz pseudomorphs after tridymite are abundant, and small (1-3 mm) spherulites are not uncommon.

Go downstream (if the water level is low enough), working toward the top of the unit. A few meters from the top the flow starts to acquire small, irregular vesicles, then becomes broken up in a flow-top breccia with lineated vesicles and ashy gray material between the blocks. This is overlain by a laminated, red tuff only a few cm thick, which lenses in and out. These felsic rocks are then overlain by a thin, amygdaloidal basalt flow with large plagioclase phenocrysts concentrated at the base; its top is intruded by a thin black diabase sill.

The Silver Beaver felsite is interpreted to have begun with eruption of glassy ash and pumice at a moderate or slow rate, producing an unwelded base, but then changed to agglutinate as hotter or less volatile-rich material became available. The bulk of the unit was produced as either agglutinate or a hot ash flow that coalesced and flowed as a unit after settling/accumulation - perhaps a Very High Temperature (Type V) rheoignimbrite of Bonnicksen et al., 1988. It subsequently crystallized in place to tridymite and feldspar.

Climb back up to the trail and walk out to the highway.

As the trip progresses up the shore we pass upwards stratigraphically to the exposed top in the Tofte-Lutsen area in southwestern Cook County. An unknown thickness of lavas was erupted on top of this sequence and now underlies the lake or was eroded off before the Portage Lake Volcanics or Upper Keweenaw sandstones were laid down on top of the NSVG here. Beyond Lutsen we start descending in the "northeast limb". Here the strata strike more easterly than the lakeshore, and dip south-southeast to south (Fig. 8).

Grand Marais sits largely on another large, small-jointed rhyolite complex which has been more easily eroded (to form the harbor) than the overlying "Breakwater trachybasalt". This is a thick transitional basalt unit that makes the "island" and breakwater and a cuesta to the west.

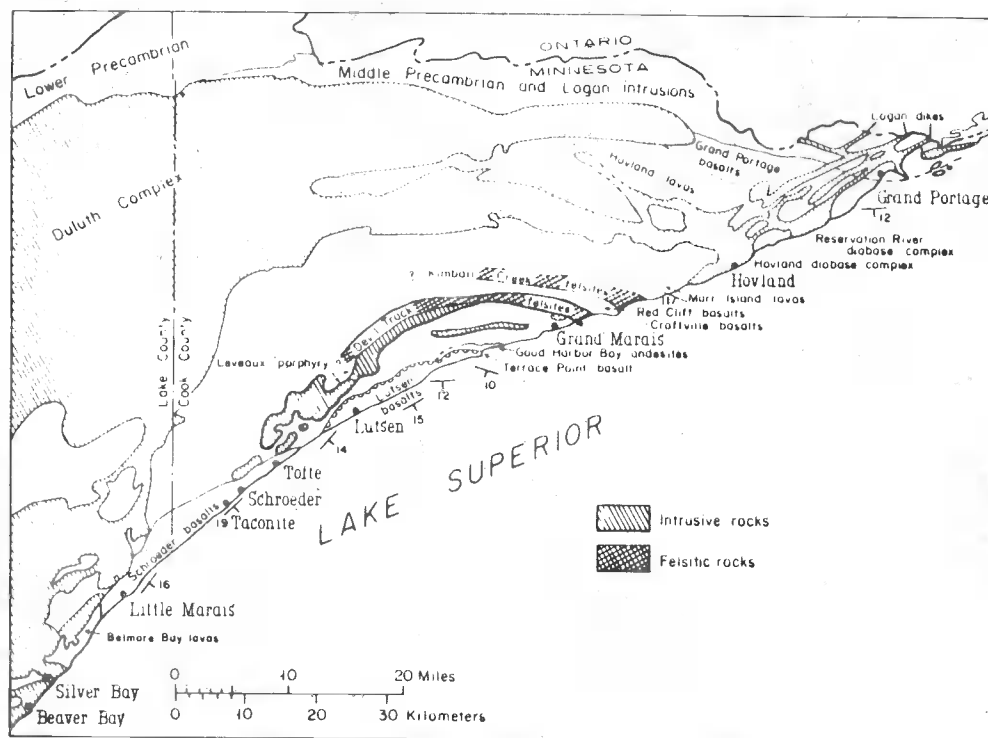


Fig. 8. Generalized geologic map of the northeastern tip of Minnesota showing continuity along strike of some of the major units of the NSVG. (from Green, 1979).

STOP 6. Devil Track rhyolite, Highway 61 opposite Five Mile Rock east of Grand Marais.

This exposure, at an abandoned wave-cut cliff of the 5000-year old Nipissing stage of Lake Superior, is fairly typical of this large rhyolite. This unit can be traced for about 40 km to the west, and is about 250 m thick. Neither its top or base is exposed, and all outcrops show this weakly flow-laminated, fine-grained, aphyric to very weakly porphyritic character, rather similar to the Silver Beaver felsite. Thin sections here also show quartz paramorphs after primary tridymite. Tom Fitz (1988) has found that the grain size of these tridymite plates increases toward the center of the unit, implying that it crystallized as a simple cooling unit (Fig. 9). No significant breccia facies has been found. The wide extent, lack of breccia or other viscous flow features other than rare lineations, aphyric texture, and crystallinity suggest that this was a very hot pyroclastic flow that completely consolidated, after emplacement, to a pool of devolatilized rhyolite magma that crystallized in place.

Assuming that its overall original shape was a segment of a sphere (it appears to pinch out at the western end but is thick through much of the rest), and that its center was at the present lakeshore (half now underlies the lake), it would have had an original volume of about 600 km³.

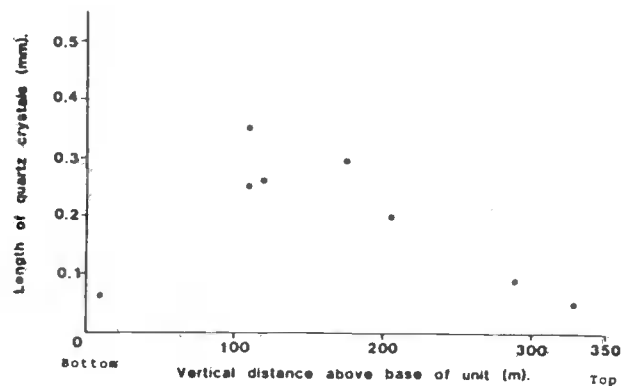
STOP 7. Kimball Creek Felsite, Lake Superior shore north of Red Cliff.

Here we are near the top of another very large (366 m thick) rhyolite. The point at Red Cliff to the south is held up by a sequence of overlying olivine tholeiite basalts. This rhyolite is weakly plagioclase-phyric, but otherwise the bulk of this flow is fine-grained, crystalline, and massive, rather like the Devil Track rhyolite. This unit also shows a network of tridymite paramorphs in the groundmass (Fig. 10), whose length is greatest near the center of the flow (Fig. 9), again indicating primary crystallization as a simple cooling unit. Here (and elsewhere) near the top, however, it is aphanitic and contains discontinuous color bands and lamellae that are probably flattened and deformed pumice fiamme. These structures are preserved here near the top because of the rapid cooling after welding, preventing the primary crystallization which obliterated them in the interior. Unfortunately the top several meters are not exposed, as is typical of these large rhyolites. One possible inference is that the top may contain easily weathered and eroded, unwelded pumice and ash. The base is not exposed either, but a few meters above, the unit shows flow-folding of thin, discontinuous streaks and lamellae (fiamme?) (Fitz, 1988). This unit is thought to have the same origin as the Devil Track rhyolite: a high-temperature rheoignimbrite.

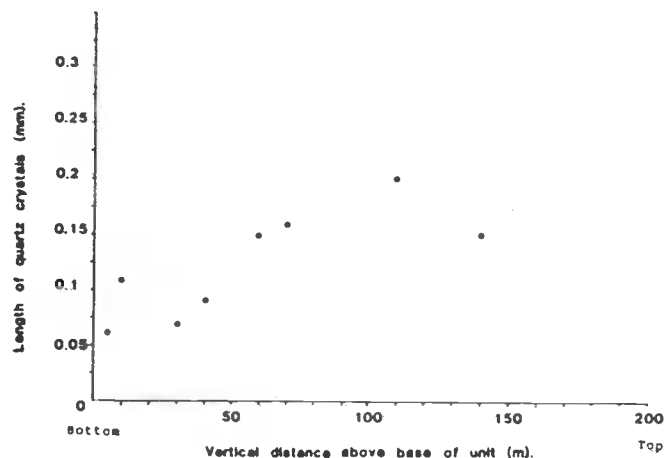
For more details on these two large rheoignimbrites see Fitz (1988).

STOP 8. Rangeline icelandite, 1 1/2 mi. E of Kadunce Creek (River).

These road cuts show fairly typical textures and structures of a large (40 m) icelandite lava flow. Toward the eastern end is the massive lower part, aphanitic to fine-grained and porphyritic; round amygdules gradually increase toward the west. Neither top nor base are exposed, but another icelandite a few miles to the northeast shows strongly stretched amygdules in an aphanitic upper crust. Phenocrysts are of plagioclase, ferroaugite, Fe-olivine, and magnetite.



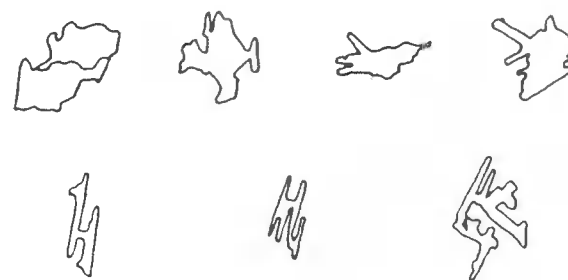
Length of quartz crystals vs. stratigraphic position in the Kimball Creek rhyolite.



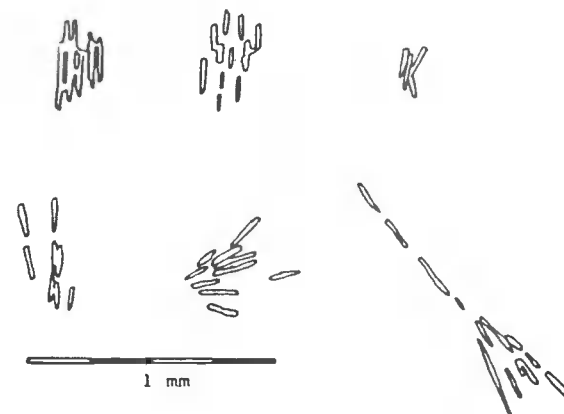
Length of quartz crystals vs. stratigraphic position in the Devil Track rhyolite.

FIG. 9

Fig. 9. Variation in lengths of tridymite paramorphs with height in the Devil Track and Kimball Creek rhyolites (from Fitz, 1988).



Anhedral quartz masses gradational to groups of fused plates in optical continuity.



Groups of plates in optical continuity, some with slight radiating pattern.

FIG. 10

Fig. 10. Tabular habits of quartz paramorphs after tridymite in the groundmass of the Kimball Creek felsite (from Fitz, 1988).

STOP 9. Red Rock Point rhyolite at Deronda Bay, Grand Portage Indian Reservation (Fig. 11).

At this locality a thick (80 m) andesite/icelandite flow (MC-3b, Table 3) is overlain by a large (>140 m) rhyolite unit (MC-7b), but the actual contact is somewhere under the beach. The beach shingle contains pieces of both, including vesicular andesite with pseudomorphs of cristobalite balls in the stretched vesicles. The top of the rhyolite is cut out by the Reservation River diabase intrusion, which also cuts it off to the west so that its lateral extent is unknown as well.

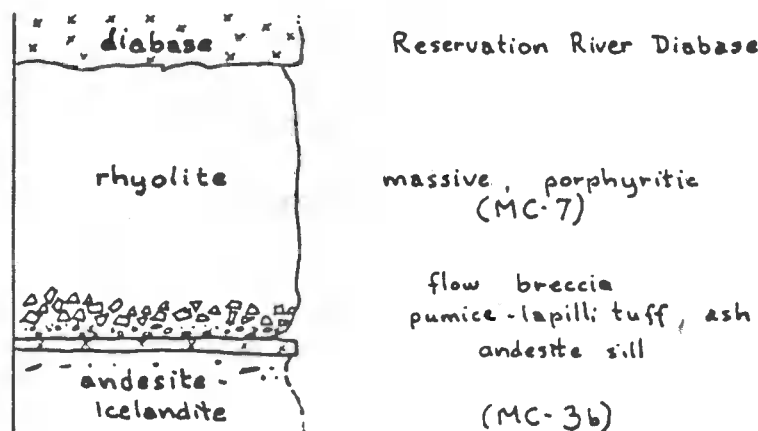


Fig. 11. Diagrammatic section of the Red Rock rhyolite at Stop 9, Deronda Bay.

On the way toward the main cliff outcrop on the south side of the bay, there are instructive low, wet outcrops and shallow underwater "exposures", accessible under favorable lake conditions, of the following gently south-dipping sequence, from bottom to top: a) porphyritic andesite or icelandite, probably part of the MC-3 complex, overlain - and probably baked by - b) a thin basaltic sill; this is overlain by, and has baked somewhat, c) a thin layer of pumice-lapilli tuff; this is overlain by d) a grayish ash bed 2-4 cm thick; then e) a rhyolitic flow-breccia (mostly underwater) made of variously-oriented blocks containing stretched vesicles. Unfortunately boulders cover the interval, only a few meters thick, between this and the cliff outcrop ahead. This is all made of red-orange, porphyritic rhyolite that does not easily give up clues as to its mode of emplacement. In some areas near the base it appears to be a breccia (simply more of the basal autobreccia of a large lava flow?). In others, faint suggestions of pumice chips and spherulites suggest that perhaps this is the basal unwelded pumice zone of a big ash flow, overlain in the cliff by the devitrified, laminated, welded zone. Because of the clear underlying breccia and the lack of obvious fiamme, I prefer the former model, although this flow does contain some broken phenocrysts. The pumice-lapilli tuff and ash tuff beds were air-falls which immediately preceded the rhyolite eruption.

Return to Duluth via Grand Marais.

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PENOKEAN STRUCTURAL TERRANES IN EAST-CENTRAL MINNESOTA

A one-day field trip associated with the
Thirty-Fifth Annual Meeting of the
Institute on Lake Superior Geology
May 3-6, 1989

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Introduction

The Penokean orogeny, which occurred near the close of early Proterozoic time (1875-1825 Ma., Van Schmus, 1976, 1980, 1981) involved deformation and metamorphism of rocks in Minnesota, Wisconsin, upper Michigan, and the Superior, Southern, and Grenville provinces in Canada (Holst, 1982; Maass and others, 1980; Cannon, 1973; Brocoum and Dalziel, 1974). Until recently, the Penokean orogeny in Minnesota was usually interpreted as intracratonic (Morey and Sims, 1976; Sims, 1976; Sims and others, 1980) with an emphasis on the role of basement rock involving "vertical remobilization" (Morey, 1979). Of fundamental importance in this interpretation is the boundary, in west-central Minnesota, between an ancient (in part 3550 Ma.) gneissic terrane and a younger (ca. 2700 Ma.) granite-greenstone terrane (Fig. 1). Morey and Sims (1976) suggested that this boundary is part of a major Precambrian crustal feature more than 1200 km long which they called the Great Lakes tectonic zone (Sims and others, 1980). They noted that rocks which overlie the granite-greenstone terrane (Animikie Group) are less deformed and metamorphosed than those which overlie the Great Lakes tectonic zone and gneissic terrane. Because of this these authors suggested that this early Precambrian boundary acted as a locus for limited intracontinental tectonic movement and rising geothermal gradients (Morey, 1979).

Recent structural investigations in the early Proterozoic Thomson Formation in east-central Minnesota (Holst, 1982, 1984c) reveal evidence for multiple deformation and document the existence of northward-directed nappes during the Penokean orogeny. One of the possible models of nappe emplacement in Minnesota would be gravity gliding off a rising diapir following the suggestions of Morey (1979) and Sims and others (1980) for intracratonic deformation. However, the high strains associated with nappe emplacement (Holst, 1985a) do not support this idea (see the values of strain above a rising diapir in Dixon, 1975). Such strains are more consistent with a plate tectonic model (Holst, 1985a, 1985b). The presence of nappes has also recently been reported further to the east in the Penokean orogenic belt (Sims and others, 1987; Klasner, et al., 1988) and Penokean volcanic rocks have been shown to be of island arc affinity (Schulz and others, 1984) resulting in plate tectonic syntheses for several areas of the Penokean orogenic belt.

The growing body of structural and petrologic evidence from Wisconsin (LaBerge and others, 1984; Sims and others, 1985) and upper Michigan (Cambray, 1977, 1978) is consistent with the structural evidence in east-central Minnesota for a convergent plate boundary model (Holst, 1984a, 1984b). Recent models of the Penokean orogeny in Minnesota involve a convergent plate margin with subduction of a passive margin, or the close of a back-arc basin (Holm, Holst, and Ellis, 1988; Southwick, Morey, and McSwiggen, 1988).

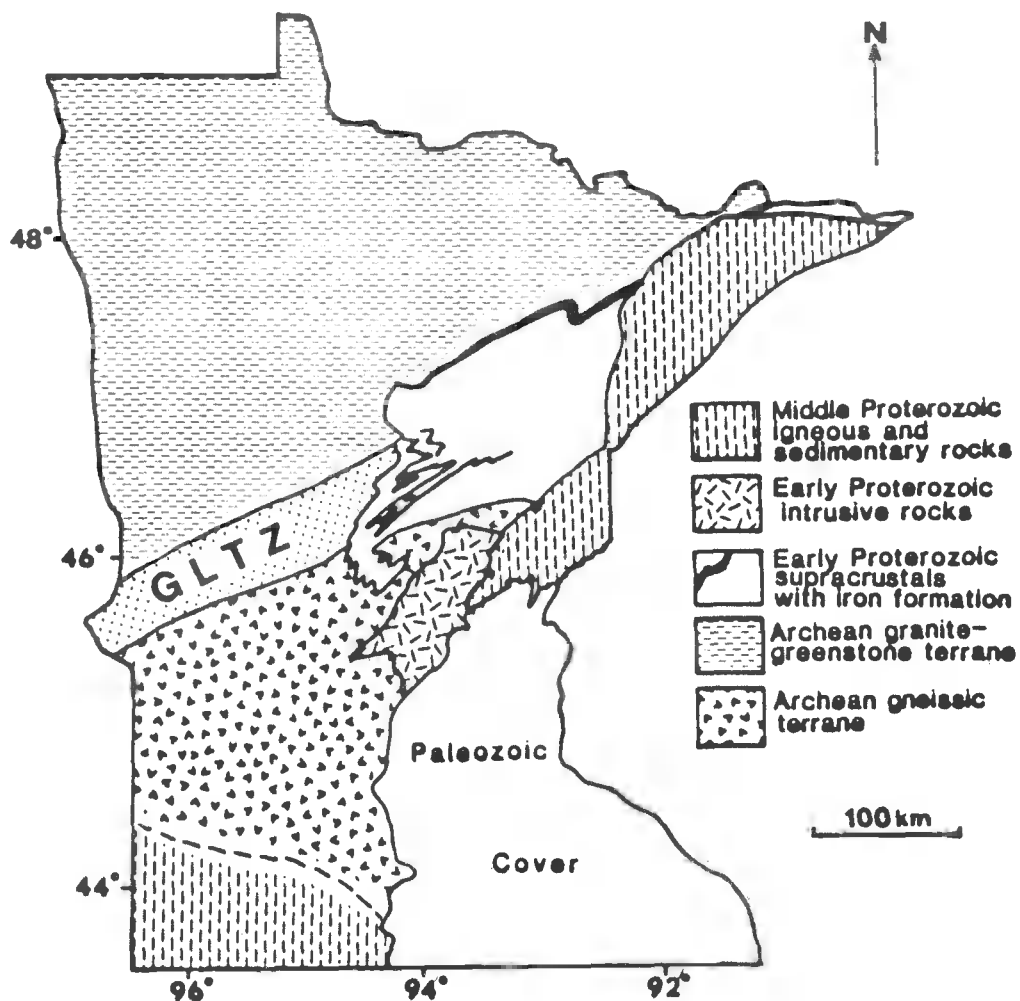


Figure 1: Generalized geologic map of the Precambrian geology of Minnesota (after Sims and others, 1980; Morey and others, 1982). GLTZ is the Great Lakes Tectonic Zone.

Geologic Setting

The Precambrian rocks of east-central Minnesota can be divided into four distinct terranes (Fig. 1): 1) Archean rocks; 2) early Proterozoic stratified rocks; 3) early Proterozoic plutonic rocks; and 4) middle Proterozoic (Keweenaw) sedimentary and volcanic rocks (Morey, 1978). A stratigraphic column for east-central Minnesota and detailed descriptions of the different rock types have been presented by Morey (1978, 1979), although recent work suggests a rethinking of some of the correlations (Morey and Southwick, 1984; Southwick and Morey, 1988; Southwick, Morey and McSwiggen, 1988).

The Archean terrane consists of a northern granite-greenstone belt terrane (ca. 2700 Ma.), a southern highly deformed gneissic terrane (in part >3550 Ma.), and a central sheared, schistose segment (Morey, 1978) also known as the Great Lakes tectonic zone (Sims and others, 1980). Along this zone, granitic plutons (2600 Ma., Sims and others, 1980) acted as a weld between the northern and southern segments forming a relatively stable craton by the end of the Archean (Morey, 1978).

