

PROCEEDINGS

Twenty - Eighth Annual Institute on Lake Superior Geology



**May 5 - 8 , 1982
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PROCEEDINGS
TWENTY-EIGHTH ANNUAL
INSTITUTE ON LAKE SUPERIOR
GEOLOGY

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May 5-8, 1982

under the sponsorship of
Minnesota Geological Survey
University of Minnesota
1633 Eustis Street
St. Paul, Minnesota 55108

G.B. Morey and John Splettstoesser

General Editors

TABLE OF CONTENTS

GENERAL INFORMATION	V
INSTITUTE BOARD OF DIRECTORS	V
LOCAL COMMITTEE	VI
GOLDICH MEDAL COMMITTEE	VI
SESSION CHAIRMEN	VII
ANNUAL BANQUET SPEAKER	VII
GOLDICH MEDAL RECIPIENT	VII
ACKNOWLEDGMENTS	VII
CALENDAR OF EVENTS AND PROGRAM	IX
ABSTRACTS	1
FIELD TRIPS	53
1. MINERAL DEPOSITS OF THE FORT FRANCES-MINE CENTRE AREA, ONTARIO	55
2. ARCHEAN GEOLOGY OF THE INTERNATIONAL FALLS-KABETOGAMA AREA, MINNESOTA	89

GENERAL INFORMATION

28th Annual

INSTITUTE ON LAKE SUPERIOR GEOLOGY

Holiday Inn

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Minnesota Geological Survey

University of Minnesota

1633 Eustis Street

St. Paul, Minnesota 55108

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ABSTRACTS

MAGNETIC INVESTIGATIONS OF THE BARAGA COUNTY DIABASE
BARAGA COUNTY, MICHIGAN

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ABSTRACT

Aeromagnetic data from parts of Baraga and Marquette Counties, Michigan are dominated by linear, east-west trending magnetic lows associated with reversely magnetized diabase dikes. Close examination of ground magnetometer profiles shows that prominent dike intrusions sometimes occur as groups of 2 to 4 small, interrelated dikes. In one case these dikes were found to thicken or converge at 2 to 3 km intervals along strike causing periodic maxima in aeromagnetic anomalies. The ground magnetometer profiles also provide evidence that normally magnetized diabase dikes may exist in close association with the more common reversed dikes at 2 sites in Baraga County.

The magnetic anomalies of Baraga County Diabase intrusions diminish in magnitude under the Baraga Plains where the dikes are covered by glacial deposits and possibly by Jacobsville Sandstone. It was found that estimates of depth to the diabase dikes in the Baraga Plains area could be used to interpret basin structure on the surface of the Middle Precambrian. The results showed evidence of a possible valley or ledge in the Middle Precambrian representing a possible buried extension of Keweenaw Bay to the southwest from L'Anse, Michigan.

Several investigators have reported cells of anomalous remanence in Baraga County Diabase outcrops. The variable intensity and small-scale complexity of magnetization in these cells argue against explaining these cells as lightning-induced magnetization. Detailed paleomagnetic sampling of two of these cells suggests that the observed patterns result from lightning-induced magnetization superimposed on dramatic susceptibility variations in the diabase. It was possible to map the probable path of current flow in both cases.

F_1 RECUMBENT FOLDING IN THE WESTERN VERMILION
GREENSTONE-GRANITE TERRANE, NE MINNESOTA

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ABSTRACT

The Vermilion Granitic Complex, a granite-migmatite terrane recrystallized in the amphibolite facies, is in fault contact along its southern boundary with the Vermilion district, a greenstone-granite terrane in the greenschist facies. Analysis of structural facing in folded Archean strata in the southern Vermilion Granitic Complex and western Vermilion district indicates that the sedimentary sequence underwent recumbent F_1 folding prior to the development of the dominant F_2 folds. A major F_2 antiform mappable across the faulted boundary between the two terranes, displays downward structural facing indicating the inversion of this portion of the sedimentary sequence prior to the F_2 folding. To the southeast, in the Vermilion district, upward structural facing is observed in F_2 folded strata. The regional change in structural facing to the southeast is attributed to crossing of the axial surface of a major F_1 nappe.

Finite strain data determined from clasts in the greenschist facies sedimentary/volcaniclastic units in the Vermilion greenstone terrane can be completely accounted for in terms of the deformation producing the F_2 folds. Locally intense F_1 folding is therefore attributed to downslope slump movement of soft sediment. However, amphibolite facies biotite schists, making up part of the same F_1 structure in the Vermilion Granitic Complex, display a pronounced S_1 foliation that developed parallel to bedding during the early stages of metamorphism. We suggest that metamorphic dehydration reactions occurring in the lower strata led to the development of high pore pressures in the upper portion of the sedimentary pile. The combination of high pore pressures and gravitational instability during the F_1 folding resulted in soft sediment slumping in the upper strata while the lower strata underwent strain and metamorphic recrystallization during F_1 folding. Soft-sediment F_1 folding in the Vermilion district could have led to a rather complex distribution of F_1 structures, because the more competent volcanic flows, such as the Ely greenstone, may have undergone a much different response to the F_1 folding.

RB-SR AND SM-ND ISOTOPIC STUDIES OF PROTEROZOIC MAFIC DIKES
IN NORTHEASTERN MINNESOTA

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ABSTRACT

A major northwest-trending mafic dike swarm of Proterozoic age intrudes the 2.7 b.y.-old greenstone-granite terrane of northeastern Minnesota and adjacent southern Ontario. Of these, two large vertical composite dikes have been selected for a combined Rb-Sr, Sm-Nd isotopic study. These dikes intrude the Vermilion Granitic Complex west of Kabetogama Lake in northeastern Minnesota. This research was undertaken to complement petrologic and paleomagnetic studies which are being done by David Southwick of the Minnesota Geological Survey and by Henry Halls of the University of Toronto.

The composite dikes analyzed in this study are nearly colinear. Although they cannot be followed continuously on the aeromagnetic maps, we infer from structural, petrologic and geochemical characteristics that they are probably parts of a single intrusive body. The sites sampled are separated along strike by about 2.5 km.

An earlier reconnaissance of this dike swarm yielded K-Ar ages ranging from 1.6 to 2.2 b.y. The eight samples analyzed for the present study plot on a single Rb-Sr isochron and define an age of 2120 ± 67 m.y. The relatively high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70449 implies that the crust was involved in the process of dike magma genesis or that the magma was contaminated during emplacement into granitic rocks. The fact that samples from inner and outer dikes of both composite dikes plot on the same isochron is suggestive that all the dikes originated from the same source.

The Sm-Nd data from these dikes do not form an isochron. Assuming that the emplacement age is 2120 m.y., then a calculation of the initial $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios for these samples reveals that the source region for the magma is LREE depleted. The combined Sr and Nd characteristics of these dikes suggest 2 conclusions: (1) the source region for these dikes appears to be in the mantle and not in the crust, and (2) the dike magma was subsequently contaminated by crustal material during passage through the crust or during intrusion.

In both composite dikes the outer dike is enriched in Rb and Rb/Sr ratio relative to the inner dike. This suggests that the inner dikes may represent a reinjection of a cumulate after the main pulse of dike injection.

STRATIFIED OCEANS AND THE ORIGIN OF IRON-FORMATION

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ABSTRACT

The great Proterozoic X banded iron-formations, typified by those of the Lake Superior region, have long presented a geochemical enigma. Vast quantities of iron must have been dissolved in and precipitated from seawater to form these deposits, yet iron is virtually insoluble in even slightly oxygenated water. Thus, many investigators have concluded that anoxic water, in which iron is more soluble, must have dominated the Proterozoic X oceans and that iron-formations were deposited as that water was oxygenated. Most have assumed that this oxygenation of the oceans was a unique event in the evolution of the atmosphere and hydrosphere caused by the first appearance, roughly 2 billion years ago, of photosynthetic organisms and hence the permanent shift from an oxygen-free to an oxygen-rich atmosphere.

In contrast, research, largely in the petroleum industry, in the past few years has shown that major parts of the world's oceans repeatedly became strongly stratified and were anoxic below the depth of surface turbulence for substantial periods of Phanerozoic time. These so-called ocean anoxic events took place during periods of major marine transgression and warm climate. Decreased oceanic circulation resulted from warm climate, and increased oceanic productivity resulted from equable climate and expanded highly productive shelf seas. These conditions combined to create an excess of organic matter over available oxygen in deep oceans which led to anoxic conditions. The recurrence of ocean anoxic events throughout Phanerozoic time periodically resulted in large quantities of anoxic ocean water having relatively high contents of dissolved Fe, Mn, and P and probably controlled the temporal distribution of deposits of these elements in Phanerozoic rocks.

Such ocean anoxic events might also have taken place during the Precambrian, and they, in addition to one-time only oxidation related to permanent changes in the atmosphere and oceans during Proterozoic X time, may have resulted in deposition of iron-formation. Thus, the major distinction from past theories is the idea that after an early oxygen-free atmosphere and ocean may have been oxidized initially in Proterozoic X time, younger oceans were probably capable of returning to anoxic conditions and depositing iron-formations even in the presence of an oxygen-rich atmosphere.

The Proterozoic X banded iron-formations of the Lake Superior region seem explainable by an ocean-anoxic-event model in which oceans were oxygenated both before and after iron-formation deposition. During periods of ocean anoxia, the deep oceans acted as geochemical sinks for iron, and the anoxic waters were enriched in dissolved iron. Iron was then precipitated in iron-formations either by upwelling and consequent oxidation during the anoxic event or by a more widespread oxygenation of the ocean as the anoxic event waned.

Iron-formations commonly occur at several stratigraphic horizons in iron-bearing regions (for instance, at least five horizons are present in the Proterozoic X of Michigan). These repeated cycles of deposition seem more consistent with a model involving repeated ocean anoxia than with models involving only one oxygenation event.

MAGNETIC ANOMALY STUDIES OF THE NORTHERN ANIMIKIE BASIN

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ABSTRACT

Except along the Mesabi Iron Range, exposures of the lower Proterozoic Animikie Group are widely scattered and wells penetrating to Archean basement are nonexistent. As a consequence, little can be inferred about the structure of the Animikie basin without the aid of geophysical data. Detailed aeromagnetic data recently acquired by the Minnesota Geological Survey have been used to elucidate the structure of the northern flank of the basin in an area of about 3500 km² in St. Louis and Itasca Counties, Minnesota.

The northern edge of the basin is characterized by a complex and typically high-amplitude (>500 gammas) anomaly expression caused by the Biwabik Iron Formation. A broad zone with smoother anomaly expression and moderate amplitudes (100-500 gammas) extends about 20 km southward into the basin and reflects the southward thickening of the essentially non-magnetic slate and graywacke of the Virginia Formation that overlie the iron-formation. The anomalies within this zone are thus assumed to arise from structures within the buried iron-formation or from sources within the underlying Archean basement. Beyond 20 km into the basin the magnetic anomaly character becomes extremely subdued, reflecting deeply buried anomaly sources beneath non-magnetic slate and graywacke.

Because the overlying slate and graywacke are essentially non-magnetic, magnetic depth estimates will indicate source tops either in the Biwabik Iron Formation or in the immediately underlying Archean basement. Therefore these depth estimates should delineate the general shape and deep structure of the Animikie basin. Depth estimates were obtained graphically from maps and by computer-based estimates along flight profiles. The results reveal a gently dipping shelf out to about 20 km south of the edge of the basin, where depths of around 1 km are indicated. A structural relief of a few hundred meters is inferred to be superimposed upon this shelf along the southwest extension of the Virginia horn. Southward from this shelf the basin appears to steepen abruptly to depths in excess of 2 km. South of 47°N the depth estimates on a broad east-trending maximum indicate depths in excess of 3 km.

The encouraging results of this preliminary study suggest that further geophysical work, including similar studies over the remainder of the basin and also seismic investigations, would be fruitful. The implied thickening of the sequence 20 km into the basin may reflect a transition from a stable shelf to the more mobile environment characteristic of the Great Lakes tectonic zone.

GRANITIC PHASES IN THE NORTHERN BORDER ZONE
OF THE VERMILION GRANITIC COMPLEX

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The Vermilion Granitic Complex is an Archean granite-migmatite terrane which has formed by the extensive emplacement of early tonalite and syn- to post-tectonic granite into supracrustal metamorphic rocks (chiefly biotite schist in the study area). Two main types of granite occur along the northern border zone: 1) a grayish-pink biotite granite (Lac La Croix Granite), and 2) a biotite-muscovite leucogranite. Geochemical and mineral studies have been undertaken to distinguish the similarities and differences between these two granite types, and to investigate the origin of the leucogranite. The results are relevant to the general problem of the origin of late-stage batholithic granites in greenstone-granite terranes.

The Lac La Croix Granite, a major component of the Complex, occurs as the late-stage intrusive batholithic phase and as the neosome portion of granite-rich migmatite. The leucogranite on the other hand occurs only as neosome portions of the schist-rich migmatite and small bodies within the biotite schist.

The two granites are similar in their Qtz-Or-Ab abundances. However, distinctive differences are seen in accessory phases and in major element and trace element chemistry. Garnet is restricted to the leucogranite, whereas magnetite is common in the Lac La Croix Granite but rare in the leucogranite. The leucogranite is significantly lower in MgO , FeO_t and TiO_2 compared to the Lac La Croix Granite. The La_N content in the leucogranite ranges from 95 to 140 x chondrite.

Sillimanite, staurolite, muscovite, and garnet are locally developed within the biotite schist. Thin veins of fine-grained leucocratic granodiorite and granite (few mm thick) and pods of pegmatite are isoclinally folded and boudinaged within the host biotite schist, and commonly are bordered by biotite selvage zones. These veins coalesce into larger lenticular leucogranite bodies. As the ratio of leucogranite to biotite schist increases, the leucogranite tends to crosscut earlier tectonic fabric.

These relationships are compatible with an anatectic origin for the leucogranite. The low MgO , FeO_t and TiO_2 content of the leucogranite may be attributed to low degrees of (1) digestion of mafic minerals (e.g. biotite, amphibole, garnet, etc.) in the source during melting. The data obtained thus far suggest therefore that the leucogranite is an anatectic melt produced from (2) supracrustal sedimentary rocks, and that it has moved syntectonically into higher portions of the metasedimentary sequence. Trace element analyses are presently underway to help model the origin of the leucogranite.

GEOLOGY OF THE CYPRESS, HANSON AND SOUTH ARM OF KNIFE LAKE AREA
B.W.C.A., NORTHEAST MINNESOTA

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ABSTRACT

Archean volcanic and volcanogenic sedimentary rocks of the Cypress, Hanson and South Arm of Knife Lake area are located within the eastern Vermilion district and lie in three of Gruner's (1941) structural segments.

The Spoon Lake segment is composed dominantly of dacite porphyry, dacite porphyry conglomerate and graywacke-argillite. The graywacke is of both the feldspathic and lithic type, and is interbedded with conglomerate. Two small fault slices of greenstone are present within the segment as are Keweenawan diabasic dikes which intrude both the igneous and the sedimentary rocks. Bedding strikes predominantly 40° to 50° E and dips steeply to the southeast and northwest. The Knife Lake synclinorium segment is composed of two units: a tuff-mafic conglomerate-mixed conglomerate unit, and a younger graywacke unit. These two units are interbedded and gradational into one another. One Keweenawan diabasic dike is present in the segment. Bedding strikes predominantly northeast and dips near-vertical to the northwest.

Significant conclusions drawn from this study and based on petrographic analysis and measurement, and interpretation of lineations, foliations and primary sedimentary structures include:

- 1) The granite pebble conglomerate of the Knife Lake greenstone unit (Gruner, 1941) is actually a greenstone pebble conglomerate.
- 2) Source areas for the metasediments are exclusively volcanic in origin. No plutonic rock fragments were observed.
- 3) No potassium feldspar grains were found either microscopically or by staining with sodium-cobaltinitrate, and no rock fragments have a composition more felsic than dacite.
- 4) No Saganaga detritus was deposited within the sediments and hence no supporting evidence for penecontemporaneous volcanism and unroofing of the Saganaga batholith, as suggested by previous investigation, was found.
- 5) Turbidite sequences in all segments are characteristic turbidites corresponding to the inner or middle lobe of a submarine fan.
- 6) The structure of the Knife Lake synclinorium segment can be accounted for in terms of three tectonic deformations. The first period of deformation produced isoclinal folds, the axes of which trend $N 40^{\circ}$ to 50° E and plunge 30° to the northeast. The second period of deformation produced a pervasive $N 54^{\circ}$ to 60° W cleavage. The third period of deformation occurred on a regional scale and

produced major longitudinal faults, which have divided the present area of study into petrographically distinct structural blocks.

REFERENCE

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IRON-ENRICHED BASALTIC FRAGMENTAL ROCKS ERUPTED IN A SHALLOW SUBAQUEOUS ENVIRONMENT, THE HEMLOCK FORMATION, AMASA QUADRANGLE, MICHIGAN

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ABSTRACT

The Hemlock Formation is a Precambrian subaqueous metavolcanic complex within the Amasa Oval in Iron County, Michigan. It is overlain by the Amasa Formation, a banded iron-formation which outlines the oval as well as the upper limits of the Hemlock. The formation is underlain by the Randville Dolomite and the Goodrich Quartzite which in turn rest on the Archean basement of Bell Creek Granite Gneiss. This study deals with the upper third of the formation in the Amasa 7-1/2 minute quadrangle just east of the town of Amasa.

Approximately 5 square miles were mapped for correlation with the previously mapped areas to the north and east in the Ned Lake and Kelso Junction Quadrangles respectively. Thirty-five samples were analyzed for geochemical correlation with pre-existing data from the Hemlock. Ten of these were re-analyses of samples taken by D. Jay Johnson (1975) and Jesse C. Dann (1978).

Significant chemical and lithologic variation occurs within the Hemlock Formation. Main lithologies consist of massive and pillowed lavas, pillow breccias, broken pillow breccias and hyaloclastites. The first basalts of the Hemlock chemically resemble oceanic tholeiites; later rocks are compositionally closer to continental tholeiites. Minor amounts of rhyolite also occur. The formation appears to have been erupted in 3 main cycles of volcanism with increasing iron enrichment (up to 24% FeO (total)). Iron-formations occur stratigraphically above the iron-rich basalts (icelandites). There may be a correlation between these enriched basalts and the deposition of the overlying iron-formations.

I infer that most of the Hemlock was erupted in shallow water because: a) there is a high percentage of interbedded volcanoclastic sediments and b) the massive lava flows, pillows and pillow fragments are generally vesicular. This implies subsidence of the basement during the emplacement of the volcanics. The Hemlock Formation reaches its maximum thickness of 7500 m on the southwest side of the oval and thins to about 750 m to the northeast. Johnson (1975) has shown that this increase is due to actual stratigraphic thickening and is not structurally related. Some time after volcanism the rocks underwent low-grade regional metamorphism (chlorite grade in the Amasa Quadrangle), which was followed by the Amasa structural uplift, producing the oval.

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STRATIGRAPHY AND LITHOLOGY OF THE GLACIOGENIC SEDIMENTS
OF THE TWO HARBORS AREA, NORTHEASTERN MINNESOTA

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ABSTRACT

Several distinct episodes of the Late Wisconsin glaciation are recorded in the Quaternary deposits of the Two Harbors and Whyte quadrangles in northeastern Minnesota. Ortho-tills and a variety of glacially derived sediments, including a clayey diamicton, are attributed to the Rainy and Superior lobe advances during the St. Croix and Automba phases that occurred after 16,000 years B.P. The lithologic characteristics and stratigraphic distribution of this glacial sedimentary pile, along with the origin of the red clay are elucidated in this study.

The oldest glaciation, associated with the St. Croix phase, is represented in the northwestern part of the Whyte quadrangle by a distinctive topography of the southwest-oriented drumlins (the Toimi drumlin field) and abandoned subglacial streams. These features are attributed to the Rainy lobe advance from the northeast. A tunnel valley, partially occupied by Sullivan Lake, and small eskers along Sullivan Creek were formed during ice stagnation, when the high velocity stream in this subglacial tunnel changed its habit from erosional to depositional. The drumlins consist of lodgement till with a strong northeast-trending fabric. Near Sullivan Lake glacial sediment is more than 5 m thick. The drift is grey to brown (10YR 4/3), sandy to stony, with a sand:silt:clay ratio of 74:22:04. Large clasts are mainly lithic fragments of granite, granophyre, greenstone, and gabbro.

The glacial sedimentation associated with the Automba phase of the Superior lobe is recorded in a complex of deposits contained mainly in the Highland Moraine. The sediments range from non-sorted, non-bedded lodgement till, to supraglacially derived debris, including gravity flow deposits and well-sorted fluvial and lacustrine sediments. The lodgement till of the Superior lobe is reddish brown (5YR 3/4), sandy to clayey, with a sand:silt:clay ratio of 60:31:09. The clasts are predominantly from the North Shore Volcanics (amygdaloidal basalt and rhyolite), granophyre and red sandstone of Keweenawan age.

The Highland Moraine is a hummocky kettle and kame topography in the northwestern part of the Two Harbors quadrangle and the southeastern part of the Whyte quadrangle. It is bordered on its western edge by a string of small lakes, marking the lateral extent of the Superior lobe. Southeast of the Highland Moraine, concentrated flows and outwash streams from the ablating Superior lobe deposited a variety of slumped glacial sediments and gravel lag debris. Sediment supplied from stagnant ice sources and meltwater from the retreating Superior lobe formed large deltaic deposits of cross-bedded sands and gravel, interfingered with thin lenses of clay-rich diamictons, and overlain by flow tills. These sediments mark the 348-366 m strandline of Glacial Lake Duluth, a proglacial lake which formed along the margin of the retreating Superior lobe. Lacustrine clays, deposited contemporaneously with the deltas, cover much of the southern part of the quadrangle below this strandline. The clay is red/brown (5YR 4/4), with a

sand:silt:clay ratio of 15:18:67, and ranges from massive, highly jointed, with pebbly "lag deposits," to finely laminated with pockets of "sand nests," to very plastic and stony. It is exposed extensively along the lakeshore, in stream valleys, and as the surficial deposit of much of the North Shore of Lake Superior.

Distinguishing between clayey till and lake clay in the Lake Superior region is problematical. Though the red clay of the south shore, the "Douglas Till," is attributed to subglacial processes (Johnson, 1980), my investigation confirms the interpretation of a lacustrine origin of the red clay along the north shore (Moss, 1977). Restricted occurrence below high level strandlines, stacked lake terraces within the region, association of "lag deposits," and fine laminations indicate a glacial lacustrine rather than subglacial origin for the clay-rich diamicton of the North Shore of Lake Superior.

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PRECAMBRIAN DIKE SWARMS: PATTERNS AND PROBLEMS

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ABSTRACT

Precambrian dikes criss-cross all the world's Precambrian shields; swarms extend for many hundreds of kilometers, and obviously represent major magmatic events in Earth history. Dikes are commonly thought to develop in a rift environment; preserved swarms along the margins of the Atlantic for example represent the earliest rift stages in the formation of this ocean during Jurassic-Triassic times. However despite considerable work on models of rifting and sea-floor spreading, little work has been done on dike swarms, particularly the enormous Precambrian ones that are not so obviously related to continental separation. A major question about these and younger swarms concerns their mode of emplacement. What is the form and location of magma chambers that fed these swarms, how has the magma flowed, and what controls the orientation of dike swarm?

Possible solutions to these questions are discussed using examples of 2^+ Ga dike swarms from the Canadian, African, Australian and Indian Shields. In particular paleomagnetic, structural and geochemical results will be given from the Matachewan-Hearst and Kenora-Kabetogama swarms that have bearing on regional structure and the direction of magma flow.

By analogy with more recent dike swarms, a working hypothesis that shows promise is that magma flow is dominantly sub-horizontal along swarms and that lateral changes in petrology, geochemistry and fabric may help to locate magma sources. This aspect is of considerable importance in most Precambrian (and younger) dike swarms for which evolutionary models have yet to be developed.

MICHIGAN'S ENERGY RESOURCES: A GEOLOGICAL PERSPECTIVE

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ABSTRACT

Michigan energy supply and demand patterns of the study year 1972 (Fig. 1) indicate in a general manner the situation as it exists in 1982. Line thicknesses represent quantities of energy in terms of their heat content. The wiggly line at top is hydroelectric power, the satellite symbol is nuclear power, and blank box above "Transp." represents the use of oil by the manufacturing industry as raw feed for plastics. In 1982 coal consumption is down by about one third and oil is up by a like amount, some of the shift to alleviate air pollution. About as much heat energy ultimately is lost as is used, because of inefficiencies of all kinds in the conversion of heat to useful energy. Michigan obtains about 1/5 of its gas and oil from in-state sources.

Based on a review of the occurrence and possible quantities of geological and non-geological types of fuels in Michigan, the writer concludes that the state has a few energy options for the future (Fig. 2). On the right, for purposes of comparison, are shown the fuel requirements for 1972. On the left are the in-state reserves utilized in 1981, with an estimate of the years that they will last. In the center are listed the resources to which Michigan might turn as the present reserves become exhausted, should some level of continued energy self-sufficiency be deemed to have economic value. Coal and peat may be less important than the bitumen- and kerogen-containing Antrim Shale. In the northern part of the lower peninsula several hundred square miles are underlain by this shale that contain between 10 and 15 gallons per ton of Fisher assay extractable oil across 30 feet.

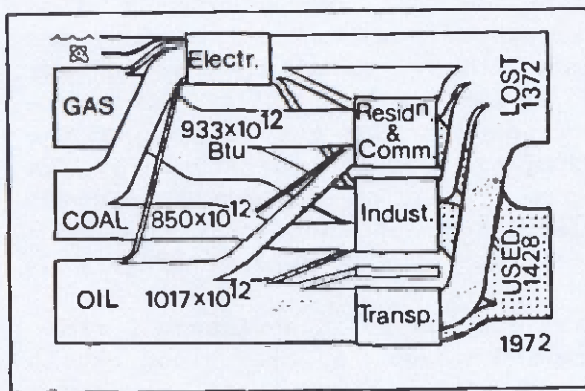


Figure 1

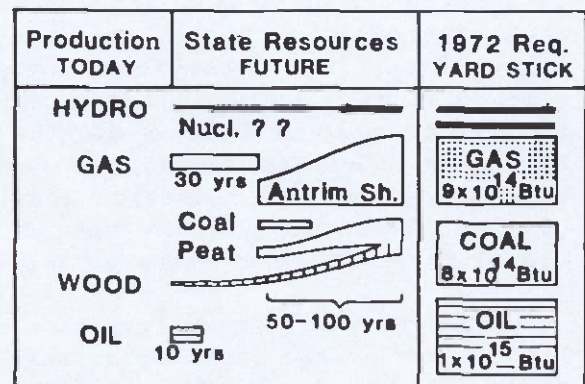


Figure 2

THE VOLCANIC ROCKS OF THE UNNAMED FORMATION,
PORCUPINE MOUNTAINS REGION,
MICHIGAN - A MIDDLE KEWEENAWAN ERUPTIVE CENTER

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ABSTRACT

The unnamed formation is a Middle Keweenawan central shield volcano (White, 1972) which crops out in the vicinity of the Porcupine Mountains in the Upper Peninsula of Michigan. Maximum surface thickness of this lensoid-shaped formation is about 8,000 ft. in the Bergland and Thomaston quadrangles. The volcanic pile gradually narrows, eventually wedging out in the Greenland quadrangle to the east and in the Little Girls Point quadrangle to the west. The formation is conformable on and is a continuation of the underlying Portage Lake Volcanics. Previously grouped with the Portage Lake Volcanics, the unnamed formation was first recognized as a separate unit by Johnson and White (1969). The distinction between the two units is that the unnamed formation contains a greater percentage of relatively acidic volcanic rocks. Overlying and locally interfingering with the unnamed formation is the Copper Harbor Conglomerate.

Spatial relationships between the various rock types within the unnamed formation were observed in the field. Samples were collected perpendicular to strike to obtain representative vertical sections of the formation. Forty-seven samples were analyzed for major and minor elements. Compositions of the lava flows within the unnamed formation range from rhyolite to basalt. Andesite is the most common rock type. Twenty-five samples from six distinct felsite bodies were analyzed. These include: 1) the felsite topping Copper Peak (Chippewa Hill), 2) the felsite that makes up the highlands of the Porcupine Mountains Wilderness State Park, 3) the Chippewa felsite located between White Pine and Bergland, 4) two quartz latite flows within the Porcupine Mountains Wilderness State Park, 5) the quartz porphyry located north of Bergland and 6) an ash-flow tuff located about 7 miles southeast of White Pine. Emphasized to a lesser extent in the study are the analyses of 15 basic and intermediate flows. Finally, 4 intrusions were chemically analyzed. They include: 1) two basaltic sills from within the quartz porphyry, 2) a diorite dike which intrudes the felsite of the Porcupine Mountains and 3) a diabase granophyre complex positioned at the base of the unnamed formation near the western edge of the Matchwood quadrangle. Evaluation of the chemical variance between and within the individual flows and intrusions is incomplete at the time of this writing.

Lavas of the unnamed formation may have erupted in an environment similar to that of the Tertiary of eastern Iceland (Green, 1977). Flood basalt flows from fissures within the Midcontinent Rift overlapped and interfingered with relatively acidic flows from the central shield volcano. At the same time, emplacement of shallow intrusions occurred at vent areas and hydrothermal activity took place locally. The central shield volcano of the unnamed formation differs from central volcanoes of the Tertiary of eastern Iceland in that the former is much larger in size and contains a greater percentage of andesite than the latter. Dike swarms which are common in

central volcanoes of the Tertiary of eastern Iceland are lacking in the unnamed formation. After volcanism, the volcanic rocks of the unnamed formation were regionally metamorphosed to the chlorite facies. Subsidence within the Lake Superior Syncline tilted the unnamed formation northward exposing a cross-sectional view of the central volcano. Further folding in the vicinity of the Porcupine Mountains resulted in the formation of the Porcupine Mountain anticline. At its center, the unnamed formation is exposed forming the highlands within the Porcupine Mountains Wilderness State Park.

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HYDROTHERMAL PROCESSES AND MASSIVE SULFIDE DEPOSITS
AT OCEANIC SPREADING CENTERS

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ABSTRACT

Active hydrothermal vents and metal sulfide deposits have been located and sampled along Pacific Ocean spreading centers, including the East Pacific Rise, the Galapagos spreading center, and the Juan de Fuca Ridge (Fig. 1). These discoveries have confirmed predictions, based on studies of heat-flow patterns, the widely distributed basal metalliferous sedimentary layer overlying oceanic crust, basalt/seawater-interaction phenomena, and volcanogenic sulfide deposits in ophiolite complexes, that fluids circulating through newly formed lithosphere at oceanic spreading centers can effectively mobilize metals and form mineral deposits on the sea floor.

A genetic model for the deposition of polymetallic sulfides at medium- to fast-rate spreading centers proposes that the heat flux from a magma chamber emplaced at a shallow level (1-3 km) below the sea floor induces convective flow and continuous recharge of seawater through permeable lithosphere from along the oceanic-ridge flanks toward the heat source (Fig. 2). The cycle continues with deep penetration along cracking fronts through the lava flows and dike complex of oceanic layer 2 to levels near the magma chamber, and is followed by upwelling of the buoyant hydrothermal fluid along fractures and faults to the sea floor. At high temperatures and water/rock ratios, hydrolytic and oxidative reactions with mafic wallrock generate a low-pH low-Eh solution capable of leaching and transporting transition metals and sulfur. Cooling of the upwelling fluid during adiabatic expansion and then its further cooling and neutralization upon subsurface mixing with ambient seawater cause deposition of sulfide minerals along subsurface channelways; rapid fluid flow results in the discharge of reduced fluid and the deposition of massive sulfide at the seafloor/seawater interface. Oxidizing conditions on the sea floor promote the development of distal silicate and oxide facies and the fractionation of Mn from Fe.

Preliminary investigations of sulfide deposits along the Pacific Ocean ridge system reveal considerable diversity. For example, on the East Pacific Rise at lat. 21°N, composite mound-chimney edifices composed of Zn, Fe, and Cu sulfides, Ca and Ba sulfates, and silica overlie basalt in a horst-and-graben terrain near the volcanically active ridge axis. Active vents are vigorously discharging high-temperature (350°-400°C) fluid rich in particulate sulfide (black smokers) and silica (white smokers); the latter host exotic communities of worms, crabs, and clams. In the southern trough of the Guaymas Basin in the Gulf of California, hot springs are depositing mounds of Fe and Zn sulfides (the unusual assemblage pyrrhotite + sphalerite) and ledges of Fe-rich talc on rapidly accumulating ponds of unconsolidated ooze and mud. In addition, hydrothermal activity generated by the intrusion of diabase sills into water-saturated sediment rich in organic material has transformed the organic material into gasoline-range hydrocarbons.

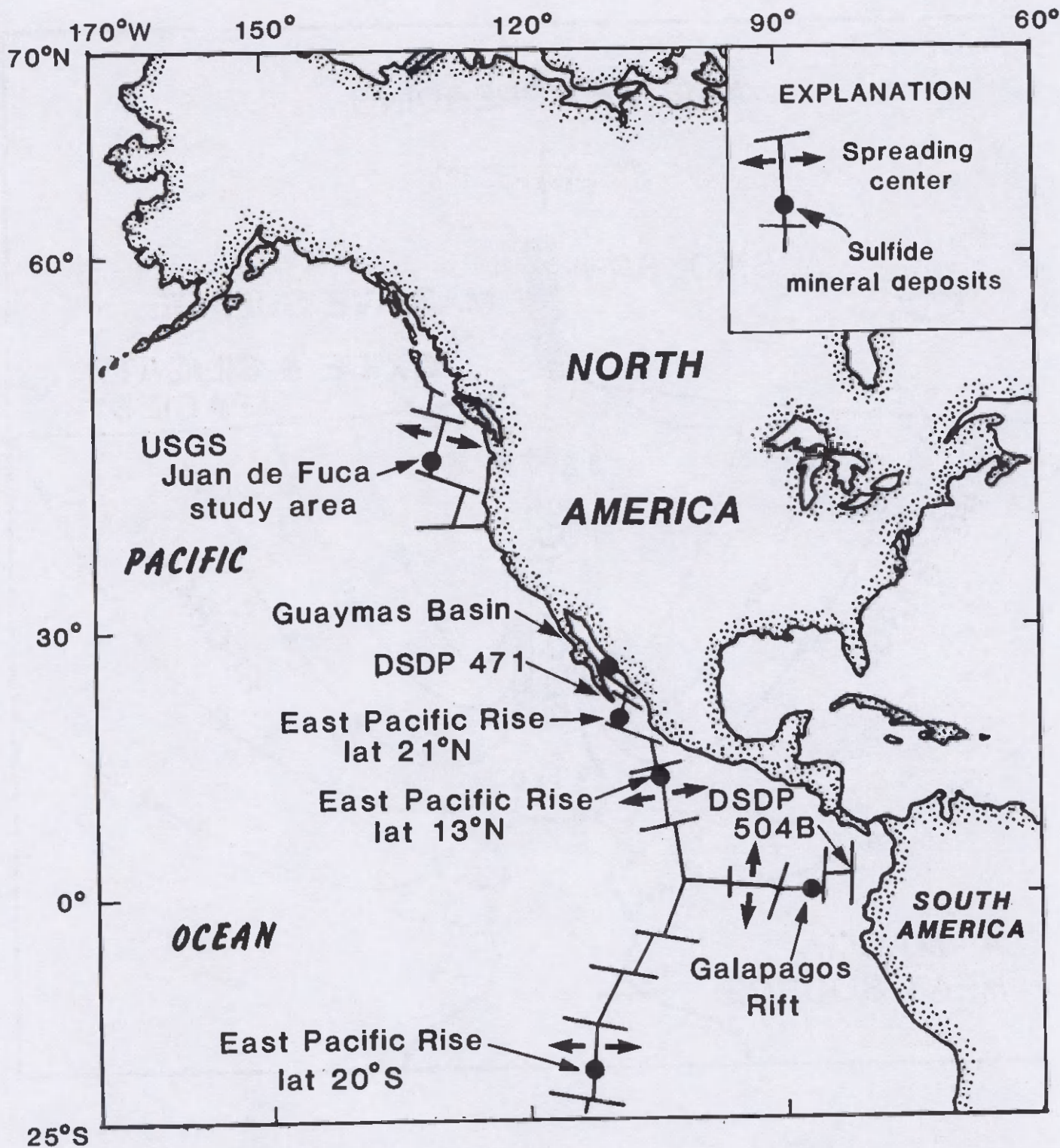


Figure 1

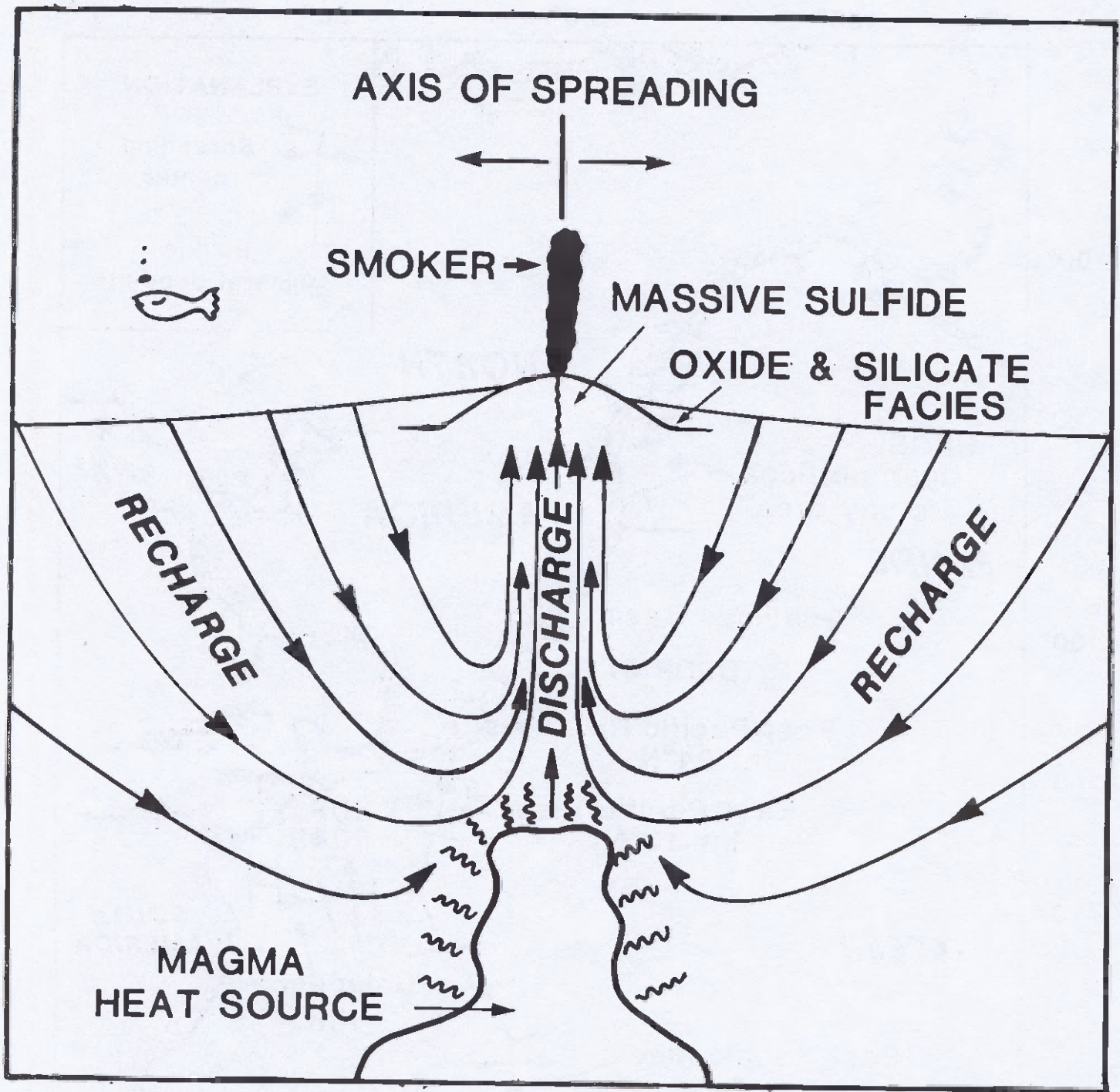


Figure 2

On the Galapagos Rift at long. 86°W, hydrothermal deposits occur along the base of normal-fault scarps bounding a horstlike central ridge. A large (1,000 m long, 150 m wide, 35 m thick) prism of Cu-rich and Zn-poor massive sulfide with numerous large inactive chimneys has formed along a south-facing escarpment. On the southern Juan de Fuca Ridge, encrustations of Zn-rich and Cu-poor massive sulfide and associated benthic organisms mark a series of hydrothermal vents and vent fields in a region underlain largely by glassy ferrobalt sheetflows. The deposits are spatially associated with a shallow cleft in the axial-valley floor.

Continued research on hydrothermal systems and polymetallic sulfide deposits on the midoceanic-ridge system will stimulate and improve current concepts in such diverse fields as ore genesis, mineral exploration, evolutionary biology, and deep-seabed mining.

A GEOCHEMICAL CORRELATION, WITH CORRELATIVE INFERENCES FROM
PETROGRAPHIC AND PALEOMAGNETIC DATA, OF THE GREENSTONE FLOW,
KEWEENAW PENINSULA AND ISLE ROYALE, MICHIGAN

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ABSTRACT

A correlation across the Lake Superior syncline between Isle Royale and the Keweenaw Peninsula of Michigan was first proposed by Lane (1898). The key to this correlation was the presence of one immense, continuous Middle Keweenawan tholeiitic flow known as the Greenstone Flow (GSF). Thickness data for the GSF on Isle Royale (Lane, 1898; 1911) and the Keweenaw Peninsula (Cornwall, 1951) imply a total volume for the GSF of 1,000 km³, which has been viewed as "a conservative estimate" (White, 1960). Huber (1973) confirmed the similarities of the GSF on Isle Royale and the Keweenaw Peninsula, and he supported the correlation. A single lava flow of such great magnitude would possibly be the world's largest. However, evidence for this correlation was based solely on field criteria. This paper is the first quantitative study to test the validity of the proposed correlation.

A total of 57 samples (34 of which were oriented) were used in this study. The samples were collected in stratigraphic sequence across the GSF at Blake Point, Isle Royale, Michigan, and at Cliff Drive and Phoenix, Michigan on the Keweenaw Peninsula. Other samples were collected from directly above and below the GSF from the latter three sites, from the GSF in the MTU experimental mine, and from a drill core through the GSF in Seneca, Michigan. The latter two sites were places where oriented sampling was not possible, and the GSF was the thinnest (45-75 m).

All rocks were analyzed by XRF for both major and trace elements. Only specimens least affected by migrating hydrothermal fluids were chosen for chemical evaluation. These sample sites were ophitic zones in the flow, which are the zones of lowest permeability and least alteration.

Thin sections were studied to observe changes in mineralogy, mode, texture and plagioclase composition. For samples with >35% plagioclase an XRD method for plagioclase determination was utilized (Smith and Gay, 1958). Type and degree of alteration were evaluated to assist in the selection of samples for geochemical analysis, and to aid in the interpretation of samples with radically different geochemistry.

Core specimens were taken from the oriented samples for paleomagnetic evaluation. Statistical results of the remanent magnetism on Isle Royale were compared to present (this paper) and previous work on Keweenaw (Books, 1972). The results were used as a correlation tool.

The GSF, an olivine tholeiite, is the thickest flow in the Portage Lake Volcanic Sequence of Michigan's Copper Country. Thicknesses range from 30 to 245 m on Isle Royale (Huber, 1973) and from 45 to 427 m on the Keweenaw Peninsula (Cornwall, 1951).

The flow is stratified due to differentiation into chemically distinct fractions, which are the pegmatitic lenses with associated granophyric dikes and sills (pegmatoids), and ophitic zones. Most differentiated are the pegmatoids whose frequency varies proportionally with total flow thickness. These coarse-grained fractions vary in thickness and shape, usually occur as stratiform features, but were also noted to occur as auto-intrusions in the columnar-jointed melaphyre on Isle Royale. Pegmatoids are permeable channelways for the deuteric and later hydrothermal fluids. Therefore, these zones are poor sites for chemical correlation in flood basalt terranes.

Ophitic areas, the major flow units, presumably occurred as continuous layers in the upper and lower sections of the GSF. In thicker portions of the GSF subophitic to ophitic lenses with intermingling pegmatoids are sandwiched between the upper (UO) and lower (LO) ophitic zones and are presumed stratigraphically discontinuous.

In summary, the UO and LO are presumed continuous throughout the flow and are low in permeability; thus they were least affected by migrating hydrothermal fluids. Therefore, the UO and LO were chosen as ideal sites for chemical correlations within the Portage Lake Volcanics.

An average GSF composition as calculated from this study was:

Major Elements (wt.%)		Trace Elements (ppm)	
SiO ₂	= 46.7	Ba	= 103.5
Al ₂ O ₃	= 15.1	Cr	= 213.4
FeO*	= 12.8	Cu	= 66.4
MgO	= 7.8	La	= 10.9
P ₂ O ₅	= 0.14	Mn	= 1675.4
		Ni	= 186.2
		Pb	= <2
		Rb	= 7.8
		S	<50
		Sc	27.9
		Sn	5.9
		Sr	= 258.7
		V	194.7
		Y	13.5
		Zn	84.4
		Zr	= 91.8

The data have revealed the following facts:

1. A remarkable chemical homogeneity can be demonstrated within ophitic sections of the GSF.
2. Similar geochemistry existed in all sites analyzed with the exception of the chlorite-prehnite-pumpellyite altered GSF from the MTU experimental mine.
3. Most flows directly beneath the GSF are chemically similar to the GSF, and believed to be part of a magmatic cycle which terminated with the extrusion of the GSF.
4. Similar petrology is found in all GSF sample sites except the altered GSF from the MTU mine.
5. Flows directly above the GSF display different chemistry and petrology in most sample sites. Petrology of flows directly beneath the GSF are similar to the GSF.

6. Statistically similar directions of remanent magnetization are found for the GSF on Isle Royale and the Keweenaw Peninsula.
7. Statistically similar directions of remanent magnetization direction are found for flows directly beneath the GSF on Isle Royale and Keweenaw Peninsula (Books, 1972) which tend to diverge away from the mean remanent magnetization direction of the GSF. However, limited data exist.

In light of all the data collected for this study, no inconsistencies were found to occur through the entire GSF. Since a possibility exists that the GSF on Isle Royale and the GSF on the Keweenaw Peninsula are two separate flows from the same magmatic cycle, a positive correlation cannot be proved.

URANIUM IN LOWER PROTEROZOIC PHOSPHATE-RICH METASEDIMENTARY ROCKS
OF EAST-CENTRAL MINNESOTA

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ABSTRACT

Exploration for uranium deposits related to the unconformity between the lower Proterozoic Thomson Formation and the middle Proterozoic Fond du Lac Formation in east-central Minnesota has defined several very low grade uranium occurrences. Most of these occurrences are associated with phosphate-rich units in the Thomson Formation, which consists dominantly of interlayered feldspathic graywacke, siltstone, and mudstone and lesser amounts of carbonaceous mudstone, dolomite, quartzite and volcanic rocks. The formation was deformed and metamorphosed under lower greenschist to middle amphibolite facies conditions during the Penokean orogeny approximately 1,870 m.y. ago.

Samples of the phosphate units from two localities were studied to characterize the uranium occurrences. The Thomson Formation at these localities occurs at chlorite grade, and the uranium in the samples averages at least 400 ppm. The phosphate units are relatively thin, having a maximum thickness of about 30 cm (Ullmer, 1981), and are intercalated with beds of black to gray recrystallized chert, and lesser amounts of carbonaceous slate and siliceous carbonates. The units consist of both conglomeratic and thinly laminated rock. The conglomerate is characterized by angular to subrounded pebbles of cryptocrystalline apatite and recrystallized chert set in a matrix of apatite, quartz, and lesser amounts of argillaceous material. Both the pebbles and groundmass contain variable amounts of carbonaceous material. The thinly laminated rock consists of interlayered apatite, quartz, and lesser amounts of argillaceous and carbonaceous material.

The textural arrangement of the uranium in these phosphate-rich samples indicates that the uranium has had a complex paragenetic history. Much of the uranium occurs evenly disseminated within the phosphatic pebbles and layers, implying that it was precipitated syngenetically with the phosphatic material, or was fixed out of the Thomson sea by the phosphatic sediments on the sea floor. Concentrations of somewhat younger uranium along planes that parallel the tectonic foliation imply secondary recrystallization, probably during the metamorphism. Additional concentrations of uranium along joint or fracture planes at an angle to the foliation indicate a postmetamorphic mobilization of the uranium.

Uranium also occurs as overgrowths around pyrite grains and as individual mineral grains. Nearly all of the pyrite grains in the samples studied are surrounded by some uranium mineralization, and many show a multi-stage history of replacement of the pyrite by a uranium phase. The individual uranium mineral grains commonly contain other phases, such as pyrite and possibly barite. These mineral grains are typically subrounded to rounded, and contain 55-75 percent UO_2 . Associated with the uranium in these grains are Pb, P, Ca, Fe, Ba, S, Ti, Cu and Zn.

Ullmer, E., 1981, A mid-Proterozoic phosphate occurrence in east-central Minnesota: Newsletter IGCP Project 156, no. 8, p. 22-25.

MINERALOGIC AND TEXTURAL VARIATIONS OF ANORTHOSITES IN THE DULUTH COMPLEX,
FOREST CENTER NW QUADRANGLE, MINNESOTA

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ABSTRACT

Although anorthositic rocks occur over 60 percent of the exposure area of the Duluth Complex, they are inadequately studied and poorly understood. The anorthosites are considered to be part of an older gabbroic sequence that was intruded by troctolite and gabbro, but this interpretation is not definitive. This report on the preliminary results of field and petrographic studies is part of a broader study to acquire new data that bear on the origin of the anorthositic rocks. Detailed lakeshore mapping of the study area (Fig. 1), which was previously mapped at reconnaissance scale in 1968 by Phinney, was conducted in the summer of 1981.

The anorthositic rocks in the Forest Center NW quadrangle appear to form a cap over troctolitic rocks, which are exposed in three separate areas. Exposed contacts between troctolite and anorthosite are commonly broad, complex zones of mixed rock types.

The anorthositic rocks are extremely variable in mineralogy, texture, and structure over most of their exposure. Igneous lamination is erratic over small distances and contacts between contrasting rock types can generally be traced only on an outcrop scale. Thus stratigraphic control is generally nonexistent. Nevertheless, three consistent contact relationships have been found:

- 1) In some outcrops, plagioclase lamination in one rock type is parallel to the contact with a contrasting rock type having discordant plagioclase lamination. This is taken to imply intrusion of the first rock type into the second.
- 2) Similarly, where plagioclase lamination wraps around a contrasting rock type, the latter is interpreted to be an inclusion.
- 3) In other exposures, contrasting rock types with concordant plagioclase lamination grade into each other across centimeter- to meter-wide zones. Rock types displaying gradational contacts are considered to be cogenetic.

Based on these relationships, which are consistent between particular rock types, three stages of anorthosite emplacement have been distinguished in the study area and are denoted as early, main, and late. A petrographic summary of the rock types of each stage is given in Table 1.

Five types of main-stage anorthosite have been identified (Table 1). Over 80 percent of the total anorthosite exposure consists of main-stage troctolitic anorthosite (TAM) and large-spotted anorthosite (LSA) in roughly equal proportions. The major difference between these two types is the texture of olivine which is interstitial in TAM and ophitic in LSA.

TABLE 1 : PETROGRAPHIC DESCRIPTIONS OF ANORTHOSES

	EARLY STAGE		MAIN STAGE				LATE STAGE	
	Troctolitic Anorthosite		Troctolitic Anorthosite		Small Spotted Anorthosite		Troctolitic Anorthosite	
	Medium	Excellent	Medium	Excellent	Large Spotted Anorthosite	Medium	Anorthosite	Anorthosite
Grain Size ¹	Medium	Excellent	Medium	Excellent	Medium - Coarse	Good - Excellent	Medium - Coarse	Medium - Coarse
Lamination	Good - Excellent				Poor - Good		Poor - Fair	Poor - Fair
PLAGIOCLASE								
Habit ²	85 - 95 %	95 - 98 %	80 - 90 %	80 - 95 %	90 - 97 %	80 - 95 %	95 - 98 %	75 - 85 %
Zoning ³	S	S	V	V	S - A	E, S	S - A	S
Inclusions	NS	NS - Osc(2-3)	V	V	NS - Osc(1.5-2)	V	NS - PS	V
	Ol	Feox + Cpx	Feox + Cpx + Ol	Feox + Cpx	Feox + Cpx	Feox + Cpx	Feox + Cpx	Feox + Cpx
OLIVINE								
Texture/Habit ⁴	8 - 15 %	None	5 - 15 %	2 - 15 %	2 - 7 %	0 - 2 %	None	8 - 20 %
Grain Size	I, Equant ≤ 2 mm		I, Anhedral 1 - 10 mm	O 2 - 6 cm	S - O ≤ 2 cm	I, Anhedral ≤ 2 mm		I, Equant 0.5 - 8 mm
CLINOPYROXENE								
Texture/Habit ⁴	0 - 5 %	≤ 2 %	2 - 10 %	2 - 10 %	≤ 1 %	5 - 18 %	1 - 3 %	0 - 5 %
Oikocryst Size	S - O 5 - 20 mm	S ≤ 5 mm	S - O 5 - 40 mm	O 5 - 40 mm	S - O 3 - 10 mm	O 5 - 40 mm	S 5 - 10 mm	O 10 - 30 mm
ORTHOPYROXENE								
Texture/Habit ⁴	≤ 1 %	Trace	≤ 1 - 3 %	1 - 5 %	Trace	Trace - 5 %	None	≤ 1 - 2 %
Oikocryst Size	R (Ol)	I ≤ 1 mm	R (Ol) - S ≤ 5 mm	R (Ol) - S ≤ 5 mm	R (Ol) - S ≤ 2 mm	S - O ≤ 10 mm		R (Ol) - S ≤ 5 mm
IRON OXIDE								
Texture/Habit ⁴	≤ 1 %	≤ 1 %	1 - 5 %	1 - 8 %	≤ 1 %	2 - 10 %	≤ 1 %	≤ 1 - 3 %
Oikocryst Size	I - S ≤ 5 mm	S ≤ 5 mm	S - O ≤ 5 - 20 mm	S - O ≤ 5 - 20 mm	S - O ≤ 1 - 5 mm	S - O ≤ 5 - 20 mm	I - S ≤ 5 mm	S - O 2 - 8 mm
OTHER MINERALS	Bio, (Ith)	(Pio)	Bio, Ith, Apt	Bio, Ith, Apt	Bio, (Ith)	Bio, Ith	(Bio)	(Bio)
TOTAL SIZE ⁵	6 - 10	2	16 - 22	19 - 22	4	6 - 8	3	5 - 12

Notes are visual approximations

1) Grain size measured normal to (010) in cumulus plagioclase; Medium = 1-4 mm, Coarse = 4-8 mm, Pegmatite = 8 mm.

2) (E)uhedral, (S)ubuhedral, (A)nhedral, (V)ariable.

3) NS - normal sector zoning, PS - patchy sector zoning, Osc(%) - oscillatory zoning with no. of cycles, V - variable.

4) (I)nterstitial, (S)ubophitic, (O)phitic, (R)ims on (Ol)ivine, (V)ariable.

5) Range represents uncertainty of rock type designation due to a lack of contact relationships.

The other three main-stage rock types occur in gradational contact only with LSA.

The early troctolitic anorthosite occurs as inclusions in both TAM and LSA. Only two occurrences of the early-stage anorthosite were found as inclusions in LSA.

Late-stage troctolitic anorthosite (TAL) intrudes all main-stage rock types. TAM and TAL are petrographically very similar (Table 1) and are distinguishable in the field only where contact relationships are observed.

Major and minor element and microprobe analyses of the anorthosites are planned in order to test and refine these field and petrographic observations.

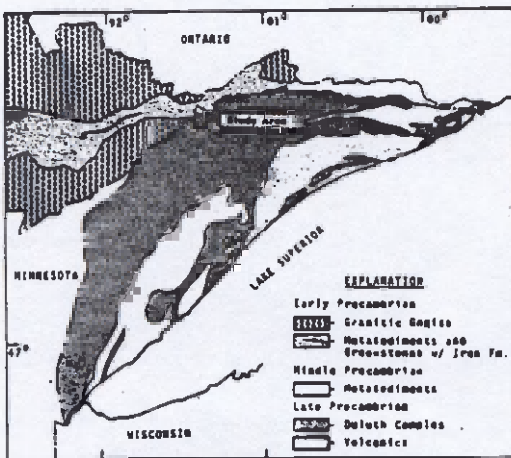


Figure 1

General geology of the Duluth Complex in the Forest Center NW quadrangle, NE Minnesota.



PROGRESS REPORT ON THE BEDROCK GEOLOGY OF THE
NORTHWEST MAP SHEET, WISCONSIN

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ABSTRACT

Precambrian rocks have been the focus of geologic mapping in the Northwest map sheet, Wisconsin since 1976. The area is bounded on the north and south by the 46° and 45° latitudes, respectively; on the east by 90° longitude; and on the west by the Wisconsin-Minnesota state boundary. Bedrock exposures in the east half of the map sheet are generally limited to river valleys; in the west the outcrops are extremely sparse, and have no obvious pattern. As a result, extensive use has been made of aeromagnetic data and available drill core and cuttings. Gravity data are too sparse in the map area to be of much value.

Archean gneisses are inferred from two outcrops and the related domal aeromagnetic patterns near Fifield and on the Chippewa River in T.39N., R.6W. Relations of these rocks to other units are not known.

Lower Proterozoic units include a dominantly metasedimentary sequence trending east-northeast centered near Park Falls. Numerous electromagnetic anomalies are known from this unit (Flambeau Anomaly of Sternberg and Clay, 1977), and those that have been drilled consist almost exclusively of garnet-bearing graphite schists with trace amounts of sulfide. Typical Proterozoic iron formations and associated carbonate rocks are known from this unit. Relations of this unit to metavolcanic units to the south are not known because of a major fault. Although exposure is poor, this metavolcanic terrane apparently extends from the central part of Price County to the southern part of Taylor County. Aeromagnetic expression and available outcrops suggest that the metavolcanic rocks north of the Jump River Fault are dominantly amphibolite facies, whereas those south of the fault are greenschist facies and more felsic. Although not seen in this map area, relations described by Myers along the North Fork of the Eau Claire River suggest that the greenschist-facies rocks unconformably overlie the amphibolite-facies rocks. These stratiform rocks were intruded by granitic rocks around 1,880 million years ago, and by granite near Radisson about 1,760 million years ago.

Two volcanogenic massive sulfide occurrences are known in these metavolcanic rocks. In the late 1960's the Flambeau and Thornapple deposits were discovered by a subsidiary of Kennecott Copper, and 4 to 6 million tons of 4 percent copper ore were identified. Exploration has continued in the area but no details are available. Mineral potential is considered good, particularly in the greenschist felsic rocks.

After deformation of the Lower Proterozoic rocks, a Middle Proterozoic conglomerate and quartzite sequence was deposited. The principal unit is

the Barron Quartzite of western Rusk and adjoining counties. Present work restricts the age of the quartzite sequence between 1,700 m.y. and 1,100 m.y. The younger is controlled by presumed Keweenaw diabase dikes in the quartzite. Recently, U.S. Department of Energy National Uranium Resource Evaluation work suggested some potential for unconformity related uranium occurrences in northern Rusk County, although no uranium anomalies were identified. Field work by DOE contractors suggested that a weakly metamorphosed regolith is unconformably overlain by the quartzite.

Keweenaw volcanic rocks on the western edge of the map sheet adjacent to Minnesota, are correlated with the Chengwatana Volcanic Group. These volcanic rocks are poorly exposed, but where studied, tend to consist of thick basalt flows that have been metamorphosed to grades ranging from zeolite to lower greenschist. Cordua and others (1979) have previously reported on the copper mineralization in both the Keweenaw volcanic rocks and the overlying Upper Cambrian sandstones. Mineral potential is not considered significant.

Faults are generally recognized from aeromagnetic signatures. The dominant structure in the western part of the map sheet is the St. Croix horst and its bounding faults including the Lake Owen, Cottage Grove and Pine Faults. Aeromagnetic lineament analysis and sparse outcrop control in the east half of the map sheet, suggest that the northeast-trending faults were active during the Keweenaw inasmuch as the Barron Quartzite is cut by the faults. We believe that at least some of the activity along these faults, particularly the Jump River and Monico faults, is early Proterozoic in age, with reactivation during the Middle and possibly Late Proterozoic. The principal northwest-trending fault, the Hawkins fault, is defined entirely from aeromagnetic lineament analysis.

Mudrey's efforts have focused in the northeastern part of the map; La Berge in the southeast corner; Myers in the south-central, and Cordua in the western parts. An early version of the east part of this map was published by Sims, Cannon and Mudrey (1978). Work in future years relating to the Precambrian rocks will be directed to improved petrographic and structural descriptions, and refined analysis of geophysical data.

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STRUCTURAL ANALYSIS OF THE DULUTH COMPLEX
FOREST CENTER NW QUADRANGLE, MINNESOTA

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ABSTRACT

We report here the results of a structural analysis of the joint, dike, and lineament orientations in a portion of the Duluth Complex. The study was initiated to document the brittle structures in the Complex and to integrate them into its structural history. Joint and dike orientations were measured in the field within a 26 km² area. Lineament azimuths and lengths were measured from a high-altitude aerial photo (scale 1:39,000) that covers approximately 1,200 km² and includes the smaller area studied on the ground.

The dominant rock types of the Duluth Complex in this area are troctolite and anorthosite (see Miller and Weiblen, this volume, Fig. 1). These rocks intrude Archean metasedimentary rocks, greenstone, and granite of the eastern Vermilion district. Plagioclase lamination and modal layering in the troctolite generally are parallel to the basal contact which trends N70°E to N50°E. The dominant structural fabric of the metamorphic country rock trends NW to E-W.

A total of 4,435 joint orientations were recorded and plotted on rose diagrams in 5° intervals. Only azimuths were recorded as most of the joints are near vertical. Three types of joints were recognized: unmineralized joints, joints filled with green chlorite (408 total), and joints filled with white sericite (169 total). The green chlorite-filled joints occur predominantly in the troctolite; 287 (94%) occur within 2 km of the contact. White sericite-filled joints are generally confined to the anorthosite.

The major differences in fracture trend are related to rock type. Figures 1a and b summarize the azimuths of all joints measured in the troctolite and anorthosite, respectively. The troctolite contains predominant joint sets at N25°-45°W, N10°-20°E and N85°W-N85°E with lesser peaks at N65°-75°W and N50°-55°E. Total joints in the anorthosite define a prominent, broad peak at N50°-85°W. Considering only the mineralized joints (Figs. 1c and d), the troctolite data retain only the N25°-45°W and N10°-20°E sets. The mineralized joints in anorthosites show considerable scatter with 4 significant and 3 to 4 lesser peaks.

Stereo plots were made of 33 diabase dikes (Fig. 2) and 34 granitic veins and dikes. Although considerable scatter is present, the mean diabase dike strikes N51°E $\pm$ 26° and dips 51° $\pm$ 22° SE (1 std. dev.). The granitic dikes, which occur only in the anorthosite, show greater variation in orientation than do the diabase dikes but generally trend NNE to E-W.

The azimuth and length of 437 aerial photo lineaments are plotted in Figure 1e. The total lineament data show a strong peak at N30°-45°E and lesser peaks at N10°-20°E and N5°-20°W.

The jointing in the study area may be attributed to several causes: (1) contraction during cooling of the contact-area rocks (we suggest that most mineralized joints may have formed in this manner); (2) upward propagation of basement structure; (3) response to regional stresses; and (4) isostatic rebound due to erosion and glacial unloading. Diabase and granite dike orientations indicate tensional stresses oriented NW-SE, normal to the Duluth Complex contact, during the later stages of Keweenaw igneous activity in the area. The predominance of N to NE lineament orientations probably is biased by glacial scour, but, nevertheless, most lineament trends may be related to joint and dike orientations. Definitive evidence of faulting was found at only one location where a fault is oriented N20°E. The extent of faulting in the area is difficult to assess due to poor exposure and complex intrusive relationships.

Figure 1 Rose diagrams of brittle structures in the Duluth Complex.

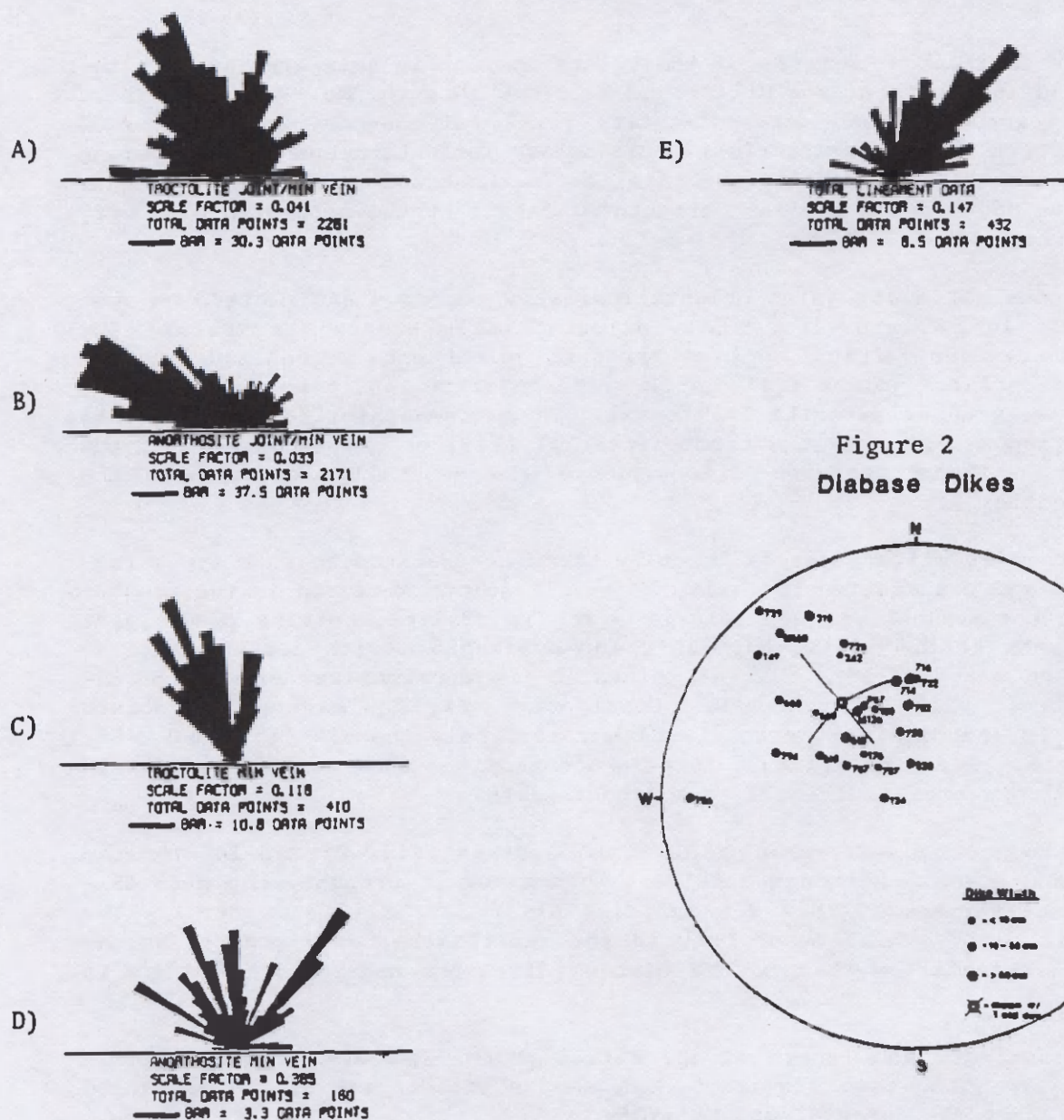
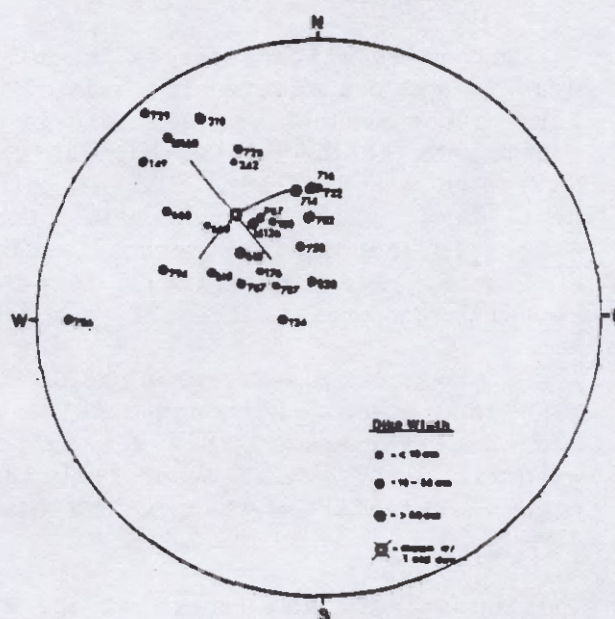


Figure 2
Diabase Dikes



STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT OF ARCHEAN
FELSIC VOLCANICS, WAWA, ONTARIO

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ABSTRACT

Archean volcanic rocks of the Wawa area, in the Michipicoten district of northern Ontario, form part of the Wawa greenstone belt. The rocks studied are situated northeast of the city of Wawa, and comprise the upper portion of a mafic-to-felsic volcanic cycle which includes the Helen Iron Formation, a volcanogenic massive sulfide-type deposit.

On the basis of preserved primary textures and structures, the rocks can be divided into: 1) massive, flow-laminated, spherulitic, and lithophysae-bearing lava domes and flows, 2) massive to well-bedded pyroclastic rocks, and 3) volcanogenic sedimentary rocks.

One series of pyroclastic rocks exhibits a marked lateral facies change, with coarse, massive beds in the central portion of the study area grading laterally eastward into thin and graded beds. The changes in grain size and bedding characteristics indicate a westerly source for the materials, while thin and graded beds suggest subaqueous deposition.

Volcanogenic sedimentary rocks at the top of the felsic volcanic succession (directly underlying the Helen Iron Formation) contain numerous sedimentary structures indicative of shallow water deposition. Paleocurrent analysis of cross-bed dip directions indicates a source to the west.

Vesiculated pillow-basalts overlie the Helen Iron Formation and are indicative of a shallow subaqueous environment.