Sedimentation into a large basin on this craton, the Animikie basin, began at about 2100 Ma. (Van Schmus, 1976). Depositional patterns reflect contrasting tectonic conditions in the northern and southern segments of the Animikie basin. A relatively thin succession (2-3 km) of predominantly sedimentary rocks (labeled the Animikie Group, Keighin and others, 1972) was deposited north of the northern front of the Great Lakes tectonic zone, whereas a much thicker and more heterogeneous succession (>6 km) of sedimentary and

volcanic rocks (Animikie and Mille Lacs Groups, Morey, 1978) was deposited south of this front (Morey, 1983; Morey and Southwick, 1984). Apparently, subsidence was relatively greater in the southern part of the basin, particularly over the Great Lakes tectonic zone and the gneissic terrane. Ojakangas (1983) has inferred the extent of the Animikie basin on the basis of sedimentological and lithological similarities in Minnesota, Wisconsin, and Michigan. Because rocks of the Midcontinent Rift system (middle Proterozoic igneous and sedimentary rocks, Fig. 1) separate the Animikie basin into two physically isolated segments, the strata in the northwestern segment are assigned to the Animikie and Mille Lacs Groups whereas those in the southeastern segment are assigned to the Marquette Range Supergroup. Correlations have been made among the Lower Proterozoic bedded rocks in Minnesota, Michigan and Wisconsin (Morey, 1983).

All stops on this field trip have been mapped historically as part of the Thomson Formation. The southern exposures have recently been assigned to other, as yet unnamed units of early Proterozoic metasediments and metavolcanics, which are older than the Thomson Formation (Southwick and Morey, 1988; Southwick, Morey and McSwiggen, 1988).

Descriptive Structural Geology

Exposures of early Proterozoic metasediments and metavolcanics historically called the Thomson Formation consist of a thick sequence of interbedded slate, slaty greywacke, metagreywacke with some intercalated volcanics. The southern two-thirds of this region, here designated the southern structural terrane, has a pervasive, nearly bedding-parallel foliation (S_1). It ranges from a slaty cleavage in the north to a schistosity in the south near the Denham Formation (Holst, 1982). Strain analysis (Holst, 1985a) has firmly established the tectonic nature of this bedding-parallel foliation. Also present in the southern structural terrane are isoclinal recumbent folds in scales ranging from cms to kms (nappes), with east-west fold axes (F_1). Both the northern and southern structural terranes have been folded into gentle to open upright folds. Fold axial surfaces strike east-west and fold axes have horizontal to gentle plunges either east or west. In the southern structural terrane these upright folds (F_2) refold the earlier isoclinal recumbent folds (F_1). A well-developed cleavage, vertical or dipping steeply to the south (axial-planar to the upright folds) is present in both the northern and southern structural terranes. In the northern structural terrane this cleavage is a well developed continuous slaty cleavage in the finer-grained units. In the units with graded bedding, and in the units with interlaminated fine and coarse layers, the continuous cleavage grades into a disjunctive spaced cleavage (terminology of Powell, 1979). The spacing of the cleavage domains ranges from continuous up to 1 cm in some of the most coarse-grained units, but it is rarely over a few mm. Cleavage domains constitute from 25% of the rock (in the thick graywacke units) to 100% (in the slates with a continuous cleavage). Domain shapes range from rough to smooth (smooth shapes predominate) with some anastomosing shapes. Within the microlithons, a weak fabric, at least, is developed everywhere, and commonly the fabric is strong to complete (terminology of Powell, 1979). In the southern structural terrane the steep foliation is a well-developed crenulation cleavage (S_2). This S_2 cleavage can be discrete but is most commonly transitional to zonal, or entirely zonal (Gray, 1977; Powell, 1979). Spacing of the cleavage domains is variable. For the most part the spaced crenulation cleavage strikes east-west and dips steeply to the south or is vertical, and axial-planar to the F_2 folds. Around some microfolds, however, the spaced crenulation cleavage may fan, or be at a constant angle (up to 40°) to the axial plane on one limb, and axial planar on the other limb. The intersection of S_1 and S_2 defines a well developed lineation in the rock, trending east-west with subhorizontal plunges. Detailed mapping has allowed a boundary to be drawn between the area of a single main Penokean deformation in the north (the northern structural terrane), and the area of two Penokean-aged deformations in the south (the southern structural terrane). This boundary was interpreted by Holst (1984c) as a nappe front because of the abrupt nature of the change across this terrane boundary, and because the refraction pattern in the early foliation just south of this boundary suggests that a nappe

front must be located in the immediate vicinity to the north.

Underlying the southern part of what has historically been called the Thomson Formation is the early Proterozoic Denham Formation. This has now been broken into upper and lower members by Southwick, Morey and McSwiggen, (1988). The rocks of this formation have been multiply deformed and metamorphosed in a fashion similar to the overlying rocks (Holm, 1986a, 1986b) and are here considered part of the same nappe terrane. The Denham Formation is a sequence of primarily quartz-rich metasedimentary rocks (metaarkose, quartzite, mica schist, and garnet-staurolite schist) with minor amounts of marble and volcanic rocks. It has been postulated to be stratigraphically equivalent to the Chocoday Group of the Marquette Range Supergroup in Michigan (Larue, 1981; Morey, 1983). Bedding strikes east-west and dips dominantly steeply. A nearly bedding-parallel foliation is present everywhere in the Denham Formation. The foliation is refracted at a higher angle to bedding in the more competent arkosic and quartzitic units. The foliation and bedding have been folded with the development, locally, of a crenulation cleavage. Orientations of axial surfaces to these folds vary from horizontal to vertical and strike east-west.

The Denham Formation also contains a very well-developed, nearly horizontal, east-west mineral and crenulation lineation. Chocolate-tablet boudinage of quartz veins occurs parallel to bedding throughout the area.

The basement to this terrane is the Archean (2700 Ma.) McGrath Gneiss which contains a poorly to well-developed foliation and a number of cross-cutting shear zones. It is a coarse-grained, pinkish-gray, biotite gneiss containing megacrysts of microcline. Some of the megacrysts are rounded, giving the appearance of augen, but many are euhedral and oriented obliquely to the foliation while still others have a sigmoidal shape and are aligned in the foliation. Sense of shear from the sigmoidal porphyroclasts (after Simpson and Schmid, 1983) indicate that the foliation developed in a dominantly dextral shear regime. The foliation is commonly well developed, strikes east-west, and varies in dip from horizontal to vertical. A nearly horizontal east-west mineral lineation ranging from crude to locally well developed is also present. The McGrath Gneiss is locally folded and is cross-cut by nearly vertical, commonly anastomosing shear zones that strike generally east-west.

In the northern structural terrane there are some late-stage features including kink bands which deform the steep cleavage in the Thomson Formation. The orientation of these kink bands is quite variable, but poles to over 100 kink bands define a single maximum on an equal-area projection (Clark, 1985). The gentle dip of the kink bands indicates a sub-vertical finite compression during their formation, estimated to be about 5% by Clark (1985).

Conditions Of Deformation

Petrographic analysis indicates that the basement and cover rocks have undergone similar conditions of deformation related to the Penokean orogeny. In all rocks analyzed, the predominant deformational processes appear to be normal crystal-plastic type, involving dynamic recovery and recrystallization. In both basement and cover rocks, quartz has undergone ductile deformation. Bending of the crystal lattice has produced undulatory extinction and, locally, deformation bands. Recovery and recrystallization are indicated by the development of subgrains and strain free new grains in and along the margins of quartz aggregates. Both brittle and ductile deformation processes have occurred in the feldspar grains. Brittle deformation is indicated in the coarser feldspar by fractures along which new grains have recrystallized. Simultaneous ductile deformation of the finer grained feldspars is indicated by undulatory extinction, recovery, and recrystallization commonly resulting in a granoblastic polygonal texture. Mica grains are relatively strain free in both basement and cover rocks, probably because of recrystallization. The textures described here indicate dominantly ductile deformation under moderate to high temperature and moderate pressure conditions.

Metamorphism

Metamorphism of the early Proterozoic sedimentary rocks in this region increases from north to south (Keighin and others, 1972). At the type locality near Thomson in the northern terrane, the Thomson Formation is metamorphosed to lower greenschist facies (chlorite zone). Within the Thomson Formation there is a progressive increase in metamorphic grade to lower amphibolite facies (garnet zone) in the south (Morey, 1979). Farther south, the Denham Formation has been metamorphosed to the staurolite zone of the amphibolite facies (indicated by the presence of a coarse-grained schist containing quartz+muscovite+biotite+garnet+staurolite). Morey (1983) has mapped the biotite, garnet, and staurolite isograds for early Proterozoic stratified rocks in Minnesota, illustrating this progressive increase in metamorphic grade from north to south and the similarity of the trend of metamorphic isograds and structural features (see Morey, 1983, fig. 7).

Petrographic analysis reveals further information about the timing of metamorphism and deformation. Progressive metamorphism during the early phase of deformation in the Denham Formation reached the garnet zone of the amphibolite facies as indicated by the presence of syntectonic garnet porphyroblasts. The peak of metamorphism, however, occurred during or after the later deformation as indicated by staurolite overgrowing both the schistosity and the crenulation cleavage.

Microprobe analysis of garnet shows only slight compositional variation and no systematic zonation (Holm, 1986a). Rocks of the southern structural terrane have recently been studied by Holm and Selverstone (1989). Using thermobarometric techniques they find temperature and pressure estimates of final equilibration increasing southward. Staurolite grade samples from just north of the Denham Formation yield final equilibration temperatures of 520-590°C and a pressure of about 7 kb (depth of about 25 km).

Petrologic and Geochemical Constraints

Penokean age volcanic rocks further to the east have been shown to be of island arc affinity (Schulz, 1983; Schulz and others, 1984). Horan, Hansen, and Spencer (1987) suggest that the early Proterozoic intrusive rocks in central Minnesota were formed at a convergent plate margin, based on isotopic and trace element analysis. They suggest that a gabbro near Mora, Minnesota may have been part of an early Proterozoic ocean crust, and thus may represent part of a suture zone. Recent geochemical and isotopic work reported by Southwick, Morey, and McSwiggen (1988) shows that island arc constituents are not a major portion of the rocks that now make up the fold-and-thrust belt of the Penokean Orogen in Minnesota. They also report that most of the basaltic rocks of the region have a continental (within plate) affinity, indicating that continental crust played a role in determining their composition.

Tectonic Modelling

Holm, Holst and Ellis (1988), using the constraints of structural geology, finite strain determinations, deformation conditions indicated by microstructures and textures, and the results of thermobarometry estimates, developed a tectonic model consisting of southward directed oblique subduction along the Great Lakes tectonic zone. According to this model intense deformation occurred in the footwall of the major thrust, which marked the boundary between downgoing and overriding plates during A-type (continental) subduction. Sedimentary rocks deposited on the footwall during loading caused by thrusting eventually became incorporated into the deformation zone. Early formed structures related to footwall deformation are a dominantly well-developed foliation in the gneiss and isoclinal, recumbent folds with a bedding-sub-parallel foliation in the southern structural terrane. Progressive metamorphism during subduction reached the garnet zone of the amphibolite facies. Various deformation inversions show that this early phase of deformation involved extreme flattening (with Z vertical) and large amounts of finite extensional strain in both the north-south and east-west directions.

Footwall deformation was followed by imbrication and accretion onto the hanging wall during uplift associated with continued compression and isostatic rebound. Later formed structures associated with imbrication and deformation within the hanging wall consist of folding of the foliation and development of shear zones in the McGrath Gneiss and open to close, upright to overturned folds in the cover rocks of both the southern and northern structural terranes. The peak metamorphic event (represented by staurolite) occurred after the later deformation at temperatures of around 520-590°C and a pressure of 7 kb (depth of about 25 km). Increasing temperature associated with decreasing pressure (uplift) is explained by conductive relaxation caused by crustal thickening and erosion.

Southwick, Morey, and McSwiggen (1988), while noting that several types of plate margin collisional models are possible, favor a collapsing back-arc basin as a model for the Penokean orogeny. They argue that the lithostratigraphic associations of the early Proterozoic supracrustal rocks in Minnesota, and the geochemical characteristics of the volcanic rocks are more compatible with a back-arc setting than with an arc-trench environment.

GUIDE TO FIELD TRIP STOPS

The location of the field trip stops is shown on Figure 2. The field trip begins at the Radisson Duluth Hotel at Superior Street and 5th Avenue West in downtown Duluth, Minnesota. Head southwest on Superior Street and in two blocks join Interstate Highway 35 going south. After 14.6 miles on I-35, take exit 242, turning south (left) on Carlton County 1. In 2.9 miles, the road crosses a spillway, turns west, and after 0.6 miles, reaches a T junction. Turn right (north) on Minnesota Highway 210, which then turns left (west) in less than 0.1 mile. In 0.2 miles, Minnesota Highway 210 crosses the St. Louis River. Pull off and park just before reaching the bridge, or cross it and park in the parking area on the south side of the road.

STOP 1 THOMSON DAM

This is the type locality of the Thomson Formation, which here consists of slates and metagraywackes. A variety of sedimentary structures may be seen, including ripple marks, load casts, convolute bedding, cross bedding, graded bedding, and sole marks. Folds with wavelengths from cm to km are present (Figure 3). They are upright to steeply inclined to the south and have subhorizontal fold axes that trend east-west. Where folds die out along trend, axes may plunge east or west as much as 60°. Two such steeply plunging folds may be seen in this area. A single axial-planar foliation is present; the foliation ranges from a continuous slaty cleavage in the fine-grained units to a disjunctive spaced cleavage in the more coarse graywacke beds. Abundant carbonate concretions and weathered concretion voids can be seen flattened in the plane of the cleavage. Strain determinations in this region using deformed concretions, mud chips, and a thin conglomerate bed to the north of the reservoir reveal strain ratios of about $X:Y:Z = 7:4:1$, with X vertical, Z horizontal and north-south (perpendicular to foliation) and Y horizontal and east-west. Quartz veins, from a few mm to more than a meter in width are present. Some exhibit pygmatic folding. Basalt dikes of presumed Keweenaw age are also present, as are kink bands and several sets of joints. The kink bands dip gently and display a single maximum on an equal-area projection with an average strike of about N70E and a dip of about 20° to the south. Many of the kink bands intersect, but the angle of intersection varies randomly between 0 and 30°. No cross-cutting pattern exists within the kink bands (Clark, 1985).

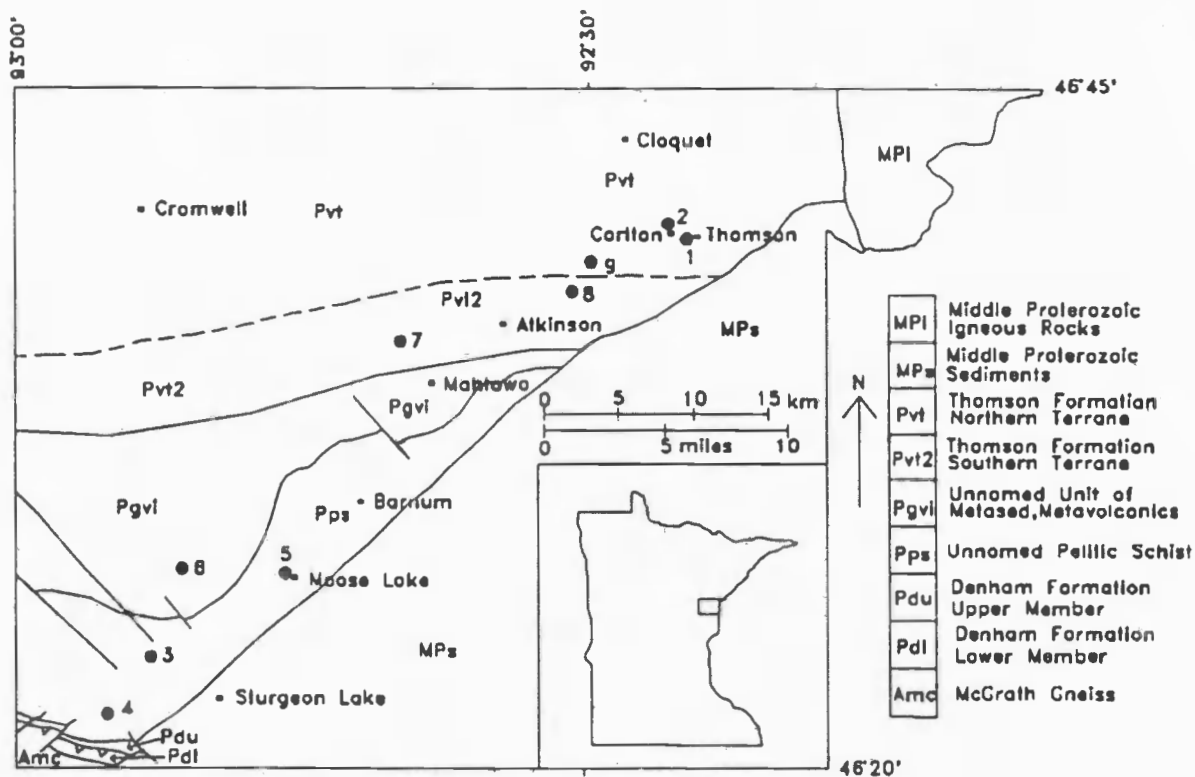


Figure 2: Geologic map of the area of the field trip (after Southwick, Morey, and McSwiggen, 1988), showing locations of field trip stops.



Figure 3: Anticline at Thomson Dam, view from the east bank of the St. Louis River, just south of the highway bridge, looking west. Drawing by Wendell Wilson.

Driving Directions: Proceed west on Minnesota Highway 210 for about 0.8 mile to the town of Carlton. Turn right (north) at the stop sign on to Old Highway 61. Proceed for one block and park in either the convenience store parking lot, or the large lot on the right side of the road. Walk north to first road cut outcrop on west side of road.

STOP 2 CARLTON ROAD CUT

Interbedded slates and graywackes of the Thomson Formation here dip to the south. A subvertical cleavage is present. A deformed load cast is present, flattened in the cleavage plane. Numerous deformed concretions with quite a range in size are present in both slate and graywacke beds. The north-south vertical joint face is the approximate XZ plane of the strain ellipsoid in the northern structural terrane of the Thomson Formation.

Driving Directions: Return south one block and turn right (west) on Minnesota Highway 210. Proceed about 3 miles to the overpass intersection with Interstate Highway 35. Proceed under the freeway and turn left on entrance ramp to I-35 South. Proceed for approximately 26 miles and take exit 209, Sturgeon Lake. Turn right and proceed into the town of Sturgeon Lake to the T junction. Turn left on Highway 61 and proceed to the first right turn, which crosses the abandoned railroad track and then turns left to the center of town. In one block turn right (at the intersection with a bar and a bank on the corners) and follow Pine County 46 out of Sturgeon Lake. The road winds past an old school and heads west for about a mile, then bends sharply to the right and heads north for a half mile, and then bends sharply left and runs due west for a number of miles. About 3.2 miles out of Sturgeon Lake (or 1.7 miles west of the second sharp bend in the road) there is a bridge over the Kettle River. Park and proceed to road cuts on the west side of the river.

STOP 3 KETTLE RIVER ROAD CUT

This bridge was constructed in the mid 1980s (the old bridge is in a farmer's field just to the northeast) and a new road cut exposes metasedimentary rocks on both the north and south sides of the road. The rocks here have been mapped historically as Thomson Formation, but are part of the "unnamed pelitic schist" unit (Pps) of Southwick, Morey and McSwiggen (1988). They are part of the southern structural terrane of the rocks deformed during the Penokean orogeny in east-central Minnesota, and are part of the Moose Lake - Glen Township structural panel of Southwick, Morey and McSwiggen (1988). The rocks here are of garnet metamorphic grade, and two foliations are observable. The early foliation is subparallel to bedding, and the later crenulation cleavage is subvertical and trends east-west. A lineation exists, parallel to the intersection of the two foliations. Recent thermobarometric work on samples from this outcrop (Holm and Selverstone, 1989) yielded final equilibration temperature estimates of 470-520°C and a pressure of around 6 kb.

Driving Directions: Continue west on Pine County 46 for about 2.8 miles. Turn left (south) on a dirt road. Follow this road south for 1.5 miles. Turn left (east) on another dirt road. After 1 mile, the "main" dirt road turns to the right (south), but continue straight ahead (east) on the "two-track" lane. In .3 or .4 mile there is a railroad crossing. Park near, but not on the railroad tracks, and walk along the tracks to the northeast. There is a long railroad cut about .3 mile northeast of the road/railroad intersection.

STOP 4 DENHAM CEMETERY RAILROAD CUT

Rocks exposed along this cut and another similar cut one-half mile to the southwest have historically been called the southernmost exposures of Thomson Formation. As at the last stop these rocks have recently been designated part of an unnamed pelitic schist unit (Pps), part of the Moose Lake - Glen Township structural panel by Southwick, Morey, and McSwiggen (1988). A number of F_2 folds are exposed in this cut. Fold axial surfaces are vertical and east-west. Fold axes are subhorizontal. The S_1 foliation which is subparallel to bedding and the S_2 crenulation cleavage (axial-planar to the F_2 folds) are most easily seen in the more fine-grained schistose units. Some of the metagraywacke units are nearly quartzites here. Again there is a east-west subhorizontal lineation. There are quite a number of early quartz veins which exhibit boudinage. The rocks here are staurolite grade and garnets are visible in many samples. Based on petrographic study, Holm, Holst and Ellis (1988) suggested that the garnets were synkinematic with the early foliation during a progressive metamorphic event, and that the thermal peak of metamorphism occurred after the later phase of deformation, as indicated by staurolite porphyroblasts which overprint both the S_1 and S_2 foliations. Thermobarometric analysis of samples from this exposure containing the assemblage staurolite+garnet+plagioclase+chlorite+ muscovite+biotite+quartz have yielded final equilibration temperatures of 520-590°C and pressures of about 7 kb (Holm and Selverstone, 1989).

Driving Directions: Return over the same route to the town of Sturgeon Lake. After crossing the abandoned railroad grade in the middle of town turn left (northeast) on Highway 61. Follow Highway 61 northeast for about 5.2 miles. Turn left at the intersection and follow Highway 61 into Moose Lake. In about one-half mile turn left (west) at the stop light in the center of town and follow Highway 27 about one-quarter mile up the hill to the railroad crossing. Park in the lot at the old train station on the west side of the road, and the south side of the railroad tracks. Walk along the tracks to the northeast to some railroad cut exposures.

STOP 5 MOOSE LAKE RAILROAD CUT

These exposures of metasedimentary rocks are also part of the unnamed pelitic schist unit (Pps) of the Moose Lake - Glen Township structural panel of Southwick, Morey, and McSwiggen (1988), and have historically been mapped as Thomson Formation. In the last decade this cut has become distinctly more overgrown, and it may be necessary to displace some vegetation to see some of the structural features here. The S_1 bedding-parallel foliation is well developed in the rocks along this cut. Early quartz veins show boudinage features documenting finite extensional strain within the plane of the early S_1 foliation. These features can be seen on outcrop faces in several orientations showing that the extension within the plane of this foliation occurred in all directions. A mineral lineation defined by muscovite streaks can be seen on the north side of the tracks at one of the first exposures as you walk in along the tracks. Several F_2 folds of various scales are present. At least one of these folds has an axial plane which dips about 60° to the south, and the S_2 crenulation cleavage is axial planar to the fold. In some exposures along this cut there are two sets of crenulation cleavages, both of which are vertical. A (presumed) Keweenaw basalt dike, vertical and trending approximately N80E is exposed in this cut.

Driving Directions: Continue west on Highway 27 for 4.0 miles. Turn right (north) off the road into the farm driveway and park. After asking permission at the house, walk north from the house, just east of a line of trees along the edge of the farmer's field to the banks of Glaisby Brook.

STOP 6 (ALTERNATE STOP) GLAISBY BROOK

Rocks of these exposures along Glaisby Brook have also been mapped historically as Thomson Formation. They are part of a unnamed unit of metasedimentary and metavolcanic rocks (Pgvi) of Southwick, Morey, and McSwiggen (1988), but are still part of their Moose Lake - Glen Township structural panel. Although the exposure is overgrown and lichen-covered, it is possible to see an isoclinal recumbent fold in this outcrop, with several minor folds of normal vergence relationship (Figure 4). This is the largest example of an F_1 fold found to date in this region.

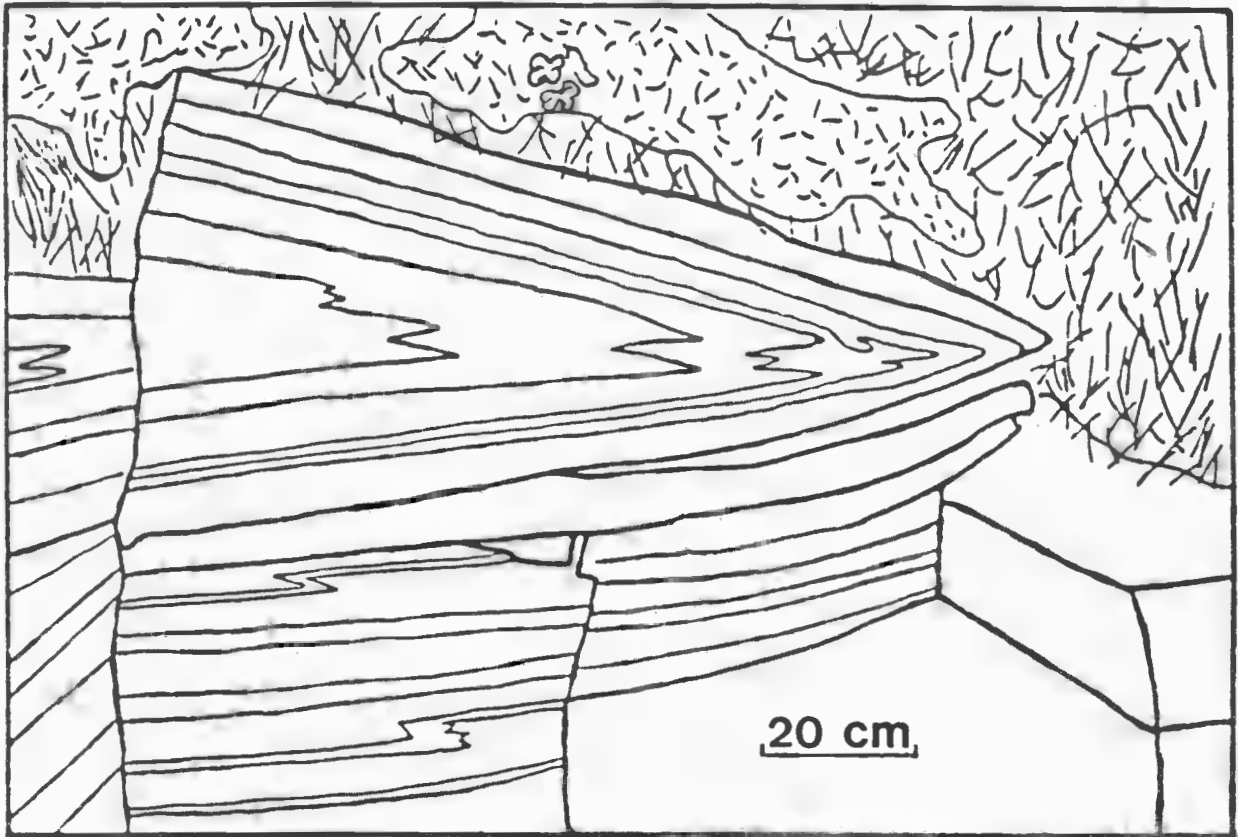


Figure 4: Sketch of F_1 fold at the Glaisby Brook outcrop about 4 miles west of Moose Lake.

Driving Directions: Return to the town of Moose Lake following Highway 27 back to the east for just over 4 miles. Turn left (northeast) at the stop light, and follow Highway 61 to the northeast (you need to turn left off the "main" road that goes to the freeway). Follow Highway 61 to the northeast passing through the town of Barnum in just over 4 miles. Continue for another 6 miles on Highway 61 to the village of Mahtowa. Turn left (northwest) on Carlton County 4 at Mahtowa. The road turns north after 0.6 miles, and then west after another 0.9 miles. Just after the turn to the west, turn right (north) onto Carlton County 7 toward Park Lake. Follow Carlton County 7 for 1.7 miles and Park. Proceed west and slightly south into the woods to a series of linear east-west outcrop ridges.

STOP 7 PARK LAKE

Rocks at this locality are part of the Thomson Formation, and contain two distinct foliations. This region has been mapped as Pvt_2 by Southwick, Morey, and Mcswiggen (1988): Thomson Formation with two foliations. The dominant foliation here is a cleavage that is parallel to bedding (S_1). The bedding (S_0) and cleavage (S_1) have been folded into open, upright subhorizontal folds (F_2) that trend east-west. A crenulation cleavage (S_2) is axial planar to these folds. In this area the crenulation cleavage (S_2) is present in most outcrops except for some of the graywacke units. The bedding-parallel foliation (S_1) is present everywhere except for a very few coarse graywacke beds. At the extreme southwest part of this exposure south of Park Lake, small scale isoclinal, recumbent folds (F_1) are present, to which the bedding-parallel foliation is axial planar (Figure 5). The S_1 foliation is at high angles to bedding only in the (rare) hinges of these F_1 folds. Some of the F_1 folds have been refolded by F_2 folds resulting in a Ramsay type 3 interference pattern.

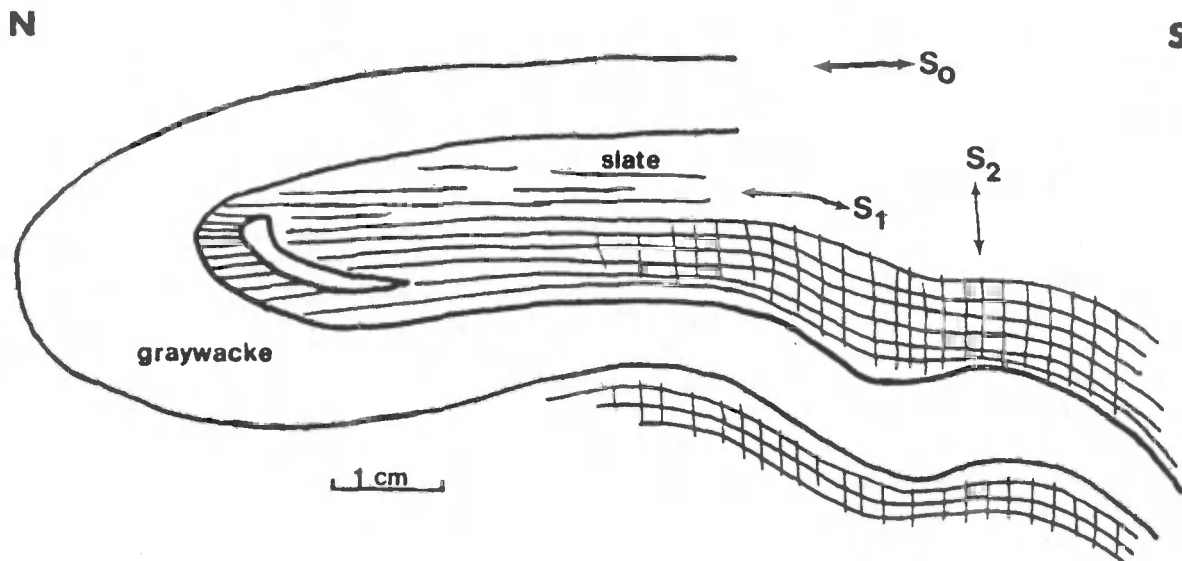


Figure 5: Sketch of a small fold at stop 7, Park Lake. Bedding (S_0) shown by the silt bed is folded into an isoclinal recumbent fold (F_1) with axial planar slaty cleavage (S_1) parallel with bedding on the limbs of the fold. Bedding and the S_1 foliation are folded by later upright folds (F_2) with the development of type 3 interference patterns (Ramsay, 1967) and a vertical crenulation cleavage (S_2).

Driving Directions: Return south by the same route (Carlton County 7 and 4) to the village of Mahtowa. Turn left (northeast) on Highway 61. Proceed northeast on Highway 61, passing through the village of Atkinson, and proceed under the freeway bridge 8.1 miles past Mahtowa. At the intersection which is 1.05 miles past the freeway bridge, turn right (south) and proceed 0.7 miles south on Gillogly Road to an outcrop on the left (east) side of the road, at the top of a hill.

STOP 8 GILLOGLY ROAD

At earlier stops on this field trip we have seen evidence for two periods of folding and foliation development in the southern structural terrane, and one main period of folding and foliation in the northern terrane. Holst (1984) argued that the early period of folding in the southern terrane also involved the emplacement of nappes. The evidence he cited for northward-directed nappes in the southern terrane included lithologic differences between the two terranes (also see Morey and Southwick, 1984, and Southwick, Morey and Mcswiggen, 1988), and the pervasive nature of the S_1 foliation in the area of its occurrence. Facing directions of F_2 folds (Figure 6) also indicate that a very large area of the southern terrane is on the upper limb of an F_1 fold. The refraction pattern of the S_1 foliation pattern in the region of this outcrop also suggests the existence of northward-directed nappes in the southern terrane, as explained below.

Several graded beds in the Thomson Formation can be seen at this locality striking east-west and dipping to the north. In the finer grained tops of these beds, a cleavage (S_1) can be observed. It is very gently folded, with horizontal axes trending east-west. If the cleavage is traced toward the bottom of a bed, it is seen to change its orientation markedly, and it becomes a spaced cleavage, dipping moderately to the south in the bottom part of the bed. A crenulation cleavage (S_2), vertical or very steeply dipping to the south, can be seen in the upper portion of the beds. Mud chips that are flattened in the early S_1 foliation are present. A line drawing of these relationships is shown in Figure 7. To interpret the pattern of this outcrop, it is useful to determine the orientation of S_0 and S_1 after the early phase of deformation, but prior to the later phase of deformation, which produced F_2 folds, the S_2 crenulation cleavage, and (very importantly for our purposes here) deformed the early S_1 cleavage, changing the geometry of bedding/cleavage vergence patterns. This can be done, at least to a fairly good approximation because we have strain data for both the southern and northern structural terranes in the region (Holst, 1985a). Results of strain determinations in the southern terrane give the finite strain which resulted from the superposition of the strain of the second deformation upon the strain of the first deformation. As the only deformational structures present in the northern terrane are those of the second deformation, the strain measured there represents the strain associated with the second deformation. By removing that strain from the finite strain measured in the south, we can approximate the strain associated with the first deformation in the southern terrane (Holst, 1985a; Holm, Holst, and Ellis, 1988). This is illustrated in Figure 8. By removing the second deformation strain from this outcrop we can reconstruct the bedding(S_0) /cleavage(S_1) geometry prior to the second deformation. The technique is illustrated in Figure 9. The graded sequence is generalized to alternating coarse and fine layers, with the attitude of bedding and the S_1 cleavage (in the finest and coarsest parts of the beds) as seen now in outcrop (Figure 9A). Removal of the strain associated with the second deformation allows a reconstruction of the geometrical relationships of these features prior to the second deformation (Figure 9B). The resulting bedding/cleavage vergence pattern (cleavage refraction pattern) is that to be expected on the upper limb and near the hinge of a large-scale isoclinal, recumbent fold (Figure 10). In the entire region of the southern terrane to the south, the S_1 cleavage is seen to be subparallel to the bedding. Significantly that is not true here, and in the outcrop 1 km to the north, along an abandoned railroad near Highway 61, the cleavage/bedding vergence pattern is the same as seen in this outcrop, although there are no graded beds there. Further, these two outcrops are very close to the boundary between the northern and southern structural terranes.

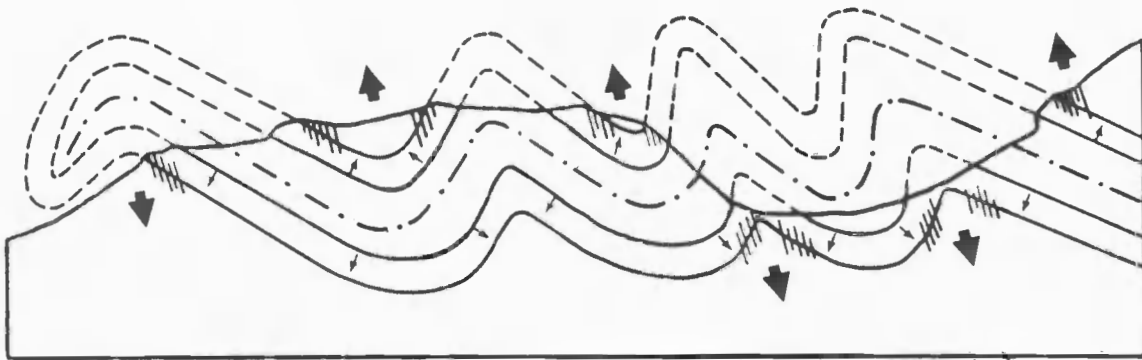


Figure 6: Illustration of facing direction of F_2 folds (after Borradaile, 1976). Dashed line is axial plane of F_1 fold. Foliation shown diagrammatically is S_2 axial planar crenulation cleavage. Small arrows indicate stratigraphic tops, large arrows indicate facing directions of F_2 folds.

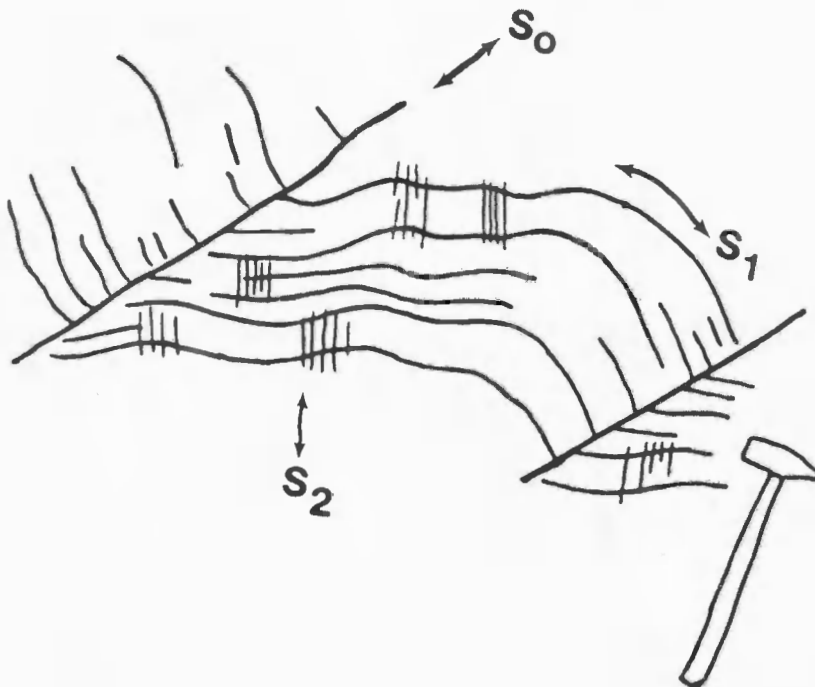


Figure 7: Line drawing of geometrical relations of bedding (S_0), early foliation (S_1), and crenulation cleavage (S_2) at Gillogly Road outcrop (Stop 8). Hammer handle is 40 cm long.

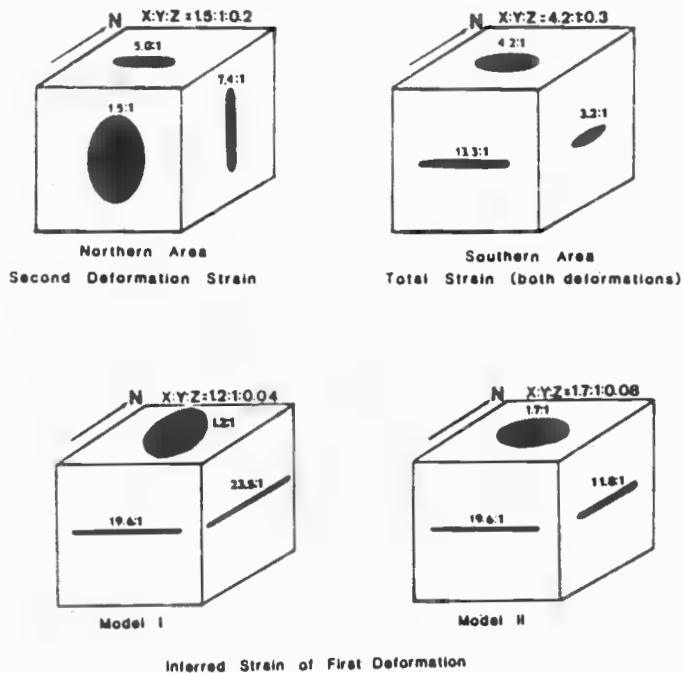


Figure 8: Representative block diagrams of the state of finite strain in the northern and southern structural terranes, and the strain inferred to have been associated with the first deformation.

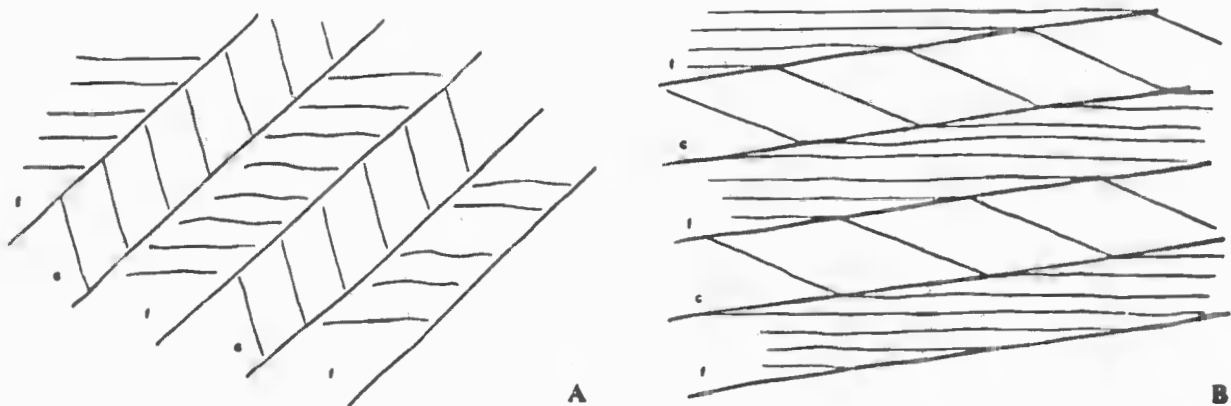


Figure 9: Bedding and cleavage at the Gillogly Road outcrop (Stop 8) (generalized to alternating coarse and fine layers instead of graded beds) showing the present geometry (A) and geometry after removal of the strain associated with the second phase of deformation (B).



Figure 10: Position on early large-scale isoclinal recumbent fold (nappe) of cleavage refraction pattern shown in Figure 9B.

Driving Directions: Return north on Gillogly Road 0.7 miles to Highway 61 and turn right (northeast) on Highway 61. Proceed for 1 mile to a road cut with outcrops on both side of the road.

STOP 9 HIGHWAY 61 ROAD CUT

The structural features seen in these exposures of the Thomson Formation are those seen at the type locality, Thomson Dam (Stop 1). Several upright, subhorizontal folds trend east-west. An axial planar cleavage is present, vertical or very steeply dipping to the south. Abundant mud chips are flattened in the plane of the cleavage. A faint vertical lineation is also present. The mud chips have been used for finite strain estimates. Some examples of cleavage refraction are present, and they show normal bedding/cleavage vergence relationships to the upright folds. No evidence has been found at this locality for the early foliation and recumbent folding seen in the southern structural terrane. At this point the boundary between the two structural terranes seems to be rather sharp.

Driving Directions: Proceed northeast along Highway 61 for 1.9 miles to an intersection with Minnesota Highway 210. Turn left (west) on Highway 210 and proceed for 0.1 miles and turn right on the entrance ramp to the freeway, I-35 North. Return to Duluth on Interstate 35.

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ROCK TYPES AND RELATIONSHIPS OF THE MELLEN IGNEOUS COMPLEX

A One Day Field Trip to the Keweenawan of the Mellen, Wisconsin Area

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Introduction

The purpose of this trip is to provide an opportunity to examine the rock-types, igneous features and relationships of the Mellen Complex. We will examine exposures that provide opportunities to compare this with other layered intrusions and make judgements on conditions and processes of formation. Critical exposures are often inaccessible for brief visits but there are many that we think you will find interesting and provide for lively discussion. A few locations we consider important but less accessible are noted and will be included if time and conditions permit.