The felsic volcanic rocks are envisioned as having been deposited in both a subaerial and shallow subaqueous environment. Volcanic center(s) to the west were topographically high areas that were periodically or continuously exposed above the water surface, whereas the flanks of the volcanoes were periodically or continuously submersed in a shallow basin.

TIDAL DEPOSITS IN THE EARLY PROTEROZOIC BASIN OF THE LAKE SUPERIOR REGION--
THE PALMS AND POKEGAMA FORMATION: EVIDENCE FOR SUBTIDAL-SHELF DEPOSITION OF
SUPERIOR-TYPE BANDED IRON-FORMATION

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ABSTRACT

The Palms Formation in Wisconsin and Michigan and the correlative Pokegama Quartzite in Minnesota are interpreted as tidal deposits formed along the margins of the early Proterozoic Animikie basin.

The well-exposed Palms Formation, which extends for 85 km along the Gogebic range, is 150 m thick and can be divided into three units on the basis of rock types and bedding styles. (1) A thin lower unit consists of thin-bedded argillaceous rocks and unconformably overlies a low-relief surface of Archean granite and greenstone and older Proterozoic sedimentary units. (2) A thick middle unit consists of thin alternating beds of argillite, siltstone and sandstone that vary considerably in texture and composition. Bedding types include parallel, wavy, cross and flaser lamination, and a variety of sedimentary structures are present. (3) An upper unit consists of thicker beds of parallel and cross-bedded sandstone.

A total of 199 cross-bedded measurements and 52 measurements of other paleo-current indicators from the Palms Formation yields a crude bimodal-bipolar distribution, with a broad primary mode to the west and a weaker mode to the east. The sandstones are mineralogically mature; most of the framework grains are rounded quartz grains. The sandstones of the middle unit have an abundant sericitic matrix, whereas those of the upper unit are texturally more mature.

The Pokegama Quartzite is exposed at only a few places along the 130 km long Mesabi range on what was about the northwest margin of the Animikie basin. However, the entire formation can be viewed in two drill cores in which it is 50 m and 26 m thick. Sedimentary sequences and the mineralogical attributes are similar to the Palms. The paleocurrent plot (N=38) is crudely bimodal-bipolar with primary modes to the north and south.

By utilization of Walther's Law of facies relationships and comparisons with modern environments, it can be postulated that both formations were deposited under transgressive tidal conditions. In this model, the lower (shaly) facies was deposited in a low-energy domain of the upper (shoreward) tidal flat, the middle facies (shale-siltstone-sandstone) was deposited on a middle tidal flat under alternating low and high energy conditions, and the upper facies (sandstone) was deposited in lower tidal flat or subtidal high-energy development.

The Palms and Pokegama formations pass upward into the Ironwood and Biwabik Iron Formations, respectively. Again using Walther's Law, it can be postulated that the iron-formations were deposited on a shelf located seaward from the subtidal sandstone facies. The "cherty" (coarser grained, thicker bedded iron oxide-chert) facies was deposited in shallower water

than was the "slaty" (finer grained, thinner bedded, iron silicate-iron carbonate) facies.

The tidal-subtidal facies model developed here provides an independent approach in evaluation of the environment of deposition of one kind of Lake Superior-type banded iron-formation. The model is primarily based upon the siliciclastic lithologies associated with iron-formation rather than upon the iron-formation itself.

SEDIMENTATION AND PETROLOGY OF ARCHEAN FELDSPATHIC QUARTZITE AND
CONGLOMERATE (SEINE SERIES EQUIVALENT), RAINY LAKE, MINNESOTA

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ABSTRACT

The greenstone belt which extends westward into the Rainy Lake area of Minnesota from Ontario includes a clastic succession of feldspathic-lithic quartzite and conglomerate. The quartzite forms an easterly trending unit about 16 km long and about 0.8 km wide, and the conglomerate forms a lens of 3 km long and 180 m thick at the top of the unit. The rocks are about vertical and top to the south as determined by abundant cross-bedding. The quartzite-conglomerate unit of the Seine Series of Ontario occupies the same stratigraphic position 26 km to the east, and continues eastward for another 40 km.

The contact of the feldspathic-lithic quartzite with the underlying volcanic rocks is not exposed in Minnesota, and the quartzite-conglomerate unit appears to be interbedded with greenschist. Thus it has been interpreted as an essentially conformable contact (Ojakangas, 1972), but structural complications and an unconformity may well be obscured by the lack of outcrop. To the east in Ontario near Mine Centre, an unconformable basal contact has been described by Lawson (1913) and Wood (1980), and Lawson also interpreted the contact in Minnesota as an unconformity.

Paleocurrent analysis of the cross-bedding, which is dominantly of the trough type, shows a strong mode to the southwest after a two-tilt correction, and the variance is a low 4051. The cross-bedding style, the lack of original shale, the abundance of original sandstone, the abundance of clayey matrix in the sandstone, and the variance are all suggestive of deposition in a braided stream environment. The associated conglomerate, which is largely clast supported with rounded clasts as large as 25 cm, contains clasts of "granite," feldspar porphyry, quartz-feldspar porphyry, quartzite, chert, and biotite schist. The conglomerate can be interpreted as a prograding alluvial fan deposit. Wood (1980) arrived at a similar interpretation for the equivalent Seine Series, and Lawson (1913) interpreted the sequence as fan conglomerates and fluvial deposits.

The sources of the detritus in the quartzite and conglomerate are interpreted to have been nearby volcanic rocks and coeval plutons intrusive into the volcanic pile. The unconformity, if present all along the belt, probably is a minor erosional surface within the volcanic-sedimentary sequence, similar to that between the Saganaga batholith and the Knife Lake Group in the eastern Vermilion district of northeastern Minnesota. It seems likely that at least moderate relief was present in the source area, perhaps along the southern edge of a long fault block, with alluvial fans adjacent to the source rapidly grading southward into a braided alluvial plain. Renewed uplift in the source area caused a progradation of the fans over the alluvial plain, at least in the Minnesota sequence. Goldich and others (1961), suggested that the tonalite on Grassy Island, just 1.3 km north of the conglomerate, was a possible source of some clasts.

Wood (1980) suggested that the turbidites of the Quetico metasedimentary unit which borders the quartzite-conglomerate on the south, may be the deep-water equivalent of the terrestrial Seine Series. The metamorphic recrystallization of the Quetico metasediments and of the equivalent biotite schists just to the south of the Rainy Lake-Seine River Fault in Minnesota makes detailed original mineralogic comparisons of original components of the biotite schist with those of the lower grade quartzite impossible. A limited study of zircon grains shows that there are differences in the varieties of zircons in the two units, and this can be interpreted as evidence of different source areas. However, horizontal movement along the Rainy Lake-Seine River Fault could have placed widely spaced sedimentary rock units which were derived from different sources because of their geographical positions, into juxtaposition. Thus, original lateral facies relationships in the Rainy Lake vicinity cannot be proven until movement along the fault is better understood.

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MINERALOGY OF GRANITIC ROCKS, WISCONSIN

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ABSTRACT

Crystallization histories have been determined for several Penokean plutons in northern Wisconsin, with emphasis on the extent and nature of mineral equilibria developed during magmatic as well as subsequent subsolidus conditions. Detailed electron microprobe analyses of minerals show that most of the compositional variation is due to incomplete equilibration during various stages of crystallization. This is preserved in some cases as zoned mineral grains, especially plagioclase. Systematic element partitioning indicates that only grains in contact or close proximity have approached chemical equilibrium. Comparison of partitioning with published experimental and empirical studies allows some mineral pairs to be used to estimate intensive parameters obtained during crystallization (e.g., plagioclase - alkali feldspar). These relations are often complicated by more than one superimposed event. Although most of the data presented are from the Penokean batholith in northern Wisconsin, comparisons with published data from the Wolf River and Montello batholiths allow definition of some spatial and temporal patterns in granitic plutonism. All three batholithic suites have peraluminous and metaluminous rocks, with peralkaline rocks absent. Some mineralogical differences between the orogenic Penokean batholith and anorogenic Wolf River and Montello batholiths are similar to differences between Mesozoic-Cenozoic granitic rocks of contrasted tectonic setting.

MINERALOGY AND METAMORPHISM OF PELITIC ROCKS, WISCONSIN

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ABSTRACT

Pelites from several locations in Wisconsin have been sampled for study. Pelitic compositions are sensitive to grade of metamorphism so that petrographic analysis to determine metamorphic assemblages can define relative pressure and temperature conditions. In addition, electron microprobe analyses of selected mineral pairs allow estimates of pressure and temperature based on comparisons with published experimental and empirical studies (e.g., garnet-biotite Fe-Mg exchange equilibria). Comparisons with published and unpublished literature allow spatial and temporal patterns of metamorphism to be determined. Two major periods of Proterozoic metamorphism are recorded in the pelitic rocks of Wisconsin, and each period may be subdivided into several events. The older period occurred 1800-2000 Mya, and reached a peak of amphibolite grade in parts of northern and central Wisconsin. This metamorphism was predominantly low pressure type (andalusite + sillimanite) with one important exception being the Powell kyanite locality where medium pressure was obtained. High pressure metamorphism (i.e., eclogite or blueschist) has not been recognized in Wisconsin, which is an important constraint on Penokean tectonic models. The younger period occurred 1600-1700 Mya, and was low grade over much of northern and central Wisconsin, reaching a peak of amphibolite grade at Waterloo.

MINERAL DEPOSITS OF THE FORT FRANCES-MINE CENTRE AREA

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ABSTRACT

The Fort Frances-Mine Centre area is part of the Rainy Lake region, an area which has played a significant role in the evolution of ideas about the Archean geology of the Canadian Shield. Since representatives of all major rock types of Archean terranes (mafic to felsic metavolcanics, wackes and mudstones, conglomerates and arenites, layered gabbroic intrusions, tonalitic intrusions and granodiorite-quartz monzonite plutons) are juxtaposed here, it was once considered a type area. In addition to the lithological diversity, a wide variety of mineral deposit types is present.

Stratiform volcanic-hosted mineralization consists of ironstones, base metal sulfides and intercalations of the two. Four sub-types are recognized. First, narrow lenses of Zn-Pb sulfides (Gagne Lake type) are overlain by chert and underlain by sulfide-bearing, altered lapilli tuff which locally consists of a chlorite-cordierite-anthophyllite assemblage. Second, wide zones of low-grade Zn-Cu mineralization (Port Arthur Copper type) consist of 1- to 20-centimeter-wide seams of massive sphalerite-chalcopyrite-pyrite which are intercalated with similar widths of barren chlorite schist. The host rock is commonly a brecciated amygdaloidal mafic metavolcanic, but felsic volcanics occur both above and below the mineralized zone. Third, Zn-Cu mineralization (Pocket Pond type) is found in black pyritic shale and in massive pyrite-pyrrhotite lenses which are conformable with chert-magnetite ironstones: grades of 1 to 2 percent Zn occur over five-meter widths. Fourth, ironstones composed of chert-magnetite, massive sulfides and minor skarn commonly contain only traces of chalcopyrite. Of the above four types of mineralization, the first two represent low-grade volcanogenic sulfides localized at particular stratigraphic horizons in areas of abundant felsic volcanoclastics. The last two types are analogous to Phanerozoic Besshi-type mineralization and are found in volcanic sequences dominated by mafic metavolcanics, gabbros and metamorphosed wackes.

Layered gabbro-anorthosite sills contain both sulfide and oxide mineralization. Chalcopyrite-pyrrhotite lenses containing minor pentlandite, molybdenite, apatite and ilmenite are distributed along the base of the Grassy Portage intrusion, the best concentrations comprising the Northrock deposits of 300,000 tons grading 1.89 percent Cu. This type of mineralization displays magmatic net and droplet textures as well as local zones of remobilized sulfides and hydrothermal alteration. At a higher stratigraphic level in the intrusion, lower grade Cu mineralization is found within a siliceous host which may represent assimilated country rock. Fe-Ti oxide mineralization also occurs in the upper part of the intrusion as lenses of disseminated to massive magnetite-ilmenite and as irregular masses of nelsonite, a rutile-apatite rock. Oxide mineralization is also well developed in the Seine Bay anorthositic sill.

Quartz vein mineralization is of two types. Molybdenite, with pyrite and local chalcopyrite, occurs in quartz stockworks and extensional veins

within granodioritic intrusions near contacts with metasedimentary country rocks. In contrast gold, along with carbonates and base metal sulfides, occurs in lenticular quartz veins associated with shear zones and saddle reefs. Gold-bearing veins occur in a variety of rock types and are restricted to zones of greenschist-facies metamorphism. They can be related to shear displacements on regional transcurrent faults and therefore represent a late stage of mineralization.

A distinctive clastic ultramafic unit is exposed within the mafic portion of the volcanic succession. It is likely of epiclastic origin and is compositionally magnesian (21 percent MgO). Local zones of foliated ultramafic rock contain disseminated Ni-Cu sulfides which may result from metamorphic remobilization.

The various types of mineralization at Rainy Lake can be related to the geological evolution of the rocks of the region. Early volcanism and related hydrothermal systems generated stratiform iron and base metal mineralization. Coeval subvolcanic sills, which possibly drove these convective systems, differentiated to yield magmatic sulfide and oxide concentrations. Granodiorite intruded the supracrustal sequence after initial folding and local stockworks developed near pluton contacts. Continued folding and metamorphism took place within a tectonic wrench zone, generating gold-bearing veins in dilational structures while remobilization of existing mineralization took place. In a metallogenic sense, copper is the only commodity which is common to all environments of mineralization: this may reflect the importance of rifts in the early history of the region.

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GOLD MINERALIZATION AND OCCURRENCES IN THE ATIKOKAN AREA

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ABSTRACT

Atikokan is situated 200 km west of Thunder Bay and earned its mining fame from the discovery of the Steep Rock Iron Range in the late 1930's. Gold, however, was discovered in the Atikokan and Mine Centre areas in the late 1800's and eventually led to one of Ontario's first gold camps.

The general geology of the area consists of early Precambrian rocks of the Wabigoon and Quetico subprovinces, separated by the east-west Quetico fault. The Wabigoon subprovince, to the north, consists of metavolcanics, minor metasediments and granitic batholiths. The Quetico subprovince consists of metasediments and granitoids. Small ultramafic plutons occur throughout the metasediments.

Within a 50-km radius of Atikokan, more than 50 gold occurrences, prospects and past producers have been discovered since the 1800's. The Atikokan gold study performed by the Ontario Geological Survey (Wilkinson, 1982) defined three types of gold mineralization in the Atikokan area; the Marmion Lake Batholith type, the contact zone type, and the metavolcanic-hosted, stratabound type. Twenty-one properties in the area were geologically mapped and sampled, researched, and petrographically and geochemically studied. Geological observations and data from the Atikokan Economic Geology Program will also be presented in discussing the types of gold mineralization, genetic models and exploration targets and techniques.

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NATURE AND SIGNIFICANCE OF SHALLOW WATER SEDIMENTARY ROCKS
IN NORTHEASTERN WISCONSIN

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Recent reconnaissance mapping in northern Wisconsin has resulted in the recognition of a shallow water, sedimentary sequence underlying the Quinnesec Formation and overlying the Bush Lake lobe (Hoskin Lake Granite) of the Dunbar gneiss dome in Florence County. These sediments were in part recognized by Dutton (U.S.G.S. P.P. 633, 1971) but were considered local deposits within the metavolcanic Quinnesec Formation. The present mapping, in conjunction with drill hole and geophysical data, show that these sediments form an outward-facing, steeply-dipping (70-80°) continuous sequence along the western, northern and eastern portions of the Dunbar dome. All the rocks in this area lie within the garnet zone of the Florence metamorphic node.

The stratigraphy of the sedimentary succession is poorly known but consists of biotite schist, quartzite, marble, calc-silicate rock, meta-arkose and graphite schist. Garnet and andalusite are present in some layers. The gross aspects of some of these rocks resemble those in the lower part of the Marquette Range Supergroup in the Menominee district to the north. Marble and associated calc-silicate rocks exposed northwest of West Bass Lake contain siliceous, possible cryptalgal structures and resemble parts of the Randville Dolomite, and a thick quartzite section exposed along the Popple River, about 3 km to the northwest, resembles the Sturgeon Quartzite. A meta-arkose unit, about 100 m thick, is exposed locally near the base of the sequence and is not unlike arkose and arkosic conglomerate of the Fern Creek Formation.

Although differences do exist (e.g. greater abundance of biotite schist-pelitic compositions), the metasedimentary rocks exposed around the western margin of the Dunbar dome have affinities with those characteristic of the basal Choccolay Group of the Marquette Range Supergroup, and a general correlation is tentatively proposed. This correlation suggests:

- 1) The rocks of the Dunbar dome represent pre-Choccolay basement in northeastern Wisconsin.
- 2) The Quinnesec Formation is definitely Proterozoic in age and may be time correlative with the Hemlock Formation of Upper Michigan.
- 3) The Niagara Fault does not represent a crustal suture zone as was recently proposed by some authors.

DUNBAR GNEISS DOME AND IMPLICATIONS FOR THE
PROTEROZOIC STRATIGRAPHY OF NORTHERN WISCONSIN

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ABSTRACT

The Dunbar gneiss dome is a newly recognized feature of the Proterozoic crystalline terrane of northeastern Wisconsin. The dome is 20 km by 30 km across, trends northwest, and has a structural relief greater than 1 km. The core of the dome is composed of complexly deformed and metamorphosed varied biotite gneisses, foliated megacrystic granite, and foliated gray tonalite. It is unconformably mantled by less deformed metavolcanic rocks of the Quinnesec Formation, and locally by quartzite, marble, meta-arkose, and biotite schist. These rocks dip steeply and face stratigraphically outward, as indicated by pillow structures in the lavas. The boundary between the core and the mantle is a zone about 500 m wide characterized by a cataclastic foliation, steeply plunging lineation, many small bodies of compositionally diverse, syntectonic granitoid rocks that are confined to the mantle, and small bodies of posttectonic granite and tonalite. Metamorphic zoning is concentric: amphibolite facies in most of the core and in the inner part of the mantle and greenschist facies in the outer part. The boundary was a zone of high strain and metamorphic intensity and associated anatexis that accompanied diapiric rise of the dome. The core is interpreted as a window exposing part of an extensive terrane that suffered dynamothermal metamorphism prior to diapirism; during diapirism intense cataclasis in the boundary zone accompanied folding in the mantle.

Despite contrasting histories, rocks of the core and the mantle have yielded nearly identical isotopic ages of about 1,860 m.y. by the U-Pb zircon method (Banks and Cain, 1969; Banks and Rebello, 1969), recalculated using new constants. This apparent early Proterozoic age for both rock assemblages contrasts with the domes in northern Michigan which, though similar to the Dunbar dome in many ways, have cores of Archean basement gneiss and granitoid rocks and mantles of early Proterozoic metasedimentary and metavolcanic rocks. Tentatively, from reconnaissance mapping the Dunbar dome appears to be just one of the several domes in northern Wisconsin having cores of Proterozoic rocks. Where dated, these basement rocks give ages of about 1,850 m.y. (W.R. Van Schmus, oral comm., 1981).

We suggest that the supracrustal rocks that mantle the domes of northern Wisconsin are underlain by an extensive early Proterozoic amphibolite-facies terrane evidently not represented in northern Michigan. The supracrustal rocks of northern Wisconsin, however, probably are coextensive with the Marquette Range Supergroup of Michigan.

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PRELIMINARY RESULTS OF A DRILLING PROGRAM ACROSS
THE GREAT LAKES TECTONIC ZONE, CENTRAL MINNESOTA

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ABSTRACT

The Great Lakes tectonic zone (GLTZ), a complex intracratonic deformed belt separating long-stable Archean greenstone-granite terrane on the north from multiply-reactivated Archean-Proterozoic gneiss terrane on the south, has been defined in east-central Minnesota, northern Wisconsin, and upper Michigan by careful mapping of the exposed geology, together with critical geochronologic and geophysical studies (Morey and Sims, 1976; Sims and others, 1980). However, in west-central Minnesota, where Precambrian basement is concealed by thick glacial drift, the trend and extent of the GLTZ have been inferred largely from regional gravity and aeromagnetic patterns.

During the past two years, a traverse across the GLTZ approximately at longitude 95°W in central Minnesota has been investigated by COCORP seismic reflection profiling and also by detailed gravity and aeromagnetic surveys. Ten holes over a distance of 60 km have been drilled into basement along this traverse to provide direct lithologic data for use in geophysical modeling (still in progress).

At two sites just north of the GLTZ, within the greenstone-granite block, the drill encountered massive, coarse-grained amphibolite derived from gabbro and a closely allied quartz-poor hornblende quartz diorite. At a site just south of the GLTZ, within the gneiss block, the drill encountered gneiss composed of tonalitic and granitic layers, grossly similar to the Morton Gneiss of the Minnesota River Valley.

Three holes drilled into the northern part of the GLTZ penetrated low-grade metavolcanic and volcanoclastic rocks of intermediate composition. Strong cataclasis is evident in two cores drilled close to the inferred north boundary. Two holes drilled into the southern part of the GLTZ penetrated well-cleaved, thin-bedded to laminated, dark gray to black slate and metasiltstone. This slate is lithologically akin to various Proterozoic slates in the Mille Lacs and Animikie Groups (although its age is not known) and thus opens the possibility that Proterozoic supracrustal rocks may occur within and near the GLTZ for some distance west of the presently mapped margin of the Animikie basin.

Biotite-hornblende diorite from an oval magnetic high near the center of the GLTZ has a panhedral or "lamprophyric" texture and is inferred to be a posttectonic, high-level pluton. Migmatized biotite paragneiss from the flank of a magnetic high about 2 km north of the inferred south margin of the zone is tentatively viewed as belonging to the gneiss terrane.

The GLTZ in central Minnesota is occupied largely by low-grade meta-volcanic and metasedimentary rocks and appears to be bounded on the north by a major steeply dipping fault zone. No direct evidence has been found

for major faulting along the south boundary, which instead may be an unconformable contact along part of its length with Archean and possible Proterozoic supracrustal rocks resting on older Archean gneiss. The ages of the supracrustal rocks in the GLTZ, and their structural relationship to granitoid rocks, remain to be demonstrated.

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WEATHERING OF ARCHEAN ROCKS AS RELATED TO IRON-FORMATIONS

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ABSTRACT

The Archean volcanic and sedimentary belts of northern Minnesota and northwestern Ontario contain many thin belts of iron-formation. The sedimentary rocks are largely conglomerate, graywacke, and slate with variable amounts of volcanic material. The composition of the sedimentary rocks indicates rapid disintegration, erosion, and deposition with little attendant oxidation and leaching.

In the earliest period, the atmosphere was accumulating H_2O , CO_2 , and N_2 due to frequent vulcanism. Basin waters were probably acidic as metals were dissolved out of the volcanic rocks at the same rate as the alkalis. Within a few million years a basin could be neutralized and iron deposited as carbonate or oxides, with residual silica deposited in alternate bands because of seasonal flocculation. Clay was not flocculated as close to shore as was iron-formation which varied from shallow to deep water facies (Goodwin, 1973).

Three types of iron-formation are present: a) the Keewatin; b) the Timiskaming or graywacke; and c) the Lake Superior-Labrador Basin. In the Keewatin type, iron occurs with chert as siderite or iron oxides; these components were derived from acid decomposition of pyroclastics with some contribution from volcanic gases. The volcanic gas quickly decomposed under acidic conditions and alumina, alkalis, and silica formed clays in deeper waters. It is believed the iron oxides and chert flocculated and precipitated closer to the sources of the decomposing volcanics, while some soluble silica and alumina, being lighter and slower to flocculate, were removed.

The Timiskaming or graywacke type of iron-formation is associated with chert and slate beds. These occur as thin beds and lenses of iron oxides deposited during quiet periods of turbidity flows, and are related to rapid sedimentation in troughs adjacent to steep mountain chains. There is little indication of active vulcanism, but bacterial action in mineral decomposition may have occurred. Decomposition of the pyroxenes and amphibole minerals in graywacke resulted in a pH of more than 9. If calcium, magnesium, and alumina were removed, the remaining iron and silica particles caused mutual precipitation.

The Lake Superior-Labrador Basin type of iron-formation occurs on the flanks or shelves of the Archean masses. These deposits may be 100 to 300 meters thick and 100 or 200 kilometers in strike length. Thin beds of carbonate, iron oxides, and chert alternate, and are typified by granular oolitic textures. The iron-formations are part of a sedimentary series of quartzite, iron-formation, dolomite, and shale or graywacke lying on a peneplained Archean surface. The sedimentary sequence is the result of transgressive seas spreading over a peneplained and glaciated surface and sorting the pre-existing sediments into sand, silt, and clay fractions.

Fine-grained materials such as volcanic ash or clays were susceptible to rapid chemical decomposition in both acid and alkaline conditions. The separation into oxides, clays and solutes may have begun very early under both volcanic acid or organic acid attack. Silica is present as quartz, microcrystalline, cristobalite, amorphous or opaline silica, and silica in solution. The two intermediate forms may alter to quartz grains, chert, clay, or be present in diatom tests.

Iron materials may have formed hydroxides, oxides, carbonate sulfide or migrated in solution. Alumina may have been removed in either acid or alkaline conditions or formed clays under normal pH conditions. The various weathering possibilities depended on temperature, moisture, and the organic and chemical environment. Iron-formations may have been a particular form of residual weathering with a substantial contribution of soluble and colloidal iron leached from nearby soils or sediments.

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SEASONAL THERMAL ENERGY STORAGE (STES) SYSTEMS IN MINNESOTA

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ABSTRACT

Seasonal fluxes of solar energy and man-made "waste" heat provide alternatives to fossil and nuclear fuels for low-grade heat. The key is STES. Large thermal storage masses must be developed at very low-unit cost because of the low energy density of stored heat. Geologic formations, structures and materials with appropriate boundary conditions can provide this capacity. A fluid heat exchange medium (air or water) is circulated through a geologic body by exploiting natural hydrogeologic characteristics or by constructing a circulation system. Diffusion and dispersion of heat are limited by suitable hydraulic and thermal boundary conditions.

A powerful Aquifer Thermal Energy Storage (ATES) test facility has been built on the St. Paul campus of the University of Minnesota to investigate storage of superheated water in a deep, confined lower Paleozoic aquifer. Water from the Franconia-Ironton-Galesville aquifer is drawn from a supply well, heated in a heat exchanger and injected in a heat storage well in the same aquifer. Heat is extracted by reversing the cycle and injecting the spent water back in the supply well with no net loss of water. The heat storage capacity and hydraulics of the water-filled, underground iron mines at Ely, Minnesota, are being investigated as the heat source for a community district heating system. Heat extracted by heat pumps from mine water at ambient underground temperature during the winter can be replenished during the summer by exchanging chilled mine water for sun-warmed surface water from an open pit above the underground workings. In Blue Earth, Minnesota, air is drawn through a grid of drain tiles buried in glacial till, extracting heat from the ground in the winter, returning heat to the ground in the summer and providing tempered air worth thousands of dollars per year in heating and air conditioning cost savings.

STES systems in deep and shallow aquifers, soils, massive impervious rocks, processed rock materials, surface water bodies and mined caverns are being investigated in a number of countries. High temperature heat sources include cogenerated or rejected heat from energy conversion and industrial processes, waste incineration, standby heating capacity and intensified solar radiation. Low temperature sources include seasonal temperature regimes in air, soil and rock, surface water, ice and ground water. Heat pumps are commonly used to interface with low temperature sources. Heat reservoirs can be used as sinks for cooling as well as sources for heating. Winter heating and summer cooling are major sinks for conventional energy resources, especially in a midcontinent climate such as Minnesota's, but the same seasonal ΔT can be converted to a major source of non-polluting thermal energy where suitable geologic formations and boundary conditions can be found for STES.

SIMILARITIES IN THE REGIONAL GEOLOGY OF INTRUSIVE ROCKS IN THE KEWEENAWAN MIDCONTINENT RIFT, THE PERMIAN OSLO RIFT, AND THE TERTIARY GEOLOGY OF THE NORTH ATLANTIC

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ABSTRACT

Intrusive rocks in the Midcontinent Rift, the Oslo Rift and the Tertiary of East Greenland, Iceland, and the Faeroe Islands, exhibit similarities in the temporal and spatial distribution of intrusive types and magma compositions. Burke and Dewey (1973) related all three areas to triple junction rifting, and Green (1977) has noted the similarities between the extrusive rocks of the Lake Superior region and Iceland.

The intrusive rocks in the Midcontinent Rift can be divided into three groups: i) Nephelinitic-carbonatitic and alkaline plutonic rocks represented by the small (< 10 km) complexes at the southern end of the Kapuskasing Structural Zone and the Coldwell Province, respectively (Fig. 1). ii) Diabasic dikes and sills which occur as quartz tholeiite and olivine tholeiite swarms flanking Lake Superior (Fig. 1). iii) The plutonic gabbroic and associated differentiates represented by the Crystal Lake Gabbro in Ontario, the Duluth Complex in Minnesota, and the Mellen Complex in Wisconsin (Fig. 1).

The spatial distribution of the intrusive units referred to above is consistent with a triple junction tectonic setting in the Lake Superior region (Fig. 1). Analogous tectonic settings have been proposed for the Oslo Rift (Fig. 2) and the Tertiary geology of the North Atlantic (Fig. 3). Similarities in the geology of the three areas may be summarized as follows:

- a) The alkaline Kangerdlugssuaq intrusion in East Greenland, the Larvik Ring Complex in the Oslo Rift, and the Coldwell Complex in Ontario all occupy similar positions relative to the rifting directions in each case and all may be construed to define a failed arm of a triple junction (Figs. 1-3).
- b) The extensive dike swarm in the Kangerdlugssuaq area of East Greenland shows six crosscutting intrusive relationships. However, the major sequences are an early high-Ti quartz tholeiite followed by olivine tholeiite of MORB affinity. The high-Ti quartz tholeiite is similar in composition to plateau basalts of East Greenland and the Faeroe Island basalts. The two compositions are analogous to the early high-Ti quartz tholeiite diabases and the second generation olivine tholeiite diabases in the Lake Superior region. In the Oslo Rift, quartz tholeiite composition is represented by fine-grained gabbroic intrusions and minor lava flows. However, no olivine tholeiite has been reported.
- c) In the Oslo Rift, the parent magma of coarse-grained gabbroic intrusions may be related to quartz tholeiite. These intrusions may be less fractionated equivalents of the early magma (Anorthositic) series in the Duluth Complex. The presumed parent magma for the Skaergaard intru-

sion, formed during the Tertiary rifting in the North Atlantic, is comparable to the proposed parent magma composition for the troctolitic-gabbroic Keweenaw intrusions.

These rift systems exhibit an expected progression of magma types of carbonatitic, alkaline, quartz tholeiite, and olivine tholeiite. Taken together, the intrusive rocks in these rift systems suggest that: 1) The relative volume of magma produced during rifting increases through the above succession and is correlated with the extent of rifting: Oslo Rift (minor), Keweenaw Rift (intermediate), North Atlantic (extensive). 2) Quartz tholeiite is an important transitional magma type between early volatile-rich and later volatile-poor magmas. 3) The Keweenaw intrusive igneous rocks provide a more complete record of magma evolution during rifting than heretofore recognized.

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FIGURES

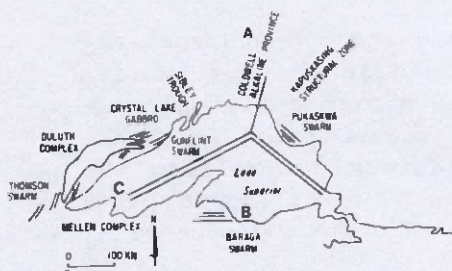


Fig. 1

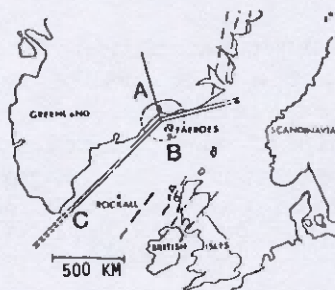


Fig. 2

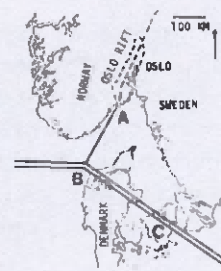


Fig. 3

- Fig. 1 - Distribution of Keweenaw intrusive rocks in the Lake Superior region.
- Fig. 2 - Schematic map of the breakup of the North Atlantic, after Brooks (1973).
- Fig. 3 - The Jutland triple junction rift, after Burke and Dewey (1973). Rifting developed basins (double line) but no magmatism. A, B, and C define the expected locus of dominant alkaline, quartz tholeiite, and olivine tholeiite magmatism, respectively, in Figures 1-3.

GEOLOGY OF THE FRIDAY BAY QUADRANGLE, MINNESOTA

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ABSTRACT

Detailed geologic mapping in the United States portion of the Friday Bay quadrangle, Minnesota, was carried out during the 1981 field season. The quadrangle is situated in the southeast contact zone of the Vermilion Granitic Complex. The rocks of the Friday Bay quadrangle, and adjacent areas, comprise a typical granite-migmatite terrane.

The oldest rocks in the Friday Bay quadrangle are high-grade metamorphic biotite schists and amphibolites. These rocks were probably originally deposited as intermediate to mafic composition volcanoclastic sediments. A general north-south compression system folded the metasedimentary sequence into a large east-west trending synform. The axes of small folds closely parallel the orientation of the axis of the large synform suggesting that folding was due primarily to a single deformation event. An early episode of anatexis produced the first neosome.

Folding and anatexis were followed by the emplacement of a large leucocratic biotite adamellite mass to the north and west of the Friday Bay quadrangle. Pressure-temperature data from feldspar composition pairs in pegmatites indicate a temperature and pressure of formation of $600-680^{\circ}\text{C} \pm 50^{\circ}\text{C}$ at 2-4 kilobars pressure. Late-stage cross-cutting dikes of pegmatite and aplite comprise the second neosome and invaded both the country rocks and the leucocratic biotite adamellite. Coarse phenoblasts of microcline were formed in the contact zone of the batholith in a late-stage feldspathization event.

Retrograde chlorite-facies metamorphism, faulting and hydrothermal alteration, and fracturing are the last events recorded in the Precambrian rocks of the Friday Bay quadrangle. Joint sets show a strong bimodal orientation. The strike and dip of the country rock layering and foliation and late-stage faulting appear to be the major factors controlling the distribution and orientation of the two joint sets. Future mapping will extend to the east, southeast and west in adjacent quadrangles.

FIELD TRIPS

FIELD TRIP I

MINERAL DEPOSITS OF THE FORT FRANCES - MINE CENTRE AREA, ONTARIO

by

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Paper 1

MINERAL DEPOSITS OF THE FORT FRANCES - MINE CENTRE AREA, ONTARIO

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TABLE OF CONTENTS

INTRODUCTION

REGIONAL SETTING

- Wabigoon Subprovince
- Quetico Subprovince
- Regional Distribution of Mineralization

GENERAL GEOLOGY

- Stratigraphy
- Structure
- Metamorphism

MINERAL DEPOSITS

- Classification
- Type 1: Metavolcanic-hosted mineralization
- Type 2: Gabbro-hosted mineralization
- Type 3: Vein mineralization
- Type 4: Ultramafic-hosted mineralization

REFERENCES CITED

FIELD TRIP I

- Introduction
- Stop 1 - Fe formation, Nickel Lake
- Stop 2 - Zn, Cu, Fe mineralization, Pocket Pond prospect
- Stop 3 - Ni, Cu mineralization, Belacoma property
- Stop 4 - Cu, Ni mineralization, Northrock Mine
- Stop 5 - Ti, Fe mineralization, Traverse Bay
- Stop 6 - Cu mineralization, Mironski showing
- Stop 7 - Mo mineralization, Bear Pass showing
- Stop 8 - Au mineralization, Stellar Mine
- Stop 9 - Zn, Cu mineralization, Port Arthur Copper Mine
- Stop 10 - Zn, Pb mineralization, Pidgeon showing

INTRODUCTION

The Archean rocks of the Wabigoon subprovince of northwestern Ontario host several producing and past-producing deposits of iron, base metals and gold. Most production has come from deposits near the subprovince margins and the following pages describe the nature and distribution of mineralization along the southwest margin at Rainy Lake.