Geology of the Mellen Area

General

The Mellen Complex includes several layered basic and related intrusions emplaced near the base of the Keweenawan volcanic pile. So far as has been determined the volcanics in the Mellen area are Lower Keweenawan nearly conformably overlying the older Proterozoic units of the Gogebic Iron Range. The lower contact of the complex is slightly discordant cutting to lower stratigraphic levels westward, beveling across the entire Proterozoic to Archean gneisses. All of the Proterozoic units have been tilted toward the northwest into the Lake Superior syncline resulting in northeast strikes and steep northwest dips. Faulting has accompanied this tilting but it is difficult to demonstrate in the field.

Paleomagnetic studies of Books, et.al.(1966) show normal polarity for the intrusive rocks of the Complex indicating Middle Keweenawan age for acquisition of its magnetism. Green(1982) places the Mellen Gabbro equivalent to the Duluth Complex but it could be slightly older. Halls and Pesonen(1982) indicate rocks of the Duluth Complex are found in contact with volcanics of normal polarity while the Mellen appears to intrude only reversed volcanics. We only know that the intrusives acquired their magnetic polarity during the normal period and they do not cut Upper Keweenawan sedimentary units.

Intrusive Units

The Mellen Complex includes two layered gabbroic intrusions the Potato River Intrusion (PRI) (Klewin 1987 & in review) on the east and the Mineral Lake Intrusion (MLI) (Olmsted, 1969; Seifert, in prep.) to the west. These are separated by the Mellen Granite (MG) which intruded the gabbro. Contacts between intrusives of the Complex are sharp, often with well developed breccias but chilling is only observed where pre-intrusive rocks are involved. Several smaller intrusives include the Rearing Pond (RP) intrusion (Olmsted, 1979) and a number of smaller gabbro and granophyre sills at the west end of the complex (Leighton, 1954)

The two larger intrusions have the size and character of layered intrusions throughout the world. The PRI is about 3.5 km. wide and extends along strike for over 30 km. The MLI is about 5 km. thick and about 15 km along strike but may have been faulted off on the west end indicating it's true length was somewhat greater. The RP is a small intrusion of elliptical plan with dimensions about 2 by 4 km.. It appears intruded into the upper part of the MLI but mapping does not indicate timing. A smaller more sill-like unit of similar petrographic character (the Picritic Zone, Figure 1) has intruded near the base of the PRI. Northwest of the MLI are several large gabbro and granophyre sills that intrude Lower Keweenawan volcanics or other

intrusions but to the west are also emplaced into older Proterozoic units (Leighton 1954). Leighton (1954) argued on the basis of differences between dip of igneous lamination and modal layering that tilting took place during intrusion. Halls & Pesonen (1982) note that the paleomagnetic pole positions of the Complex lie on the APW curve without structural correction indicating tilting prior to acquisition of polarity. This permits tilting prior to or during intrusion but is not conclusive.

Petrology

The Mellen Complex may be classified into three distinct types of intrusives. The PRI and MLI are coarse grained feldspathic gabbros that range from olivine rich to anorthositic compositions (Tables 1 & 2). Plagioclase and olivine are largely cumulus while pyroxenes more commonly occur as postcumulus oikocrysts. Rhythmic layering is rare but lamination is well developed roughly parallel to the regional structure (Leighton, 1954; Olmsted, 1969; Klewin, 1987). The RP and the Picritic Zone of the PRI are more mafic picritic intrusions that represent pulses of unique magma. The RP in particular is somewhat more primitive than the others having much higher Mg#s and more calcic plagioclase in addition to higher mafic mineral content. The third intrusive type is the Mellen Granite.

Cryptic zoning is observed in the larger intrusions indicating that some in situ fractionation occurred (Olmsted, 1969; 1979; Klewin, 1984). These (PRI & MLI) are zoned from gabbroic or anorthositic gabbro compositions through ferrodiorites to granitic rocks. There is some evidence that excessive amounts of granophyre resulted from addition of crustal minimum melt material (Seifert, in prep).

Two distinct granites occur at Mellen. Brick red granophyre often forms the uppermost units of the layered intrusions (Olmsted, 1969, Klewin 1987). It is also found intrusive into gabbros or metavolcanics in the western part of the complex (Leighton, 1954). Granophyres display spectacular simplectite textures in which quartz occurs intergrown with alkali feldspar in micrographic, radiating fringe and vermicular patterns (Leighton, 1954). Where these granitic units are thickened the above textures give way to hypidiomorphic granular with only minor intergrowth features. This is well displayed at a granite boss in the western part of the area called St. Peters Dome (sic.)

In contrast with the granophyre is the Mellen Granite. This medium to coarse porphyritic granite is one of the younger intrusives of the complex. It has intruded both the PRI on the east and MLI to the west. On the south it has intruded both Keweenawan volcanics and siltstones of the underlying Tyler formation. The nature of the upper contact is not well known as exposure is poor. At this time only preliminary analytical work has been accomplished on this intrusive so its chemical nature poorly known

Descriptions of the Intrusions

Potato River Intrusion

General

The PRI forms the eastern half of the Mellen Complex (Fig. 1) and will be the subject of the first part of the trip. In general, the PRI is poorly exposed, being mostly covered by unconsolidated Pleistocene sediment and heavy forest and many of the exposures are deeply weathered. Relief in the area is generally less than 150m with the highest hills underlain by resistant lower Keweenawan volcanics. The best exposures of intrusive rocks are scattered glacially scoured outcrops and along drainages. The overall length of the PRI is 33 km. It is divided approximately in half by a fault along the Tyler Forks River into a narrow and a much wider segment. The width of the intrusion ranges from about 1 km. to 4.5 km. averaging 3.6 east of the Tyler Forks River where the trip is focused.

Basal and roof contacts of the PRI are roughly concordant with the enclosing volcanics and with the regional structure. While the PRI is largely enclosed by volcanics it cuts into the underlying Proterozoic units near its western end. Rare xenoliths of metabasite have been found near the base of the intrusion.

Pm = Proterozoic
metasedimentary rocks
Ks = Keweenaw
sedimentary rocks
Kv = Keweenaw
volcanic rocks
Ar = Archean rocks



C-3

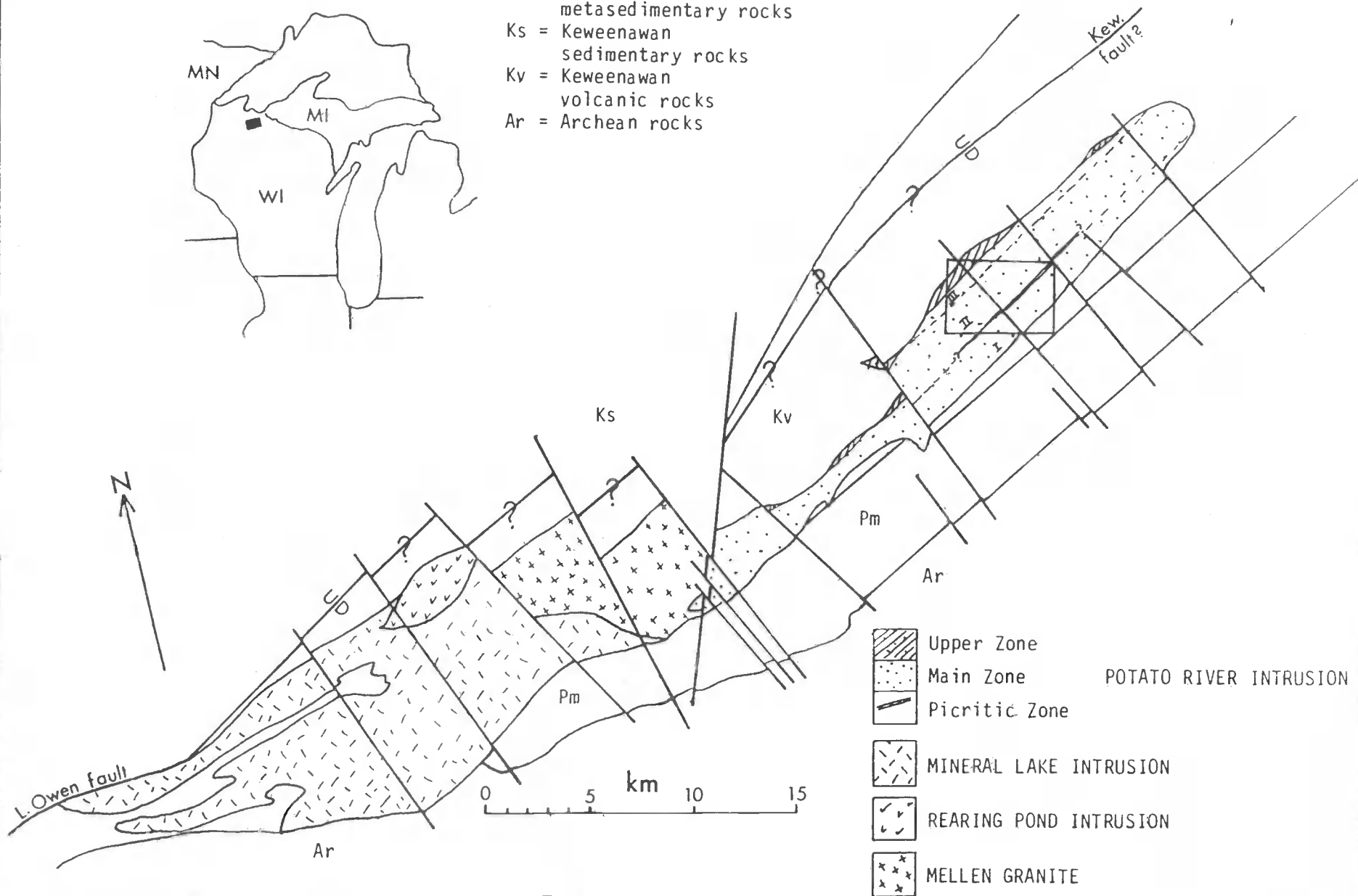


Figure 1

Exposures of plagioclase-rich rocks commonly exhibit lamination of the plagioclase laths. Tabet and Mangham (1978) reported an average orientation of N64°E, 84°NW. Occurrences of rhythmic layering with average orientation N57°E, 64°NW are restricted to the Picritic Zone near the middle of the PRI. Contacts between gabbroic rocks are typically gradational.

The PRI has been divided into several zones based on lithology (Fig.1; Klewin, in review). Lowermost is a poorly exposed Border Zone of highly altered olivine gabbro cut by rare contemporaneous or later dikes. Where exposed, the Border Zone is irregular in thickness, ranging up to 2 m. Most of the intrusion is assigned to the Main Zone of medium grained rocks ranging from olivine gabbro (at the base), leucogabbro and quartz gabbro to ferrogabbro (toward the top). The average thickness of the main zone is 3300 m. Present locally at the top of the intrusion is an Upper Zone of intrusive granite and granophyre. On the basis of trace element geochemistry (Klewin, in review) the granophyric rocks appear genetically related to the Main Zone rocks but coarser grained granitic dikes and irregularly shaped granitic intrusions (large dikes?) near the top of the intrusion west of the Tyler Forks River are not. The thickness of the Upper Zone ranges from zero locally to 120 m. Finally, midway into the Main Zone is the distinctive intrusive Picritic Zone consisting of picrite and troctolite. The thickness of the Picritic Zone is estimated to be 175 to 200 m. The Main Zone is further divided into Main Zones I, II and III. Main Zone I occurs below the Picritic Zone, is 850 m thick and consists of olivine gabbro and olivine leucogabbro. Main Zone II, above the Picritic Zone, is 1650 m thick and consists of olivine gabbro, olivine leucogabbro, gabbro and quartz-bearing leucogabbro. The arrival of cumulus augite occurs near the top of Main Zone II. The boundary between Main Zones II & III is marked by the arrival of cumulus Fe-Ti oxides. Main Zone III consists of quartz gabbro, quartz leucogabbro and ferrogabbro. Average thickness is 800 m. The arrival of cumulus apatite occurs in Main Zone III.

Petrography and Mineral Chemistry

Most of the Potato River Intrusion is composed of olivine gabbro and olivine bearing leucogabbro. Primary mineralogy is plagioclase, olivine, clinopyroxene, orthopyroxene, Fe-Ti oxides and apatite. Major cumulus minerals are plagioclase and olivine. Plagioclase typically forms normally zoned lath-shaped to blocky grains. Olivine is subhedral to anhedral and unzoned. Clinopyroxene is anhedral and forms oikocrysts where it is intercumulus and is often moderately zoned. Orthopyroxene is less common and occurs as inverted pigeonite. Ilmenite and titanomagnetite occur as small oikocrysts or interstitial patches or as skeletal cumulus grains in the ferrogabbros. Apatite typically occurs as tiny included grains but is larger and cumulus in the ferrogabbros. Quartz gabbro is marked by intercumulus micrographic intergrowths of quartz and alkali feldspar. Late stage gabbro also contains Ca-amphibole, and rarely fayalitic olivine and pigeonite.

Excepting the Picritic Zone, plagioclase composition ranges from An₇₁ to An₃₆; olivine Fo₆₃ to Fo₃₁ and augite Wo₄₄En₄₄Fs₁₂ to Wo₄₃En₃₂Fs₂₅. Even in the granophyric rocks the augite never becomes ferroaugite attesting to the modest degree of iron enrichment in the intrusion.

Main Zone rocks are mostly ortho- and mesocumulates, with a notable lack of adcumulus growth of plagioclase or olivine. Adcumulate troctolites, however are found in the Picritic Zone. The granophyric rocks exhibit spectacular radiating sheaves of intergrown quartz and alkali feldspar. Modal layering is rare but occurs in the Picritic Zone and planar lamination of plagioclase is common in the gabbros. The universal occurrence of the latter and almost total lack of the former throughout the complex is an interesting point that bears on processes and conditions during emplacement. Contacts between different gabbroic rocks are gradational supporting the single magma pulse hypothesis (excepting the Picritic Zone).

As judged by textural and structural relations the parent magma was saturated with both olivine and plagioclase. Subsequent arrivals as cumulus minerals were: augite (after 72% solidified), Fe-Ti oxides (after 75% solidified) and apatite (after 78% solidified). The cumulus minerals seem to come in gradually but this may be more apparent than real due to the very poor exposure.

References on the Potato River Intrusion

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Mineral Lake Intrusion General

As noted above the Mellen Complex is divided near its midpoint by the Mellen granite. West of the MG are the Mineral Lake and Rearing Pond intrusions (Olmsted, 1969, 1979) along with several smaller sills that make up the western part of the complex.(Leighton 1954). Exposure here is probably somewhat better than that found to the east. Many similarities and several important differences may be found between the two halves of the complex. Some of these will be considered here.

Like the PRI the Mineral Lake Intrusion is hyperfeldspathic with cumulus plagioclase and olivine. A ubiquitous feature is the alignment of plagioclase laths while modal or rhythmic layering is uncommon. The lower third of the MLI has been termed anorthositic olivine gabbro and represents that portion in which both olivine and plagioclase are cumulus. Above about 1500 m above the base olivine becomes less common and the rock grades to gabbroic anorthosite. This unit, over 2000 m thick is composed of over 80% plagioclase with minor pyroxene and Fe-Ti oxides. In many exposures the rock is true anorthosite and the lamination almost perfect. In glacially polished exposures where clinopyroxene oikocrysts are abundant the rock has a decided spotted appearance.

Near the top of the intrusion the feldspathic rocks give way to ferrodiorite which in turn grades upward through granodioritic to granitic or granophyric units. In the western part of the complex are found several areas of abundant granophyre to the point appearing excessive if one accepts the hypothesis that their origin is entirely through fractionation of a gabbroic parent. These granophyres are often intrusive into enclosing gabbros often forming spectacular breccias. It is unfortunate that none of these is easily accessible for your inspection. Recent isotope and trace element studies on the MLI suggest that this evolved felsic section includes a crustal component and was emplaced and differentiated as a separate conformable intrusion at the top of the anorthositic unit (Seifert et.al.,1985; Seifert, in preparation).

The upper contact of the MLI is with the overlying Rearing Pond intrusion as well as what are presumed to be Lower Keweenawan volcanics, now strongly recrystallized by contact metamorphism. Because of poor exposure it has not been possible to observe contact relations between the MLI and the RP intrusion so relative age is in doubt. It is suspected that like the case of the Picritic Zone of the PRI the closeness of timing prevented any chilling. The basal contacts of the MLI with underlying volcanics and hornfels are equally poorly exposed and what is exposed is often complicated. Considerable reduction of grain size is observed at the base but composition of these rocks disallow their use as parent magma.

Petrography and Mineral Chemistry

Modal analyses of representative rocks are found in Table 1. At first note the rocks labeled "Chill Zone" appear ordinary candidates but chemistry indicates they are somewhat evolved. Likewise their mineral compositions are evolved in comparison to the rocks immediately above. Overlying the basal rocks is an olivine rich zone(MG-4) that is probably not

continuous although better exposure might refute this. This mafic rich zone grades upward over 1000 -1500 m with olivine decreasing and plagioclase increasing. In this portion of the intrusion plagioclase lamination is not well developed. Pyroxene and Fe-Ti oxides are both intercumulus throughout this level. At about 1500 m above the base a very coarse "pegmatitic" unit is encountered that appears to be roughly parallel with the base. It is in this region only where modal layering has been observed. While it is not known if this horizon is continuous it has been mapped over a distance of about three km.. This is about the level where olivine becomes rare and the rocks above are rich in plagioclase and are laminated.

Olivine, now Fe-rich reappears as a cumulus phase in the ferrodiorite where plagioclase, pyroxene, oxides and apatite are cumulus. The very Fe-,Ti-,P-rich nature of this requires that fractionation played a substantial role in their development although in addition contamination by crustal material cannot be ruled out. Upwards, intercumulus granophyre becomes important while amphiboles replace olivine and pyroxene as common phases and modal apatite decreases. At one level large euhedral zircons are abundant.

Excepting the basal chill zone, plagioclase averages about An60, ranging to rims of An20 in the most felsic units. Moderate normal zoning about An10 is common but less so in the more feldspathic accumulates. Plagioclase in the basal Chill Zone is more strongly zoned but has an average value of An42. This corresponds with the whole rock chemistry. Olivine ranges from Fo65 near the base to Fo25 in the ferrodiorites. The Chill Zone olivines have intermediate values. Clinopyroxene values are Wo42En39Fs19 to Wo35En25Fs40 in the ferrodiorite demonstrating somewhat more Fe-enrichment than in the PRI.

Rearing Pond Intrusion

The Rearing Pond Intrusion is unique in several respects, although it somewhat resembles the Picritic Zone of the PRI. It is emplaced at the top of the MLI and with the exception of its extreme western end where it intrudes metavolcanics it is enclosed entirely by other intrusive rocks. Like the Picritic Zone it is composed of olivine rich rocks and exhibits some modal layering. Textures and mineralogy were studied by Olmsted, 1979, but much work remains to understand its chemistry. Based on mineralogy it too is differentiated but not to the degree of the MLI. Olmsted 1979, proposed an elongated funnel shape for the intrusion and on the basis of orientation of layering suggested that it has experienced the tilting typical of the region. Near its outer perimeter is found a peridotite layer composed largely of cumulus olivine with intercumulus clinopyroxene and plagioclase. The uppermost rocks are gabbro and quartz gabbro lying above a large central troctolitic unit.

Abundant olivine in the RP averages about Fo80 and is rather strongly serpentinized. The very high Mg#s of the rock analyses are in line with this primitive composition. Plagioclase composition ranges from An85 in lowermost rocks to An50 in the gabbro. Pyroxenes are equally primitive with compositions CPX En49Wo46Fs5 and OPX ranging from En80 in the troctolite and peridotite to En68 in gabbro.

While time will not permit extensive study of this intrusion we will make one stop that will provide an opportunity to examine two of the three major rocktypes.

References to the Mineral Lake and Rearing Pond Intrusions.

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- _____, 1979, Crystallization history and textures of the Rearing Pond gabbro, northwestern Wisconsin. Am.Mineral., v.64, p844-855.
- Seifert, K.E., Peterman,Z.E. and Windom,K.E., 1985, Mineral Lake layered intrusion, NWWisconsin. Geol. Soc. America Abs. with Prog.,17, p.712.
- _____, in prep., Geochemistry of the Mineral Lake pluton, NW Wisconsin.

Field Trip Stop Descriptions

Potato River Intrusion

All of the stops are on county forest land, the roads are quite good there should be no difficulty with access. Watch for ticks in the spring, logging trucks in the summer, deer hunters in the fall and snowmobiles in the winter. The locations are shown in Fig. 2 which shows a portion of the Saxon 7.5' quadrangle map. The intrusion essentially parallels WI Hwy.77 between Mellen and Hurley. The trip begins at the intersection of highways 77 and 122 in Upson, WI.

STOP 1 along Hwy. 122 north of Upson. Picritic Zone rocks.

Proceed north from Upson on Hwy. 122 over the range of hills that marks the Keweenawan, Powdermill Group lavas. When the road straightens to a northerly heading (~4.5 mi. N of Upson) look for a gravel road to the right (E). Turn onto the gravel road and park after about 50 m. South of the road is a small outcrop of massive troctolite (Tables 1&2) of the Picritic Zone. On the south side of the outcrop the basal contact of the Picritic Zone with altered pegmatitic gabbro of the Main Zone can be seen. The troctolite is massive and has adcumulate texture. Plagioclase grains in this rock are equant in shape opposed to lath-shaped as in the other troctolites. Olivine is anhedral and appears to have undergone considerable adcumulus growth. With careful study you can observe small grains of Cr-rich spinel in the troctolite (>7 wt.% Cr₂O₃; whole rock Cr up to 500 ppm). In terms of texture (massive, adcumulate), mineral composition (the most primitive, An₇₀, Fo₆₇), and Cr-spinel; this outcrop is unique in the Potato River Intrusion. It may represent an addition of mafic magma unrelated to the rest of the Picritic Zone.