Studies of Rainy Lake mineralization have been supported by the Mineral Deposits Section of the Ontario Geological Survey. Discussions in the field with A.C. Colvine and J. Wood of the OGS have been valuable in clarifying the data presented. Some of the following material has been adapted from OGS summary of field work reports prepared by the author.

S.T. Spivak drafted the figures. Typing and drafting services for this manuscript were funded in part by proceeds from the 1977 LSI meeting at Thunder Bay.

REGIONAL SETTING

The Archean rocks of the Mine Centre-Fort Frances area lie within a boundary zone between the Wabigoon and Quetico subprovinces of the Superior structural province. In the Rainy River District of Ontario and adjacent parts of Minnesota, this boundary is defined by a system of steeply-dipping dextral wrench faults, the largest of which are the Quetico and Seine River-Rainy Lake faults (Fig. 1). These major wrench faults bound a "wedge" of crust which is structurally discordant from both subprovinces but, because of gross lithological similarity, is generally considered part of the Wabigoon subprovince.

Wabigoon Subprovince

The structure of the Wabigoon granite-greenstone terrane is dominated by domal features of variable size. The largest of these, such as the Rainy Lake complex and Irene-Eltrut Lakes complex, are greater than 50 km in diameter and are composed of smaller gneissic domes, central batholiths and marginal crescent-shaped granitoid intrusions. The larger complexes and small gneissic domes have been interpreted as first and second order gneiss diapirs which are the product of gravitational, solid state remobilization of tabular batholiths beneath a supracrustal sequence (Schwerdtner et al., 1979). Supracrustal metavolcanic and metasedimentary rocks now occupy the margins of the gneissic domes with the largest stratigraphic thicknesses preserved between first-order structures. Metavolcanic lithologies dominate and comprise metabasalt flows with local accumulations of flows, and pyroclastic and epiclastic rocks of intermediate to felsic composition.

Metasedimentary rocks such as conglomerate, wacke, mudstone and iron-formation commonly form units within the volcanic sequences. A dolomite unit with algal stromatolite mounds occurs within the supracrustal rocks at Steeprock Lake. Numerous stocks, commonly of quartz monzonite, intrude the supracrustal rocks (Fig. 1). Wabigoon subprovince supracrustal rocks

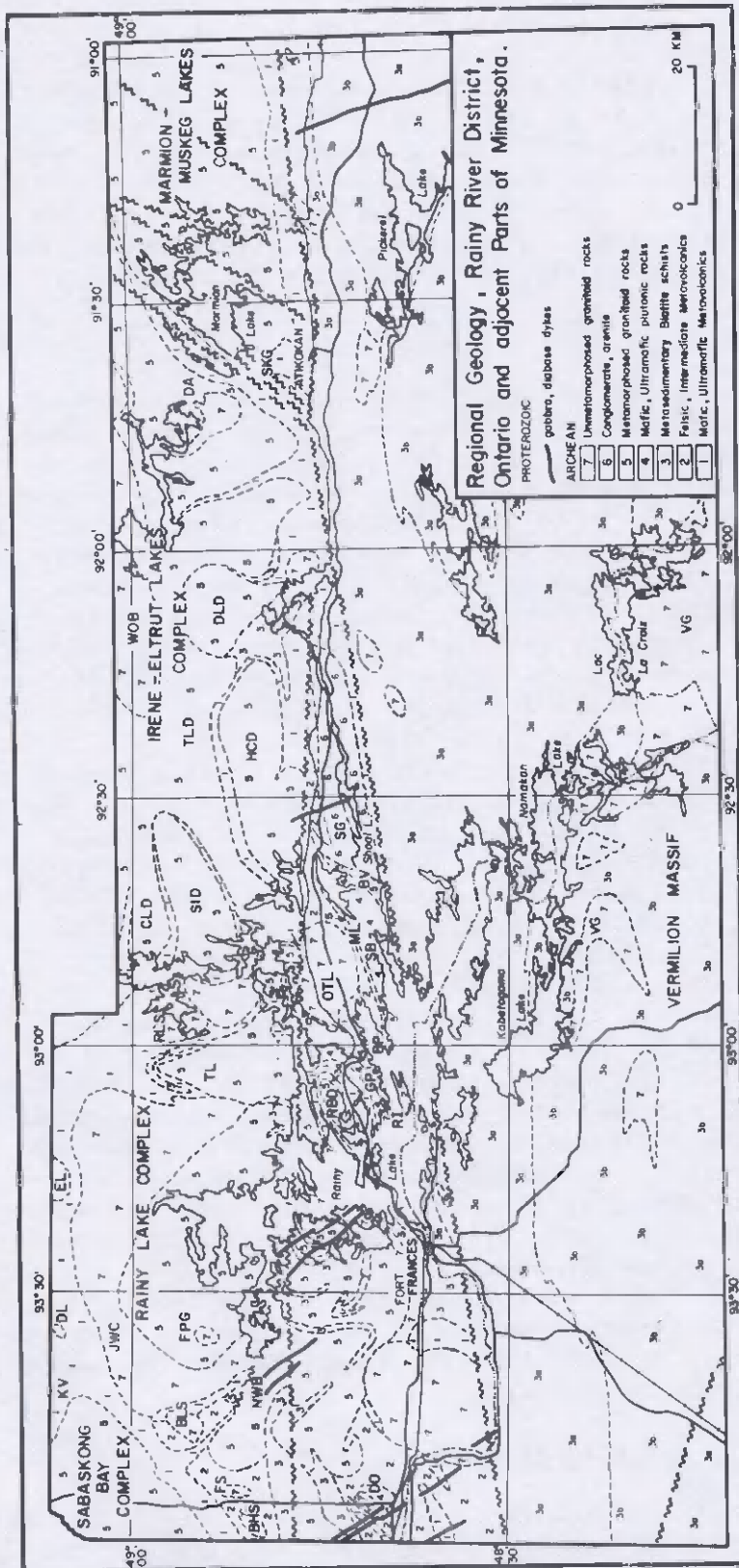


Figure 1: Regional Geology (RBD: Rice Bay Dome, BP: Bean Pass pluton, GP: Grassy Portage intrusion, RI: Rest Island granite, OTL: Otter Tail Lake pluton, ML: Mud Lake pluton, SB: Seine Bay intrusion, BV: Bad Vermilion tonalite, SG: Seine Group, VG: Vermilion Granite).

are metamorphosed to assemblages characteristic of the greenschist and amphibolite facies (Ayres, 1978). Patterns of metamorphism are closely related to those of the gneissic domes such that highest metamorphic grades are indicated adjacent to the first-order structures. With the exception of a few northwesterly-striking Proterozoic diabase dikes, most of the Wabigoon subprovince rocks in the Rainy River District are of Archean age. Although there is discrepancy among ages derived by different geochronological methods, it is clear that the rocks of the area were thermally active in the interval 2700 to 2400 Ma. The oldest ages reflect widespread igneous activity whereas successively younger ages are likely the result of metamorphism, metasomatism, and crustal uplift.

Quetico Subprovince

The structure of the Quetico subprovince contrasts with that of the Wabigoon. It is characterized by a consistent strike of metasedimentary units sub-parallel with the Seine River-Rainy Lake fault. Near the northern boundary, low-grade metasedimentary rocks of the Quetico subprovince dip steeply and display three discrete cleavage sets; an early set is subparallel with east-trending bedding but has a more northerly strike, whereas a second set with an even more northeasterly strike makes a moderate angle with bedding. A late set includes crenulation cleavage and kink bands which strike northwesterly and deflect the other cleavages as well as bedding. The metasedimentary strata commonly display good graded bedding and younging directions that despite some reversals, are dominantly northward (Hawley, 1930; Merritt, 1934; Ojakangas, 1972; Harris, 1974; Wood et al., 1980; this study). Southward, the metasedimentary rocks become migmatitic and primary structures and cleavage are obscured. Schist-rich and granite-rich migmatites possess bedding-parallel foliations which are folded into large, open, shallow plunging structures which trend east-west (Southwick, 1972; Southwick and Sims, 1980). Major antiforms are commonly cored by massive granitoid bodies of irregular shapes (Fig. 1). These granites occur within a migmatitic terrane, the Vermilion Granitic Complex, which occupies the central part of the Quetico subprovince. The metasedimentary biotite schists are metamorphosed to assemblages indicative of a southward increase in metamorphic grade (Pirie and Mackasey, 1978). Pelitic rocks with greenschist facies assemblages (chlorite-sericite; chlorite-biotite) are found just to the south of the subprovince boundary whereas amphibolite facies assemblages (biotite-cordierite-staurolite-garnet-sillimanite; biotite-garnet-andalusite-staurolite; and biotite-garnet-sillimanite) have been observed in the central part of the subprovince (Southwick, 1976; Pirie and Mackasey, 1978). The observed sequence of assemblages is consistent with moderate metamorphic pressures of 2 to 4 kb and temperatures ranging as high as 600°C. Geochronological data from this part of the Quetico subprovince show that most igneous and metamorphic events were broadly contemporaneous with those in the Wabigoon subprovince.

Regional Distribution of Mineralization

The Rainy River district of Ontario and adjacent parts of Minnesota were the site of intensive prospecting for gold in the 1890's. Gold production from small mines in the interval 1893-1902 came principally from

two areas, Mine Centre and Atikokan: these were known as the Lower Seine and Upper Seine gold regions, respectively. Total production at that time and during subsequent activity reached 25,000 oz. Au and 3,000 oz. Ag. The deposits are concentrated along the subprovince boundaries and are related spatially to the major faults and their splays (Fig. 2). In the early part of the 20th century, some exploration for iron in this region resulted in limited production from the Atikokan Iron Mine, near Sapawe, between 1907 and 1911. The major iron ore deposits at Steeprock Lake were developed during World War II and production began in 1945, continuing until 1979. Low grade iron-formations also are common in the region and tend to be concentrated near the subprovince boundaries. Several significant prospects containing base metals also have been discovered. Two broad types are present: zinc-copper mineralization occurs at specific horizons within the metavolcanic succession and copper-nickel mineralization is associated with mafic and ultramafic rocks, particularly intrusions (Fig. 2). Although some of these prospects have been extensively developed, very limited base-metal production has been reported from this region. Clearly there is a strong spatial correlation between known mineralization and the subprovince boundary. In particular, mineralization representing all of the above types is concentrated within the boundary zone in the Rainy Lake area.

GENERAL GEOLOGY

Stratigraphy

The stratigraphy of Archean rocks at Rainy Lake has long proved a source of controversy. The mapping of A.C. Lawson (1913) established a stratigraphic nomenclature which included the dominantly metavolcanic Keewatin Group, metasedimentary biotite schists of the Couthiching Group, and the conglomerate-bearing Seine Group. Using the principles of structural superposition, Lawson interpreted the Couthiching Group to be the oldest, followed in turn by the Keewatin Group and the Seine Group. With the exception of disagreement by Grout and his coworkers (Grout et al., 1951), this stratigraphic interpretation has prevailed until recently (Poulsen, 1980a; Wood et al., 1980). Unfortunately, previous interpretations were based on observations around the Rice Bay dome where it can be shown that structural superposition is not a valid stratigraphic tool. As a result, a revised stratigraphic column (Table 1) is based upon data obtained from recent mapping by the Ontario Geological Survey (Wood et al., 1980; Harris, 1974; Poulsen, 1980b; Poulsen, 1981). The spatial distribution of the units is shown in Figure 1.

Structure

Two regional faults are exposed within the map area (Fig. 3). In the north, the Quetico Fault is represented by a 700 m-wide fault zone which includes mylonite, blastomylonite and, locally, ultramylonite and pseudotachylite. The mylonitic fabric strikes east and parallels the fault zone. The mylonitic rocks are commonly offset by small dextral faults and, locally, small folds are superimposed on the mylonite. Rocks of the Wabigoon subprovince are exposed north of the fault.

TABLE 1. TABLE OF LITHOLOGIC UNITS FOR THE MINE CENTRE-FORT FRANCES AREA

LITHOLOGIC UNIT	DESCRIPTION
Fault rocks (12)	Schists, mylonites, cataclastites developed on heterogeneous lithologies
	Fault Contact
Dyke rocks (11)	Diabase, gabbro, lamprophyre, quartz-feldspar porphyry
	Intrusive Contact
Unmetamorphosed granitoid rocks (10)	Granite, granodiorite, monzonite, monzodiorite, quartz monzonite, quartz monzodiorite
	Intrusive Contact
Metamorphosed conglomerate and sandstone (9)	Conglomerate, arkose, subarkose, lithic arenite, lithic arkose
	Angular Unconformity
Metamorphosed granitoid rocks (8)	Tonalite, trondhjemite, granite gneiss, quartzofeldspathic gneiss***
	Intrusive Contact
Metamorphosed gabbroic rocks (7)	Gabbro, melagabbro, leucogabbro, anorthosite, quartz gabbro, quartz diorite, meta-diabase **, amphibolite
	Intrusive Contact
Metamorphosed wackes and mudstones (6)	Biotite schist, biotitic siltstone, slate, wacke, mudstone, migmatite (biotitic paleosome)
Metamorphosed chemical strata and related clastic rocks* (5)	Chert, chert-magnetite, pyrite-pyrrhotite, pyritic slates, slate, siltstone, wacke
Ultramafic metavolcanic rocks* (4)	Metamorphosed lapilli-tuff, tuff, magnetic chlorite schist
Felsic metavolcanic rocks (3)	Metamorphosed rhyolite and rhyodacite flows, amygdaloidal flows, tuffs, lapilli-tuffs, lapillistone, agglomerate and quartz sericite schist
Intermediate metavolcanic rocks (2)	Metamorphosed andesite to dacite flows, pillowed and amygdaloidal flows, chloritic tuffs, lapilli-tuff, agglomerate, breccia and quartz-chlorite schist
Mafic metavolcanic rocks (1)	Metamorphosed basaltic flows, mafic tuffs, amphibolite, chlorite schist, migmatite (amphibolitic paleosome)

NOTES

- Although the table represents the broad stratigraphic order among these rock types, local intercalation of lithologies is common.
- ** Sills of this type are common throughout the volcanic succession and constitute a substantial fraction of the total thickness of metavolcanic rock.
- *** Not necessarily orthogneiss.

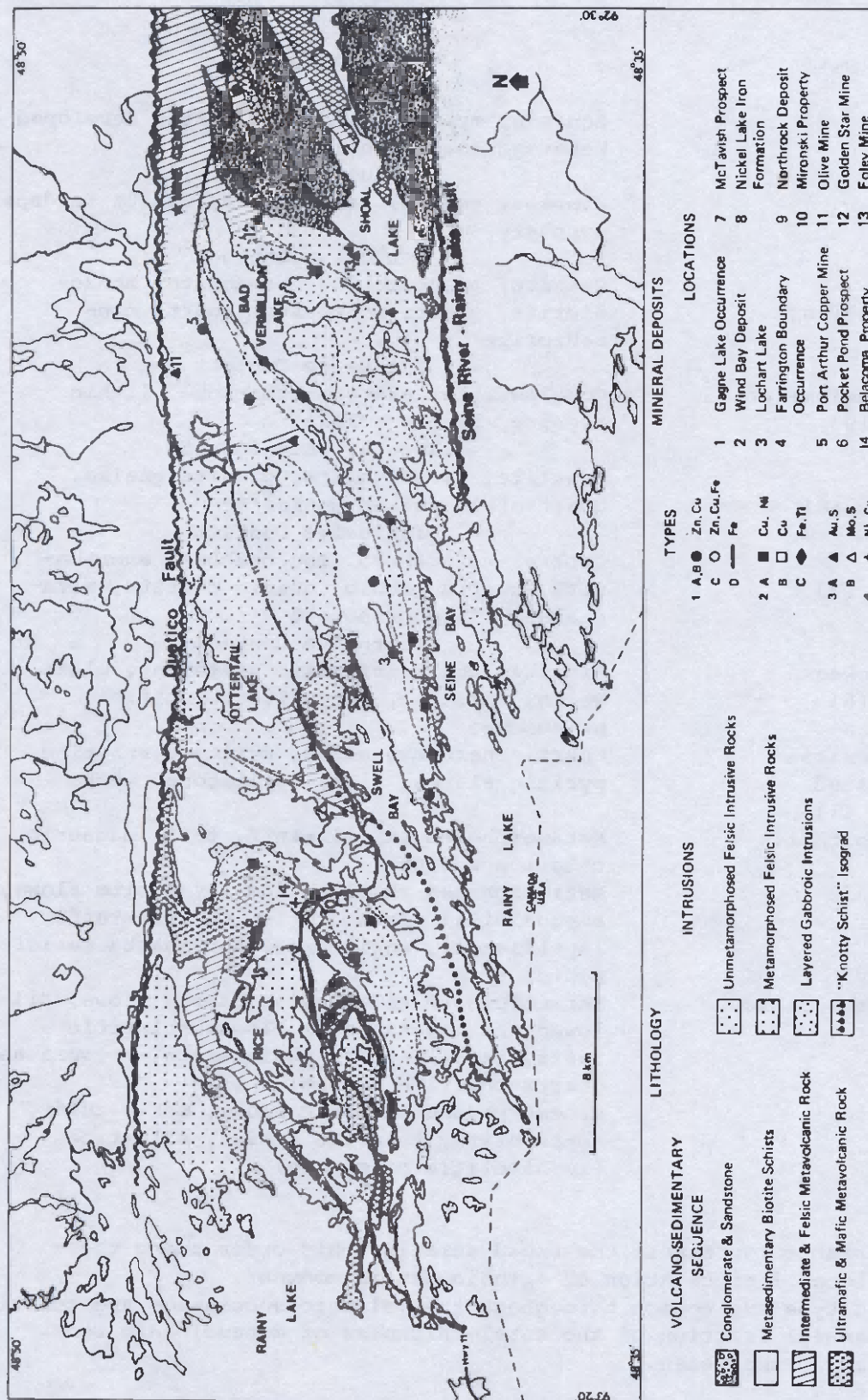


Figure 3: Lithology and mineral deposits, Fort Frances-Mine Centre area.

In the south, the Seine River-Rainy Lake Fault is expressed as phylitic shear zone which strikes easterly. The rocks to the south of this fault are largely metasedimentary biotite schists of the Quetico subprovince.

At least three fold sets may be recognized in the area between the faults. The youngest of these consists of small folds, F_3 , which have northwesterly-striking axial surfaces. These folds are commonly metre-sized and possess an axial planar crenulation cleavage. Kink bands also are common in this fold set. Ductile shear zones, particularly well developed in coarse-grained rocks, also tend to strike northwesterly and may be genetically related to the F_3 fold set.

F_3 folds may be observed superimposed on the cleavage and minor folds of an older set. These F_2 folds plunge northeasterly and southwesterly and vary in wavelength from a few centimeters to a few kilometers. Axial surfaces dip steeply and are commonly coplanar with a strong penetrative cleavage. The F_2 folds and cleavage are dominant in defining the structural grain of the region and strongly influence the distribution of lithologic units.

Of importance is the fact that F_2 folds in the Rice Bay-Bear Pass area face downward. Observations of stratigraphic tops, based on graded beds and pillow lavas, contradict the structural order so that antiformal features such as the Rice Bay dome are stratigraphic synclines. Overturned beds with dips as low as 45 degrees have been observed. The entire significance of the downward facing is undetermined, but it is clear that an earlier deformation must have taken place in order to invert the stratigraphic sequence (Poulsen et al., 1980). Large, recumbent F_1 folds are important to an understanding of the distribution of lithologic units in the Rice Bay Dome area (Fig. 4). Eastward in the Mine Centre area, the structure appears to be a simple northward-facing limb of a large upright fold (Fig. 5). The transition from ductile to brittle deformation is evidenced by the pervasive development of mesoscopic-scale shear zones. Two fundamental shear-zone orientations exist: one set with right-hand sense of displacement parallels the major faults and strikes approximately east and the other conjugate left-hand set strikes to the north-northwest.

These systematic orientations and senses of displacement are equally well developed on northward- and southward-facing sequences, and involve all rock types. The shear zones are interpreted to broadly postdate folding. These zones are consistent with the interpretation that the dominant structure in the area is a right-hand wrench zone of which the two boundary faults are merely the most obvious manifestation.

Metamorphism

The rocks exposed between the two boundary faults have been metamorphosed to assemblages characteristic of the greenschist and amphibolite facies. The transition from greenschist to amphibolite facies indicates a northwestward increase in grade and involves both regional and

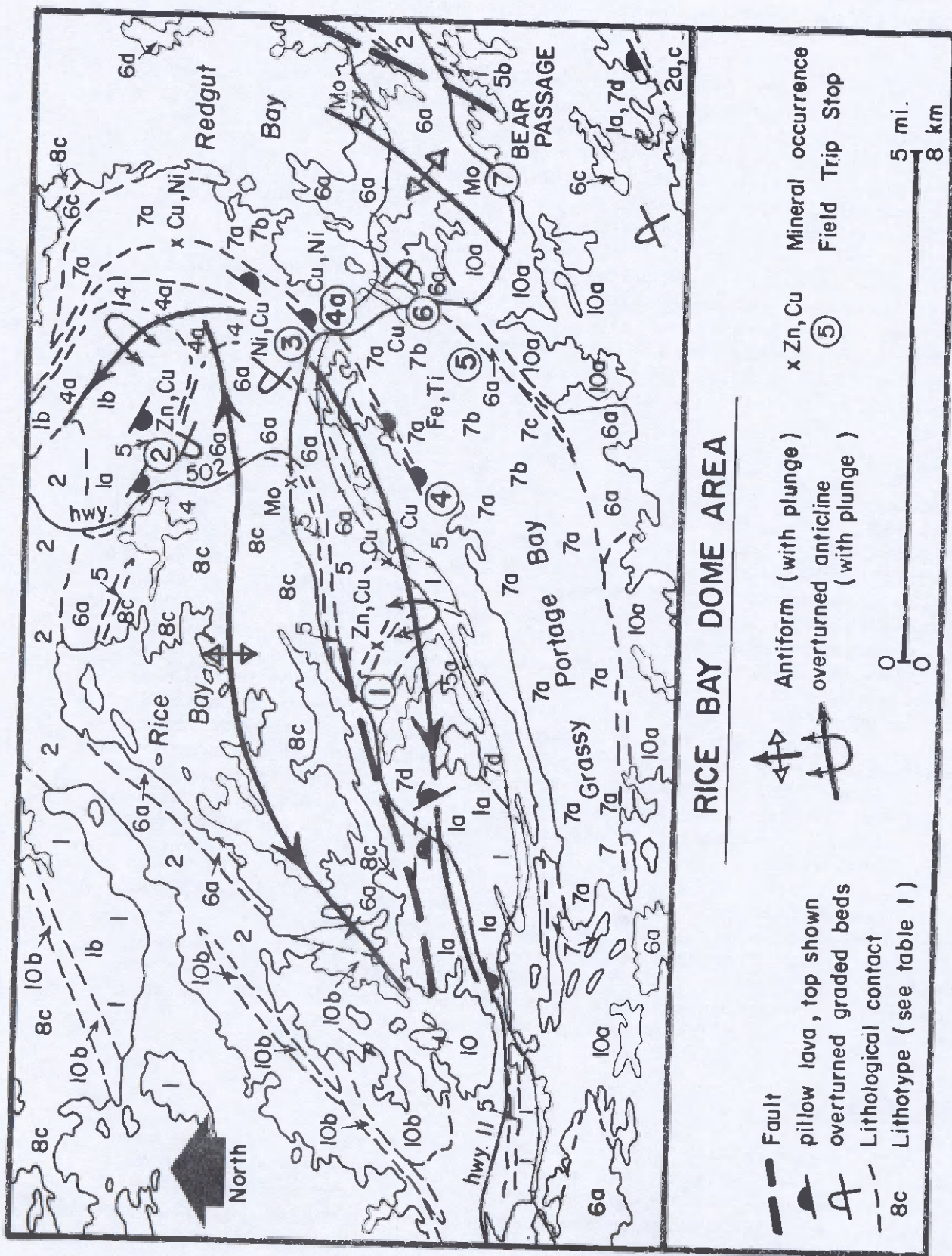


Figure 4: Geology of the Rice Bay Dome area. Rock types are keyed to Table 1. Note the recumbent anticline which is refolded over dome.

contact metamorphism (Fig. 3). In the greenschist facies, chlorite schists are common and chloritoid with chlorite and white mica are present in the Shoal Lake area. Staurolite, andalusite, sillimanite, garnet, Mg-chlorite and biotite form an unaltered prograde assemblage in the Bear Passage area, and diopside-bearing amphibolites occur along the northeast margin of the Rice Bay Dome. Abundant evidence of retrogressive metamorphism exists throughout the area. The northwestward increase in grade within the boundary zone contrasts with a similar southward increase in the Quetico subprovince.

MINERAL DEPOSITS

Classification

The Rainy Lake area has a long history of mineral exploration and exploitation since the discovery of gold at Mine Centre in 1893. At that time, three deposits, the Olive, Golden Star, and Foley, were worked, and coupled with renewed activity during the 1930's, a total production of approximately 485 kg of Au and 20 kg of Ag was realized (Beard and Garratt, 1976).

The noted similarity of iron-formations at Nickel Lake with those at Michipicoten led to exploration around the turn of the century. Diamond-drill programs in 1920 and 1955 defined a minimum of 2 million tonnes of magnetite-ilmenite mineralization hosted by anorthosite and gabbro north of Seine Bay (Rose, 1969).

Since the mid 1950s, exploration in the region has been focused largely on the search for base metals. The discovery of copper in gabbro at Grassy Portage Bay in 1958 led to the development of a 70 m two-compartment shaft and a 200 m drift through the mineralization by Northrock Mines Limited in 1973. Recent exploration programs have investigated zinc-copper mineralization hosted by metavolcanic rocks. Numerous occurrences have been evaluated by diamond-drilling and geophysical methods but, to date, no economically viable deposits have been outlined.

In total, over 75 individual mineral properties have been developed to various degrees. Recent mapping by the Ontario Geological Survey (Poulsen, 1980b; Poulsen, 1981) was initiated to identify the geological settings of the different mineralization types with an objective of establishing exploration criteria for this area. All significant occurrences of mineralization have been considered in terms of stratigraphic setting, mineralogy and deposit morphology. These characteristics form the basis of the deposit classification shown in Table 2. Scattered minor occurrences, on which there has been no development, have been noted but are not included in the table. The spatial distribution of selected deposits is shown in Figure 3.

Descriptive aspects for each deposit type may be illustrated by data from all occurrences of that class with particular emphasis on the largest and most completely developed properties.

TABLE 2. MINERAL DEPOSIT CLASSIFICATION FOR FRANCES-MINE CENTRE AREA

TYPE	NUMBER OF PROPERTIES	EXAMPLES	FIELD TRIP STOP NO.
1 - Stratabound mineralization hosted by felsic to mafic metavolcanics			
A: Sphalerite-galena-chalcopyrite associated with siliceous volcanic rocks	2	Gagne Lake <u>Pidgeon</u>	10
B: Sphalerite-chalcopyrite associated with intermediate to mafic amygdaloidal volcanic flows, tuffs and breccias	9	Wind Bay, <u>Port Arthur</u> <u>Copper</u>	9
C: Sphalerite-chalcopyrite associated with iron formation	4	McTavish, <u>Pocket Pond</u>	2
D: Lean iron formation - mainly chert-magnetite and massive pyrite-pyrrhotite, minor chalcopyrite common	13	Reef Point, <u>Nickel Lake</u> , Shoal Lake	1
2 - Mineralization hosted by layered gabbroic intrusions			
A: Chalcopyrite associated with gabbro and leucogabbro near the base of sills	7	<u>Northrock</u> Island Bay	4
B: Disseminated chalcopyrite associated with siliceous phases of the intrusions	1	<u>Mironski</u>	6
C: Ilmenite-magnetite-apatite-rutile lenses in the upper portions of the intrusions	4	<u>Traverse Bay</u> Seine Bay	5
3 - Vein mineralization			
A: Quartz-gold sulfide veins in shear zones	26	Foley, <u>Stell</u> Golden Star	8
B: Quartz-molybdenite-pyrite veins in unmetamorphosed granitoid rocks	6	<u>Bear Pass</u>	7
4 - Disseminated chalcopyrite-pyrrhotite mineralization hosted by ultramafic metavolcanics	1	<u>Belacoma</u>	3

Type 1: Metavolcanic-hosted mineralization

Zinc-copper mineralization at Rainy Lake occurs in a number of specific volcanic environments. The mineralization at Gagne Lake (Type 1A) consists of lenses of massive sphalerite and galena, as wide as 20 cm, which parallel similar overlying pyritic layers. Rocks of the footwall to the south of the mineralized zone consist dominantly of rhyolitic lapillistone which locally contains a distinctive spotted alteration of chlorite and centimeter-sized porphyroblasts of pinitized cordierite. The hanging-wall rocks consist of fine-grained siltstone and chert which locally form a coarse breccia having clasts as much as 50 cm in diameter. On strike with the mineralization, the breccia contains clasts of massive pyrite. Although drilling to date by Armstrong-Hupchuk has shown the mineralization to be very thin, the geologic setting and alteration show a resemblance to many volcanogenic massive sulfide deposits (Sangster, 1972).

Mineralization at the Pidgeon property occupies a similar setting. Here en echelon lenses of sphalerite-galena-chalcopryrite with iron carbonates are conformable with siliceous metavolcanic rocks.

A diamond drill intersection of approximately 2 m (7 ft) true width yielded assays of 0.53% Zn, 1.76% Pb. Low Ag values as high as 0.3 oz. per tonne have been reported from sulfide-rich material. Pyritic blebs in felsic lapilli tuff typify the zones of footwall alteration which are laterally more extensive than individual sulfide lenses.

Although the Type 1B occurrences are similar in mineralogy to the massive sulfide deposits (sphalerite, pyrite, pyrrhotite, chalcopryrite, minor galena), they possess a number of distinctive characteristics. The host rock is commonly an amygdaloidal, brecciated, intermediate to mafic metavolcanic rock. The mineralization occurs as discrete seams 1 to 20 cm wide which are separated by substantial widths (1 to 20 cm) of barren chloritic host rock.

At the Wind Bay property, a typical drill section through 50 m of tuffaceous chlorite schist yielded two mineralized zones, 7 m and 8.6 m in true width, which averaged 1.5% Zn and 0.2% Cu and 1.1% Zn and 0.09% Cu, respectively (George Armstrong, personal communication, 1980). Where the quartz-chlorite schist is only weakly deformed, primary features such as angular fragments and amygdules are recognizable, suggesting a derivation from volcanic flows and tuffs. The distinctive chlorite schist unit is underlain to the south by rhyolite lapillistone and tuff which, near the mutual contact, contains alteration consisting of abundant pyrite and pyrrhotite blebs with minor chalcopryrite. The chlorite schists are overlain by relatively unaltered quartz-eye rhyolite tuffs. The stratigraphic succession and locally the mineralized zones, are dissected by three laterally extensive mafic sills which are slightly discordant to the strike of metavolcanic rocks.

At the Port Arthur Copper Mine, the stratigraphic setting of the mineralization is virtually identical to that at Wind Bay. Here, the amygdaloidal and brecciated nature of the chloritic host rock is clearly

evident. Diamond drilling by Stratmat Limited revealed a zonal arrangement of copper and zinc within the host (Fig. 6). Zinc-rich zones are underlain to the south by copper-rich mineralization. The latter was mined in 1916 and a few carloads of material grading approximately 3% Cu were shipped to British Columbia.

The mineralized horizon is succeeded abruptly to the north by a cherty horizon approximately 1 m wide which in turn is overlain by felsic quartz-eye tuffs which forms a thick hanging-wall sequence.

Nine occurrences of the Wind Bay-Port Arthur Copper type occupy a single stratigraphic horizon which is exposed over a strike length exceeding 25 km. These are thought to represent poorly focused discharge of metals over a large area. Although these deposits collectively represent a substantial accumulation of base metals, no single prospect has been shown to have sufficient metal content or tonnage to be economically viable at this time.

Likewise, mineralization of Type 1C represents substantial dispersion of metal with resulting low grade.

At Pocket Pond (Figure 1) significant quantities of sphalerite and chalcopyrite are associated with iron-formation which is dominantly composed of chert-magnetite and sulfide-bearing carbonates. The base metals are hosted by a unit of pyritic, black shale and siltstone which is immediately beneath the iron-formation. A single drill intersection through this mineralization yielded assays averaging 1.73% Zn and 0.09% Cu over a true width of 10 m (George Armstrong, personal communication, 1980). Chip sampling across a similar zone by Noranda Mines at the McTavish Option, Nickel Lake, yielded average assays of 0.3% Zn and 0.1% Cu (Resident Geologist's Files, Ontario Ministry of Natural Resources, Kenora). A second type of mineralization, more massive than this, occurs at the main showing at Pocket Pond where a small lens of massive pyrrhotite-sphalerite less than 0.5 m wide occurs in a laterally extensive lenticular zone of massive pyrrhotite-pyrite. The sulfides are here overlain stratigraphically by a 0.3 m layer of chert-magnetite.

The host rocks for all of the type 1C mineralization are quite mafic and consist of basaltic flows and coarse-grained amphibolites which likely represent metadiabase sills. Ultramafic clastic rocks and turbidite-type metasedimentary rocks occur at higher stratigraphic levels. Iron-formation (Type 1D) is a common constituent of the predominantly mafic volcanic terrane in the western part of the study area at localities such as Nickel Lake and Reef Point. There is a common association of chert-magnetite beds immediately adjacent to a massive pyrite-pyrrhotite zone, which at some localities contains minor chalcopyrite. Total thicknesses of a few metres are rarely exceeded and whereas the immediate host is commonly a biotitic metasedimentary rock, the iron-formations are broadly associated with sections in which metabasalt is abundant.