Return to Hwy.122 and proceed N about 200 m to a second gravel road, this time to the left (W), and drive about 200 m W and park. Directly south is another outcrop of Picritic Zone rock. Here again the base of the Picritic Zone with underlying Main Zone pegmatitic rock can be seen. The Picritic Zone rock in this exposure is an olivine rich picrite containing up to 50 modal % olivine. The texture is massive to layered with faint rhythmic layering visible in places. Large oikocrysts of clinopyroxene enclose olivine and plagioclase. Cr-spinel is lacking and whole rock Cr content is in the range of 150-200 ppm. Nickel content is also low for such olivine rich rocks in the range of 700-750 ppm. Inasmuch as the An and Fo contents are not high relative to the rest of the intrusion, this outcrop may represent a zone of accumulation of mafic minerals.

STOP 2 Along the Potato River. Top of Main Zone II.

Continue west on the gravel road about three miles where the road ends at a turn-around. Just to the west is the Potato River and a small waterfall. The rock here is quartz-bearing leucogabbro (Tables 1 & 2). In a small outcrop just up from the river the distinctive reddish color of weathered interstitial Alk-Feldspar can be seen. This rock is composed of plagioclase, clinopyroxene, Fe-Ti oxides and interstitial patches of micrographically intergrown quartz and alkali-feldspar. The feldspar contains some iron which produces the red color when altered. The outcrop in the river provides an excellent example of lamination of plagioclase grains. The outcrop is cut by aphanitic basaltic dikes. Further north along the river the intrusive nature of the Upper Zone rocks can be seen.

STOP 3 Along gravel road west of Upson. Main Zone I.

Retrace the route to Upson via Hwy 122. Turn right (W) on Hwy.77, proceed about 3 miles and turn right (N) on a gravel road, proceed ~ 2.5 miles and park along road. Several low outcrops along the road are typical of Main Zone I. They are olivine gabbros (Tables 1 &

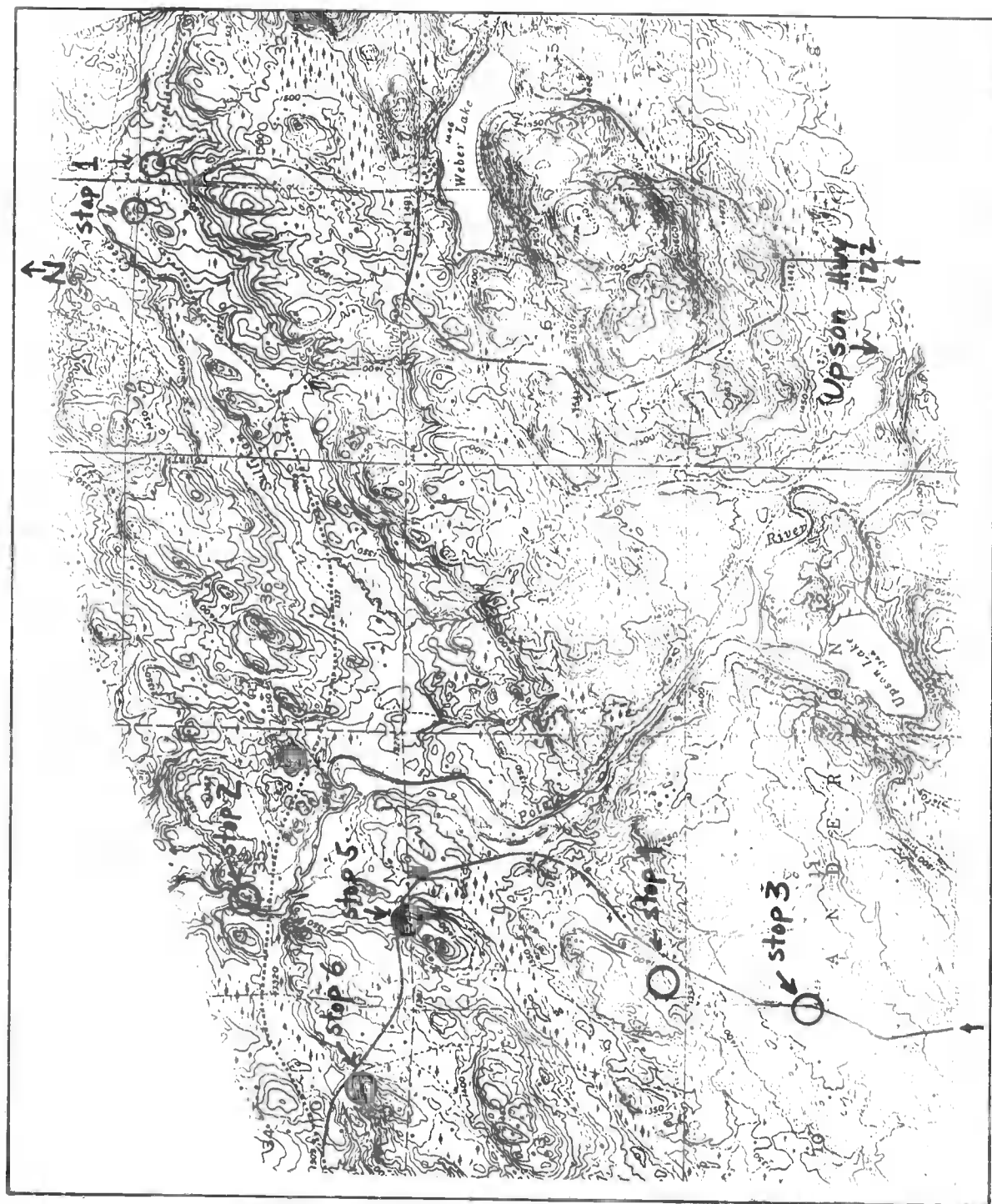


Figure 2

Table 1 Modes

SAMPLE	ROCKTYPE	PLAG.	OL	CPX	OPX	OXIDE	HLBD.	BIOT.	AP	K-SPAR	QZ	OTHER
MINERAL LAKE INTRUSION												
"6-5-65"	Chill Zone	51.2	3.6	20.2	10.8	5.4	3.8	4.5	TR			
Ave.MG56-8	Chill Zone	55.5	2.5	*32.5		5.0		4.0	TR			
MG-4	Olivine Gabbro	20.0	40.0	*38.0		1.0		1.0				
MG-6	Gabbro	40.0		*59.0		1.0						
MG-9	Gab. Anorthosite	80.0		*18.0		2.0						
"11-9"	Gab. Anorthosite	79.5	9.3	2.9	5.1	1.4	1.7	1.7	TR			
"3-10"	Gab. Anorthosite	78.0		*12.7		0.7	9.2	0.4				
"25-42"	Ferrodiorite	61.5	14.3	*11.9		6.2	1.3	1.8	2.9			
MG-16	Q. Monzodiorite	40.0	TR			2.0	30.0	5.0		10.0	13.0	
MG-17	Q. Monzodiorite	30.0		*8.0		TR	12.0			30.0	20.0	
MG-18	Granophyre							3.0		49.0	48.0	
MG-19	Granophyre					2.0					30.0	*68.0
POTATO RIVER INTRUSION												
84-40D	Troctolite	76.0	20.0	3.0		1.0						
83-28C	Picrite	25.0	55.0	15.0	2.0	3.0						
84-43B	Q. Leucogabbro	66.0		25.0		2.0				2.0	5.0	
84-71A	Granophyre	65.0		5.0		5.0			TR	10.0	5.0	TR
84-49A	Olivine Gabbro	65.0	15.0	15.0	3.0	2.0						
84-51B	Layered Troctoli	52.0	45.0	1.0	1.0	1.0						
84-53D	Olivine Gabbro	64.0	18.0	15.0		3.0						
84-54C	Quartz Gabbro	50.0		40.0		5.0				1.0	4.0	
REARING POND INTRUSION												
W-39	Ol Gabbro	54.6	13.8	25.6	5.4	0.6						
W-163	Troctolite	52.8	39.7	5.1	2.2	0.6	0.6					
W-74	Peridotite	24.3	72.4	0.2	2.2	1.1						
W-6	Gabbro	55.6	0.5	13.2	15.7	0.3	14.6	0.1	TR			
W-164	Gabbro	52.7		25.5	7.6	4.3	1.0	3.2	0.4	0.4	3.0	TR

*Includes CPX & OPX undistinguished

* Largely altered granophyric material

Table 2 Analyses

Mineral Lake Intrusion										Mellen Granite	Rearing Pond	
Oxides	M0 55,56 58 Ave.	M0 - 4	M0 - 9	M0 - 14	25-42	M0 - 16	M0 - 17	M0 - 18	M0 - 19	Mean n=4	RP Mag	87-11P
SiO2	47.70	44.30	50.40	48.30	43.56	56.40	60.00	74.40	75.60	69.26	44.47	37.22
TiO2	2.57	1.86	1.23	0.87	3.31	1.75	1.67	0.26	0.16	0.45	1.18	0.32
Al2O3	15.40	9.66	24.10	22.60	13.61	15.20	14.20	12.80	12.40	13.88	18.86	4.30
FeOt	14.60	20.70	5.65	8.42	20.60	12.50	9.46	2.29	1.92	4.00	7.84	16.41
MnO	0.21	0.28	0.08	0.10	0.31	0.18	0.13	0.04	0.04	0.07	0.11	0.27
MgO	6.62	14.30	2.06	5.42	3.66	2.31	1.91	0.18	0.08	0.40	10.90	29.19
CaO	8.76	6.05	10.90	10.40	9.35	5.33	5.27	0.62	0.38	1.45	10.13	2.85
Na2O	2.75	1.98	4.30	3.86	2.62	3.39	4.15	3.90	4.07	3.47	1.89	0.13
K2O	0.38	0.42	0.76	0.10	0.42	2.11	2.28	5.47	5.35	5.61	0.36	0.09
P2O5	0.44	0.20	0.39	0.33	1.67	0.54	0.60	0.04	0.03	0.05	0.12	0.01
LOI	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.04	ND	ND
TOTAL	99.43	99.75	99.87	100.40	99.11	99.71	99.67	100.00	100.03	99.68	95.86	90.79
Mg #	45	55	39	53	24	25	26	13	7	15	71	76
CIPW Norms												
Ap	0.96	0.44	0.85	0.78	3.67	1.18	1.31	0.09	0.07	0.11	0.27	0.02
Mt	2.36	3.34	0.92	1.99	3.35	2.02	1.53	0.37	0.30	0.65	1.32	2.91
Il	4.91	3.54	2.34	1.65	6.34	3.33	3.18	0.50	0.31	0.87	2.34	0.67
Or	2.25	2.48	4.49	0.59	2.50	12.47	13.49	32.44	32.06	33.56	2.21	0.58
Ab	23.35	16.74	30.69	28.80	22.30	28.70	35.17	29.84	32.20	29.73	16.65	1.21
An	28.65	16.22	44.21	43.90	24.28	20.04	13.41	2.84	1.13	5.80	43.65	11.96
NE	0.00	0.00	3.08	2.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Q	0.00	0.00	0.00	0.00	0.00	7.62	10.45	29.48	30.04	21.32	0.00	0.00
Di	10.05	10.27	6.12	4.41	9.79	2.48	7.56	0.00	0.52	1.00	6.34	2.82
Hy	16.50	8.40	0.00	0.00	13.29	21.46	13.17	3.63	2.55	6.20	2.18	9.48
Ol	10.40	38.14	6.70	15.90	13.83	0.00	0.00	0.00	0.00	0.00	24.58	70.06

M055,56,58AVE, ChillZone, M0-4, Ol.Gabbro, STOP 7; M0-14,M0-9, Gab.Anorthosite, STOPS 9 & 10
 25-42 Ferrodiorite, M0 - 16, 17, Q. Monzogabbro, STOP 11
 M0 - 18, 19, Granophyre, STOP D
 RPMA0, Troctolite; 87-11P Peridotite, STOP 12

Table 2 Analyses

Potato River Intrusion

PRI Estimated Bulk Compositions

	84-40D	83-28C	84-43B	84-71A	84-49A	84-51B	84-53D	84-54C	MZ I	PZ	MZ II	MZ III	UZ
SiO ₂	46.06	40.91	51.10	61.98	47.98	44.35	48.56	49.31	48.64	47.46	50.88	50.74	62.27
TiO ₂	0.41	0.99	1.63	0.77	1.12	0.23	1.62	3.49	0.97	0.75	1.25	3.01	1.71
Al ₂ O ₃	20.20	6.06	19.62	13.76	19.59	14.36	19.48	15.65	18.70	17.91	20.62	14.87	12.89
Fe ₂ O ₃	2.27	3.76	1.94	5.23	1.78	2.56	2.89	3.36	1.58	1.90	2.03	4.98	4.31
FeO	7.92	23.32	5.72	5.28	8.12	14.56	7.88	9.28	9.10	10.31	6.36	9.78	5.68
MnO	0.12	0.33	0.12	0.16	0.12	0.21	0.13	0.17	0.13	0.15	0.12	0.21	0.19
MgO	9.16	19.67	3.58	1.07	6.57	14.70	5.40	4.22	7.86	9.50	4.51	3.11	2.01
CaO	10.26	4.80	11.73	3.20	11.17	6.75	9.49	10.47	10.13	9.23	10.77	9.01	3.73
Na ₂ O	2.29	0.86	3.07	3.90	2.61	2.05	2.92	2.74	2.66	2.50	3.06	2.86	3.55
K ₂ O	0.23	0.16	0.51	3.18	0.44	0.20	0.54	0.61	0.32	0.38	0.47	1.16	3.65
P ₂ O ₅	0.01	0.06	0.17	0.11	0.12	0.02	0.17	0.29	0.07	0.03	0.13	0.76	0.44
LOI	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
TOTAL	98.93	100.92	99.19	98.64	99.62	99.99	99.08	99.59	100.16	100.12	100.20	100.49	100.43
Mg#	66	61	50	18	59	65	52	42	61	62	54	31	31
<i>CIPW Norms</i>													
Ap	0.0	0.1	0.4	0.3	0.3	0.1	0.4	0.7	0.2	0.1	0.3	1.8	1.0
Mt	3.3	6.4	2.8	2.5	2.6	3.7	4.2	4.9	2.3	2.8	2.9	7.2	6.3
Il	0.8	1.9	3.1	1.5	2.1	0.4	3.1	6.6	1.8	1.4	2.4	5.7	3.3
Or	1.4	0.9	3.0	19.1	2.6	1.2	3.2	3.6	1.9	2.3	2.8	6.9	21.6
Ab	19.4	7.2	26.0	33.6	22.1	17.4	24.7	23.2	22.5	21.2	25.9	24.2	30.0
An	44.2	12.1	38.3	10.8	40.4	29.4	38.5	28.6	38.1	36.5	41.1	24.3	8.5
NE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Q	0.0	0.0	2.4	14.1	0.0	0.0	0.0	3.7	0.0	0.0	0.6	7.0	17.5
Di	5.4	9.1	15.4	4.0	11.6	3.2	6.2	17.6	9.5	7.4	9.4	12.8	5.9
Hy	3.7	12.2	7.8	14.1	5.4	4.1	15.8	10.6	9.8	7.1	14.8	10.6	6.5
Ol	20.8	49.9	0.0	0.0	12.5	40.5	3.2	0.0	14.0	21.5	0.0	0.0	0.0

84-40D Massive Troctolite, 83-28C Picrite, STOP 1; 83-43B, Q.Leucogabbro, 84-71A, Granophyre, STOP 2
 84-49A, Ol.Gabbro, STOP 3; 84-51B, Layered Troctolite, STOP 4; 84-53D, Ol.Gabbro, STOP 5; 84-54C, Q.Gabbro, STOP 6
 Estimated Bulk Compositions: MZ I, Main Zone I; PZ, Picritic Zone; MZ II, Main Zone II;
 MZ III, Main Zone III; UZ, Upper Zone

2) composed of cumulus plagioclase (An64-62) and olivine (Fo62-57) along with intercumulus clinopyroxene and Fe-Ti oxides.

STOP 4 Along gravel road west of Upson. Rhythmic layering in the Picritic Zone.

Continue about one mile N along the gravel road to an overgrown logging road to the left. There is active logging in the area and roads spring up from year to year. To distinguish the correct one there should not be a road to the right directly opposite this one as there are in other places. Park on the overgrown road and walk W up a slight hill to the top (50-100 m). At the top of the hill turn right (N) into the woods 100-200 m. Here is a low outcrop of layered troctolite of the upper part of the Picritic Zone. The distinctive feature of this rock is rhythmic modal layering. Plagioclase (An67.5) rich and olivine (Fo63.5) rich layers alternate on the scale of centimeters. Lath-shaped plagioclase grains are laminated in the leucocratic layers. Here the plagioclase and olivine are more calcic and magnesian respectively than in the adjacent Main Zone rocks but less so than in the massive troctolites. This part of the Picritic Zone is the only part of the intrusion that exhibits rhythmic layering. What do you make of that?

STOP 5 Along gravel road W of Upson. Main Zone II rocks.

Continue along gravel road about 1.5 miles. As the road turns left to round a hill stop when you are heading W and park. The hill is underlain by olivine gabbro of the Main Zone II (Tables 1 & 2). This is cut by a typical Keweenawan high Ti-P dike. This is about the highest occurrence of olivine gabbro in the intrusion. Plagioclase here is not strongly laminated, its composition is about An60 and olivine composition is about Fo55.

STOP 6 Along gravel road rest of Upson. Main Zone III rocks.

Continue on the gravel road for about 1 mile until there is another hill just to the left. If you reach a small lake on the right you have gone too far. This hill is composed of quartz bearing gabbro of the Main Zone III (Tables 1 & 2) also cut by a diabase dike. The rock here is composed of cumulus plagioclase, clinopyroxene and Fe-Ti oxides with interstitial quartz and alkali feldspar. This is the lower part of the Main Zone III; after the appearance of cumulus oxides, but before cumulus apatite.

Return to Hwy.77, turn right (W) toward Mellen which is about 13 miles. On reaching Mellen proceed N on Hwy.13 through town about 1 mile. Turn right on Hwy 169 to Gurney following the signs to Copper Falls State Park where we will eat lunch.

STOP A

You are encouraged to walk the short distance along the trails to and just beyond Brownstone Falls where the contact between the volcanics (reversed polarity) and the upper Keweenawan may be seen. Continuing along the path beyond the Brownstone Falls you are proceeding up section through the Copper Harbor Conglomerate, the Nonsuch Formation and into the lower part of the Freda Sandstone. As you will see the units are vertical here with strike about N60E. The uppermost volcanics at the Brownstone Falls are rhyolite flows overlying basalt. One of us at least (JFO) thinks the Mid- Upper Keweenawan contact here is a fault. What's yours?

Mellen Granite Brief optional stops along the road in both cases to observe the porphyritic granite.

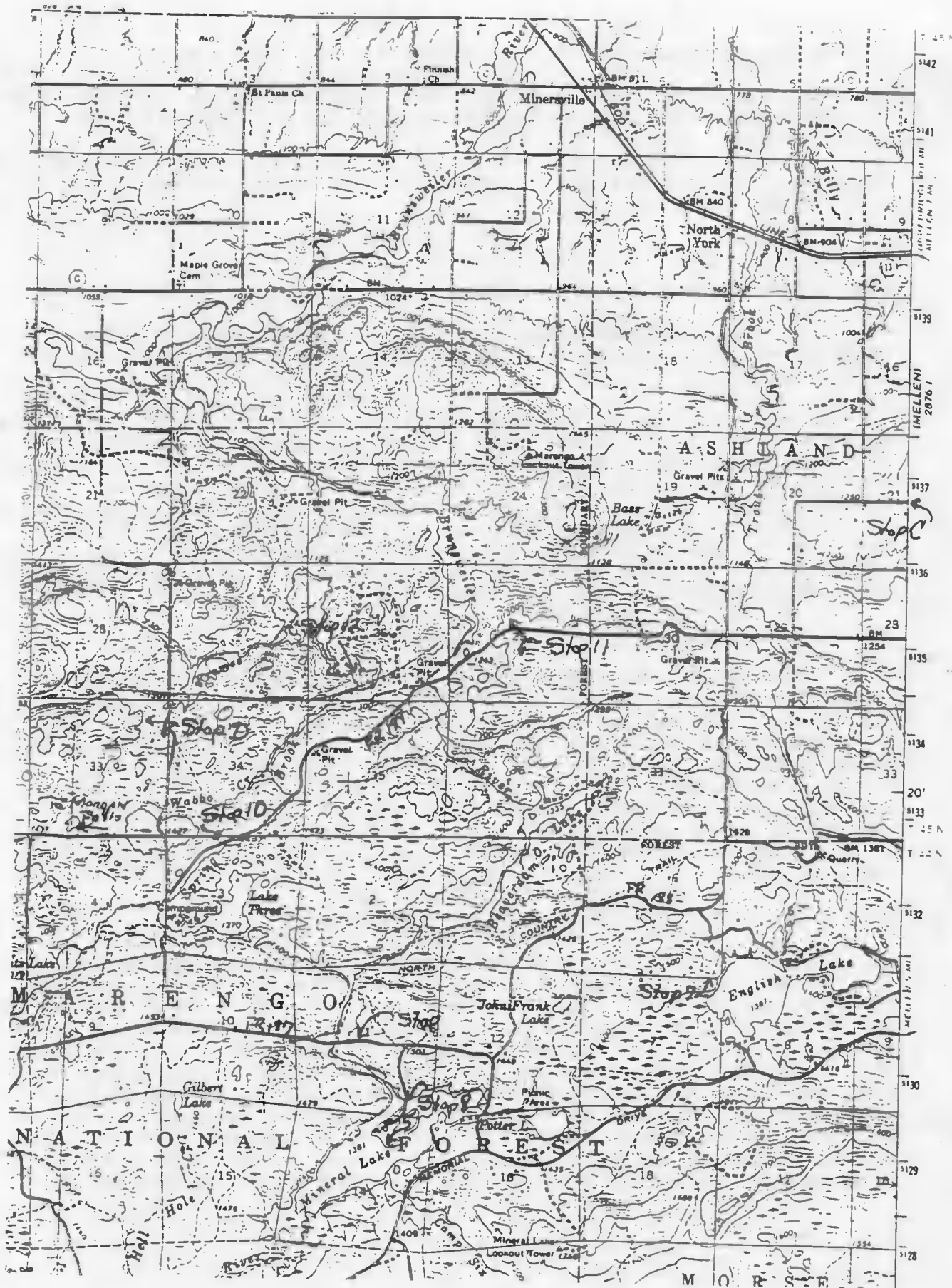


Figure 3

STOP B Intrusive Breccia along the W side of Hwy 13 about 1 mile N of Mellen.