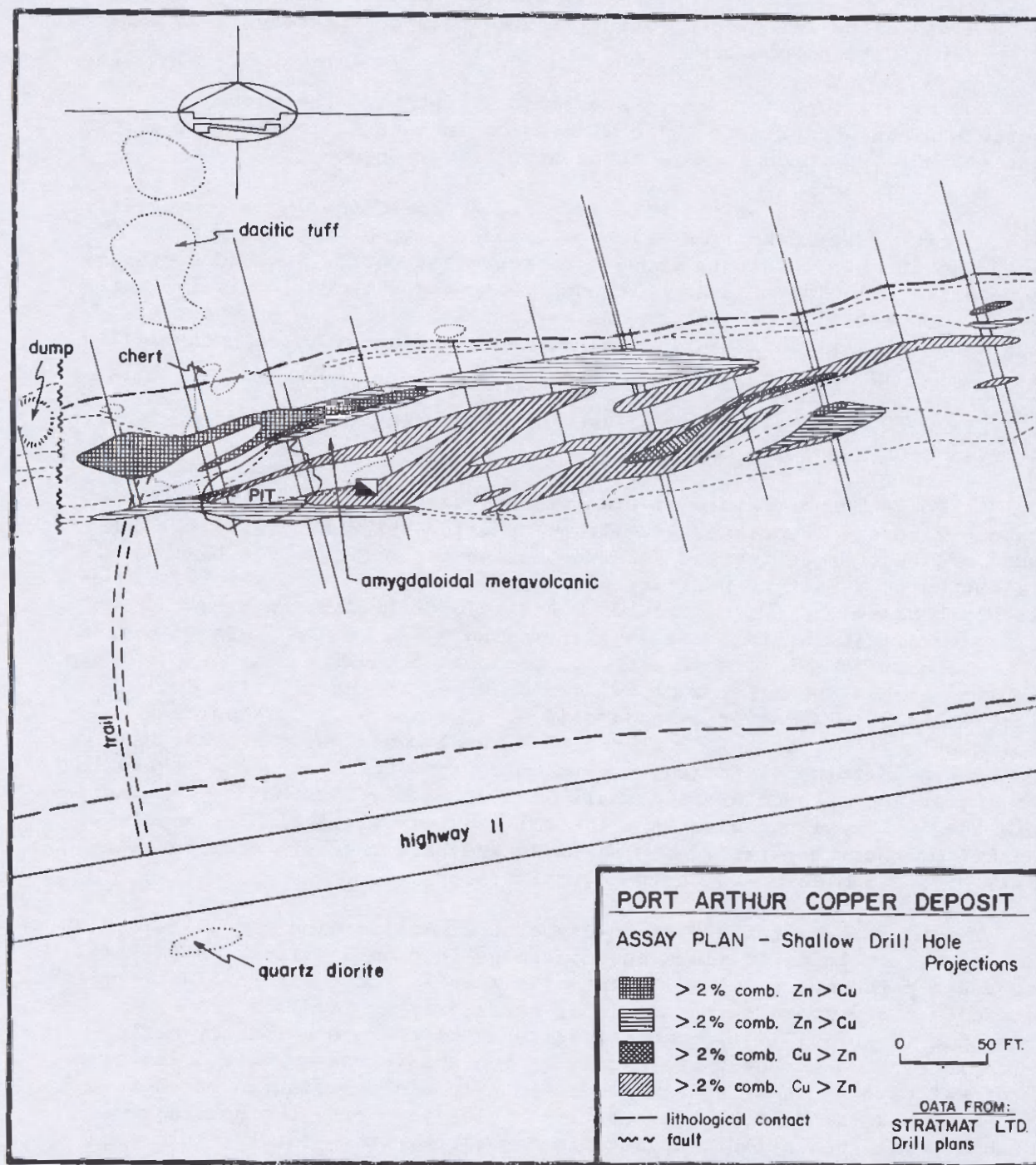


Figure 6: Assay plan of the Port Arthur Copper deposit. Values shown are the vertical projections of shallow diamond drill intersections and nominally represent the distribution of metals approximately 75 feet below surface.

Type 2: Gabbro-hosted mineralization

Two large, steeply dipping, layered gabbroic sills, the Grassy Portage and Seine Bay-Bad Vermilion intrusions, are exposed in the study area. Layering is expressed by modal variations in mineralogy, chemical variations across strike, and rhythmic mineral layering, which is well exposed in the Redgut Bay area. Rock compositions range from melagabbro to anorthosite, and internal layering suggests that Grassy Portage intrusion faces southward, whereas the Seine Bay-Bad Vermilion intrusion faces northward. The basal part of the latter intrusion is truncated by the Seine River-Rainy Lake Fault. Mineralization occurs at three specific horizons in the intrusions. Basal segregations of chalcopyrite-pyrrhotite-pentlandite (Type 2A) form important occurrences along the northern margin of the Grassy Portage intrusion. The best example of this type occurs at the Northrock deposit, where 300,000 tonnes of material grading 1.89% Cu have been outlined. The mineralization is hosted by gabbro, metagabbro and leucogabbro near the base of the Grassy Portage intrusion at the contact with pillow lava and pillow breccia. Mineralization consists of heavy disseminations of chalcopyrite and pyrrhotite with minor pentlandite and pyrite. Ilmenite, apatite and molybdenite are present locally. The sulfide minerals show textures which suggest a magmatic origin, whereas sulfide veins and local hydrothermal alteration show evidence of deuteric or metamorphic remobilization. The deposit consists of three en echelon lenses, each approximately 50 m long and 10 m wide. Several other occurrences of similar type are exposed along strike from the deposit for 8 km to the northeast.

Near the top of the Grassy Portage Intrusion, disseminated pyrrhotite-chalcopyrite mineralization is related to siliceous zones within the intrusion (Type 2B). Known as the Mironski showing, this occurrence was drilled by Phelps Dodge Corporation of Canada Limited in 1966 and again by Belacoma Mines Limited in 1978. Approximately 300,000 tonnes of material grading 0.8 percent Cu are present (Harris, 1974). Although these zones may represent granophyric differentiates, their sharp contacts and generally blocky nature suggest that they are assimilated blocks of country rock near the roof of the intrusion.

In the central to upper levels of both intrusions, substantial accumulations of iron-titanium mineralization (Type 2C) occur as lenticular zones of disseminated to massive magnetite + ilmenite with local apatite-rutile.

Type 3: Vein mineralization

Quartz veins are common throughout the study area. Although most are unmineralized, two particular types host gold and molybdenite mineralization. Gold-bearing veins (Type 3A) in the area have been developed and exploited intermittently since the 1890s. In most cases, the veins may be related to discrete shear zones and commonly occupy a central first-order fissure (Figure 7c). Second-order veins are foliation-normal, but third-order sets are foliation-parallel.

The principal veins range in width from 10 cm to 2 m and are composed primarily of quartz with minor carbonate and local tourmaline. Visible

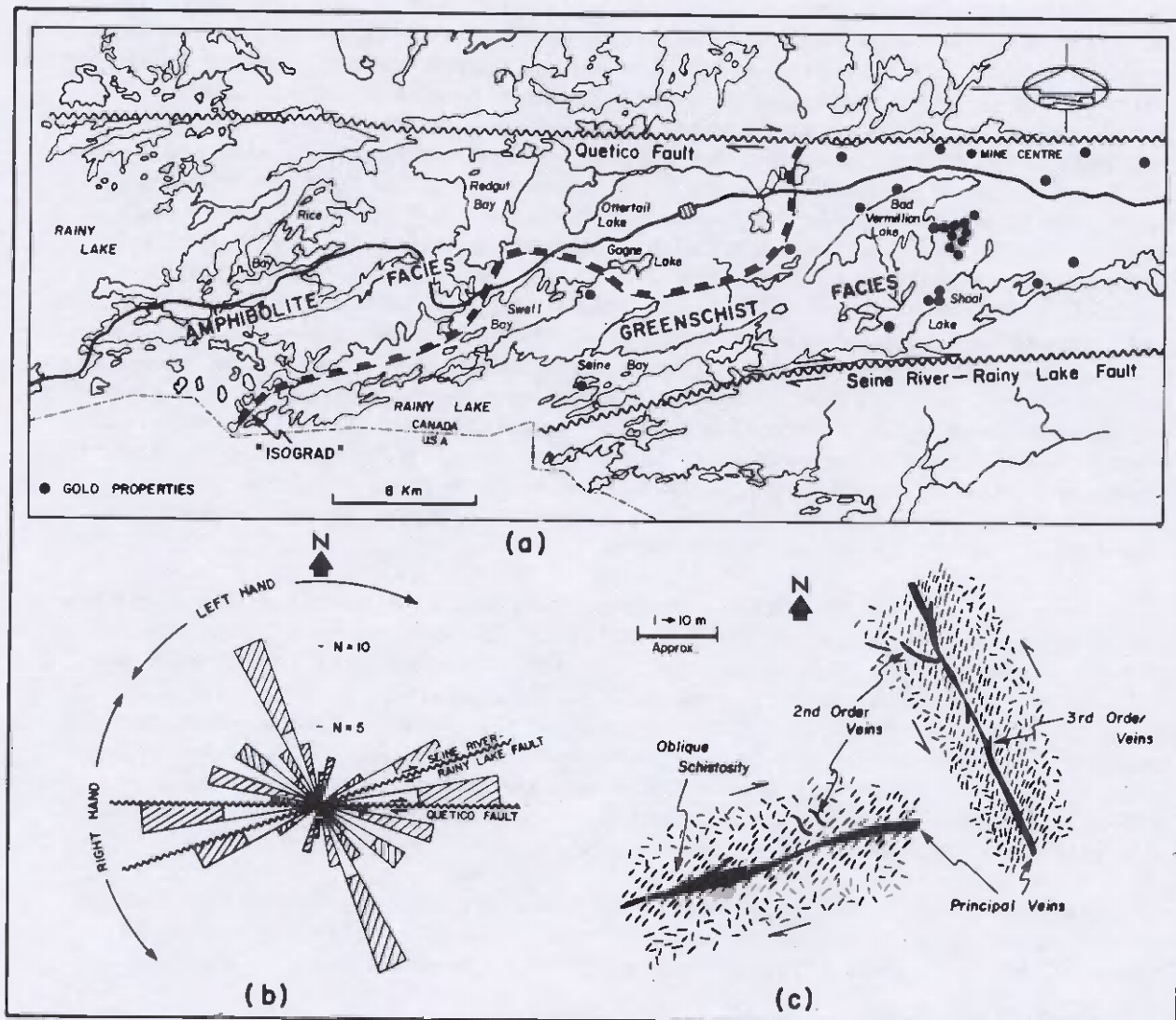


Figure 7: Gold deposits of the Rainy Lake area.

- Metamorphic controls on gold mineralization.
- Rose diagram depicting the orientation and displacement senses of mesoscopic ductile shear zones.
- Schematic diagram illustrating the relationship of gold-bearing quartz veins (principal veins) to ductile shear zones. Such zones are well developed in coarse-grained plutonic rocks.

gold and electrum were identified in a few veins and sulfide minerals are present in substantial quantities. Pyrite, sphalerite, galena, chalcopyrite, arsenopyrite and argentite are common. Scheelite has been reported from gabbro-hosted quartz veins near Swell Bay (Harris, 1974).

Gold content of veins is variable, but a study of available assay data suggest that grade as high as 15 ppm Au may be realistically sought over widths of approximately 1 m. This represents the approximate average grade of the two most successful past producers, the Olive and Golden Star Mines (Beard and Garratt, 1976).

The shear zones are systematically oriented and show senses of displacement consistent with a right-hand wrench zone (Figures 7a,b). The shear zones and their gold-bearing veins are found in most lithologies in the area (Table 3), but there is a clear affinity for a coarse-grained felsic plutonic host of the earlier tonalite - trondhjemite suite. Although shear zones are present throughout the study area, only those which occur in rocks metamorphosed to the greenschist facies contain gold-bearing vein systems (Figure 7a). The above relationships suggest a late-tectonic emplacement of the veins in rocks which readily formed dilatant zones at metamorphic grades suitable for precipitation of gold.

TABLE 3. LITHOLOGIC CONTROLS ON GOLD-BEARING QUARTZ VEINS,
MINE CENTRE-FORT FRANCES AREA

<u>Host Rock Type</u>	<u>Number of Veins</u>
Tonalite, trondhjemite	46
Felsic, intermediate metavolcanic rocks	16
Metadiabase, amphibolite	9
Metabasalt, chlorite schist	5
Gabbro, anorthosite	4
Conglomerate	1
Quartz monzonite-granodiorite	0
 TOTAL NUMBER OF VEINS	 81
 TOTAL NUMBER OF PROPERTIES	 26

The molybdenite-bearing veins (Type 3B) in the Bear Pass-Rice Bay area show no evidence of shear zone development. These generally show sharp contacts with undeformed granodiorite or quartz monzonite and are spatially associated with contacts with biotite schist. The best occurrence is located on Highway 11 at Bear Pass, where molybdenite and pyrite are abundant in tensional quartz veins in the Bear Pass pluton (Figure 4). The veins strike northerly and westerly and the best mineralization is located in veins near the pluton margins. A number of other quartz-pyrite-molybdenite occurrences are related to dikes and sills of granodiorite well removed from the main plutons. The majority of molybdenite occurrences are restricted to areas of amphibolite facies metamorphism.

Type 4: Ultramafic-hosted mineralization

The magnetic, clastic ultramafic unit in the Rice Bay-Redgut Bay area hosts a number of showings of low-grade copper-nickel mineralization, referred to as the Belacoma property. Disseminated pyrrhotite with some chalcOPYrite occurs as blebs and stringers in narrow zones of foliated ultramafic metavolcanic rocks. Reported grades are variable with best grab samples assaying as much as 0.29 percent Cu, 1.23 percent Ni, 0.17 percent Co, and best diamond-drill intersections of 0.45 percent Cu and 0.12 percent Ni over 0.55 m (Resident Geologist's Files, Ontario Ministry of Natural Resources, Kenora). Away from the mineralized areas, the ultramafic metavolcanic rocks contain approximately 1150 ppm Ni (average of 4 samples) indicating that metamorphic remobilization may have produced the low-grade sulfide zones.

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FIELD TRIP I: DESCRIPTIONS OF FIELD STOPS, K.H. Poulsen, leader

The field trip is designed as a one day excursion illustrating the types and setting of mineralization at Rainy Lake. It begins from Fort Frances and involves as many as 10 stops, depending upon the size of the group. The scenic lookout at Bear Pass is a suitable lunch stop. Many of the properties visited are PRIVATE and are under development intermittently. PLEASE USE DISCRETION in gaining access and in sampling. Proceed eastward from Fort Frances on Highway 11 to the Windy Point Bridge

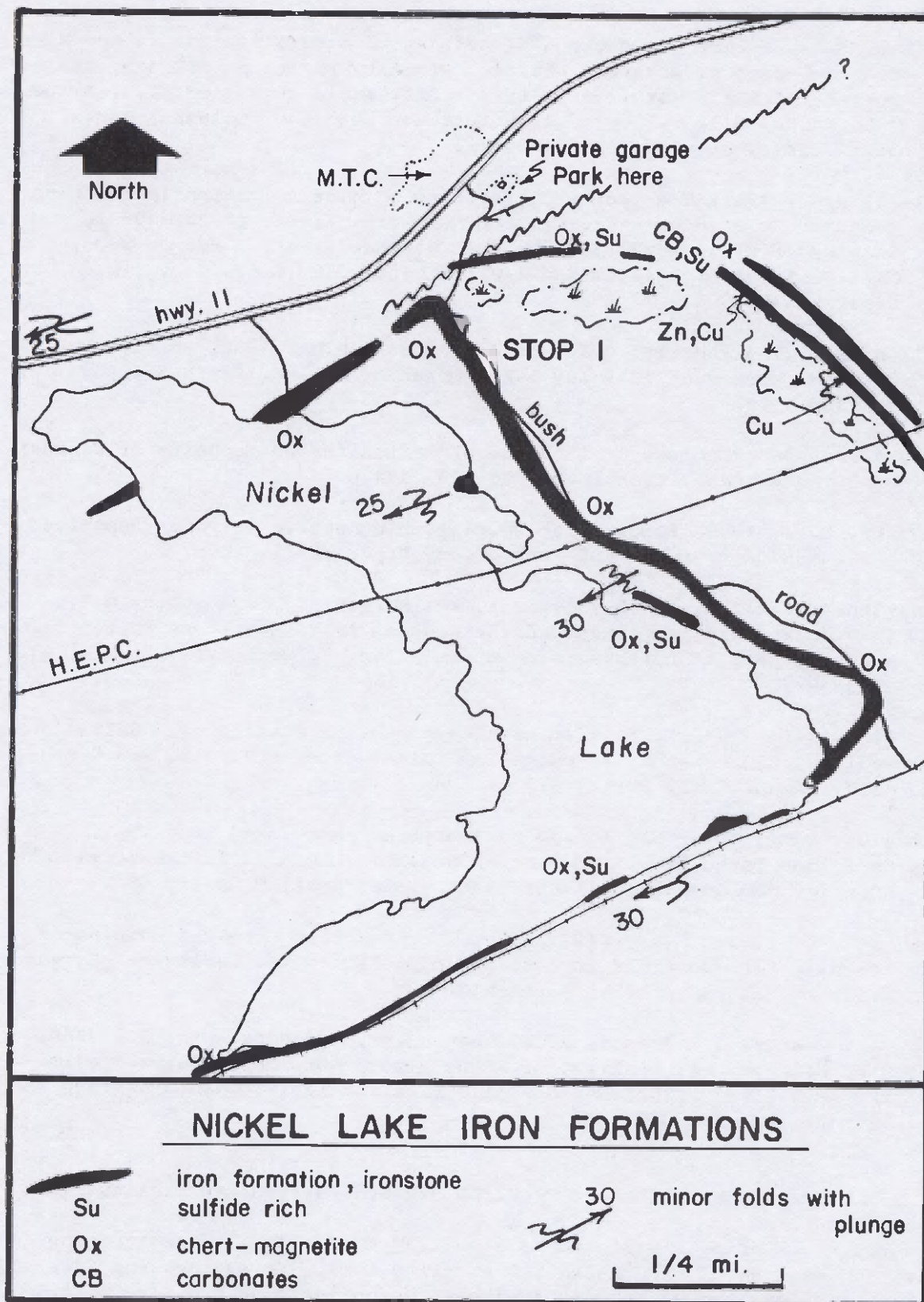


Figure 8: Field trip stop no. 1.

approximately 13 miles (21 km) from downtown Fort Frances. SET MILEAGE. Proceed eastward for 4.4 miles (7 km) to a side road to the right immediately opposite the Ministry of Transportation garage and sand dome. Park and walk southward for approximately 1000 feet (300 m) along the private road (Fig. 8) to an outcrop 50 feet (1.5 m) south of the main gate.

STOP 1 - Nickel Lake Iron Formation

The chert-magnetite iron-formation exposed here is typical of many occurrences in the area. At Nickel Lake, the iron-formation is hosted by amphibolites and defines a major synformal fold which mimics the shape of the lake (Fig. 8). The minor folds which are prominent in this outcrop are coaxial with the major structure and are of tectonic origin as evidenced by axial planar cleavage exposed in a small glaciated outcrop approximately 100 feet (30 m) further south. The iron-formation is too lean to be of economic significance but a shaft on the south side of the lake investigated the possibility of base metals associated with a massive pyritic horizon immediately adjacent to the chert-magnetite-grunerite iron-formation. At Reef Point, 6.2 miles (10 km) west of here, metamorphic segregation of magnetite produced a somewhat enriched material which was mined in from a small open pit in the mid-1950's.

Return to Highway 11, proceed approximately 2.5 mi. (4 km) eastward to Highway 502. Turn left and proceed 1.6 miles (2.6 km) northward to a dirt road just past a creek. Turn right and drive approximately 400 feet (120 m) and park. Walk to each of the localities shown in Figure 9.

STOP 2 - Pocket Pond Zn-Cu-Fe occurrences

At this prospect, zinc and copper have been located at two horizons within a mafic succession. The selected localities shown on Figure 9 illustrate the nature of the mineralization as well as the host rocks.

Locality 2a: metasedimentary rocks

Structurally, these outcrops of biotite schist are located on the northeast margin of the Rice Bay Dome as confirmed by the bedding orientation observed at this locality. The rocks are part of the historic Coutchiching Group of Lawson (1913) and were once thought to be basal to the volcanic sequence exposed to the northeast. The "knotty" beds here consist of the mineral assemblage garnet-biotite-muscovite and sillimanite.

Locality 2b: magnetic ultramafic rock

This small outcrop is composed of the magnetic ultrabasic unit which is better exposed at Stop 3. It is cut here by an amphibolitic dike.

Locality 2c: metabasalt

Pillowed metabasalts here face southwestward. This facing direction can be confirmed at three other localities on this prospect and coupled with the northeasterly dip, indicates that the succession here is structurally inverted. The amphibolite facies metamorphic assemblage in these

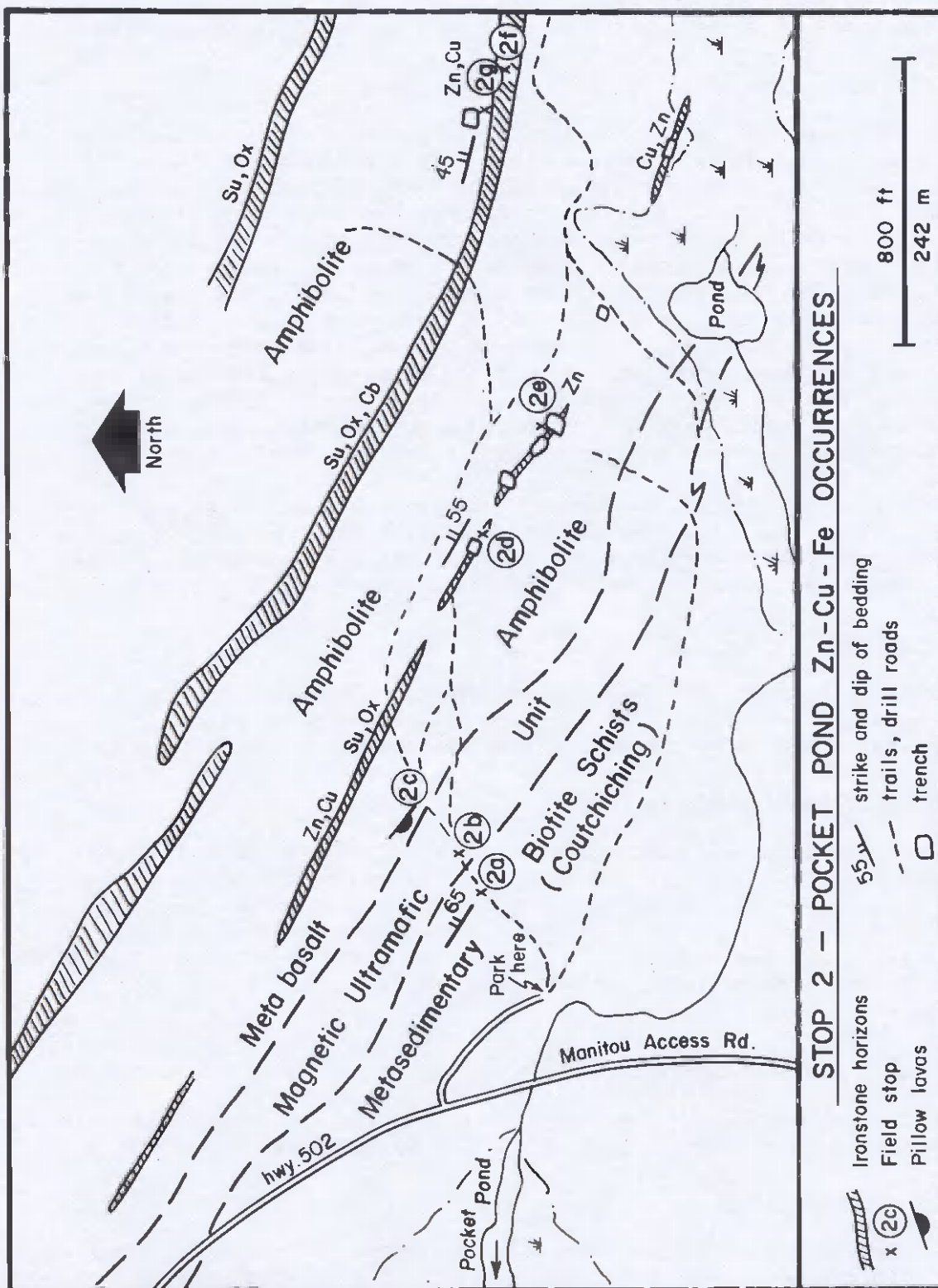


Figure 9: Field trip stop no. 2.

rocks contains diopside; this is consistent with the appearance of sillimanite at Locality 2a.

Locality 2d: lean massive sulfides

This pit exposes a lens of massive pyrite-pyrrhotite with minor chalcopyrite. A narrow chert-magnetite unit stratigraphically overlies the massive sulfides. The generally mafic nature of the host rocks adjacent to the pit can be noted.

Locality 2e: main pit

CAUTION: DEEP HOLE

In this pit, the extension of the zone exposed at the previous locality has been excavated. A narrow zone of massive pyrrhotite-sphalerite grading to as much as 14% Zn was discovered here and a few loose pieces of similar material may be found on the dump. Diamond drilling showed that this zone had limited depth extent and that grades, averaged over 10-foot widths, were only of the order of 1 to 2% Zn.

Locality 2f: Oxide facies iron-formation

This small outcrop exposes thinly bedded chert-magnetite. This unit has been traced across the entire property and is immediately overlain to the southwest by a narrow garnet-pyroxene-epidote skarn.

Locality 2g: pyritic black shale

This unit stratigraphically underlies the iron-formation. In addition to pyrite, the shale contains finely disseminated sphalerite: a diamond drill intersection yielded 1.73% Zn over 32.5 feet. A similar unit in the Nickel Lake area also contains low copper and zinc values.

Return to Highway 502, return southward to Highway 11 and turn left, eastward. Proceed east for 1.1 miles (1.8 km) and stop at right. Walk through the bush 600 feet (180 m) northward to outcrops at south side of a pond (Fig. 10).

STOP 3: Ultramafic-hosted Cu-Ni

Locality 3a: These small outcrops expose a clastic rock composed dominantly of fine-grained ultramafic material. The rock is magnesian rich (21% MgO) and both clasts and matrix contain finely disseminated magnetite. A small percentage of amphibolitic clasts also are present. The origin of this unit is unknown but possibilities include an ultramafic pyroclastic, an epiclastic rock derived from ultramafic flows, or a product of magnesian metasomatism. It is of interest that this unit is identical chemically and texturally to the Steeprock "ash-rock" which is conformable with the hematitic iron ore at Atikokan, 62 miles (100 km) to the east.

Proceed approximately 700 feet (210 m) eastward around the south side of the pond to small pits beside the bush road.

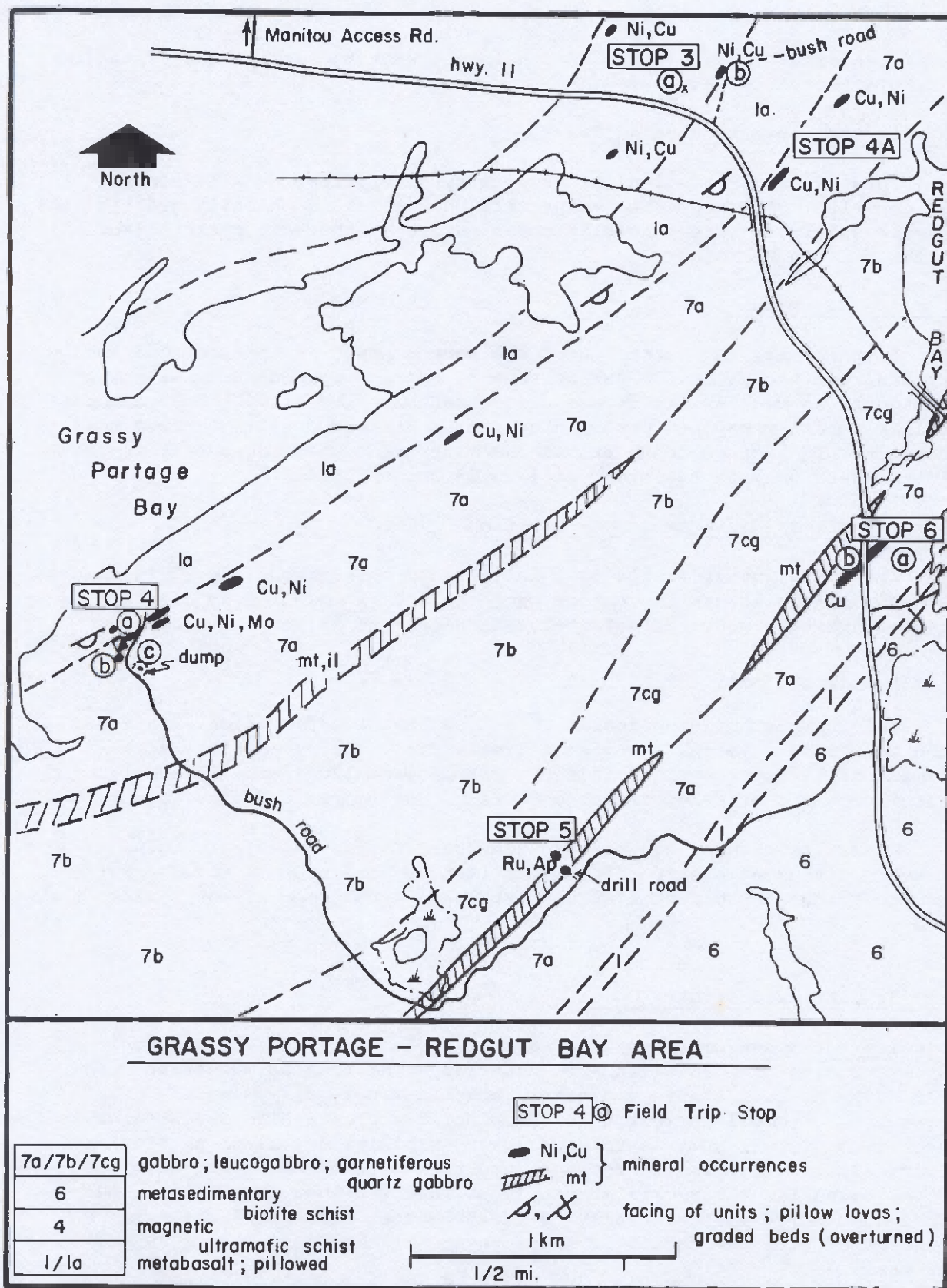


Figure 10: Field trip stops no. 3, 4, 5, and 6.

Locality 3b:

These pits have been developed on foliated mineralized equivalents of the ultramafic unit. Finely disseminated chalcopyrite and pyrrhotite are present and assays of grab samples average approximately 0.3% Cu, 0.1% Ni, 0.03% Co.

Return to Highway 11 and proceed 1.6 miles (2.6 km) southward; turn right on a dirt road. CAUTION - THIS ROAD IS VERY ROUGH AND NOT SUITABLE FOR LOW-RIDING VEHICLES. Proceed to the end of the road (it may be necessary to walk part way). Note that alternate Stop 4A, north of the railway overpass on Highway 11, serves to illustrate some of the features of Northrock-type mineralization in a trench a few hundred feet from the highway (Fig. 10).

STOP 4: The Northrock Deposit

This deposit was discovered in 1959 by Noranda prospectors. Subsequent development, followed by options to Seemar and Northrock Mines, led to the sinking of a 200-foot-deep two-compartment shaft in 1973; a 600-foot drift was driven eastward on the 125-foot level. The drift cut through the three lenticular ore zones and sulfide-rich material was stockpiled. Walk to outcrops at the northwest corner of the hoist building.

Locality 4a: These are the footwall rocks to the Grassy Portage Sill. The pillowed metabasalts here extend southwestward from the vicinity of the previous stop and throughout this distance indicate southward younging.

Walk directly south past the west side of the building across the contact with the metagabbro. Walk towards the dump and stop at an outcrop to the right of the cleared area.

Locality 4b: This is a typical exposure of metagabbro in the Grassy Portage Sill. The plagioclase: mafic mineral ratio is variable locally and in the area of the deposit ranges from melagabbro to leucogabbro. The sill consists of uraltized pyroxene and altered plagioclase (An50).

Locality 4c:

The dump material is divided into waste (east side) and ore (west side). In the dump, representative specimens of mineralized material can be obtained. Particular types include: bleached chalcopyrite-rich ore; net and droplet-textured sulfides in dark gabbro; "spotted" ilmenite-rich material with biotite rims on ilmenite cores; apatite-bearing ores; and molybdenite-bearing ore (rare).

Return towards Highway 11; Stop 0.9 mile (1.5 km) from the highway at a small clearing to the left (Fig. 10).

STOP 5: Fe-Ti oxide mineralization

A small outcrop in the clearing exposes disseminated magnetite in a fine-grained matrix composed of chlorite and actinolite. Fine-grained apatite can be observed in thin section.

Walk northward along an abandoned drill road for approximately 300 feet (100 m) to an outcrop at trail side. Here green apatite and reddish brown rutile crystals comprise an irregular mass of "nelsonite". Such rocks are well known associates of anorthosites and are thought to result from liquid immiscibility in an Fe-Ti-P enriched melt. At this locality the rutile poikilitically encloses abundant quartz so that TiO_2 grades do not exceed a few percent.

Return to Highway 11, turn left and proceed back northward approximately 0.3 mile (0.5 km) to a road leading to the right. Stop here and walk northward along the east side of Highway 11 to the north side of the outcrop (Fig. 10).

STOP 6: Disseminated Cu, Mironski occurrence

The light-coloured siliceous rock exposed here contains fine disseminated chalcopyrite and pyrrhotite. The mineralization was discovered in 1966 as a result of highway construction, and subsequent drilling by Phelps-Dodge Ltd., and later by Belacoma Mines, has outlined approximately 300,000 tonnes grading 0.8% Cu. The siliceous host rock consists of quartz-plagioclase-biotite and may represent either a siliceous differentiate of the gabbroic intrusion or an assimilated country rock. The latter appears to be more likely as this outcrop is near the top of the intrusion where blocks of metavolcanic rock also are present.

A trail, beginning on the opposite side of the highway, leads westward to a number of small exposures and pits which illustrate the nature of the mineralization. Magnetite-ilmenite mineralization, which is likely continuous with that exposed at Stop 5, was intersected in drill holes just to the north of these exposures.

STOP 7: Mo Mineralization, Bear Pass

These outcrops of granodiorite of the Bear Pass pluton contain a set of northwesterly striking quartz veins which contain pyrite or pyrite + molybdenite. Veins range in width from 0.5 cm to 30 cm and are spaced approximately 0.5 m apart. Quartz-pyrite-molybdenite occur nearest to the bridge, whereas to the west, quartz-pyrite veins give way to sulfide-free veins. To the northeast, across Bear Pass, the International Nickel Company drilled 5 holes in 1966 to evaluate a similar vein set. Assays up to 0.65% MoS_2 over 1.5 m were reported but values are erratically distributed.

Traces of copper were also reported. In total, molybdenite mineralization is distributed over an area approximately 700 x 150 m. The quartz veins in the Bear Pass pluton appear to be extensional in nature, have sharp contacts with the granodiorite, and locally possess bleached alteration selvages at the wallrock contact. Some molybdenite occurs as disseminations in the wallrock.

Reset mileage and continue eastward along Highway 11; mileage 12.2 (19.5 km) Turtle River Road; mileage 13.8 (22.2 km) turn right on a private dirt road, continue to fork in the road, turn around and return back

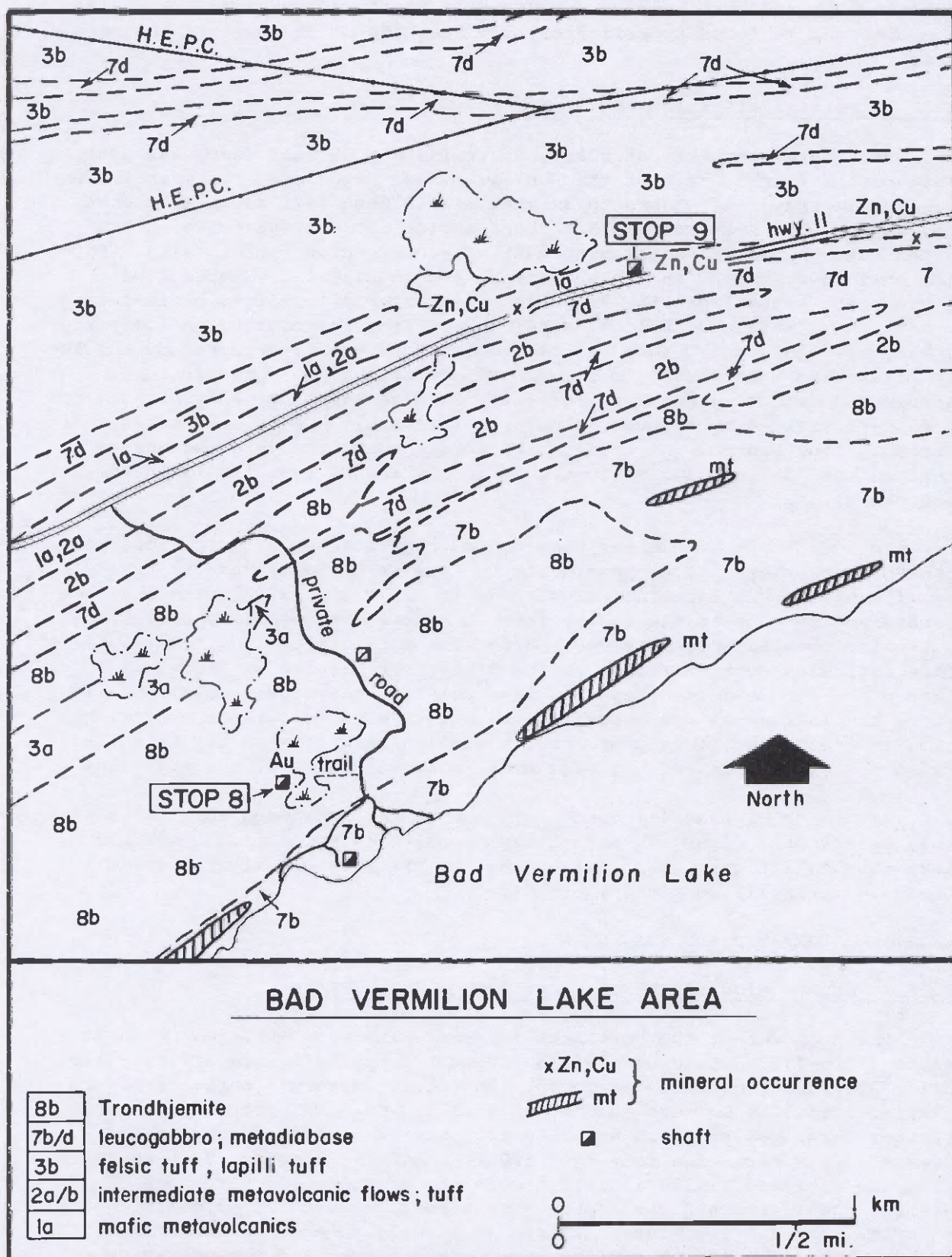


Figure 11: Field trip stops no. 8 and 9.

along the road for approximately 1/8 mile (0.2 km). A trail leads westward through the bush, across a marsh to a series of outcrops. A shaft and dump may be found approximately 200 feet (60 m) due west of the marsh (Fig. 11).

STOP 8: Au mineralization, Stellar Mine

This three-compartment shaft, approximately 50 feet deep, was sunk in 1934 on the Rainbow vein of the Stellar Mining Property. The vein is lenticular in shape and widens to as much as 3.8 feet (1.2 m) halfway down the shaft. The host rock is a carbonate-rich chlorite-sericite schist which forms a dextral shear zone cutting equigranular trondhjemite. Note the oblique foliation in the shear zone and the local development of third-order veins (see Fig. 7c). The vein material consists of laminated quartz and ankerite with local siderite, pyrite, pyrrhotite, chalcopyrite, sphalerite, galena and rare visible gold. Gold values reported during the shaft sinking were erratic but averaged approximately 1 oz. per tonne across the vein to a depth of 24 feet. Surface sampling along strike from the shaft yielded much lower values, approximately 0.2 oz. per tonne across 3-foot widths. At the time of development, the vein was traced on surface for 150 feet (45 m) to the northeast and 60 feet (18 m) to the southwest.

In addition to the shear zone-hosted quartz veins, the outcrops near the shaft provide a good opportunity to examine the equigranular trondhjemite of the Mud Lake intrusion. The trondhjemite, along with the gabbro-anorthosite to the south, forms a concordant, possibly subvolcanic, intrusive complex which has been mapped for a length of 19 miles (30 km). This intrusive complex resembles the Bell River Complex at Mattagami, Quebec and the Beidelman Bay-Pike Lake Complex at Sturgeon Lake, Ontario where the intrusions are thought to relate to massive sulfide mineralization in overlying volcanic strata. A similar relationship may exist between this intrusion and the base metal mineralization at the next stop.

Return to Highway 11; turn right and proceed eastward for 1 mile (1.5 km), pull to the right of the highway opposite a trail leading northward into the bush (Figure 11). Walk along the trail to the cleared area beside a water-filled pit (Figure 6).

CAUTION - DEEP PIT AND OPEN SHAFT.

STOP 9: Zn, Cu Mineralization, Port Arthur Copper Mine

The open cut of the Port Arthur Copper mine was developed during the winter 1916-1917. Later in 1917 a 100-foot-deep shaft with a first-level drift 200 feet long were developed. In total, "several" carloads of ore grading 3 to 3.5% Cu were shipped to Trail, B.C.. The property was further developed by a 5,000-foot drill program in 1956 by Stratmat Limited. A mineralized zone over 600 feet (180 m) long and 75 feet (23 m) wide was outlined. Mineralization consists of seams and stringers of pyrite, sphalerite and chalcopyrite in a host composed of amygdaloidal chlorite schist. The mineralization is crudely zoned (Fig. 6) with a zinc-rich north zone, toward the stratigraphic top, and a copper-rich

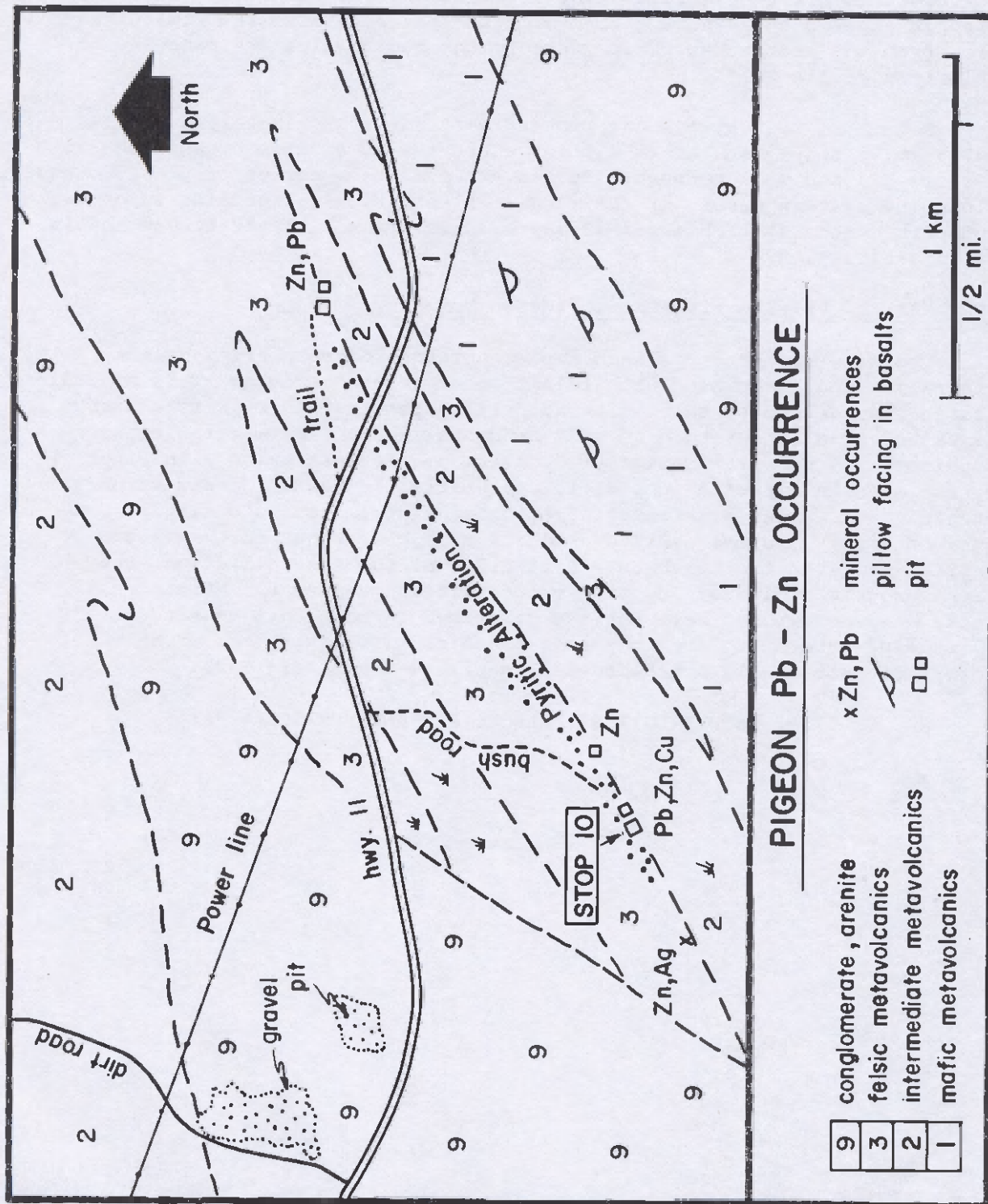


Figure 12: Field trip stop no. 10.

south zone. Good samples of mineralization may be found in the dump. The distribution of mineralization can be noted by the "rusty" appearance of the outcrop surface. Good exposures of unmineralized amygdaloidal meta-volcanic rock can be noted just east of the open cut. A siliceous, "cherty" unit which caps the mineralization is exposed in the northwestern part of the main outcrop. Small outcrops in the clearing north of here expose unmineralized, carbonate-bearing, dacitic tuff. These give way northward to quartz-eye tuff. The footwall rocks to the mineralized zone are not exposed here and a gabbro-diorite sill separates the mineralization from the nearest volcanic rocks to the south which are composed of chloritic felsic tuff.

Return to Highway 11, and proceed east for approximately 6.4 miles (10.3 km). Stop just before a point where the power line crosses the road (Figure 12) and walk through a "cut-over" area to a series of pits located along the eastern margin of the ridge. Alternatively, roadside exposures and pits northeast of Highway 11 may be examined to illustrate the setting of mineralization.

STOP 10: Zn, Pb mineralization, Pidgeon Property

The pits and outcrops here expose stratabound sphalerite-galena mineralization associated with felsic volcanoclastic rocks. This mineralization was tested by short diamond drill holes in 1969 by Kerr Addison Mines and by a longer hole in 1978 by Hanna Mines. The mineralization consists of lenticular masses of sphalerite-galena-ankerite with minor pyrite and chalcopyrite in a siliceous, sericitic host. Quartz veins are present and suggest some remobilization of mineralization during metamorphism. Spotted pyritic alteration is ubiquitous in the felsic lapilli tuffs to the northwest (footwall?) of the mineralization: the Hanna program indicated low zinc values within this zone. Hanging wall rocks are not exposed here but are described in core logs as "andesite". A roadside outcrop to the northeast contains minor magnetite iron-formation overlain by southward-facing pillow lavas (Fig. 12).

END OF TRIP. RETURN TO FORT FRANCES AND INTERNATIONAL FALLS.

FIELD TRIP II:

ARCHEAN GEOLOGY OF THE INTERNATIONAL FALLS-KABETOGAMA
AREA, MINNESOTA

by

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W.C. Day, Minnesota Geological Survey, St. Paul, 55108

and

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Paper 1

GENERALIZED GEOLOGY OF THE RAINY LAKE AREA, MINNESOTA

by

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INTRODUCTION

The Rainy Lake area is in the western part of an east-northeast-trending metavolcanic-metasedimentary sequence more than 300 km long and 10 to 30 km wide that lies adjacent to and astride the International Boundary. It is bounded on the south by the Vermilion Granitic Complex (Southwick, 1972; Southwick and Sims, 1980) and on the north in Ontario by another massif of granitic rocks of probable similar age. Primary zircon ages and whole-rock Rb-Sr ages from the Rainy Lake area suggest that all of the rock-forming events, except for the mafic dikes, occurred between 2700 and 2750 m.y. ago (Peterman and others, 1972).

Reconnaissance mapping was undertaken in the late 1960's; this has been published as the International Falls 1:250,000 sheet (Southwick and Ojakangas, 1979a). More details on the geology can be found in a report on the then-proposed Voyageurs National Park (Minnesota Geological Survey, 1969) and in Ojakangas (1972).

The supracrustal rocks in the Rainy Lake area north of the Rainy Lake-Seine River fault (Figure 1) are part of the larger Wabigoon metavolcanic-metasedimentary belt. They are a diverse assemblage of sedimentary, extrusive, and intrusive rock types, generally metamorphosed to the upper greenschist facies, and have an estimated aggregate thickness of 2400 m (Ojakangas, 1972). In contrast, the biotite schist to the south of the Rainy Lake-Seine River Fault has a metamorphic mineral assemblage characteristic of the amphibolite facies. However, the change in metamorphic grade across the fault is somewhat transitional rather than sharp. The schist south of the fault has a minimum thickness of 3600 m.

For descriptive purposes it is useful to consider the geology of the Rainy Lake area as consisting of three lithologic belts. The central belt consists of a complex assortment of mafic to intermediate metavolcanic and hypabyssal rocks and is referred to in general terms as the greenstone belt. The greenstone belt is flanked on the north by a belt of metagraywacke (passing through Ranier; see stops 1 and 9 of the Trip II field guide in this volume), and on the south by another belt of metagraywacke that may or may not be correlative with the metagraywacke to the north. The south belt of metagraywacke is broken by the Rainy Lake-Seine River fault (see stop 11 of the field guide). A fourth important lithostratigraphic unit in the area consists of feldspathic-lithic quartzite and conglomerate. This clastic succession occurs within the central greenstone belt (see stops 2 and 8 of the field guide).

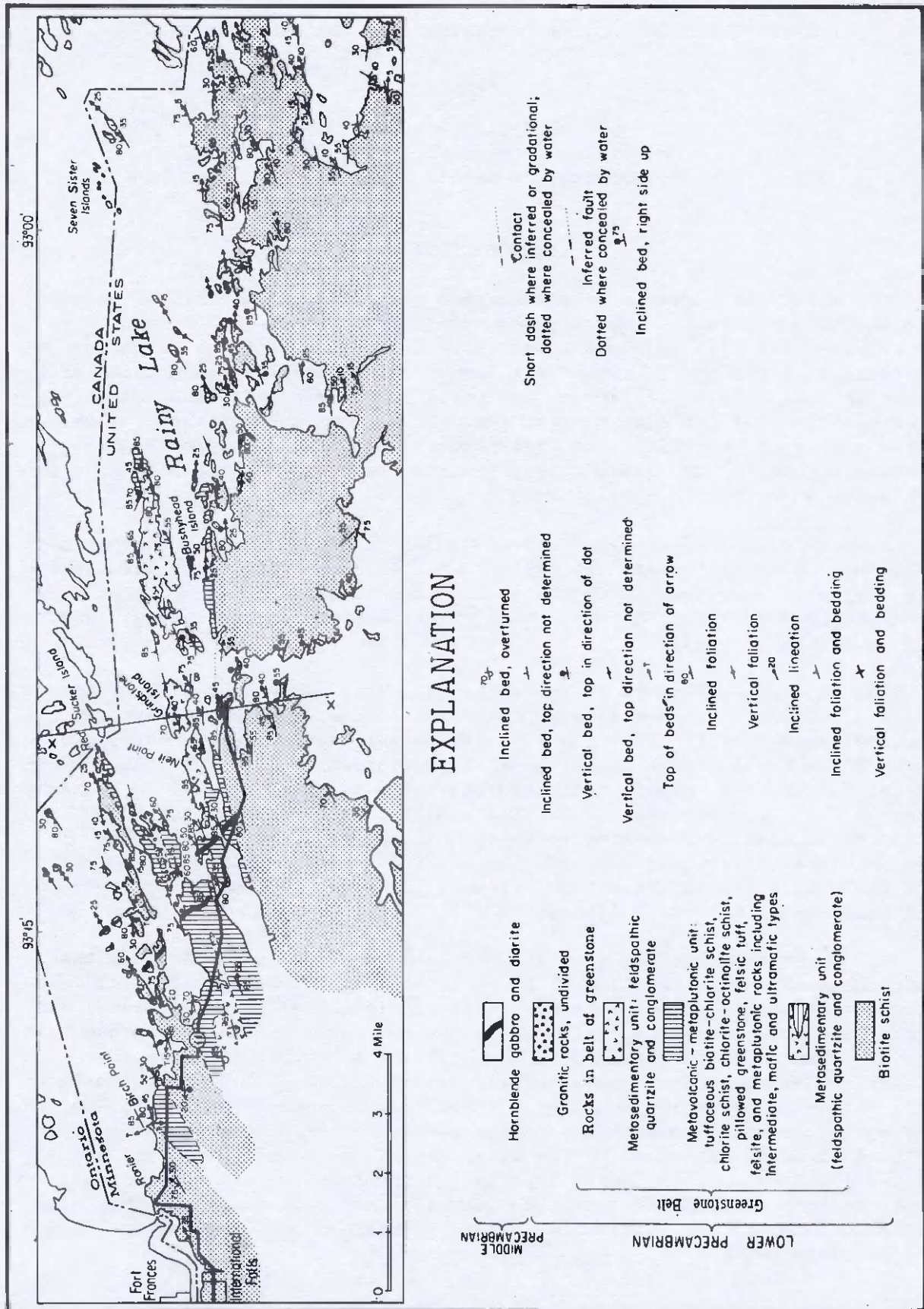


Figure 1. Geologic map of the western part of the Rainy Lake area, Minnesota. From Ojakangas (1972).

The stratigraphic and structural relationships among the greenstone, the two belts of metagraywacke, and the feldspathic quartzite-conglomerate sequence have been debated for decades. The problems are discussed briefly in later sections.

Most volcanic-sedimentary rock types in the Rainy Lake area are schistose and many are sheared, making recognition of primary rock types difficult. Small bodies and dikes of granitic rocks intrude the metamorphic rocks. Some of these previously have been called Laurentian granites (Lawson, 1913; Hart and Davis, 1969; Peterman and Goldich, 1970). Late mafic dikes (2100-2200 m.y.) cut all rocks in the region (Hanson and Malhotra, 1971).

Exposures are generally limited to the lake shores and islands, and to inland knobs of the Kabetogama Peninsula. For several kilometers to the south, large muskeg swamps obscure the geology.

Metagraywacke

The metagraywacke on both sides of the belt of greenstone is characterized by medium- or dark-gray beds that are generally from 5 to 35 cm thick but are as much as 1.2 m thick. An excellent foliation, generally parallel to bedding, is given by well-aligned biotite. Original grain shapes and sizes have been obliterated by recrystallization. Most samples are composed of 50-60 percent plagioclase, 20-40 percent quartz, and 10-15 percent biotite. Minor minerals include chlorite, muscovite, garnet, sillimanite, staurolite, hornblende, tourmaline, epidote, apatite, and pyrite. Southwick (1972) described related biotite schists farther to the south in greater detail.

The original succession probably consisted of alternating beds of graded graywacke sandstones and generally thinner mudstones, the latter now constituting the more biotite-rich beds. Original bedding survived the metamorphism. Graded beds have been obscured by metamorphism at most localities, but can be detected even in some highly recrystallized schists. Other sedimentary features, including concretions, flame structures, and load casts on the bottoms of a few beds, are rare. Turbidity current deposition on submarine fans provides a likely model for sedimentation.

Quartzite-Conglomerate Unit in the Greenstone Belt

Feldspathic-lithic quartzite and conglomerate constitute a clastic succession within the predominant volcanogenic rocks of the greenstone belt. This succession is described in Ojankangas (1972), in the abstract by Ojankangas and Olson in this volume, and in stops 2 and 8 of the field guide in this volume. It has been interpreted as a braided fluvial-alluvial fan association.

Metavolcanic Rocks in the Greenstone Belt

A complex volcanogenic association that includes tuffaceous schist, felsic tuff, felsite, greenschist, pillowed greenstone, iron-formation,

felsic hypabyssal rocks, metadiorite, metagabbro, peridotite, and anorthosite, makes up most of the greenstone belt and is intercalated with the quartzite-conglomerate unit described above. Shearing is pervasive in all the rocks, and positive identification of rock types generally requires microscopic study. Chlorite, amphibole, and epidote impart a green color to the rocks.

Tuffaceous schist, consisting of interstratified thin fine-grained beds and laminae of biotite-rich, chlorite-rich, and sericite-rich composition, occurs in a zone near the southern edge of the greenstone belt adjacent to the southern metagraywacke belt, and extends from Jackfish Bay to the vicinity of Cranberry Island. Another major body is on Jackfish and Red Sucker Islands at the northern edge of the belt. These rocks are interpreted to be tuffaceous because they are associated with coarser felsic tuffs, and because they contain scattered felsic volcanic rock fragments and large plagioclase grains (volcanic?) in a recrystallized matrix of fine quartz and plagioclase, which makes up about two thirds of the rock.

Minor felsic tuff is interbedded with greenschist at several localities. Exposures at the eastern end of Dryweed Island appear to consist of lapilli tuff.

Felsic flows occur in a few small exposures. Fine-grained, dense meta-andesite or metabasalt, commonly with deformed pillows, constitutes a poorly exposed 360-meter-wide unit along the shoreline east of Birch Point, near the western end of Rainy Lake. Other much smaller exposures are present on islands.

Rocks mapped as greenschist consist of thinly bedded, fine-grained chlorite schist, chlorite-actinolite schist, and actinolite schist. This rock type is common throughout the belt of greenstone; it occurs both north and south of the quartzite-conglomerate unit (Fig. 1).

Sheared and altered metaplutonic rocks of variable composition constitute the bedrock of several small islands, especially in the eastern part of the belt. A small island just off the northeast corner of Grindstone Island is composed entirely of serpentized peridotite. Anorthosite comprises the one small island of the Seven Sister Islands that is on the United States side of the International Boundary.

Northern Zone of Granitic Rocks

Medium-grained granitic rocks are common in the western part of Rainy Lake, especially on the Ontario mainland and islands, and constitute the southern edge of a large area of granitic rocks that lies to the north of the Rainy Lake volcanic-sedimentary sequence. On the Minnesota side of the International Boundary, gray, biotitic granitic rocks occur on several of the small islands. The granitic rocks have the general composition of granodiorite. A large body of gray, sheared tonalite occurs on Grassy Island and on the adjacent islands and mainland, and is intrusive into greenschists.

Late Mafic Dikes

Two well-exposed mafic dikes, from 45 to 75 meters wide, which are the youngest rocks in the area, are present on the islands in the western part of Rainy Lake and several additional dikes are exposed sporadically in the vicinity of International Falls. These dikes strike N. 30-40° W. and are vertical. They appear to be aligned with similar dikes in Canada and southward in Minnesota, and are part of a major dike swarm in the western part of the Canadian Shield (Southwick and Day, 1981).

STRUCTURAL INTERPRETATION

The major structural grain of the region is east-northeast, and is given by major fold axes, faults, shear zones, bedding, and foliation. Most of the bedded rocks are inclined steeply; the only exception is in the Brule Narrows to Saginaw Bay area to the east, where gentle open folds are present. Lineations--mainly elongated minerals, schistosity-bedding intersections, and minor fold axes--generally plunge 30°-50° ENE. Both northwest- and northeast-trending lineaments, some of which represent minor faults, can be seen on aerial photographs.

Lawson (1913) interpreted the belt of greenstone and associated rocks to be synclinal, with the quartzite unit (which he called Huronian) in the core and conglomerate (also called Huronian), greenstone (called Keewatin), and biotite schist (called Couthiching) forming successively older units both north and south of the quartzite (Fig. 2A). Grout (1925a), noting that all the cross beds in the quartzite face southward, interpreted the major structure to be anticlinal, and interpreted quartzite to lens out near the eroded crest of the anticline and to be absent on the north flank (Fig. 2B). It is noteworthy, however, that the northern conglomerate unit mapped by both Lawson and Grout appears to consist of a few minor lenses at best, and should not be assumed to be the same unit that is present to the south on Neil Point. Furthermore, greenschist occurs both stratigraphically below and above the feldspathic-lithic quartzite and conglomerate; thus, these latter rock types are interbedded with greenschist. Lawson (1913) said these sediments were deposited upon a major unconformity. Such an unconformity is indeed exposed to the east in Ontario (Lawson, 1913; Wood, 1980) and could be present, but hidden, in Minnesota as well. If so, it may be a minor unconformity. (See the abstract by Ojakangas and Olson in this volume.)

Data obtained during my study permit a different structural interpretation involving both folding and faulting (Fig. 2C). Nearly all stratigraphic tops in the belt of greenstone on Rainy Lake face southward, indicating a lack of major folding within the belt itself. The metagraywacke (biotite schist) that lies south of the greenstone unit faces northward, as previously noted by Merritt (1934, p. 356) in an area several kilometers to the east, but at the same stratigraphic position. Also, most metagraywacke just north of the greenstone faces northward. Folding alone cannot account for these relationships; a major longitudinal fault along the southern boundary of the belt, parallel to the strike of the rock units, seems necessary, and a fault along the northern boundary of the greenstone belt apparently also is required.

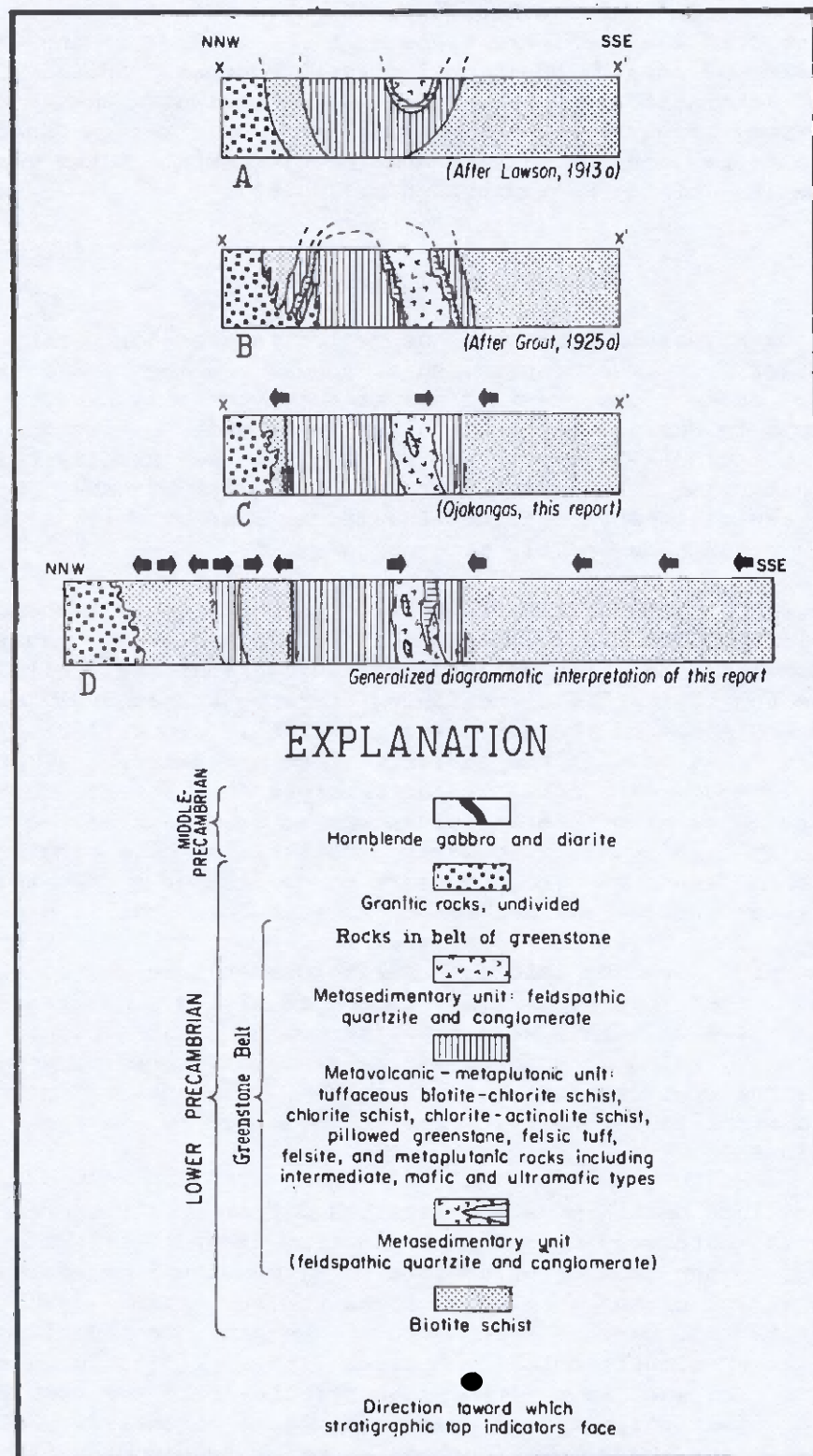


Figure 2. Diagrammatic geologic sections showing structural interpretations of Lawson (1913), Grout (1925a), and this report. Arrows indicate directions of stratigraphic tops. Line of section X-X' shown on Figure 1. From Ojakangas (1972).

Evidence of a major fault along the southern boundary of the belt includes widespread crinkling, abundant quartz veins and pods, silicification, slickensides, and cliffs (fault scarps?). Canadian geologic maps show a major fault on line with this fault and extending more than 200 km to the east. Hawley (1930) and Merritt (1934), both of whom studied this fault zone east of Rainy Lake, concluded it is a right lateral fault. The metamorphic grade (higher in the southern block of biotite schist and lower in the northern greenstone block) indicates that the southern block also moved upward relative to the greenstone block. This fault is now called the Rainy Lake-Seine River fault in Minnesota (Southwick and Ojakangas, 1979b). Additional structural data and interpretations can be found in Ojakangas.

Of structural significance to the Rainy Lake area is recent work by Poulsen (1980) and Poulsen and others (1980). Poulsen has mapped nappe structures in Ontario just 15 km to the north of the area under discussion here. The possibility of such structures being present in Minnesota must be considered in any future detailed mapping. This is of relevance to the "Coutchiching problem," the stratigraphic positioning of the metagraywacke units (biotite schist) relative to the greenstones. The problem was discussed at some length by Ojakangas (1972).

Paper 2

GEOLOGY AND GEOCHEMISTRY OF THE VERMILION GRANITIC COMPLEX

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INTRODUCTION

Archean granite and migmatite of the Vermilion Granitic Complex form the southwestern portion of the Quetico subprovince, a major petrotectonic division of the Superior Province of the Canadian Shield that extends eastward from northern Minnesota into Ontario. The northern margin of the Vermilion Granitic Complex grades into a broad belt of biotite schist which is truncated on the north by the Rainy Lake-Seine River fault (Southwick and Ojakangas, 1979a); the fault marks the north boundary of the Quetico subprovince in Minnesota. Metavolcanic and metasedimentary rocks of the Rainy Lake area, part of the Wabigoon subprovince, abut the biotite schist across the fault (Figure 1). The southern contact of the Vermilion Granitic Complex is defined by the Vermilion fault, south of which are the metavolcanic and metasedimentary rocks of the Vermilion district. The western end of the Vermilion Granitic Complex is defined by the convergence of the Rainy Lake-Seine River fault and the Vermilion fault. Bedrock exposure is quite extensive in the eastern portion of the complex, but the quality and quantity of outcrop diminish westward as the thickness of glacial cover increases.

History of Investigations

During the summer of 1887 H.V. Winchell, H.W. Fairbanks, W.F. Trussel and two "Indian canoe-men" set out in two birchbark canoes from Tower, Minnesota to conduct a geologic expedition in northern Minnesota, journeying through the Rainy Lake and Kabetogama Lake region. They went from Vermilion Lake north up the Little Fork River to the international boundary, and then eastward along Rainy Lake River (as the Rainy River was then known) to "Chadierre Falls" and Fort Frances. From there they proceeded along the south shore of Rainy Lake, south into Black Bay, portaged into Kabetogama Lake, and circumnavigated the Kabetogama peninsula by traveling eastward through Namakan and Sand Point Lakes and then coming back westward through Rainy Lake. During this first expedition Winchell and his colleagues described the rocks and presented the earliest ideas for their origin.

Grout (1923, 1925b, 1926) presented detailed lithologic descriptions, geochemical analyses, and a geologic map of the Vermilion Granite, the name applied by Grout to the terrane now called the Vermilion Granitic Complex. Geochronological work on rocks from the area was initiated by Goldich and others (1961) who determined a K-Ar age for the main batholithic phase of the Vermilion Granite (now termed the Lac La Croix

Granite) of about 2,550 m.y. Peterman and others (1972) reported a Rb-Sr whole rock-isochron age of $2,680 \pm 95$ m.y., with an $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of 0.7005 ± 0.0012 . Jahn and Murthy (1975) determined a more refined Rb-Sr whole rock-isochron age of $2,700 \pm 50$ m.y., with an $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of 0.7004 ± 0.0003 .

Recent reconnaissance geologic mapping of the Vermilion Granitic Complex and the Minnesota portion of the Rainy Lake area was begun in 1968 by D.L. Southwick and R.W. Ojakangas of the Minnesota Geological Survey. Ojakangas published a description of the geology in the Rainy Lake greenstone belt in 1972, and the same year Southwick described the granitic rocks south of Lake Kabetogama, which he termed collectively the Vermilion granite-migmatite massif. In 1980 Southwick and Sims replaced the informal term Vermilion granite-migmatite massif with the formal name Vermilion Granitic Complex, and renamed the Vermilion Granite of Grout (1925b) as the Lac La Croix Granite. The most recent geologic map, at scale 1:250,000, was published by Southwick and Ojakangas (1979a).

Lithologic Units

Lithologic nomenclature used here will be that established by the IUGS Subcommission on the systematics of igneous rocks (Streckeisen, 1973). The three most important rock units in the Vermilion Granitic Complex are migmatite, granite, and early plutonic rocks (Figure 2). The migmatite has been divided by Southwick (1972) into schist-rich and granite-rich types depending on the neosome/paleosome ratio. The paleosomes of the migmatite are biotite schist, amphibolite, early migmatite, and early plutonic rocks, and the neosomes are two-mica leucogranite and grayish-pink biotite granite. The latter is similar to and presumably cogenetic with the Lac La Croix Granite, the dominant batholithic phase of the Vermilion Granitic Complex. The leucogranite neosome is present in small quantities within the biotite schist north of the complex and is the dominant neosome in schist-rich migmatite. Pink granite is the dominant neosome in migmatite classed as granite-rich. The early plutonic rocks within the complex range from granodiorite through tonalite/trondhjemite to quartz diorite and form small, generally irregular masses. These rocks represent the first igneous activity in the area, having been invaded on all scales by the 2,700 m.y.-old Lac La Croix Granite. The radiometric age of the early plutonic rocks is as yet undetermined.