Blocks of gabbro enclosed in coarse grained granite. Note how it is possible to mentally fit many of the gabbro fragments back together. Also note lack of chilling of the granite.

Proceed N on Hwy 13 about 1 mile and turn left onto County Hwy C. Continue W about 3 miles where road turns right (N), continue N 1/2 mile. Turn left on gravel road proceed W about 1/2 mile to top of rise.

STOP C Massive Mellen Granite cut by dikes.

Stop at top of hill where you see outcrops of granite on both sides of road. This is private land so please respect the owners fence. Walk south of the road to examine textures and dike occurrences.

Continue along road, first W one mile then S one mile to a T in the road. Turn right (W) proceed W 1/2 mile to a 4-corners. Turn left (S) (This becomes National Forest Road 188.) continuing for about 2 miles to a gravel road left to English Lake. Please be respectful here as the natives are sometimes unfriendly. Turn left (roughly S) into the English Lake road, proceeding about 1/4 mile to an unimproved but passable road to the right. Look for a sign stating the name E. Ceres. Proceed carefully about 1/4 mile looking for a fork to the right. There is an inconspicuous 2-wire power line overhead that follows this fork of the road. If you arrive at a cottage on the lake you have gone too far. Return to the top of the hill. Park in the fork far enough so others can pass to the cottage.

STOP 7. Basal contact of the Mineral Lake intrusion.

Walk along under the power line (200 m) to the third power pole that is planted in the outcrop. The hill drops rapidly here into a small valley. Look for many drill core holes in the rock. Most of the rock exposed here is fine grained gabbro but the rock on the SE corner of the outcrop is hornfels. Look for this contact and look for inclusions of hornfels within the fine grained gabbro. The texture of the gabbro here at the contact is intergranular with very elongate plagioclase (An42-45). (6-5-65 & MG 55 etc. Tables 1 & 2). (Ol.~Fo40, Cpx. Wo40 En34 Fs26) Note that back along the power line away from the contact the rock gradually becomes more coarse and the texture subophitic. Proceeding southwesterly through the woods across a small valley to the top of the next hill where there are a number of outcrops of basal olivine rich gabbro (MG-4). Return via the power line.

STOP 8 Olivine Gabbro and "Pegmatitic" and Layered Zone.

Return to FR 188. Turn left, W, proceed about 2.5 miles to intersection with FR187. Turn right, continue westerly about 1/2 mile to a driveway left into the home of Harold Smith, proceed about 1/2 mile to the house. Park near the house and seek permission. Walk down to the beach and left to the south end of the beach and into the trees to the first outcrop. This is an olivine gabbro about 600 m above the base of the intrusion. Return to the car and back along the road about 3/8 mile to the base of a steep rise in the road. Small outcrop on W side of the road of very coarse "pegmatitic" gabbro. This unit has been mapped over two miles along the north side of Mineral Lake and beyond and represents an important horizon in the intrusion. If the water in the lake is very low we may cross the river where it exits the lake to examine modal layering that occurs just above the pegmatite. Olivine continues as a minor phase above this level but is no longer abundant. The rock is exceptionally feldspathic above.

STOP 9 Briefly: Spotted Anorthositic Gabbro

Return to FR 187, turn left (W) about 1/2 mile to a large outcrop on the right. (Just before this exposure look for low blasted outcrops on either side of the road which are good places to collect this rocktype.) Poikilitic Anorthositic Gabbro (MG-14, 11-9). An excellent example showing a common texture. Plag. An60, Ol. Fo65, Opx En66, Cpx Wo42, En39, Fs19.

STOP 10 Briefly Laminated Gabbroic Anorthosite

Continue W on FR187 about 1.5 miles then north at "Pine Stump Corner" and then about one mile past the Lake "3" Campgrounds, turn right NE on FR 189 go 5/8 mile stop at what was once a small gravel pit on the left side of the road, now quite overgrown. Large polished outcrop of anorthositic rock in back wall of the pit (MG-9). Plag. An60, Cpx Wo37, En29, Fs34.

STOP 11 Ferrodiorite, Monzogabbro etc. (Transition Zone)

Continue along FR 189 Cross Brunsweller River at 2 miles, continue about 3/4 mile beyond the river to where the road turns to an E direction. Walk straight S into the woods about 150 m where an irregular EW ridge exposes black rust stained Ferrodiorite (25-42; Plag. An45, Ol. Fo24, Opx. En37, Cpx.Wo38 En24 Fs38) note cumulate and laminated texture and conspicuously finer grain size. Retrace your path back crossing the road to the north side working your way north along the west side of the hill. Several outcrops here show gradually increasing reddish felsic content (MG-16, 17).

STOP 12 Rearing Pond Intrusion

Turn around and go back over the Brunsweller River past a gravel pit on right and turn right on woods road a few meters beyond. Continue northerly about 1/2 mile, turn left continue another 1/2 mile or less, then left again, and left again in about 1/4 mile. (If you encounter a bridge over a brook go back.) After the last turn proceed cautiously about 100m to a brook where the road ends. An outcrop on your left is peridotite (W-74, similar to 87-11P) of the lower part of the Rearing Pond intrusion. Walk along what remains of the road (a path by now) cross the brook jumping rocks, and pick up the remains of the road on the other side. A few meters beyond the brook search to the right of the path for the remains of a picnic grounds (a couple of fire places is all that's left) and several large cliff like outcrops beyond. We will work our way around to the left and circle the hill studying the rocks and their textures and features as we proceed (RPMag, 87-11T and W-163). This is the remains of a State trout hatchery that was abandoned at the beginning of WWII. Good Archaeology here.

STOP D Granophyre Time Permitting

Return to FR 189, turn right and return to FR 187. Proceed N on FR 187, 1.5 miles to the inflection point of an "S" turn (Large Outcrop on right) park on left W side of road. A few meters SW into the woods is an outcrop of a granitic rock. From this point proceed on a heading of 290 about 300 meters, eventually up a fairly tiring hill. Good exposures of Granophyre here. (MG-18, 19)

STOP E Alternate Granophyre exposure. Morgan Falls.

From the intersection of FR 187 & 198 go N 1/2 mile, turn left on FR 193 following the signs to Morgan Falls. Park in the lot provided and walk the trail to the falls. This is a spectacular 100 foot high waterfall over the brick red granophyre. Contact of granophyre and gabbro can be seen west of the falls along the upper part of the ridge.

GENERAL GEOLOGY AND STRUCTURE OF ARCHEAN ROCKS OF THE VIRGINIA HORN AREA, NORTHEASTERN MINNESOTA

J.L. Welsh, D.L. England, D.A. Groves, E. Levy

Introduction

The "Virginia Horn" refers to the prominent Z-shaped outcrop pattern of Animikie Group rocks present in the Virginia-Eveleth area of the Mesabi Range (Fig. 1), and reflects the broad northeasterly trending anticline and syncline into which these rocks have been folded. These Proterozoic rocks unconformably overlie Archean basement rocks, which are exposed north of the Mesabi Range along the Laurentian Divide. Supracrustal metavolcanic and metasedimentary rocks and assorted small intrusive bodies of the basement complex occur along a narrow strip which extends from Mountain Iron on the west to the Aurora vicinity on the east, and which are bordered by the Giants Range Complex on the north. These rocks are particularly well exposed in the anticlinal axis of the Virginia Horn, and have been the recent focus of gold exploration.

Previous Work

Until recently, Archean rocks in the Virginia Horn area have received little attention, and little has been published on these rocks. Brief descriptions of Archean rocks in the area were first provided by Leith (1903) as a result of his investigations into the geology of the Mesabi District. J.W. Gruner also investigated the Archean rocks during his studies of the Mesabi District, and reported an occurrence of visible gold in a felsic porphyry body (Grout, 1937). Sutton (1963) developed a more detailed geological map of the area, based largely on Gruner's work, and provided petrographic descriptions for some metasedimentary rocks and the felsic porphyry bodies.

The metavolcanic and metasedimentary rocks in the Virginia Horn area have in the past been correlated with the Ely Greenstone and the Knife Lake Series, respectively, of the Vermilion District (e.g. Grout et al., 1951). As these rocks are physically separated from the Vermilion District by the Giants Range Complex and were correlated only because of lithologic similarity, designations of Ely Greenstone and Knife Lake Series for rocks in the Virginia Horn should no longer be used.

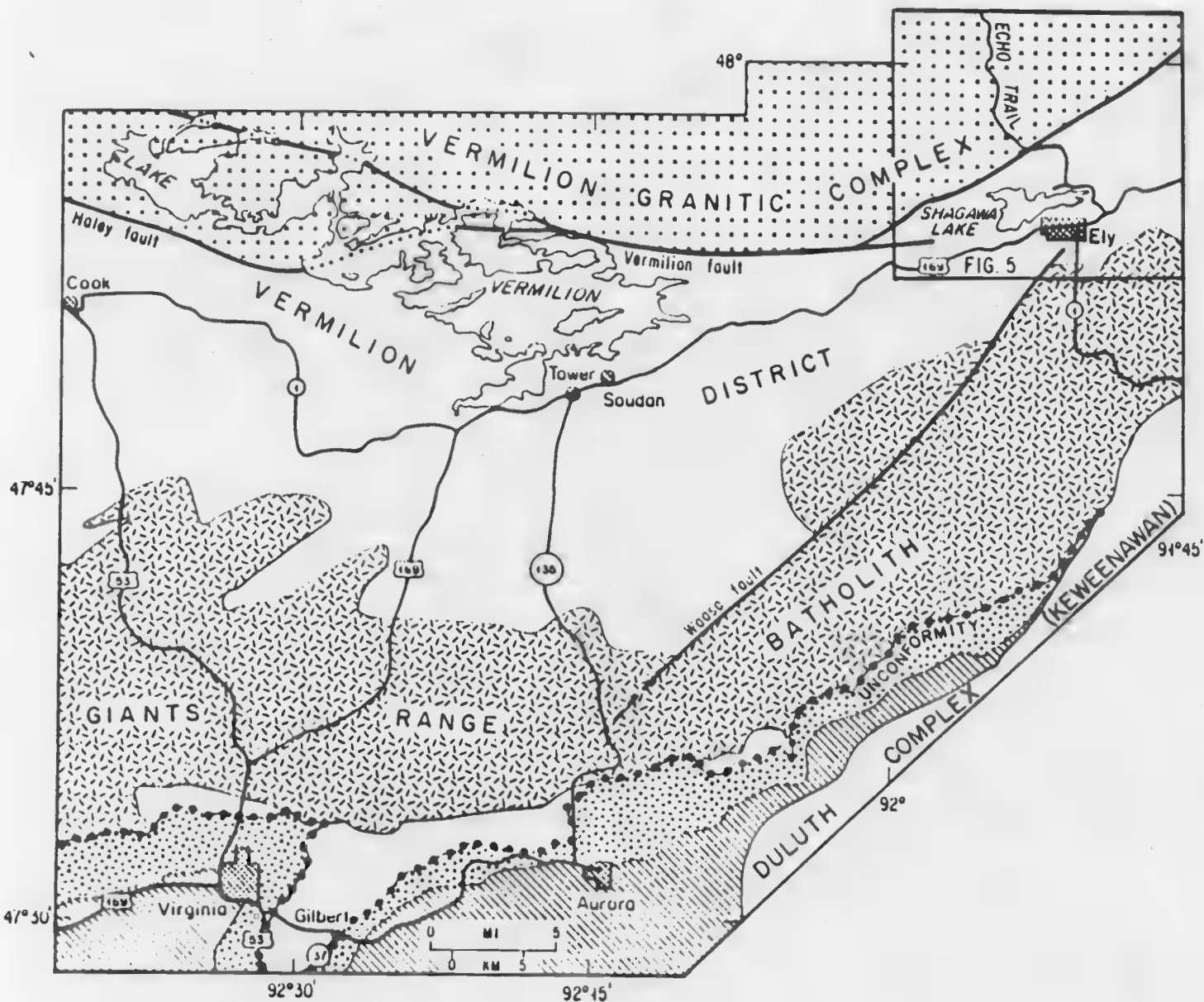


Figure 1. Regional map of the field trip area showing the geologic framework and the major roads. The dotted contact is a major unconformity separating gently dipping Proterozoic strata of the Animikie Group (on the south) from deformed Archean rocks. The Animikie Group, consisting of the Pokegama Quartzite and Biwabik Iron-Formation (open circles) and the Virginia Formation (diagonal rule), is invaded by gabbroic rocks of Keweenaw age (1000 Ma) in the southeast corner of the map area. The field trip stops are all within Archean terrane.

Lithologic Units

Supracrustal metavolcanic and metasedimentary rocks comprise the bulk of Archean rocks of the area. Also included in this sequence are a number of small felsic intrusive bodies, the most important of these being a dacite(?) porphyry body, which is the target of current mineral exploration.

Metavolcanic rocks of the region occur in two separate areas, the north and northwest, and the southeast (Fig. 2); and are separated by a central band of metasedimentary rocks. Significant portions of the contacts between the major metasedimentary and metavolcanic sequences, and probably all contacts between these sequences, are faults. The northern metavolcanic sequence is also in fault contact with the Giants Range Complex between the Pike River and Highway 53 north of Virginia.

Metavolcanic Rocks

Metavolcanic rocks consist primarily of grayish green to dark green, fine- to medium-grained, massive to locally pillowed or brecciated flows. While chemical analyses of these rocks have yet to be obtained, the rocks appear to be predominantly of intermediate composition. Dacitic(?) fragmental rocks are interlayered with the flows in the southernmost part of the area and north of Biwabik. Coarser grained, probably intrusive metadioritic or metagabbroic rocks also occur within this sequence, as do finer grained mafic dikes.

Foliation in the metavolcanic rocks is generally not well developed. Typical greenschist facies assemblages of chlorite-albite+actinolite+epidote are present. Secondary minerals include calcite and sericite.

Metasedimentary Rocks

Metasedimentary rocks of the area are subdivided into three fault-bounded units: a northern unit of moderately to highly altered, relatively quartzose metagraywackes, a central conglomeratic unit, and a southern unit of metagraywackes.

Southern metagraywackes. This unit comprises the bulk of the metasedimentary rocks of the region. Numerous outcrops occur south of Hwy. 135. These rocks consist predominantly of interbedded graywackes and slates. Quartz in these rocks averages 5-10%, rarely exceeding 15%. When normalized to exclude matrix, all rocks contain greater than 50% lithic fragments, with

felsic to felsic-intermediate clasts predominating. Intermediate to mafic clasts, though not abundant, are normally present. Detrital hornblende occurs in graywackes at one locality. Minor amounts of sericite are ubiquitous. Moderate to abundant sericite and carbonate are locally present, especially in more highly strained zones.

These sandstones are turbidites, with Bouma A, AB, ABC, and E divisions discernable. Coarse clasts are rare, though some pebbly units do occur.

Altered metagraywackes. Outcrops of this unit are not as abundant as the graywackes to the south. These rocks consist of moderately to highly altered, felsic volcanic-rich metagraywacke. In contrast to the southern metagraywackes, these rocks contain 10-25% quartz and generally do not contain clasts of intermediate to mafic composition. Secondary sericite and carbonate are abundant, in some places comprise as much as 60% of the rock. It is likely that this alteration is related to the quartz feldspar porphyry bodies that have intruded this sequence.

Beds tend to be thick, with a fair development of grading. Where discernable, Bouma A, AB, and ABC divisions (after Walker, 1984) predominate.

Conglomeratic Unit. This unit is typically a dark green, heterogeneous, conglomerate. It is a composite unit, comprised of various subunits based on differences in clast lithology. The subunits are typically heterolithic, though one distinctive monolithic unit and units of pyroclastic affinity occur within this sequence. The subunits are difficult to trace along strike, and at least two of these subunits are in fault contact with each other.

Clasts are normally rounded and of volcanic origin, but consist of various compositional types, generally of felsic to intermediate affinity. Particularly interesting are clasts of euhedral brown hornblende. These hornblende clasts are not rounded and suggest a crystal tuff origin. One distinctive subunit is monolithic, with angular to subangular andesitic clasts, and was probably deposited as a debris flow. It too contains clasts of brown hornblende. With the exception of the monolithic unit, the conglomerates are typically clast-supported. The matrix of the conglomerates is generally chloritic; quartz is rare in the matrix.

Origin of the Metasedimentary Rocks

The conglomerates are interpreted to be upper fan channel deposits, deposited by mass flow mechanisms. The graywackes are interpreted to be proximal to mid-fan deposits, deposited by turbidity currents. The two graywacke units are also compositionally different, and neither compositions are compatible with those of the conglomeratic unit. Nor are they compositionally compatible with the adjacent metavolcanic units. These relationships support the notion that all three sedimentary units are in fault juxtaposition, being parts of different submarine fans. The fans were located on the flanks of volcanic edifices, for all the detritus is volcanogenic.

Felsic Intrusives

A series of quartz-feldspar (probably dacite) porphyry bodies intrude the altered metagraywackes along a narrow belt trending approximately N80E, and also appear to intrude the southernmost exposures of metavolcanic rocks along the contact with the altered graywackes. These bodies are recognizable for the most part by their conspicuous ovoidal quartz phenocrysts. Although not present in all rocks, these phenocrysts typically vary in amount from 2-5% and range in size from .5 cm to 2 cm. Plagioclase phenocrysts comprise 20-30% of the rock, range in size from 2 mm to 1.5 cm, and are nearly pure albite in composition (Sutton, 1963). The phenocrysts are set in an aphanitic, white to greenish-gray matrix of quartz and feldspar. Secondary sericite and carbonate (siderite or ankerite) are abundant, giving the rock its white to greenish color. Finely disseminated sulfides are associated with quartz-carbonate veins and vary greatly in amount from one location to another. Common sulfides are pyrite and arsenopyrite, with rare sphalerite and chalcophyrite.

At least one non-porphyritic phase (it is microporphyritic in thin section) cuts the main porphyry body. Numerous, generally aphanitic, felsic dikes also cut the southern group of graywackes. A few of these intrusives contain quartz phenocrysts, but most do not. In thin section these dikes contain 30-50% plagioclase microphenocrysts in a fine felsic matrix.

Structure

Upon first examination, these rocks appear to be relatively undeformed; beds typically strike N60-70E. However, it has been determined that these rocks have been subjected to at least three

periods of folding, and have been cut by a significant northeasterly trending fault/shear system (Welsh, 1988).

Folding

F₁ folds have not been recognized in the field, but are identified by reversals in structural facing. F₂ folds are tight to isoclinal, trend northeasterly, and are steeply plunging. While a few F₂ folds are visible in outcrop, most are identified by reversals in stratigraphic facing. Cleavage (S₂) trends are consistently parallel to the axial planes of the F₂ folds. Minor folds with gentle south-plunging axes have been recognized in three localities, and are tentatively designated as F₃.

Faulting

These rocks have been cut by a complex northeast trending fault/shear system which roughly coincides with the axis of the Virginia Horn (Fig. 2). In the northern part of the area most displacement appears to have been taken up along the Pike River Fault (Welsh, 1988). Outcroppings adjacent to the fault exhibit the effects of considerable ductile shear. In the southern part of the area, a number of subparallel, probably en echelon, fault strands cut through metasedimentary rocks and appear to link with the Pike River Fault. The contact between the metasedimentary rocks and metavolcanic rocks to the southeast is also a fault. Here north-topping metavolcanic rocks are juxtaposed against south-topping metasedimentary rocks. These en echelon faults are interpreted as being part of a strike-slip duplex (after Woodhouse, 1986).

Strain in these rocks is concentrated into narrow zones of ductile shear associated with these faults. Clasts along the margins of the conglomerate are distinctly flattened in the plane of foliation. Clasts internal to the body are generally not as flattened, but appear to be elongated in the vertical direction.

Movement along this system was probably complex. Although offset marker units have not been identified, map patterns suggest sinistral drag, as beds are typically rotated to a N40-50E strike in the vicinity of the Pike River Fault. En echelon quartz-filled tension fractures in the dacite porphyry also support a sinistral sense of shear. Other kinematic indicators, however, such as minor Z-folds, and asymmetric pressure shadows on porphyroclasts suggest that the (latest?) sense of shear was dextral. In addition, high angle slickensides are associated with the en echelon strands of the duplex and indicate vertical movement at some time in the structural history of the area.