DESCRIPTIONS OF UNITS IN THE VERMILION GRANITIC COMPLEX

Biotite Schist

Biotite schist is widely distributed within the complex and also occurs as a separate mappable unit that flanks the complex on the north and west. Within the complex the biotite schist occurs as more or less intact blocks surrounded by granite and also as an important component of the paleosome of migmatitic rocks. It is an equigranular, medium- to fine-grained schist composed dominantly of quartz, plagioclase, and

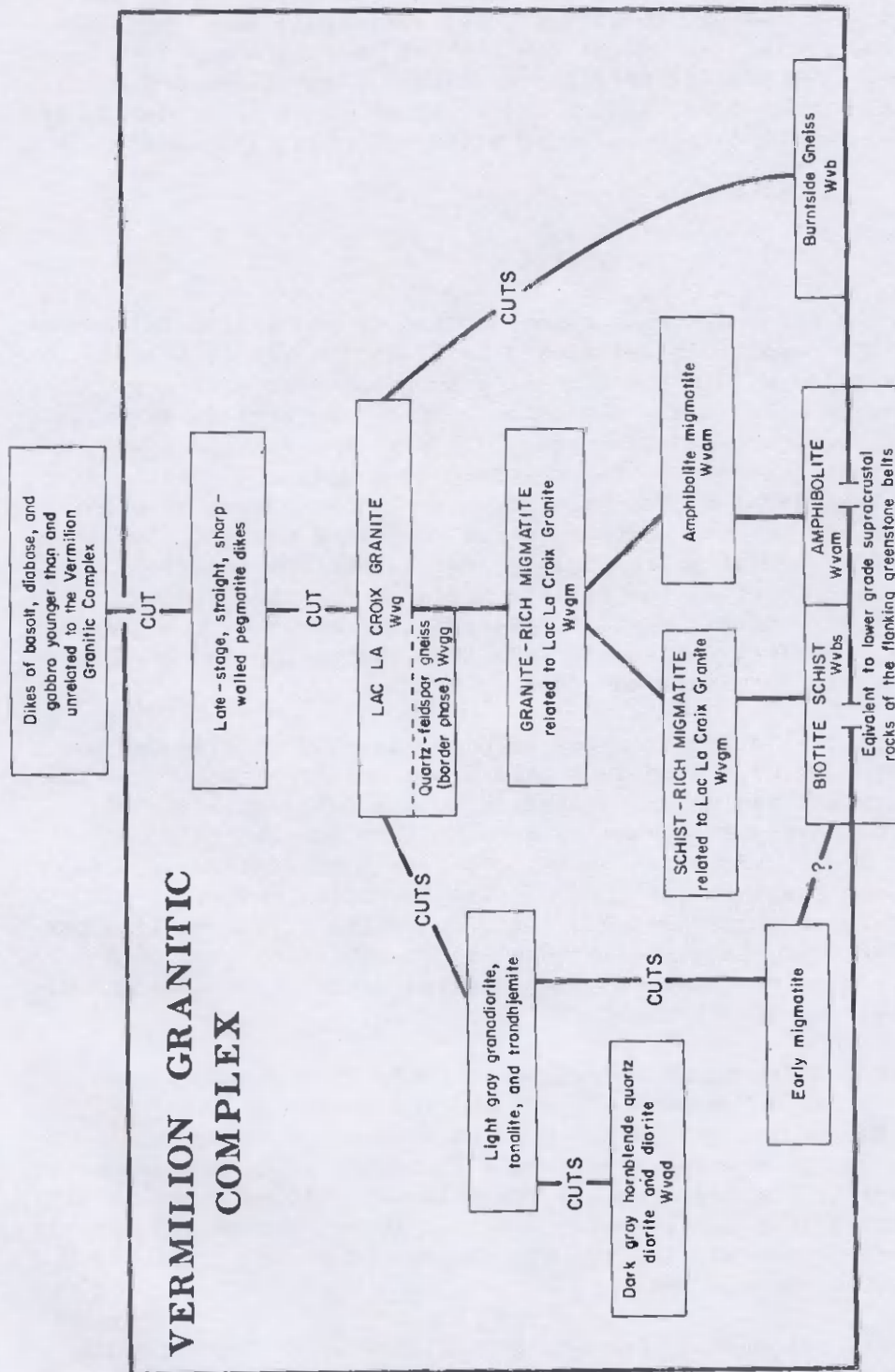


Figure 2. Schematic diagram of the interrelationships among lithologic subdivisions of the Vermilion Granitic Complex. Intrusive units are arranged with the youngest at the top of the diagram. Names spelled out in the capital letters are the more abundant components of the complex.

biotite. Bedding and graded bedding are widely preserved. Oriented biotite defines the strong schistosity, which is regionally parallel to bedding. Isoclinal folding is common in the biotite schist, with quartz and feldspar "sweat-out" pods and stringers being folded congruently.

The mineralogy of the biotite schist north of the Vermilion Granitic Complex is fairly constant, reflecting the chemical homogeneity of the graywacke protolith. However, there are local variations among bedding horizons within the schist, as on the south shore of Kabetogama Lake by Chippewa Lodge (T. 69 N., R. 22 W.), where garnet, staurolite, and sillimanite occur in aluminous beds, and on the south shore of Sugarbush Island in Kabetogama Lake, where felsic horizons with poikiloblastic plagioclase occur.

Migmatite

The broad-scale structure within the dominantly migmatitic terrane in the west part of the complex is delineated by foliation within the paleosome. Large folds within the migmatite trend roughly east-west, parallel to the major structural fabric in the flanking greenstone belts (Southwick, 1972; Southwick and Ojakangas, 1979a). The fold patterns outlined by schistose paleosomes are preserved even into the granite-rich portions. Southwick (1978) states "the structural consistency of migmatite paleosomes in the western portion of the Vermilion Granitic Complex, even in rocks that are chiefly granite, indicates that the granite fraction, whatever its origin, was emplaced in a manner that did not completely disrupt structural trends in pre-existing rocks." The granite seems to have been passively injected, with some flattening and broadening of the pre-existing folds within the country rocks.

The eastern portion of the complex is predominantly massive Lac La Croix Granite, which incorporates less than 5 percent xenoliths. The percentage of supracrustal inclusions increases to the west, with the lithology grading regionally from massive granite through granite-rich migmatite to schist-rich migmatite (Figure 1). In a general sense, the Lac La Croix component within the neosome also decreases westward. Southwick (1972) argued that the schist-rich migmatite of the western portion of the complex represents the injected and remobilized roof of a batholith cored by massive granite. The inferred depth of emplacement was on the order of 9-12 km (pressure of 3-4 kb).

The structure and fabric of the migmatite vary on the outcrop scale, depending on the amount of neosome present and the manner of its emplacement. In the schist-rich migmatite the neosome is commonly interlayered with the paleosome, producing a stromatic structure (Mehnert, 1968). Small granitic stringers within the paleosome blocks commonly are boudinaged and thrown into small-scale isoclinal folds. These leucocratic stringers which are as narrow as a few millimeters in width, typically are bordered by a biotite selvage zone.

The granite-rich migmatite presents several fabric styles depending on the degree of paleosome assimilation and manner of granite emplacement.

Where the granitic neosome is dominant, paleosome blocks (up to ten meters in size) are rafted in neosome. Some paleosome blocks are sharp and distinct, typical of an agmatic migmatite, many have the pronounced flow fabric of a schlieren migmatite, and many are the ghostly, digested remnants characteristic of nebulitic migmatite (Mehnert, 1968). The contacts are especially diffuse around tonalite blocks that are contained in Lac La Croix Granite. The feldspar "halo" surrounding such inclusions is interpreted as representing alkali metasomatism, with the introduction of potassium into the tonalite, and of calcium and sodium into the granite.

The neosome of the schist-rich migmatite is white to light pink leucogranite. This is a coarse-grained to pegmatitic material composed dominantly of quartz, microcline and plagioclase. Muscovite, biotite and chlorite are common minor minerals. Garnet, epidote and zircon occur as accessory minerals.

As discussed earlier, the leucogranite in the schist-rich migmatite is intimately enfolded and boudinaged with the paleosome. Poikiloblastic microcline and plagioclase are developed in thin stringers within biotite schist without disruption of biotite foliation in the surrounding paleosome. Southwick (1972) suggested that this texture indicates a replacement origin or metasomatic growth of feldspar during metamorphism. This texture can be seen especially well on the south end of the roadcut 6.6 miles north of Cusson, Minnesota along U.S. Highway 53.

The neosome of the granite-rich migmatite is predominantly grayish-pink Lac La Croix Granite. The local mineralogy and chemical composition of the granite vary with the degree of paleosome digestion. The neosome also varies with the amount of mixing between the leucogranite and Lac La Croix granitic phases. This is seen along the Crane Lake Road, north of the junction with the Echo Trail.

Early Plutonic Rocks

Granodiorite, trondhjemite, tonalite, and quartz diorite represent the earliest igneous activity in the Vermilion Granitic Complex. Although these rocks occur as relatively minor intrusive bodies, they hold a key to understanding the early geologic and geochemical evolution of the region. In most cases crosscutting relationships easily establish relative ages, but radiometric dating has not been conducted on these earliest phases to determine their absolute ages.

Two early plutonic units are large enough to show on the 1:250,000 scale geologic map by Southwick and Ojakangas (1979a). One is an east-west trending body of biotite-hornblende quartz diorite which crops out along the Ash River Trail 3 km south of Sullivan Bay of Kabetogama Lake (Figure 1). This rock has a massive, medium-grained hypidiomorphic texture. Modal proportions of the leucocratic minerals are plotted in Figure 3a. The melanocratic minerals hornblende and biotite comprise up to 35 percent of the unit. This biotite-hornblende quartz diorite is crosscut by numerous dikes and irregular masses of biotite granite and granodiorite. The amphibole and oxide phases display interesting textural

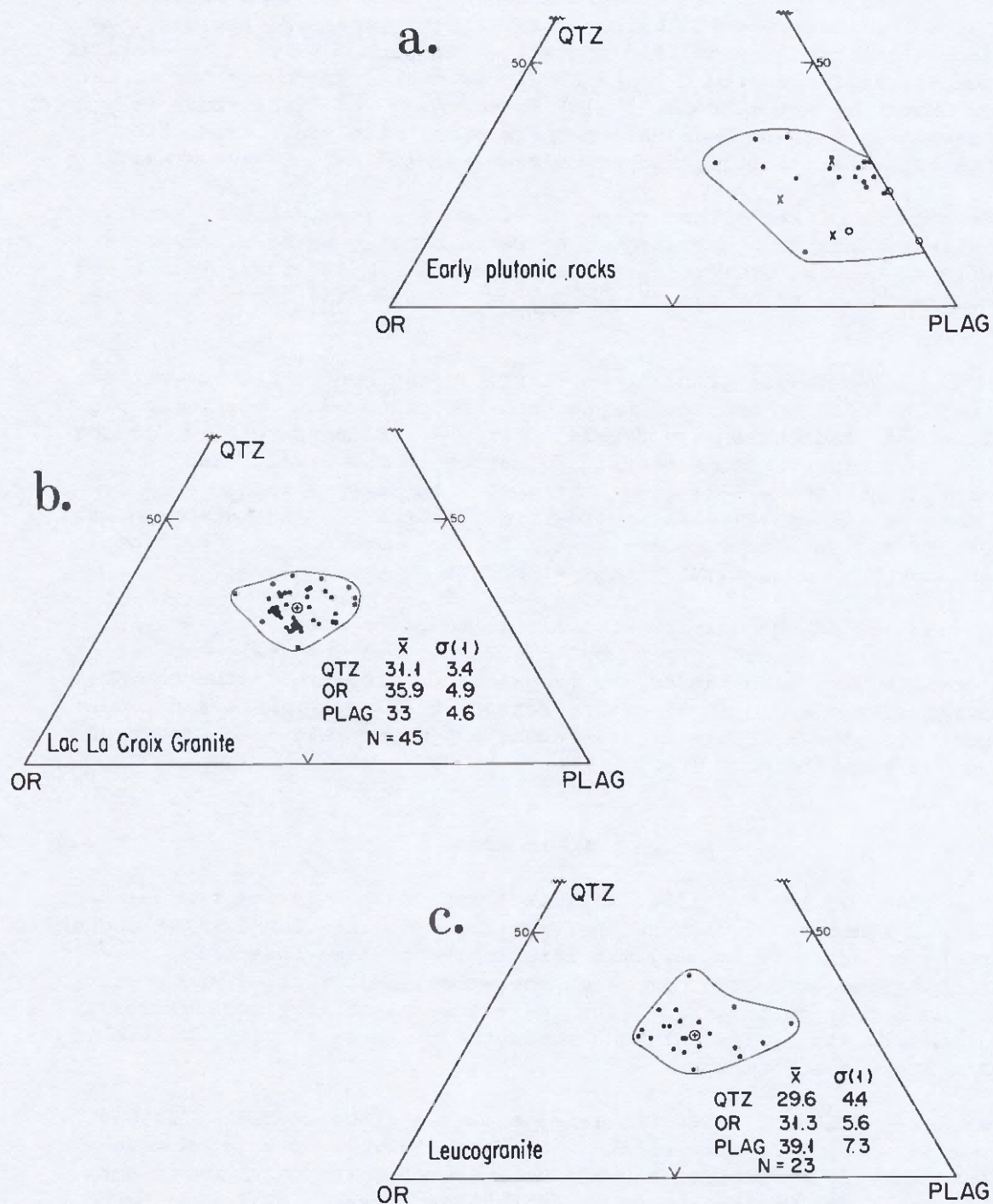


Figure 3. Modal abundances of Or-Qtz-Pl. Data taken from Southwick (1972), Rye and Roy (1978), and unpublished data on file at Minnesota Geological Survey.

a) Early Plutonic Phases: o-granodiorite along Ash River; x-granodiorite on west side of Pelican Lake; • -small bodies and neosomes of early migmatites.

b) Lac La Croix Granite

c) Leucogranite

relationships in this quartz diorite, with magnetite/hematite intergrowths forming fine exsolution lamellae along cleavage traces within the central portion of the amphibole (ferrohastingsite).

The other early plutonic phase which has significant areal exposure is a weakly foliated, coarse-grained, biotite-hornblende granodiorite that occurs at the west end of Pelican Lake (Figure 1). Modal proportions are plotted in Figure 3a. The granodiorite occupies the nose of a broad westward plunging fold, with the east-west-trending limbs extending into granite-rich and schist-rich migmatite. Due to poor exposure, the stratigraphic position of this body is uncertain, but it is considered to be an early plutonic phase.

The biotite tonalite and trondhjemite within the Vermilion Granitic Complex occur as dikes and small irregular bodies intruding metamorphic country rock. Locally these create an early migmatite which is crosscut by Lac La Croix Granite and by leucogranite. The tonalite and trondhjemite are light gray, weakly foliated, medium- to coarse-grained, and hypidiomorphic in texture. They intrude the country rock along foliation, and in places are folded syntectonically with it.

Granite

Lac La Croix Granite

This very mass of granite is fairly homogeneous in composition, is medium- to coarse-grained, and has hypidiomorphic granular texture. Floating blocks of partly digested biotite schist and amphibolite make up no more than 5 percent of the rock within the area mapped (Southwick and Ojakangas, 1979a). Isolated megacrysts of microcline, ranging from 1 to 15 cm in length, are widespread. Pegmatitic and aplitic dikes cut the granite along parallel fractures, suggesting that solidification of the batholith was followed closely by fracturing and injection of late-stage granitic material. Figure 3b shows the modal range of the dominant medium-grained granite of the Lac La Croix.

Granite of the Lac La Croix type forms the neosome of migmatite that flanks the intrusion. The color of the granite in the migmatite diverges from the characteristic grayish-pink of the massive interior to a lighter pink or pinkish-white. The granite in the migmatite is better foliated than in the massive interior; and it also tends toward a coarser, sub-pegmatitic texture. Magnetite is a common accessory mineral in the massive interior of the Lac La Croix, generally forming medium-grained subhedral crystals. In the border neosome and late-stage pegmatites the magnetite occurs as large (0.5 to 2 cm) euhedral crystals. Grout (1923, 1926) first noted this occurrence and surveyed these magnetite pegmatites for possible economic exploitation.

Leucogranite

The second main category of granite in the Vermilion Granitic Complex is a gray to white two-mica leucogranite. The leucogranite is restricted

TABLE 1. Major-element Composition of rocks in the Vermilion Granitic Complex

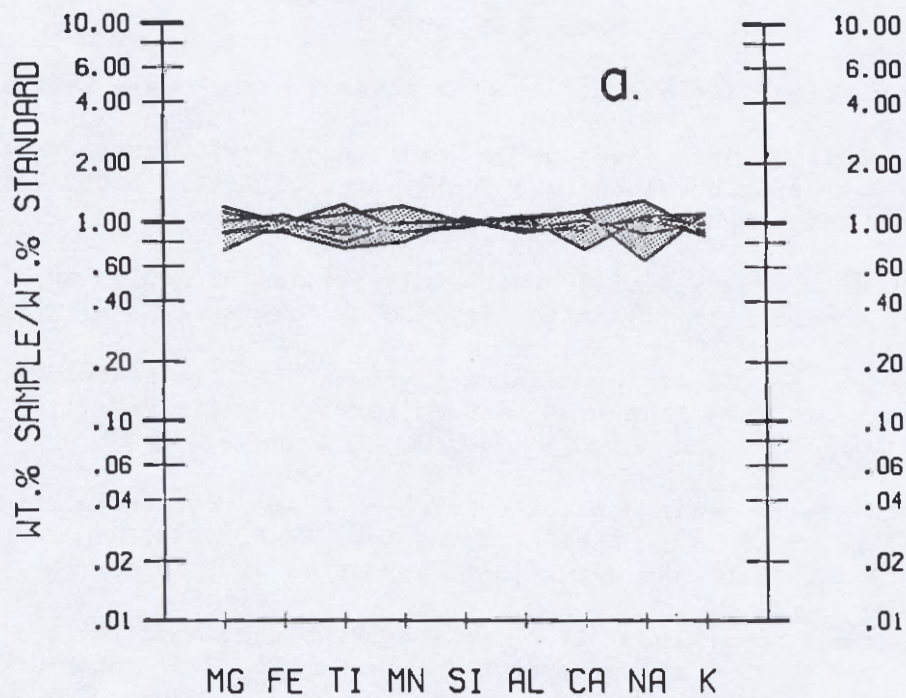
	SiO ₂	Al ₂ O ₃	TiO ₂	MgO	FeO(t)	CaO	Na ₂ O	K ₂ O	MnO	No. Samples	Total*
1) Biotite Schist ave.	63.8 +1.06	16.1 +1.14	0.63 +0.10	2.40 +0.42	5.79 +0.27	2.72 +0.39	3.66 +0.71	2.93 +0.27	0.10 +0.01	7	98.13
2) Lac La Croix ave.	73.4 +1.32	14.7 +0.48	0.19 +0.05	0.35 +0.08	1.42 +0.29	0.88 +0.19	2.64 +0.87	5.81 +0.49	0.02 +0.01	5	99.41
3) Leucogranite ave.	73.7 +1.01	15.3 +0.65	0.10 +0.07	0.13 +0.06	0.57 +0.22	0.90 +0.35	2.60 +0.87	5.65 +1.05	0.02 +0.01	10	98.97
4) Amphibolite	49.1	14.1	1.50	9.10	11.40	11.78	1.56	1.05	0.19		99.78
5) Amphibolite	53.4	15.9	1.11	6.58	8.21	7.63	3.74	1.82	0.12		98.96
6) Amphibolite	47.5	14.1	0.74	9.03	13.05	11.48	2.88	0.92	0.22		99.92
7) Amphibolite	54.5	13.2	1.00	6.73	11.68	7.80	3.28	0.94	0.19		99.27
8) Trondhjemite	69.0	16.9	0.23	0.73	1.84	3.50	6.30	0.93	0.03		99.46
9) Granodiorite	70.4	16.8	0.30	0.75	1.79	2.73	5.62	1.26	0.02		99.67
10) Tonalite	64.7	19.90	0.50	1.78	33.00	4.21	3.564	2.19	0.05		99.87
11) Tonalite	65.2	17.5	0.74	1.90	3.16	5.29	4.06	1.61	0.06		99.52

- H₂O not determined
Analyses done using atomic absorption with at least ten determinations on each element per sample.

NOTES FOR TABLE 1

- 1) Biotite schist (average of 7 rock analyses), Kabetogama Lake area.
- 2) Lac La Croix Granite (average of 5 rock analyses), interior of batholith, 1 km spacing along Echo Trail, east of Little Sioux Indian River, Shell Lake quad.
- 3) Leucogranite (average of 10 rock analyses), small bodies in biotite schists and schist-rich migmatite, Kabetogama Lake area.
- 4) Medium-grained clinopyroxene-hornblende amphibolite paleosome, 0.8 km (0.5 mi) west of Crane Lake Road on U.S. Forest Service Vermilion Falls Road, SW $\frac{1}{4}$ NW $\frac{1}{4}$, sec. 35, T. 67 N., R. 17 W., Echo Lake quad. (8-11-VGM-14).
- 5) Foliated coarse-grained biotite-hornblende amphibolite paleosome, 3.0 km (1.9 mi) south of Crane Lake on Crane Lake Road, NE $\frac{1}{4}$ SE $\frac{1}{4}$, sec. 35, T. 67 N., R. 17 W., Echo Lake quad. (8-10-VGM-10A).
- 6) Foliated medium-grained clinopyroxene-hornblende amphibolite paleosome, 4.6 km (2.9 mi) west of Elephant Lake on U.S. Forest Service Cusson Road, NE $\frac{1}{4}$ NW $\frac{1}{4}$, sec. 19, T. 66 N., R. 18 W., Elephant Lake quad. (8-12-VSM-4).
- 7) Coarse-grained amphibolite paleosome, NW $\frac{1}{4}$ SE $\frac{1}{4}$, sec. 22, T. 65 N., R. 16 W., Picket Lake quad. (8-9-VAM-3).
- 8) Light-gray biotite trondhjemite, same location as 6 (8-12-VSM-1).
- 9) Biotite granodiorite, same location as 6 (8-12-VSM-3).
- 10) Light-gray hornblende biotite tonalite, same locations as 4 (8-11-VGM-15).
- 11) Foliated light-gray hornblende-biotite tonalite, U.S. Highway 53, 2.9 km (1.8 mi) west of St. Louis Co. Road 122 (8-14-VGM-A).

BIOTITE SCHIST



METAGRAYWACKE

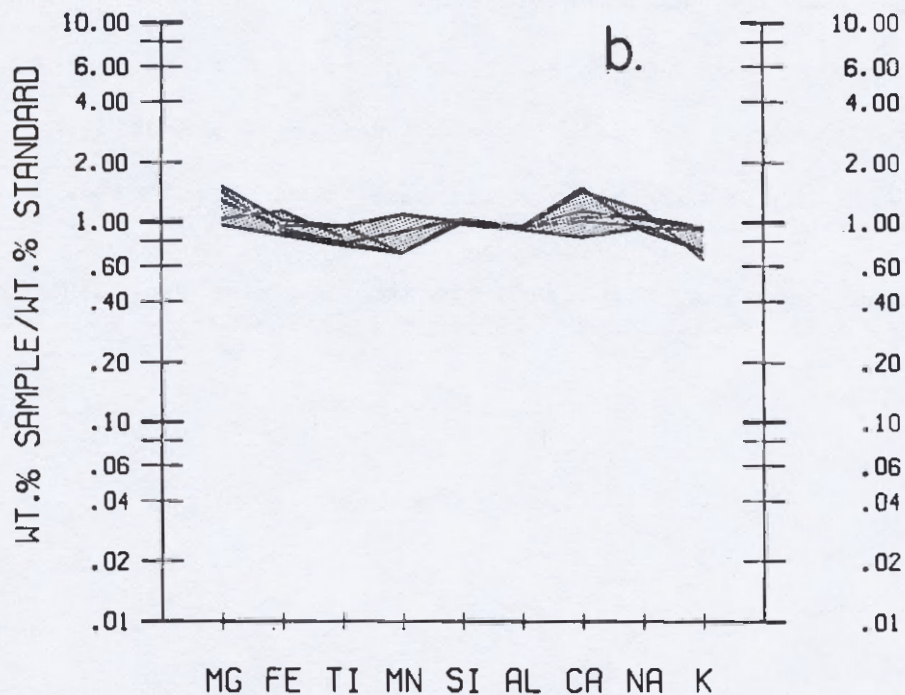


Figure 4. Major-element data normalized against average biotite schist from Kabetogama Lake area.

a) Biotite schist at Lake Kabetogama. Note narrow range in composition.

b) Metagraywacke from neighboring greenstone belts.

to the neosome of schist-rich migmatite and to small bodies within biotite schist along the northern border of the complex. The leucogranite varies greatly in mineralogy, texture, and geochemistry.

Figure 3c shows the modal variability of the leucogranite. The leucogranite contains small but persistent amounts of primary muscovite and garnet. Garnet typically makes up a few percent of the leucogranite whereas it is totally absent from the Lac La Croix Granite. Magnetite, on the other hand, is a common accessory in the Lac La Croix but is rare in the leucogranite.

The texture of the leucogranite varies locally from medium-grained hypidiomorphic granular to coarse-grained pegmatitic. Different textural subunits of the leucogranite commonly cut across one another (as at Wooden Frog Campground; Stop 13, field trip II, this volume). These textural subunits are thought to be cogenetic and virtually coeval.

Possibly the most significant feature of the leucogranite is its relation to the deformation history of the biotite schist. Along the south shore of Kabetogama Lake the leucogranite is isoclinally folded with biotite schist; the leucogranite has been boudinaged along isoclinal fold limbs, and thickened within hinges. Physically indistinguishable leucogranite also cuts discordantly across these folds. The seemingly incongruent timing of leucogranite emplacement is best explained by continual mobilization of granitic material during deformation of the biotite schist.

GEOCHEMISTRY

Biotite Schist

Major- and trace-element analyses were made to determine the geochemical nature of the biotite schist in the Kabetogama Lake region. To obtain representative chemical analyses, rock samples were selected from the least-weathered massive beds of schist. An average of seven separate analyses is listed in Table 1. Figure 4a displays the range of major elements for the specimens, normalized against the average schist. Although beds with aluminous and quartzofeldspathic compositions do occur locally, the typical biotite schist has fairly constant modal mineralogy. This consistency is reflected in limited variation in major element abundances.

Figure 4b shows the major element composition of volcanogenic graywacke from neighboring terranes normalized against the average composition of the biotite schist. Two new analyses of metagraywacke from the Rainy Lake greenstone belt are displayed, along with published values for the Knife Lake Formation (Arth and Hanson, 1975), a metasedimentary rock from Wabigoon subprovince (Williams, 1978) and a sample of Coutchiching metagraywacke (Goldich and Peterman, 1978). The only significant variation is the higher MgO content of the neighboring metagraywackes. The observed higher MgO content could reflect a more mafic original composition within the metagraywackes, or it could reflect chemical adjustments during metamorphism. In any case, the major element

composition of the biotite schist from the Kabetogama Lake region is very similar to that of neighboring volcanogenic metasedimentary rocks.

In Figure 5 the rare earth element (REE) content of a biotite schist from the Kabetogama Lake area is compared with that of a metagraywacke from the Rainy Lake greenstone belt at Ranier, Minnesota. Also depicted are the REE content of metasedimentary rocks from the Knife Lake Formation (Arth and Hanson, 1975) and from the Crystal Lake area of Ontario (Williams, 1978). The REE content of the biotite schist from the Kabetogama Lake area is clearly within the range of volcanogenic metagraywacke from neighboring terranes.

From the earliest observations there has been general agreement that the protolith for the biotite schist was bedded graywacke. Alexander Winchell, in the 16th Annual Report of the Geological and Natural History Survey of Minnesota (1888, p. 367) states, "the crystalline schists appear to me to have been original sediments which have been partly decomposed and fixed in new combinations while in a semi-plastic state occasioned by heat and alkaline waters." Even though our methods of investigation are more sophisticated, nearly one century later the same view is held.

Amphibolite

Four samples from amphibolite inclusions within Lac La Croix Granite were analyzed for major element abundance (Table 1); trace element content was determined for one of these samples (Table 2). In Figure 6a the major elements are normalized against a low-Ti basalt from the upper member of the Ely Greenstone in the Vermilion district (Schultz, 1980). This standard was chosen because basalts like those in the Vermilion district to the south are likely protoliths for the amphibolite xenoliths. Outlined in Figure 6b are the ranges for Ely basalt reported by Schulz (1980) and Arth and Hanson (1975), and for Newton Lake basalt (Schulz, 1980). This plot gives a feel for the normal range of major elements in neighboring basalts. Although there is distinct diversity in the geochemistry of the individual amphibolite xenoliths, their major element data do display basaltic affinity. There is a significantly higher K_2O content in the amphibolite xenoliths, which could be a result of metasomatism by the enclosing granite.

The chondrite-normalized REE content of one amphibolite xenolith is plotted in Figure 7, along with a sample of basalt from the Newton Lake Formation (Arth and Hanson, 1975). Williams (1978) reported REE contents for two amphibolite inclusions within early tonalite from the Crystal Lake area, Ontario, and noted that the normalized REE patterns were flat (approximately 11 x chondrites), very similar to the Newton Lake basalt. The overall REE content of the analyzed amphibolite inclusion is less than that of these other metabasalts (7-9 x chondrites). In addition, the inclusion has a depleted light REE profile ($La/Sm_n = 0.75$), similar to Type I ocean floor tholeiitic basalts identified by Bryan and others (1976).

There are two viable hypotheses for the origin of the amphibolite xenoliths. One possibility is that they are cognate inclusions, repre-

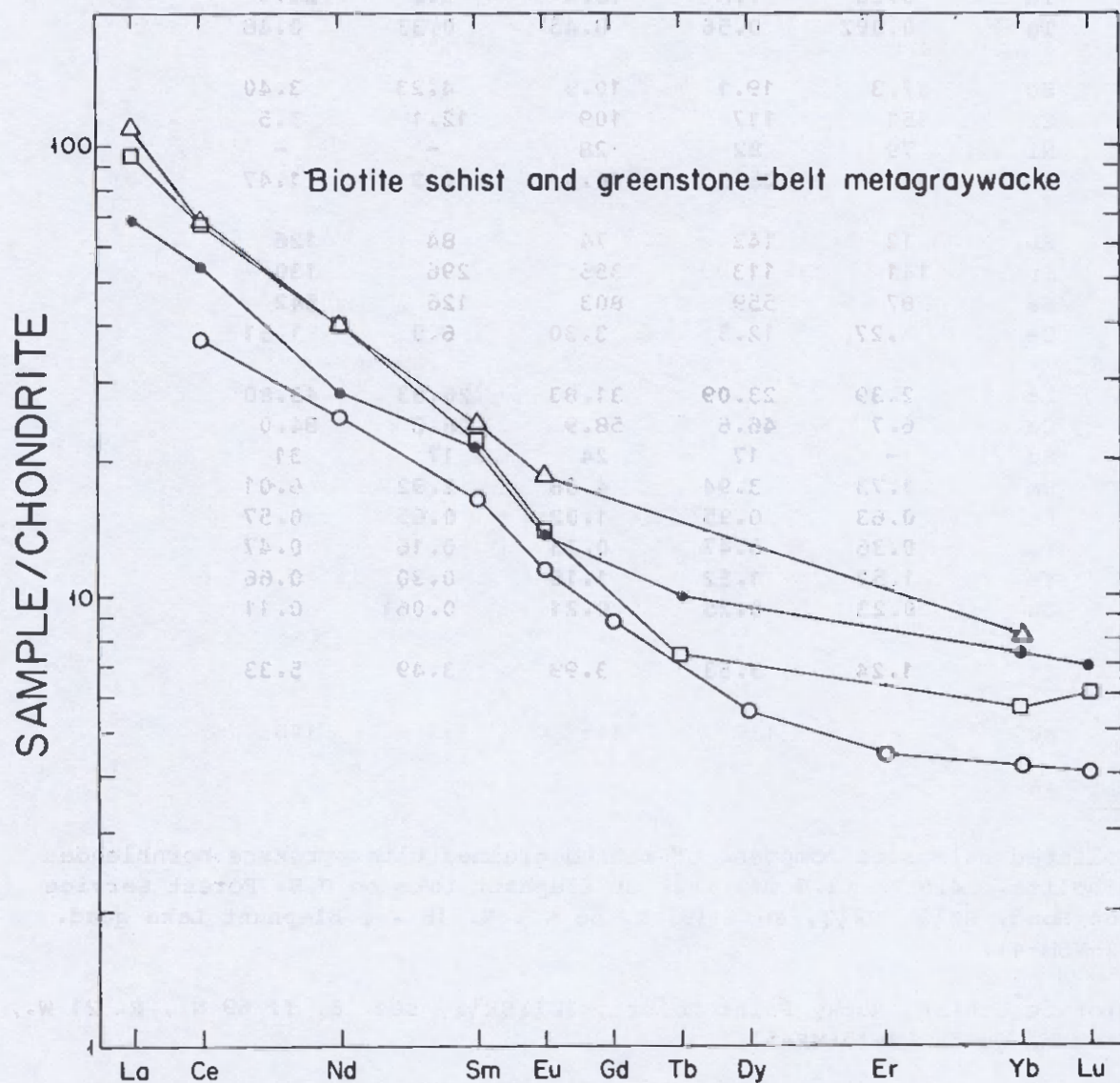


Figure 5. REE plot of: ● -biotite schist (Kabetogama Lake); □ -metagraywacke (Ranier, Mn); △ -metagraywacke, Crystal Lake, Ontario (Williams, 1978); ○ -metagraywacke, Knife Lake Group (Arth and Hanson, 1975). Normalized against chondrites (Haskin and others, 1968).

TABLE 2. Trace element abundances in rocks of the Vermilion Granitic Complex, in ppm

	1	2	3	4	5
U	-	2.5	2.8	1.7	1.8
Th	0.20	7.8	10.4	6.2	24.9
Ta	0.092	0.56	0.45	0.33	0.48
Sc	37.3	19.1	10.9	4.23	3.40
Cr	151	117	109	12.1	3.5
Ni	79	82	28	-	-
Co	51.0	25.5	16.5	6.3	1.47
Rb	12	142	74	84	126
Sr	141	113	355	296	130
Ba	87	559	803	126	542
Cs	.27	12.3	3.30	6.0	1.51
La	2.39	23.09	31.83	26.83	43.80
Ce	6.7	46.6	58.9	48.8	84.0
Nd	-	17	24	17	31
Sm	1.73	3.94	4.38	2.92	6.01
Fu	0.63	0.95	1.02	0.65	0.57
Tb	0.36	0.47	0.35	0.16	0.47
Yb	1.52	1.52	1.15	0.30	0.66
Lu	0.23	0.25	0.21	0.061	0.11
Hf	1.24	3.53	3.99	3.49	5.33
Zr	-	134	145	133	148

NOTES:

1) Foliated paleosome composed of medium-grained clinopyroxene hornblende amphibolite. 4.6 km (2.9 mi) west of Elephant Lake on U.S. Forest Service Cusson Road, NE $\frac{1}{4}$, NW $\frac{1}{4}$, sec. 19, T. 66 N., R. 18 W., Elephant Lake quad. (8-12-VSM-4)..

2) Biotite schist, Rocky Point Resort, SW $\frac{1}{4}$ SE $\frac{1}{4}$, sec. 6, T. 69 N., R. 21 W., Kabetogama quad. (8-15-MS-5).