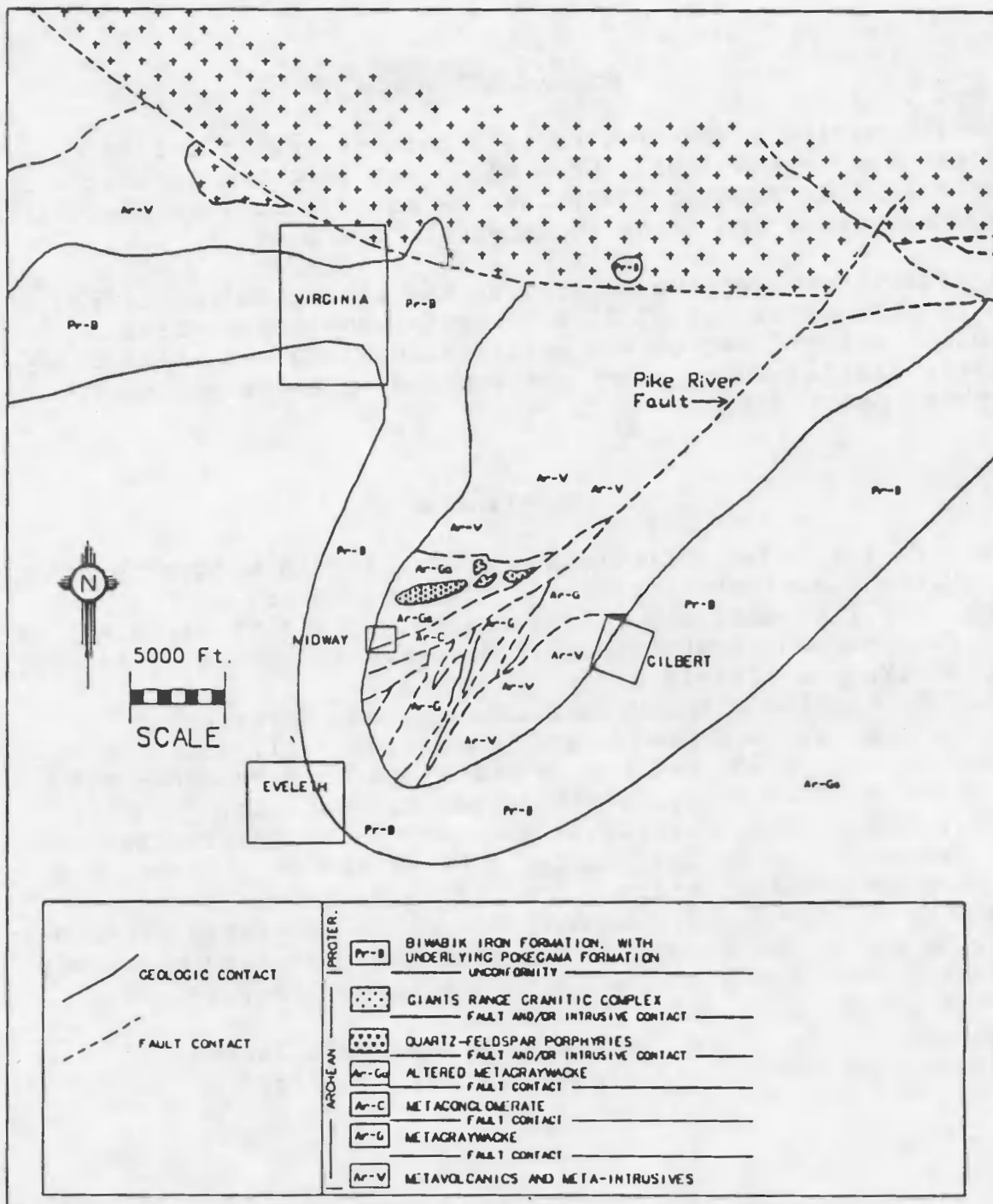


Figure 2. Generalized geologic map of the Virginia Horn area showing the Pike River Fault System.

Economic Geology

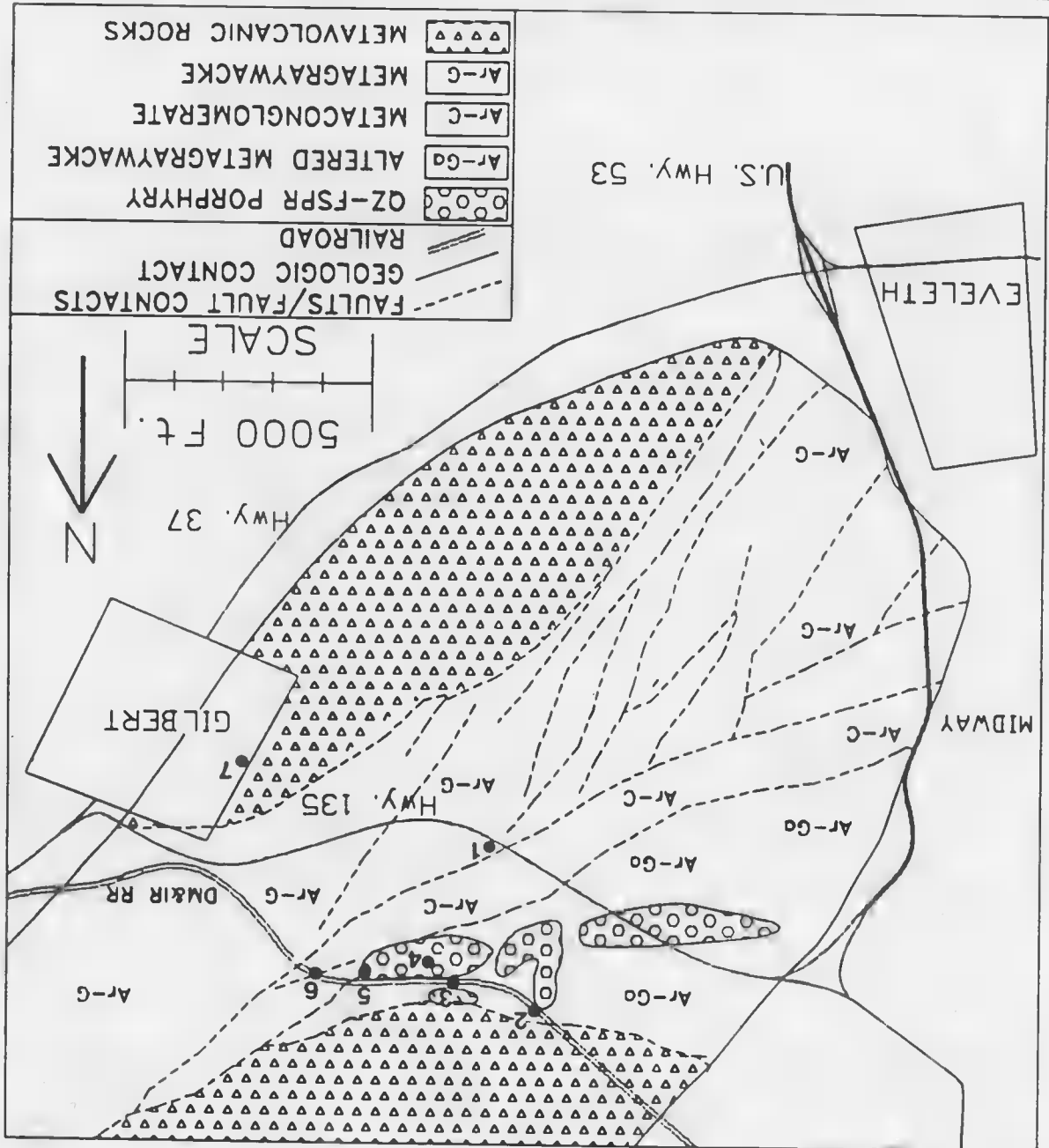
The dacite porphyry body is a current target for gold exploration in the area. Gold was first reported in this unit by Gruner in 1924 (Grout, 1937), and is associated with the quartz-carbonate veins and shear zones within the body.

Sericite-carbonate alteration has also been identified with the fault/shear zones of Pike River System (Welsh, 1988). Although silicification and sulfidation along the shear zones appears minimal where rocks are exposed, these zones merit further investigation.

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Figure 3. Map showing the Archean geology of the Virginia Horn area. Adapted from James Welsh and Eric Levy.



Road Log

From Duluth, travel north along U.S. 53 to Eveleth. Pass through Eveleth, and turn right at the intersection of U.S. 53 and Minn. 135, and proceed toward Gilbert for 1.5 miles, turning left at dirt road (with gate). Stop at gate.

STOP 1. Entrance to Viking Explosive property. At this locality the contact between the southern graywacke-slates and the conglomeratic unit can be observed. Rhythmically bedded turbiditic graywackes are exposed on the east side of the access road. Though tops are difficult to discern here, tops are north. Careful examination of the outcrop reveals that the sediment layers are disrupted along faults at low angles to bedding. Small scale isoclinal folds are also present.

Rhythmically bedded, more highly sericitized graywackes also occur on the west side of the access road north of the gate, but with tops reversed. A prominent 'Z' kink fold is also displayed in these metasediments.

Outcrops on the west side of the access road occupying the higher ground, and exposed along the highway are in the conglomeratic unit. Here the conglomerate is heterolithic, consisting of various felsic volcanic clasts in a chloritic matrix. Evidence of grading occurs in outcrops on the south side of the highway, and indicate south tops.

The contact between the graywackes and the conglomerate is a phyllonite, and is exposed along the west edge of the access road. Clasts in the conglomerate along the contact are flattened as a result of the strain. Minor asymmetrical 'Z' folds in the phyllonite can be seen in thin section, as are small Z-style kinks. A secondary cleavage, probably the result of pressure solution is also developed in the phyllonite.

The phyllonite is interpreted to represent a strand of the Pike River shear zone, and appears to run along much (and perhaps along the length) of the contact between the graywackes and the conglomerate. The contact between the conglomerate and the altered graywackes is also highly strained and altered, and probably represents another shear zone. The "Z" structures associated with these shear zones indicate dextral shear.

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Proceed back along Hwy. 135 toward Virginia for about 1/4 mile and turn right secondary road. Follow this road for approximately one mile, and turn right on dirt road to landfill. Proceed to DM&IR Railroad Tracks and park. Walk east for approximately 1/4 mile, until first outcrops are reached.

STOP 2. At this locality two feldspar porphyry "dikes", generally lacking quartz phenocrysts, are interfingered with graywackes. Both the metasediments and porphyry are extensively altered with sericite and iron carbonate. The porphyry contains abundant quartz-iron carbonate veins and abundant disseminated pyrite. J.W. Gruner reported visible gold at this locality (see Grout, 1937).

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Continue eastward along the railroad tracks for approximately 1/3 mile to the next set of outcroppings.

STOP 3. Metagraywackes of the altered graywacke unit.

These graywacke-slates are more thickly bedded than the rhythmically bedded turbidites of Stop 1. The rocks are deformed, and show good bedding-cleavage relationships. The high angle between bedding and cleavage suggests that these outcrops occur in the nose of a fold, and top relationships from other graywacke outcrops in the area support this interpretation. Cleavages are gently folded, possibly the result of intrusion of the dacite porphyry. The contact with the porphyry occurs approximately 50 feet south of the south exposure, and is relatively sharp.

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From these outcrops walk south to the outcrops near the abandoned buildings which are in sight.

STOP 4. Rhude and Fryberger prospect.

Numerous outcrops of quartz-feldspar porphyry have been stripped at this location. In general the QFP consists of quartz phenocrysts (.5-2 cm/2-5%) and plagioclase phenocrysts (2 mm-1.5 cm/25-30%) set in a greenish aphanitic groundmass of quartz, feldspar, and sericite. Fine-grained disseminated pyrite and arsenopyrite occur in variable amounts throughout the area, particularly in association with quartz-carbonate veins.

The non-porphyritic phase of the intrusion is present at this location. It can be seen cross-cutting the main porphyritic body on an east-southeasterly trend. Located under the power line to the west is a rotated, rafted sedimentary inclusion within QFP. (As you survey the outcrops take note of the attitudes of the quartz-carbonate veins, and how fracturing affects these veins, and their relationship to foliation.

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From these outcrops proceed east along the railroad tracks for approximately 1/3 mile (about 100 yards before the large railroad cut), to the outcrop on the south side of the tracks.

STOP 5. Newmont Prospect

This historical occurrence first received attention at the turn of the century. C. K. Leith's (1903) exemplary study of the geology of the Mesabi Range described the older volcanic and sedimentary rocks of the Virginia Horn area. He noted the presence of "porphyritic granite" with secondary sericite, chlorite and quartz at this locality. In 1924, Dr. John Gruner led a field party through the Virginia Horn area and collected several gold-bearing samples from "rhyolite porphyry". Petrographic descriptions of these samples were published by F. F. Grout (1937), and he noted grains of gold in several samples.

On the south side of the railroad grade approximately 1/4 mile east of the old Hercules powder plant, outcrops of quartz, feldspar porphyry flank a stream channel within a narrow topographic low. A flat, glaciated outcrop on the east side of the stream exhibits several quartz and quartz-carbonate vein sets within variably sericitized and silicified QFP.

At this location, a prominent, steeply-dipping vein set strikes approximately N-S. Adjacent wallrock contains very fine-grained, disseminated pyrite and arsenopyrite within a gray-green aphanitic groundmass. The N-S veins occupy en echelon tension fractures which flank narrow shear zones striking N40E. The attitude of the tension veins to the shear planes indicates a left-lateral sense of shear. Other vein sets within the QFP include 1) foliation-parallel quartz-carbonate veins within shears, and 2) subhorizontal quartz-carbonate veins occupying conjugate fractures. Gold mineralization is associated with several vein sets.

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Continue east to large railroad cut.

STOP 6. Conglomeratic unit.

The most extensive exposures of the coarse volcanoclastic unit occur at this locality. Here the unit can be divided into two subunits which are separated by a fault, a monolithic unit and a heterolithic unit. The northwestern 250 feet of the railroad cut is marked by a remarkably monolithic, generally matrix supported conglomerate. The clasts are quite irregular in both size and shape, are angular to subrounded, and unsorted. Clasts are of porphyritic hornblende andesite. The matrix is chloritic, and contains hornblende crystal clasts. This unit is interpreted to have been deposited by debris flow, probably subaqueous lahars.

In the southeastern half of the cut, the rocks are marked by distinct morphologic and lithologic differences from the north. The remainder of the conglomeratic unit is generally like these rocks at the southeast part of the railroad cut. They are generally heterolithic and clast supported, and often have normal and inverse to normal grading. The matrix contains very little quartz, but locally contains euhedral brown hornblende clasts? These conglomerates are thought to be upper fan channel deposits.

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Upon returning to vehicles drive to Gilbert. From town, turn right and proceed uphill toward school.

STOP 6. (optional) Outcrops behind Gilbert High School athletic field.

These outcrops contain the best exposures of pillowed metavolcanic rocks in the area. The pillows strike roughly east-west (note the northeasterly trend of the contact with the metasedimentary rocks to the west), and top north. (The metasedimentary sequence to the west generally tops southeast along the contact). The pillows at this locality are truncated by massive volcanics along a N25E trend. Whether this contact represents an intrusive contact or shear has not been determined. However, foliation along this contact, minor quartz veining, and apparent drag of the pillows into the contact suggest right lateral shear. Confusing the matter are the presence of pillows on the far northwest corner of the outcrop area.

FIELD TRIP 4, PART B

ARCHEAN GOLD OCCURRENCES AND THEIR STRUCTURAL SETTINGS: WESTERN AND CENTRAL VERMILION DISTRICT

Leaders: D.L. Southwick, P.J. Hudleston, R.L. Bauer, W. Ulland

INTRODUCTION

Several recent publications have highlighted the important role played by ductile shear zones and faults in the later stages of transpressional tectonism in the western Vermilion district of northeastern Minnesota (Sims, 1976; Bauer, 1985; Hudleston and others, 1987, 1988). These papers also provide useful summaries of the regional structural geology, and we refer interested readers to them for background and further references on the deformational history of the area.

Various lines of evidence indicate that the deformation responsible for the regional ENE cleavage in the Vermilion district was the second to affect the area, or D_2 . The regional cleavage therefore is labelled S_2 and the folds to which it is related are F_2 structures. Finite strain studies (Hudleston, 1976; Schultz-Ela, 1988) and sense-of-shear observations imply that D_2 was a transpression that involved regional north-south flattening, steeply to moderately plunging extension, and dextral shear. The most important structures to form in the later stages of D_2 were zones of intense ductile or brittle-ductile shear such as the Mud Creek shear zone and the shear zones near Shagawa Lake. More brittle dextral faults, such as the Vermilion fault and its subsidiary breaks, may be still later manifestations of the same transpressional regime.

Structural studies in gold-mining districts in the Superior Province of Canada have demonstrated that shear zones were instrumental and perhaps critical in the localization of gold ores (Colvine and others, 1988, and references therein). The clear spatial association between shear zones and the most important classes of greenstone-belt vein deposits of gold has prompted much interest in shear zones as exploration targets. For this reason exploration geologists have been working in the shear zones of the Vermilion district for several years, and they have found shear phenomena and even some major shear zones that were not recognized in published mapping by geological surveys.

Because of the widespread academic and applied interest in shear-zone phenomena, we here describe five outstanding and easily accessible shear zone outcrops in the Vermilion district where the features of the rocks can be readily observed and debated.

ROAD LOG AND STOP DESCRIPTIONS

The log begins at the intersection of St. Louis County route 408 (Mud Creek Road) and state highway 1-169 approximately 11.5 miles east of Soudan (Fig. 1 and 2).

0.0 Intersection of county route 408 and highway 1-169. Proceed north on 408 and drive cautiously; road is crooked and hilly and carries a surprising volume of traffic.

3.7 Mud Creek; park vehicles on accessible high ground and disembark; walk to outcrops.

Stop 1. The Mud Creek shear zone; outcrops near the crossing of Mud Creek Road over Mud Creek: SE1/4SE1/4 sec. 5, T. 62 N., R. 14 W.

Several small outcrops in the valley of Mud Creek illustrate various small-scale structures characteristic of rocks that have undergone intense shear strain, all attributed to D_2 .

The best exposures are in scrub just north of the creek and within about 100 m of the road on the east side. The best example of local S_2' and F_2 developed in a lens of otherwise uniform S_2 is here (see Fig. 3). In general S_2 is subparallel to the margins of the Mud Creek shear zone (N. 70° E.). Locally, it has been perturbed and rotated clockwise about 40° , to form folds with a secondary crenulation cleavage (S_2') developed parallel to the axial plane. Both cleavages can be traced from within the perturbed zone outward to merge into a single planar fabric, S_2 , in the surrounding rock. Good examples of en echelon tension veins can also be found in nearby outcrops.

On the outside of the first bend in the road north of the creek is a roadcut in a pinkish quartz sericite schist, a rock produced by intense shear. Nice shear bands (or C' planes; see Fig. 4) are developed in this rock, which is rendered friable by the closely spaced and intersecting S and C' planes.

A number of features of these outcrops provide indicators of sense of shear, and these are consistently dextral. They include shear bands (or C' planes); local development of S_2' where S_2 has been perturbed and rotated clockwise; and formation of Z folds in S_2 foliation (most commonly in association with S_2') and in quartz veins. Although well developed in highly sheared rocks such as at Mud Creek, similar features can be found through much of the Vermilion district, increasing in the intensity of development as the Vermilion fault is approached.

The Mud Creek shear zone is flanked on the north by pillowed greenstone (upper member of the Ely Greenstone) that is moderately deformed except in narrow shear zones, and on the south by assorted felsic tuff, tuff-breccia, block breccia, and the reworked sedimentary equivalents of these (tuffaceous member of the Lake Vermilion Formation). Sims and Southwick (1980, 1985) interpreted the highly schistose material within the shear zone to have been derived chiefly from fine-grained felsic to intermediate tuff belonging to the Lake Vermilion sequence. It is now recognized that shear zones of this magnitude commonly contain the sheared equivalent of many different rock types, all reduced to a more or less common "fault rock" composed chiefly of quartz, sericite, and chlorite. The phyllonitic rocks of the Mud Creek shear zone are similar to the "fault rocks" along the Rainy Lake-Seine River fault zone in southern Ontario (Poulsen, 1983, 1986) and to those associated with many other strike-slip fault zones elsewhere in the Superior Province. The westward extent of the Mud Creek shear zone beneath Lake Vermilion has not been established.

3.7 Return to vehicles; continue northwest on Mud Creek road

5.0 Low, rusty outcrop of quartz vein and enclosing quartz-sericite-chlorite schist at edge of road on east (right) side. Park vehicles on shoulder where room permits; walk to roadside outcrop.

STOP 2A. Several outcrops of sheared, locally altered and veined metabasalt near Mud Creek Road at the southern boundary of Superior National Forest: SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 31, T. 63 N., R. 14 W.

Many of the small-scale manifestations of intense dextral shear that were seen at the previous stop are seen to somewhat better advantage in these exposures. The most interesting and informative outcrop is located about 500 ft. into the woods east of the road (follow well beaten path), where phyllonitic quartz-sericite-chlorite schist displays excellent C' shear bands and S₂' crenulations. Brown quartz-carbonate alteration zones, disseminated pyrite, and narrow, tectonized quartz veins indicate former hydrothermal activity in this shear zone segment. Grab samples of the altered rock reportedly yield high gold assays, but the occurrence has not been explored further because of proximity to protected lands of the Boundary Waters Canoe Area.

5.0 Return to vehicles; Continue north and west on Mud Creek road following for about a mile a fault 'scarp' (ridge of higher grade rocks immediately N. of the Vermilion fault and the road) westward.

6.2 Park - fairly straight stretch of road with ridge immediately to the north.

STOP 2B. The outcrop is about 500 ft. from the road on the logged ridge running WSW from the road: NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 36, T. 63 N., R. 14 W.

The Rice Creek gold prospect is located in a zone of highly deformed and altered rock here called the Vermilion deformation zone. The VDZ is bounded on the north by the Vermilion fault and on the south by the Mud Creek shear zone. The VDZ features widespread carbonate and sericite alteration as well as several gold showings. Gold is usually associated with ankerite and pyrite and occasionally with green mica and tourmaline.

The Rice Creek showing is located approximately 1,000 feet south of the Vermilion fault at the south contact of a chert iron formation. Rocks with elevated gold values together with sericite-green mica-carbonate rocks were found on a small dump created by early explorers for iron ore. The outcrop source of this material can also be seen.

Gold up to 2 ppm is associated with pyrite and ankerite in a dark brecciated chert. This chert is in contact with sheared sericite carbonate rocks. Subsequent drilling has found that similar gold values exist at the north contact of the iron formation and in shears in the iron formation as well as in shears in a chlorite-sericite-carbonate schist lying between the north contact of the iron formation and the Vermilion fault.

6.2 Return to vehicles; turn around and drive south on Mud Creek Road back to highway 1-169.

12.4 Junction with 1-169; turn left (east) toward Ely.

21.0 County route 88 enters highway from left (north). Turn left, cross abandoned railroad grade, and turn right onto dirt track. Disembark from vehicles and walk east to abandoned quarry.

STOP 3. Longstorff Bay shear zone; quarry and natural exposures in the SE1/4 sec. 36, T. 63 N., R. 13 W., west of Ely.

Major shear zones form a bifurcating, wishbone-shaped trace that roughly corresponds to the outline of Shagawa Lake (Fig. 5). These zones are collectively referred to here as the Shagawa Lake shear zones. The three arms of this shear zone system are informally referred to by the respective bays of Shagawa Lake that they transect: The Olson Bay shear zone and the Longstorff Bay shear zone in western Shagawa Lake and the Spaulding Bay shear zone in eastern Shagawa Lake. The Olson Bay and Spaulding Bay shear zones follow the trace of the Shagawa Lake fault, which is inferred to be a tectonically long-lived structural feature. This family of shear zones is equivalent to the D₂ structures, such as the Mud Creek and Tower-Soudan shear zones of the western Vermilion district.

The Longstorff Bay shear zone, the best exposed of the three, deforms felsic tuff, agglomerate, and graywacke of the Knife Lake Group and a lamprophyre sill along the contact between the Knife Lake Group and the Newton Lake Formation (this stop). Lens-shaped islands of unsheared, mildly deformed lamprophyre occur locally within the shear zone. The zone terminates to the west against the Wolf Lake fault.

Although no continuous outcrop was found across any of the Shagawa Lake zones, indirect evidence suggests that the Longstorff Bay zone may be as wide as 600 m and the Spaulding Bay zone (next stop) may be as wide as 1.2 km. The absence of physical markers that could be correlated across the zones, together with the incomplete exposure of the zones, has inhibited estimates of the amount of shear displacement.

Locality 3a: Sheared lamprophyre in quarry pit.

Intense shearing has produced a strong mylonite foliation along the southern margin of the lamprophyre sill exposed in this quarry. Former pyroxene and hornblende megacrysts, now dark-green spots of actinolite + chlorite, occur in the less deformed lamprophyre to the north of this exposure. The spots are highly flattened in the foliation and have a weak to moderate linear aspect. Their shape is a typical product of the high flattening strains displayed within the Shagawa Lake shear zones. Small-scale shear bands and actinolite foliation fish from this outcrop area indicate a dextral sense of shear; however, these features were observed only in cut hand samples and are not readily distinguished in outcrop. Small (centimeter scale) symmetric crenulations and chevron folds deform the foliation locally and are believed to have formed during the later stages of shearing. Kink bands interpreted to be younger features unrelated to the development of the shear zones are well developed locally.

Locality 3b: Sheared tuff of the Knife Lake Group.

A narrow dirt road southeast of the quarry and the abandoned railroad grade leads to an abandoned section of highway. A small outcrop of highly sheared Knife Lake tuff that contains numerous kink bands crops along the north side of the abandoned highway to the east of the dirt road intersection.

- 21.0 Return to vehicles; retrace route to 1 and 169 and then to left (east) back through Ely.
- 25.1 Minnesota route 1 turns south toward Illgen City; continue east on highway 169 toward Winton.
- 26.1 County route 88 (signs for Echo Trail) enters from left (north); turn left onto route 88.
- 28.1 Prominent roadcuts on either side of road; park on shoulder and disembark.

STOP 4. Spaulding Bay shear zone exposed in cuts along County route 88, NW1/4 sec. 23, T. 63 N., R. 12 W.

The Spaulding Bay shear zone occurs primarily in the Knife Lake Group, although it affects adjacent variolitic pillow basalts of the Newton Lake Formation to the north and units of the Ely Greenstone to the south. This shear zone presumably extends toward Fall Lake, farther to the east, but this has not been verified by publicly available mapping.

Locality 4a: Sheared tuff of the Knife Lake Group.

Highly sheared tuffaceous rocks of the Knife Lake Group near its contact with the Newton Lake Formation are exposed here. The rocks contain local concentrations of sulfide mineralization and abundant kink bands.

Locality 4b: Sheared Newton Lake basalt.

Variolitic pillow basalt and more massive flows of the Newton Lake Formation are cut by discontinuous shear zones at this outcrop. Strain analyses using varioles from this unit indicate high flattening strains ($k=0.06$ and 0.10) with X plunging moderately to the southwest. Weak shear bands with spacings on the order of 5 cm are visible on some of the vertical outcrop faces at a high angle to the shear zones.

This is the end of Field Trip 4. Return to vehicles, turn around, and retrace route to Ely.

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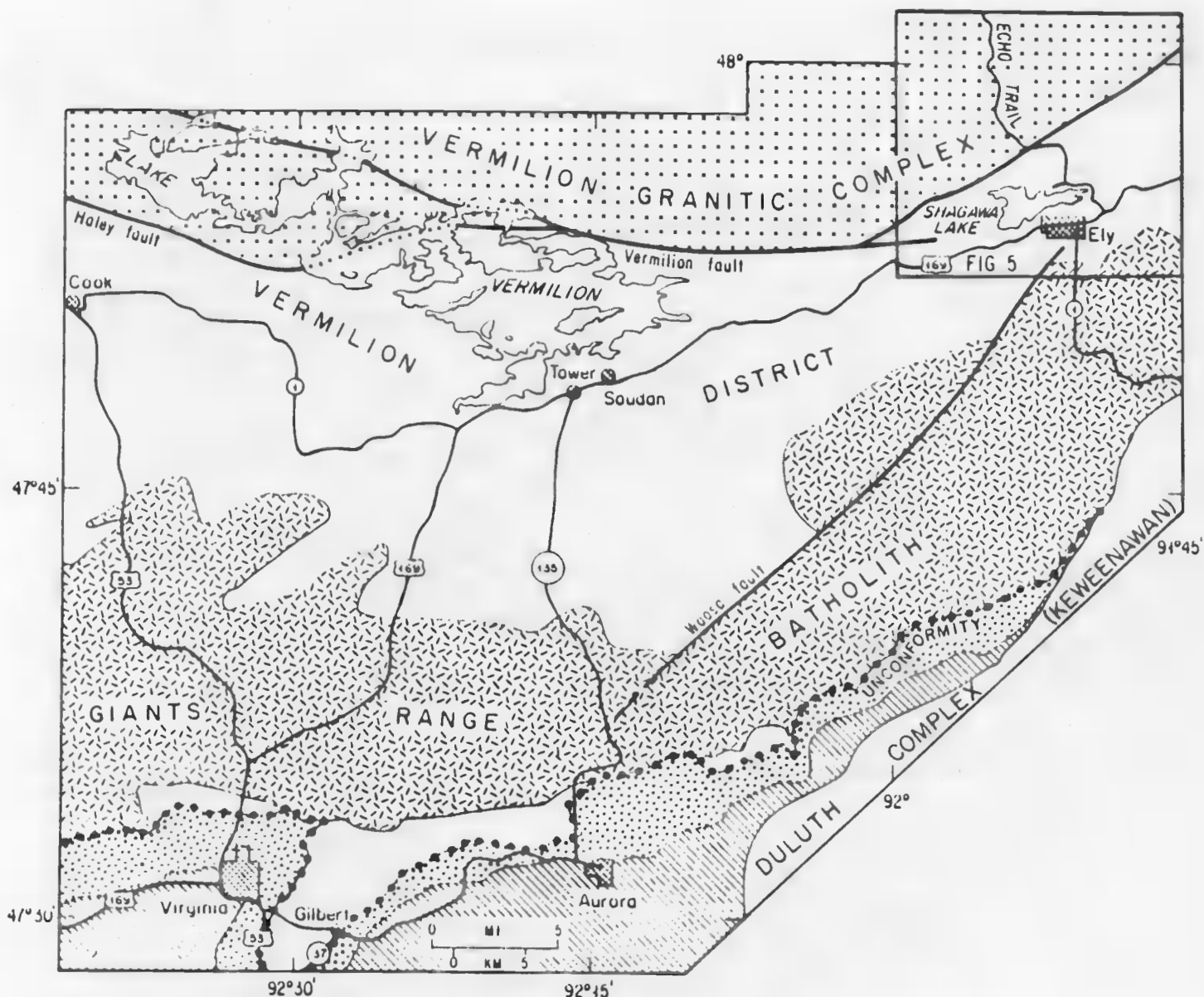


Figure 1. Regional map of the field trip area showing the geologic framework and the major roads. The dotted contact is a major unconformity separating gently dipping Proterozoic strata of the Animikie Group (on the south) from deformed Archean rocks. The Animikie Group, consisting of the Pokegama Quartzite and Biwabik Iron-Formation (open circles) and the Virginia Formation (diagonal rule), is invaded by gabbroic rocks of Keweenawan age (1000 Ma) in the southeast corner of the map area. The field trip stops are all within Archean terrane.

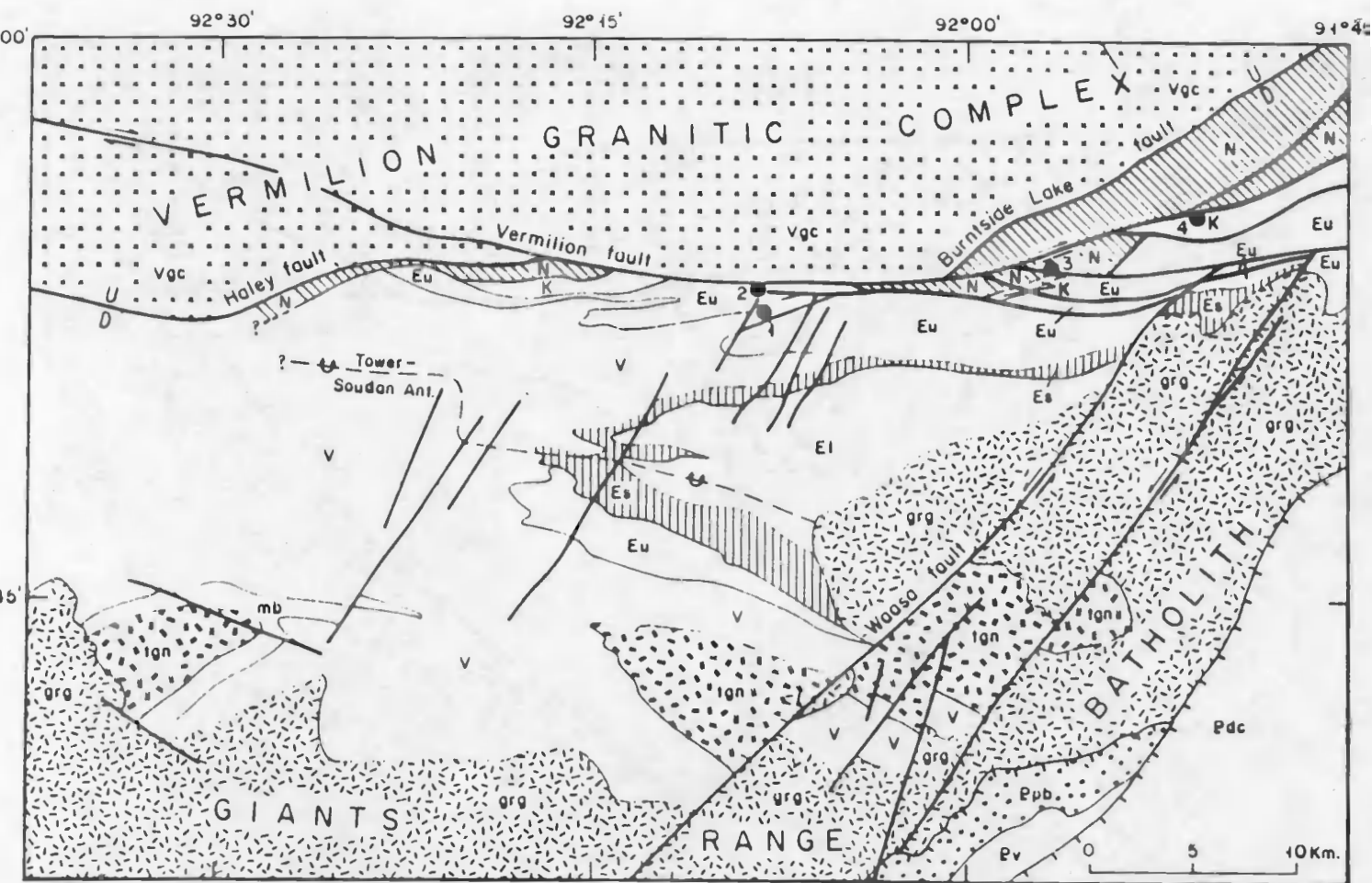


Figure 2. Geologic sketch map of the field trip area showing approximate stop locations. Modified from Green and Schulz (1982) and Sims and Southwick (1985). Map explanation is on the facing page.

EXPLANATION FOR FIGURE 2

Pdc	Duluth Complex; various gabbroic rocks	Middle Proterozoic (ca. 1100 Ma)
———— INTRUSIVE CONTACT ————		
Pv	Virginia Formation; turbidite	Early Proterozoic (ca. 2000 Ma)
Ppb	Pokegama Quartzite (tidal deposits) overlain by Biwabik Iron-Formation	
~~~~ MAJOR UNCONFORMITY ~~~~~		
grg	Giants Range batholith; granitoid rocks	
vgo	Vermilion Granitic Complex, granitoid rocks, paragneiss, migmatite	
———— INTRUSIVE OR FAULT CONTACT ————		
N	Newton Lake Formation; tholeiitic and komatiitic metabasalt; numerous sills	Late Archean (ca. 2700 Ma)
K	Knife Lake Group; sedimentary rocks of mixed volcanic provenance	
V	Lake Vermilion Formation; volcanic-derived sedimentary rocks, mainly of dacitic provenance	
Eu	Ely Greenstone, upper member; chiefly tholeiitic metabasalt	
Es	Ely Greenstone, Soudan Iron-formation Member; cherty iron-formation interbedded with felsic to mafic volcanic rocks	
El	Ely Greenstone, lower member; chiefly calc-alkaline metabasalt	
mb	Metabasalt (unnamed); probably Ely equivalent	
tgn	Tonalite gneiss, paragneiss, amphibolite; stratigraphic position uncertain	

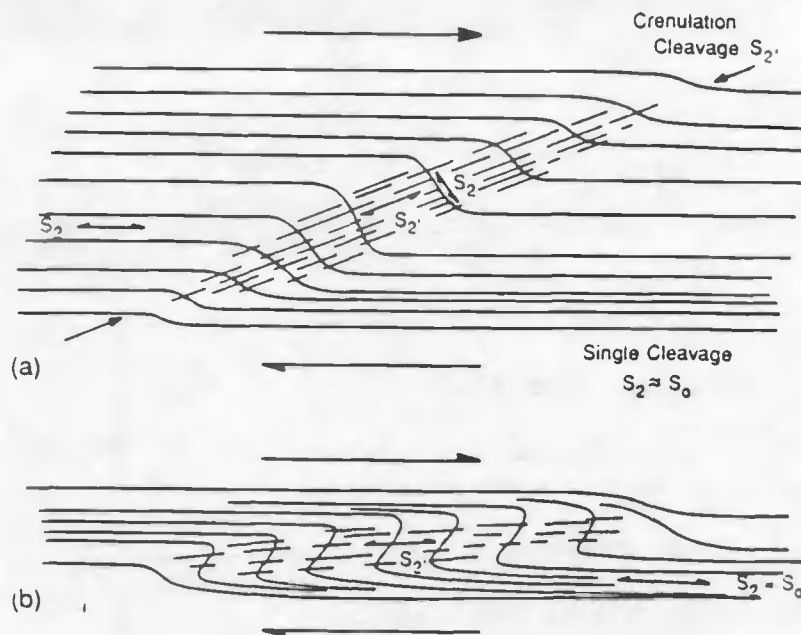


Figure 3. Schematic illustration of the development of  $F_2'$  folds and  $S_2'$  cleavage during a simple deformation that also produced the foliation ( $S_2$ ) being folded.

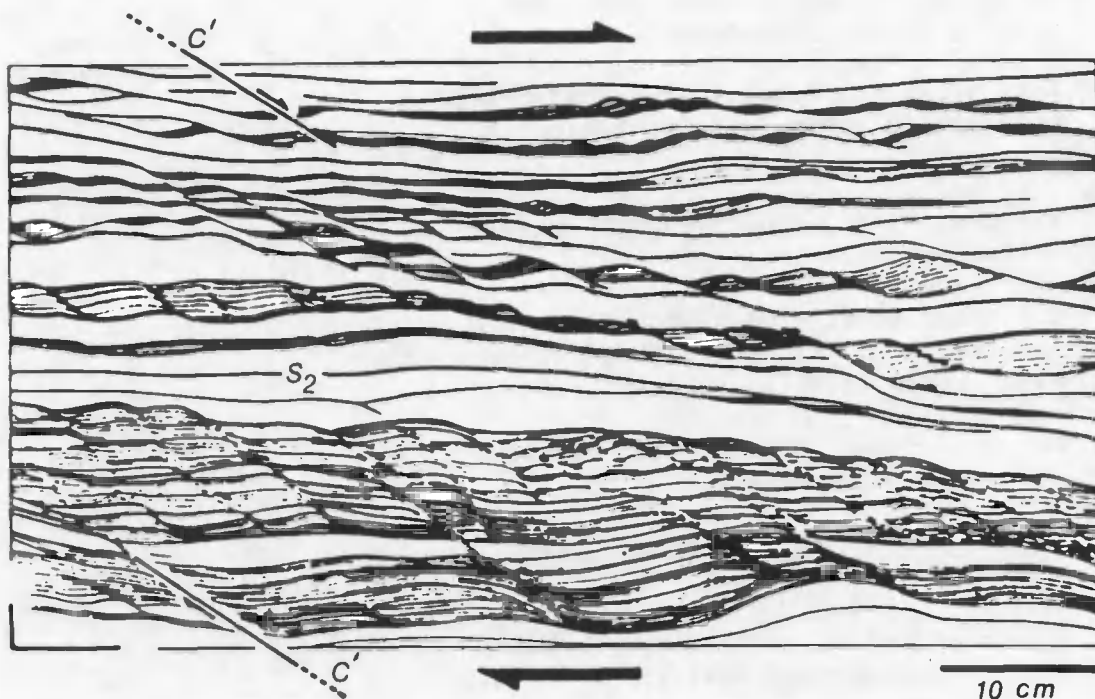


Figure 4.  $C'$  surfaces or shear bands. These develop in rock that has previously acquired a strong planar foliation due to very high shear strain. The  $C'$  surfaces are new surfaces of slip that cross the main foliation at moderate angles; slip on them is in the same sense as the overall sense of shear in the shear zone. Modified from Malavieille (1987).

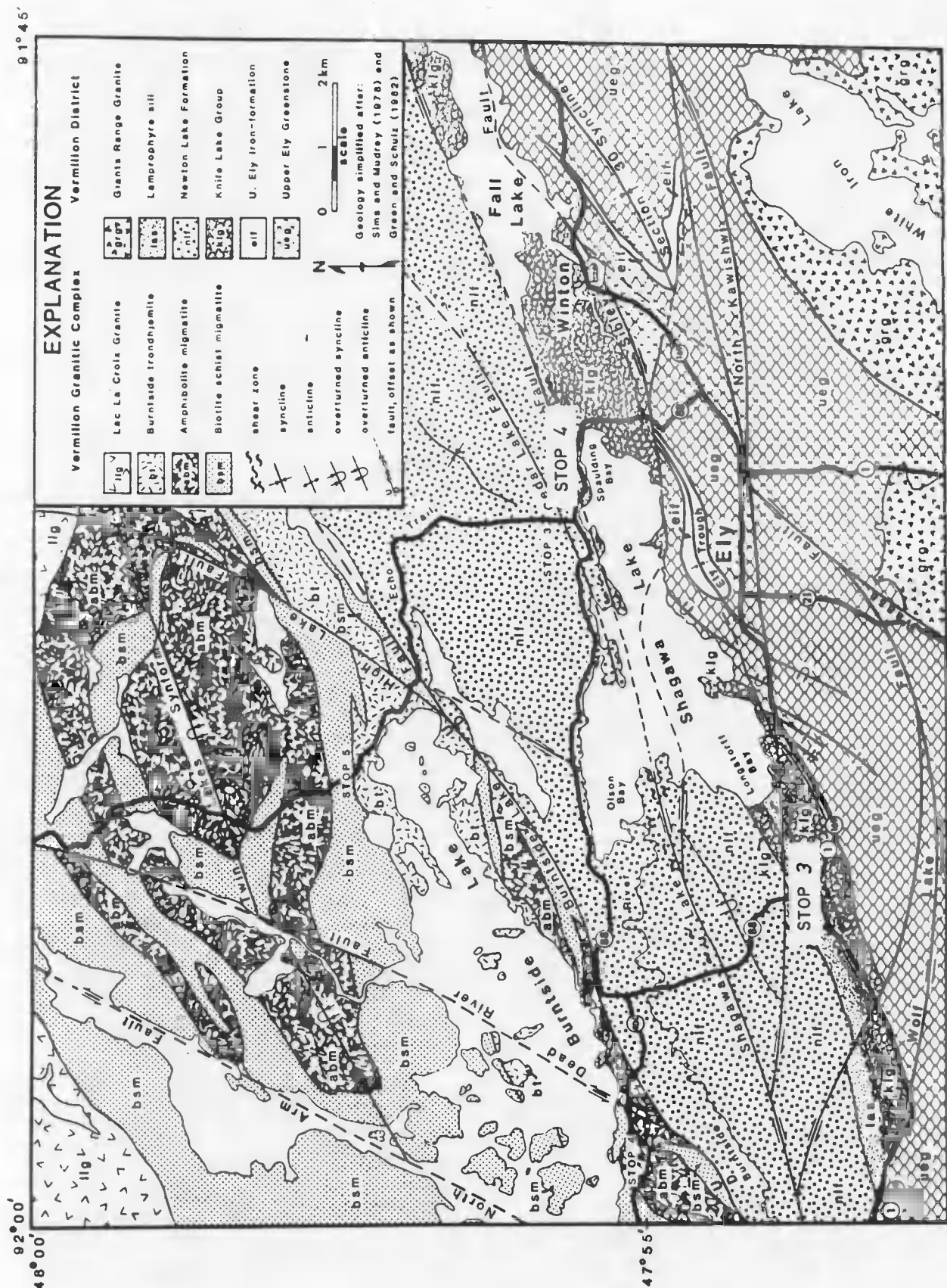


Figure 5. Generalized geologic map of the Shagawa Lake area showing locations of stops 3-4. Geology modified from Sims and Mudrey (1978) and Green and Schulz (1982).