3) Metagraywacke, Ranier, MN (8-19-7).

4) Early tonalite, 4.3 km (2.7 mi) west of Crane Lake Road on U.S. Forest Service Vermilion Falls Road, NW $\frac{1}{4}$ SE $\frac{1}{4}$, sec. 33, T. 67 N., R. 17 W., Kabustasa Lake quad. (8-11-VGM-19).

5) Lac La Croix Granite 2.4 km (1.5 mi) east of Little Sioux Indian River on Echo Trail, SE $\frac{1}{4}$ NW $\frac{1}{4}$, sec. 1, T. 65 N., R. 15 W., Shell Lake quad. (VLG-4B).

Neutron activation; analyses done by Klaus Schultz at Washington University, St. Louis, Mo.

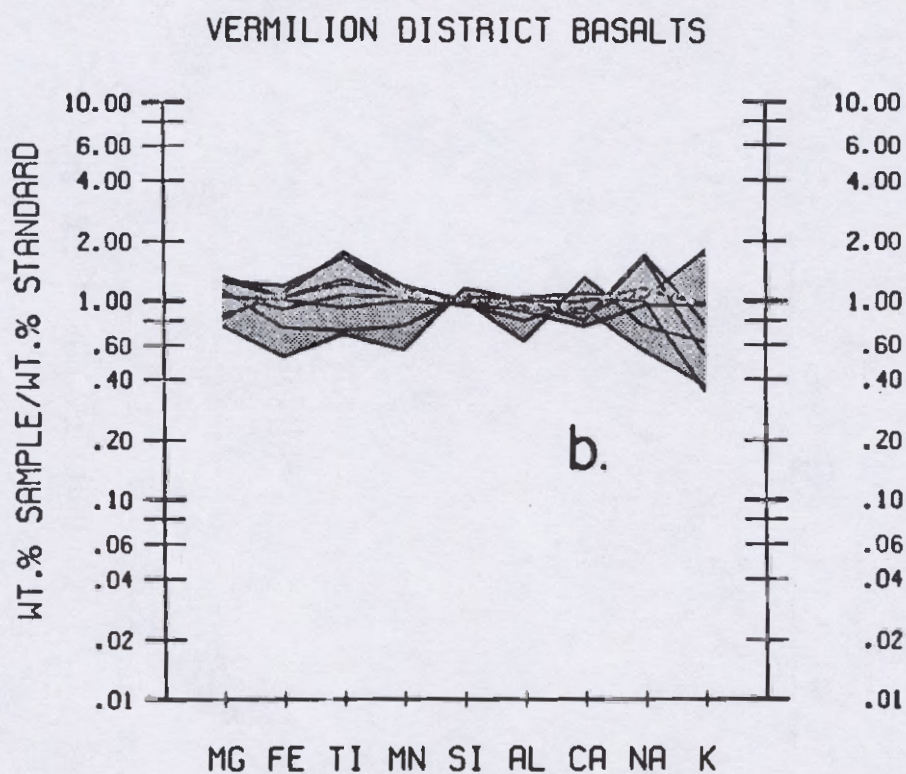
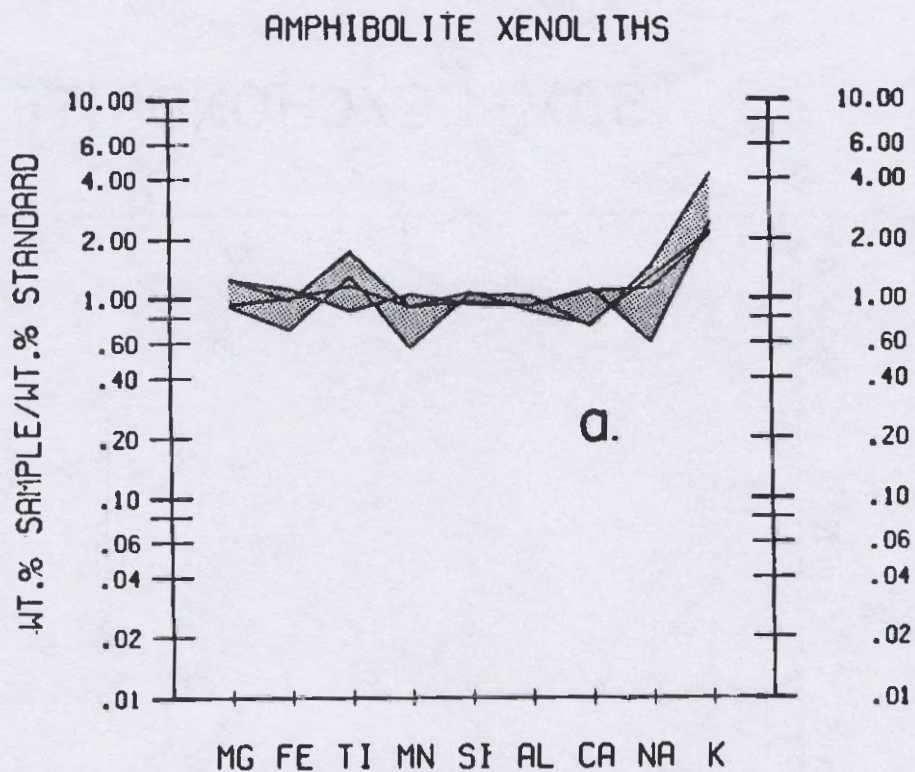


Figure 6. Major-element data normalized against low-Ti basalt from upper member of Ely Greenstone (Schulz, 1980).
 a) Amphibolite xenoliths within Vermilion Granitic Complex.
 b) Ely and Newton Lake basalts.

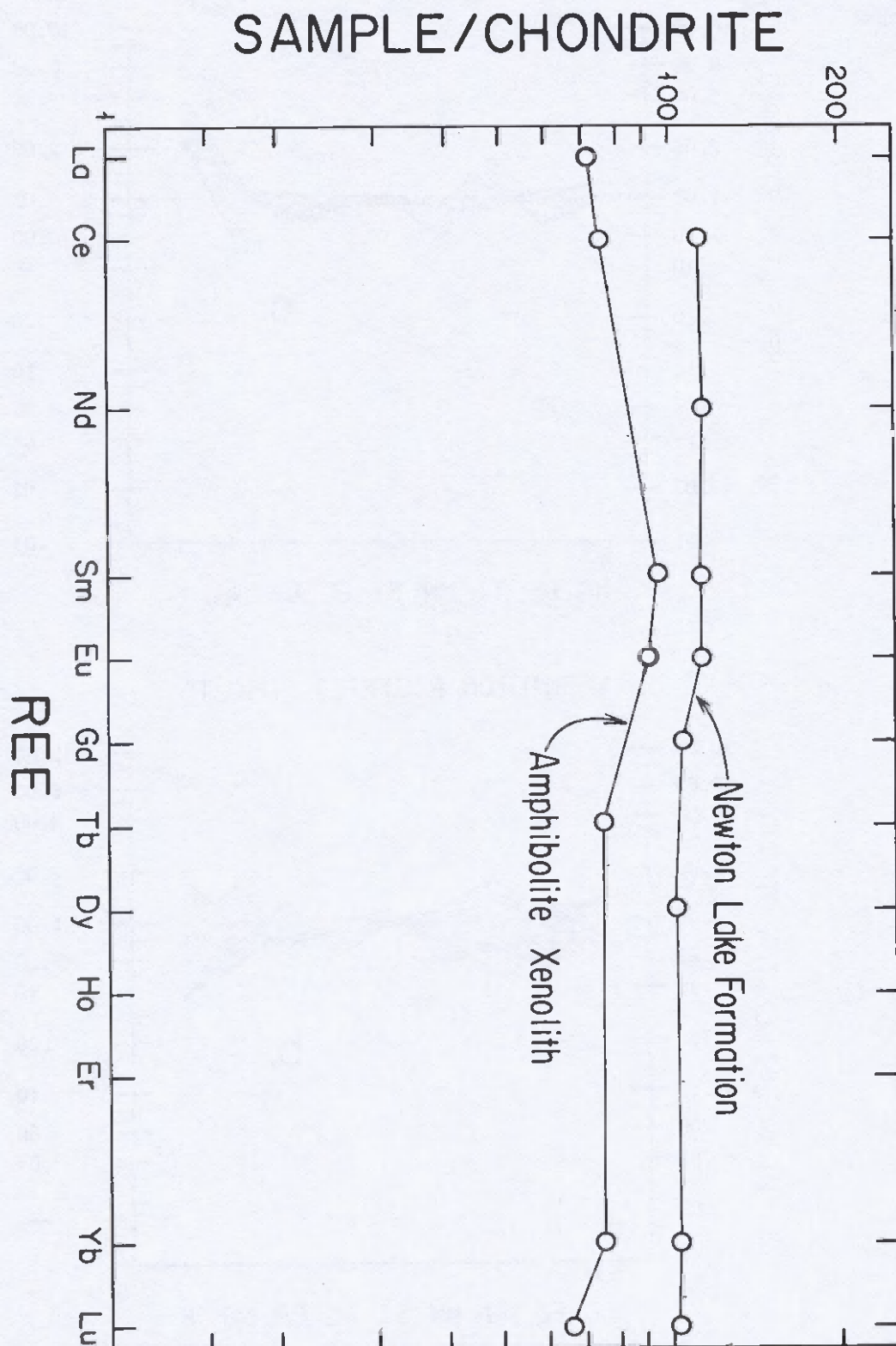


Figure 7. REE plot of amphibolite xenolith and basalt from Newton Lake Formation. Normalized against chondrites (Haskin and others, 1968).

senting unmelted residuum from the source region, that were brought up within the rising granitic diapir. The residual phase from partial melting of a graywacke should have a light REE content of 15 to 20 x chondrites, and a heavy REE content of 3-5 x chondrites (Arth and Hanson, 1975). This character is not displayed in the analyzed amphibolite xenolith.

The second hypothesis is that the amphibolite xenoliths were simply country rock which was intruded by and entrained within the rising granitic melt. This is supported by the basaltic major element affinities and trace element abundances in the analyzed samples. This does not mean to imply that all of the amphibolite xenoliths within the complex have this origin, but the analyzed samples seem to have been country rock that was incorporated by the encroaching granite.

Early Plutonic Rocks

Major element abundances were determined for four samples of the trondhjemite-granodiorite suite (Table 1). The trace element content for one sample was determined (Table 2). For each of these rocks the Al_2O_3 is greater than 15 wt%, placing them in the high- Al_2O_3 trondhjemite group of Barker and others (1976). Major element analyses for three trondhjemite samples previously obtained by Southwick and Sims (1980) are plotted in Figure 8a along with the four new analyses. An average of these seven was used for normalization in Figures 8a and 8b.

A wide composition spread within this class of rocks is seen in Figure 8a. This is not surprising since the rocks occur as separate small bodies throughout an area of more than 1000 km². Factors such as differences in source rock composition, mineral fractionation during transport and emplacement of the melt, and subsequent metamorphic overprinting would contribute to the chemical variations observed.

Figure 8b shows major element compositions for the Saganaga Tonalite and Northern Light Gneiss. Systematic variations can be seen in FeO and TiO₂, which remain in constant ratio even though their absolute abundances vary. A Fe-Ti mineral such as ilmenite in the source basalt could have buffered the FeO and TiO₂ during melting, resulting in the systematic behavior seen in the derived tonalites.

The major element composition of the early trondhjemite-granodiorite suite of the complex is very similar to those of the Saganaga Tonalite and the Northern Light Gneiss. The only discrepancy is in the TiO₂ content, which could reflect relative TiO₂ abundance in the source rock. More data are needed in order to delineate this difference. The chondrite-normalized REE abundances for one sample are plotted in figure 9. Also depicted are the ranges for the Saganaga Tonalite and the Northern Light Gneiss (Arth and Hanson, 1975). The trondhjemite has a steep negative pattern ($\text{La}/\text{Lu}_n = 45$), and no Eu anomaly. The Light-REE content is approximately 3 times greater than that of the Saganaga tonalite, while the heavy REE abundances are quite comparable. The overall REE content is very similar to the Northern Light Gneiss.

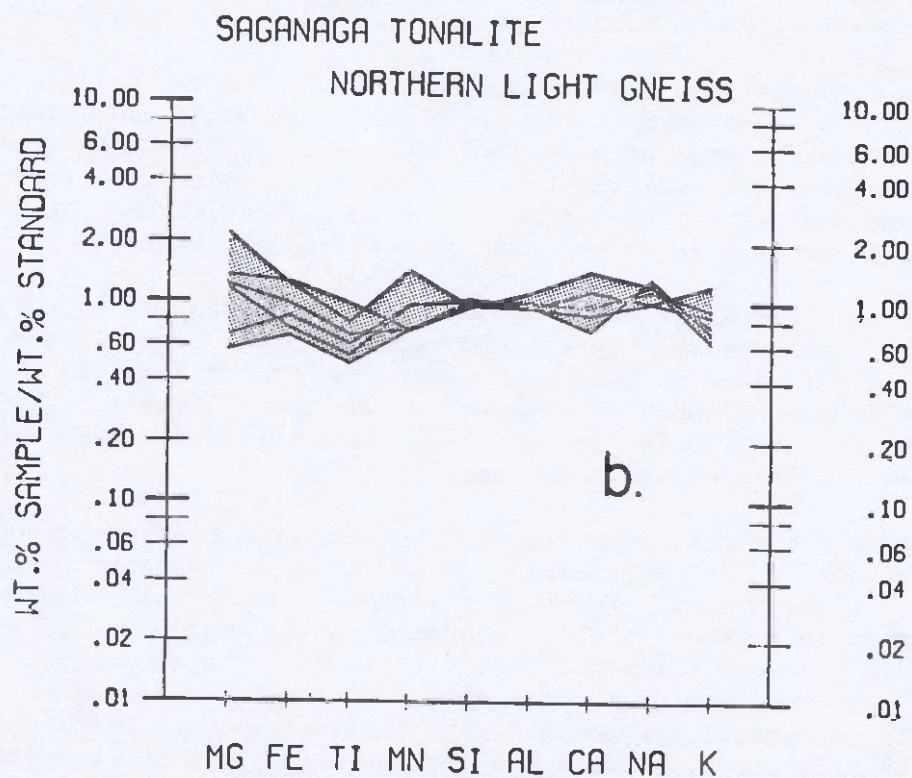
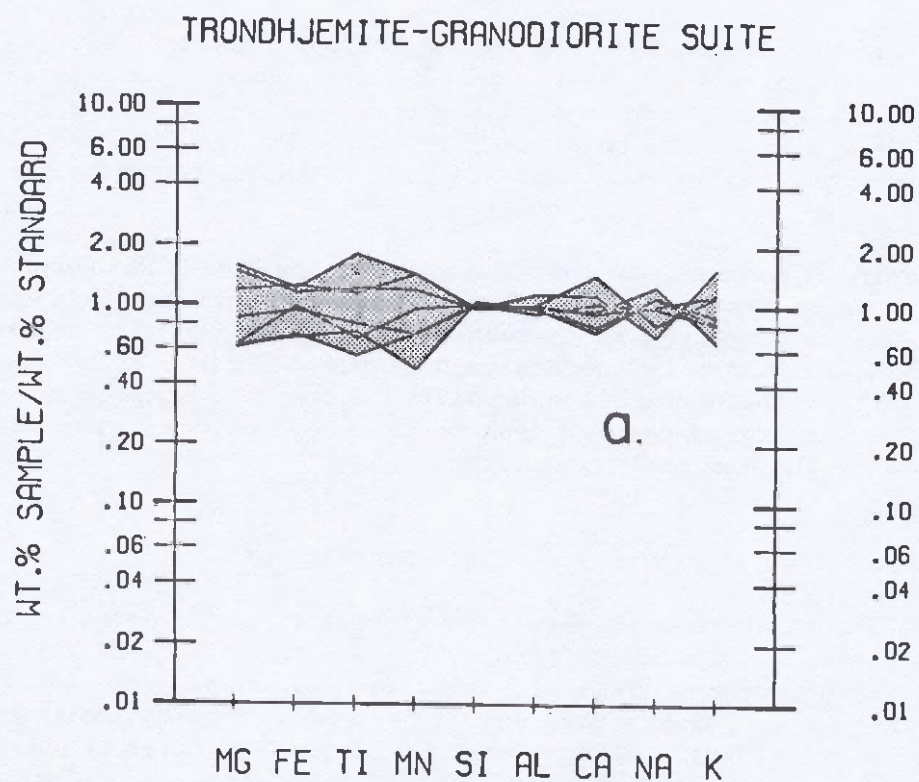


Figure 8. Major-element data normalized against average of seven early plutonic trondhjemite-granodiorite samples.

a) Trondhjemite-granodiorite suite, Vermilion Granitic Complex.

b) Saganaga Tonalite and Northern Light Gneiss.

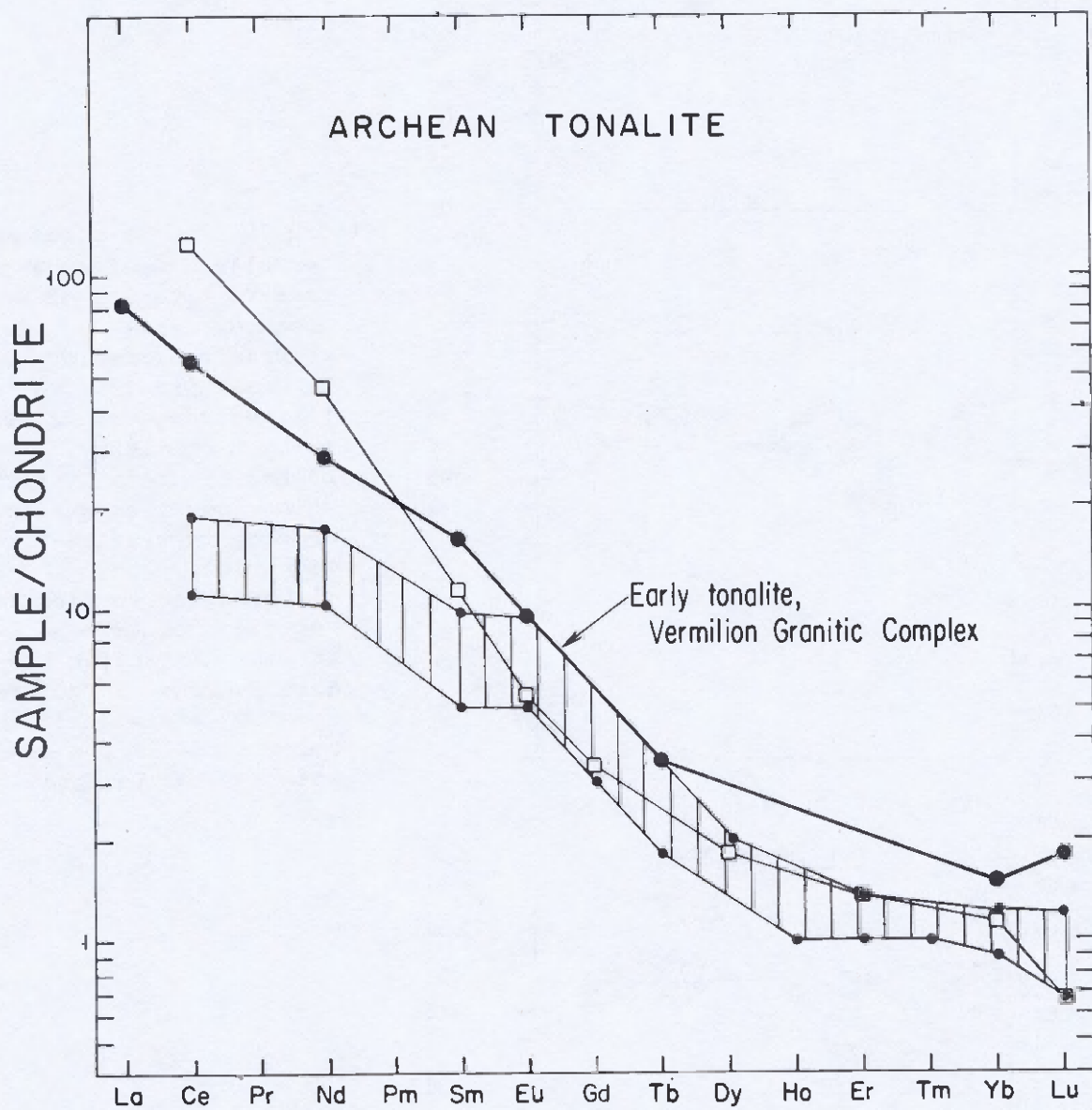


Figure 9. REE plot of early Archean tonalites from northern Minnesota. ●-early tonalite, Vermilion Granitic Complex; □-Northern Light Gneiss; shaded area is Saganaga Tonalite. Normalized against chondrites (Haskin and others, 1968).

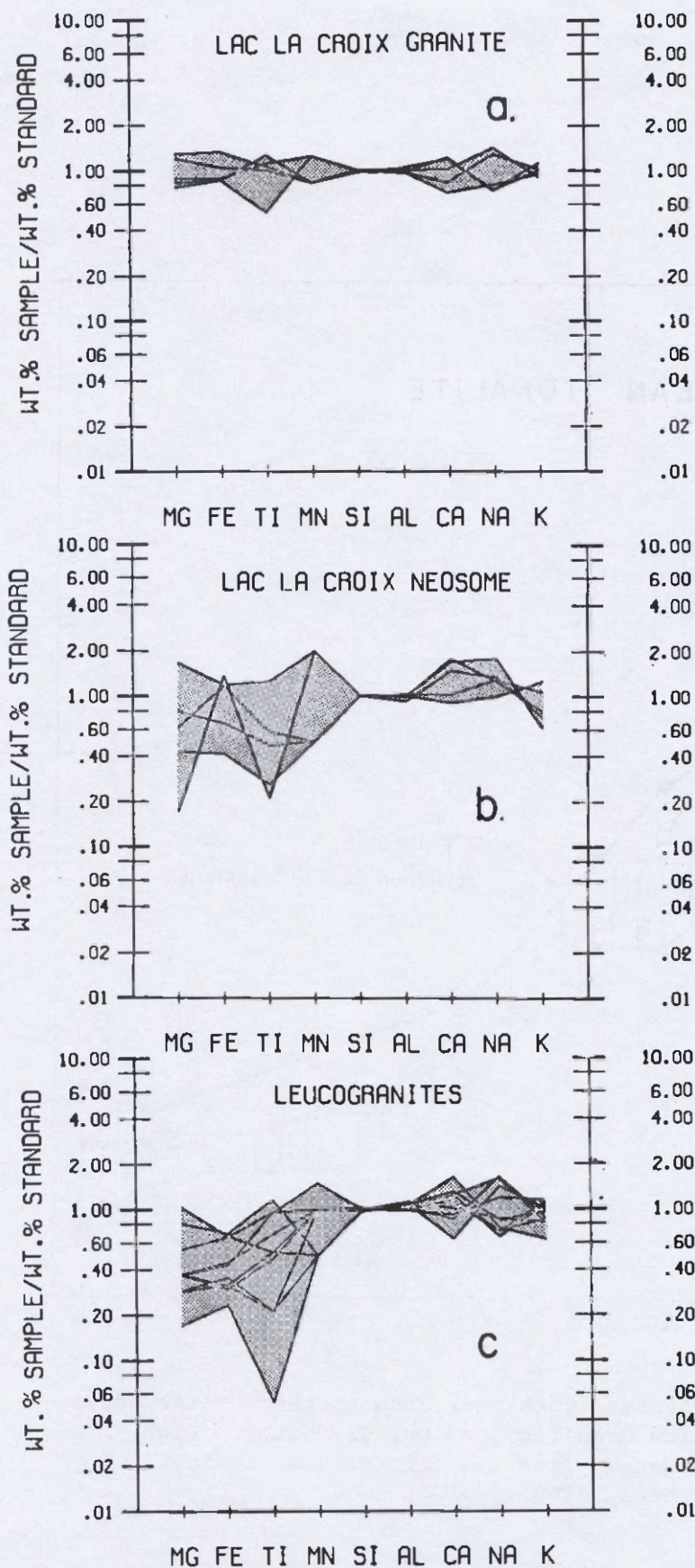


Figure 10. Major-element data normalized against average massive interior of Lac La Croix Granite.

a) Massive interior of Lac La Croix Granite. Note limited range in major element chemistry.

b) Lac La Croix Granite which comprises granitic neosome in granite-rich migmatite.

c) Leucogranite from the northern border zone of the Vermilion Granitic Complex. Note average of MgO , $FeO(t)$ and TiO_2 are significantly below those of the massive interior Lac La Croix.

Hanson and Goldich (1972) and Arth and Hanson (1972, 1975) advanced a partial melting model for the origin of the Saganaga Tonalite and Northern Light Gneiss. They argued that Archean tholeiitic material was metamorphosed to amphibolite or eclogite grade, and upon 20% partial melting would produce the REE content observed. This model is consistent with the experimental work of Green (1973). In order for this model to produce REE abundances found in the trondhjemite of the Vermilion Granitic Complex, the degree of partial melting would have been less (<5%) and/or the source basalt was slightly enriched in light REE.

Granite

Lac La Croix Granite

Five rock samples spaced approximately 1 km apart within the massive interior of the batholith were analyzed to establish a representative average composition for the Lac La Croix Granite. This average for the major elements is listed in Table 1, and is used for normalizing granite compositions in Figures 10a-c. Figure 10a displays the narrow range in major element composition for the massive Lac La Croix. The individual compositions of five Lac La Croix neosome portions from granite-rich migmatite are plotted in Figure 10b. As can be seen, there is a greater diversity in neosome compositions relative to the massive interior. This probably reflects country rock assimilation which has contaminated these granite neosomes.

Plotted in Figure 11 is a new REE analysis from the massive interior of the Lac La Croix Granite, compared with the field for Giants Range granites (Arth and Hanson, 1975). Both the Lac La Croix and Giants Range granites have steep negative chondritic patterns, high Ce content (between 100-45 x chondrites), a negative Eu anomaly, and low Lu content (3.5-2.5 x chondrites). Arth and Hanson (1975) proposed that the batholithic granites were derived from 20-50% partial melting of a short-lived (<50 m.y.) graywacke source at crustal depths. Sims (1976) proposed that this depth was between 9 and 12 kilometers (2-3 kbars).

The low $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio (0.7004) indicates that the source for the Lac La Croix was relatively young at the time of melting. This dictates that the batholithic granite did not melt from early or middle Archean sialic crustal material. However, tonalitic to granodioritic plutonism did occur early during the evolution of the complex. Therefore, it is feasible that the batholithic granite may have melted from slightly older tonalite and granodiorite, or from short-lived graywacke, as Arth and Hanson (1975) originally suggested.

Rye and Roy (1978) investigated the Th-U-K systematics of the Vermilion Granitic Complex, trying to delineate the origin of granite within the migmatite. If the migmatite formed by in situ partial melting in a closed system, the sum of the thorium and uranium in the paleosome plus neosome should equal the original starting protolith composition. Rye and Roy found that the radioelement content within the migmatite exceeded by 2 to 3 times the presumed Knife Lake-like starting

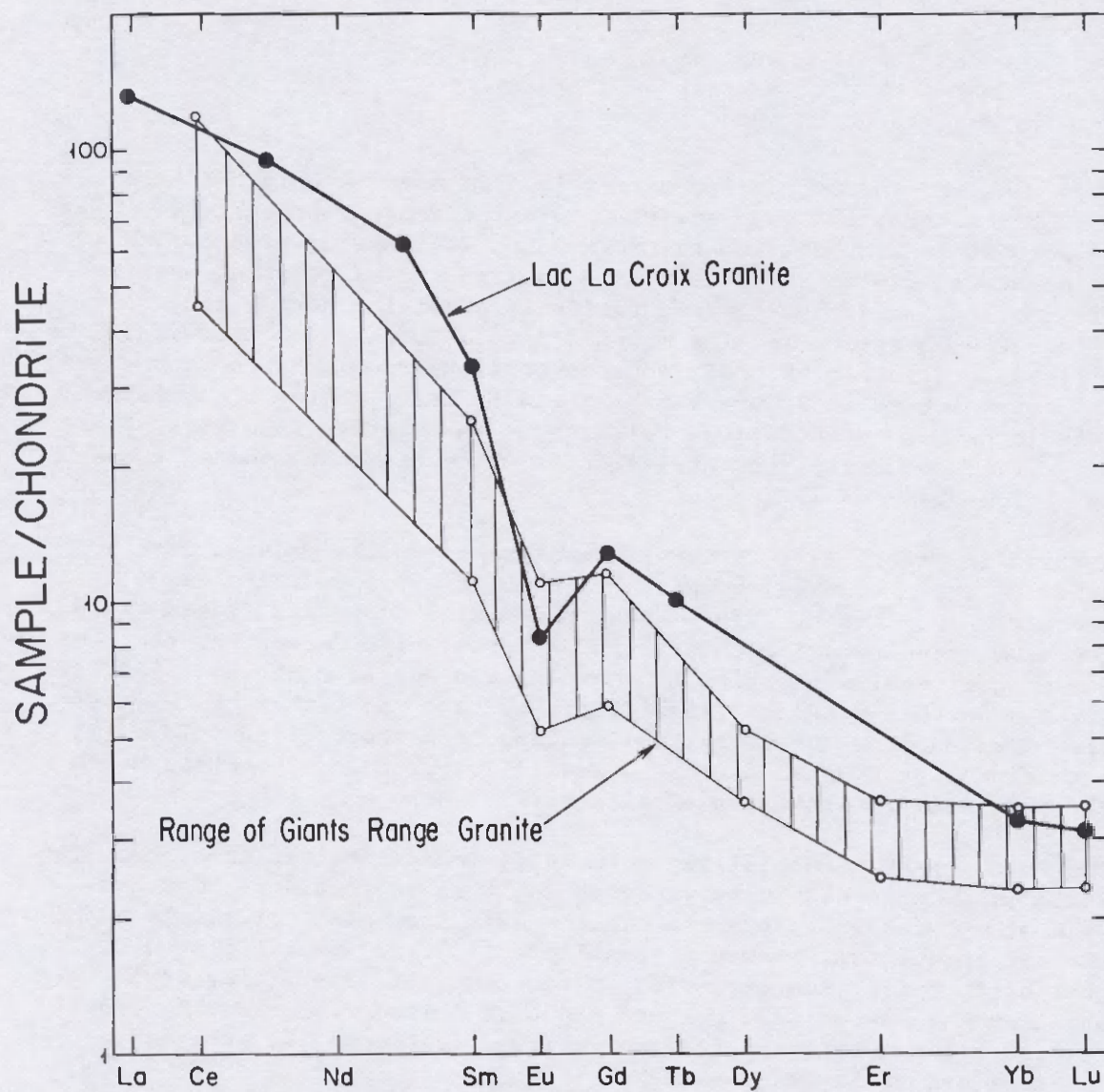


Figure 11. REE plot of Lac La Croix Granite and range of Giants Range Granite. Normalized against chondrites (Haskin and others, 1968).

composition. They concluded that the additional thorium and uranium were introduced into the migmatite system by the granitic leucosome component, possibly having been transported in the volatile phase derived from the intruding granitic batholith.

Leucogranite

Major element abundances were determined on 10 leucogranite samples from the northern border zone of the Vermilion Granitic Complex. An average for these is listed in Table 1. The individual analyses are plotted in Figure 10c, normalized against the average Lac La Croix granite. Clearly there is a wide range in major element composition within the leucogranite, and some overlap with the Lac La Croix composition field. The distinguishing feature between the two granite types is that the MgO, total FeO, and TiO₂ abundances in the average leucogranite are well below the observed values for the Lac La Croix. This may be attributable in part to higher modal abundances of magnetite and biotite in the Lac La Croix (Tables III-22 and III-24; Southwick, 1972).

The origin of the leucogranite is ambiguous and complex, with field evidence allowing two end member hypotheses. The granite melt may have been generated from biotite schist during ultrametamorphism as an in situ melt phase, or it may have been produced within a separate source region and injected into the biotite schist. The best evidence for the local-source hypothesis is found in the biotite schist along the northern border zone of the complex. There, one can observe narrow pegmatitic "sweat-out" pods and thin granitic and granodioritic stringers which are bordered by a biotite selvage zone depleted in leucocratic minerals. These thin stringers are syntectonically deformed with the biotite schist, and coalesce into larger veins and small, irregular bodies. Evidence for the injection hypothesis is best seen within the schist-rich migmatite. Paleosomes of biotite schist are rafted within leucogranite, the borders of which are sharp and distinct, without obvious mineral depletion zones or mafic selvages.

A plausible explanation for the origin of the leucogranite is a combination of both end-member hypotheses. In this scenario, anatectic melt was generated within a volcanogenic metasedimentary pile at crustal levels during regional metamorphism and deformation. This melt phase was continually being formed and remobilized syntectonically within the metasedimentary rocks, infiltrating into the structurally higher portion of the pile. The initiation of the early anatectic melt may have been triggered by heat and volatiles derived from the rising mass of Lac La Croix Granite.

Summary Model for the Origin of the Vermilion Granitic Complex

A framework for the petrogenesis of the Vermilion Granitic Complex is outlined below. This is an iterated version of the history proposed by Southwick (1978). This model is founded on the geologic mapping and structural studies of Southwick (1972), Southwick and Ojakangas (1979a)

and Southwick and Sims (1980). The geochemical guidelines for this model are the major and trace element arguments presented above, and those by Goldich and others (1972), Arth and Hanson (1975), Barker and Arth (1976), and Rye and Roy (1978).

1) Trondhjemitic-granodiorite magmas were melted from amphibolite/eclogite at mantle depths (10 kb; 30 km) leaving a residue of garnet, pyroxene and/or hornblende. This early magma rose to the surface and vented, providing volcanogenic detritus for the graywacke sequence. Small bodies of cosanguinous trondhjemite-granodiorite liquids penetrated those sedimentary rocks, creating the early migmatite. Basaltic volcanism added a mafic component to the supracrustal sedimentary sequence.

2) The supracrustal rocks were buried, regionally metamorphosed, and tectonized. Incipient anatexis occurred, producing liquid of the leucogranite suite. This leucogranite was continuously formed and underwent syntectonic mobilization into higher portions of the supracrustal pile.

3) At deeper crustal levels (9-12 km) magma of the Lac La Croix Granite was generated from more complete partial melting of graywacke and/or plutonic rock of the tonalite-granodiorite suite. This episode of melting left a residue of plagioclase, amphibole, garnet, and pyroxene or biotite. The low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio suggests that the source for the Lac La Croix Granite was younger than 50 m.y. at the time of melting.

4) The Lac La Croix magma rose diapirically into the supracrustal rocks and early migmatite. This rising diapir may have been the heat source that initiated and/or perpetuated melting within the metasedimentary rocks.

5) The granitic diapir passively intruded along the pre-existing structural grain, assimilating and entraining portions of the country rock. Granite-rich and schist-rich migmatites were formed, depending on the amount of granite intruded into the country rock. Volatile-rich fluids accompanied the granite neosome, concentrating radioelements in the roof and border zones of the diapir.

6) The structural effect of the granite emplacement was to broaden and flatten earlier regional folds. The western portion of the Vermilion Granitic Complex was near the roof of the granite diapir.

FIELD TRIP II:

ARCHEAN GEOLOGY OF THE INTERNATIONAL FALLS-KABÉTOGAMA AREA, MINNESOTA

R.W. Ojakangas, W.C. Day, and D.L. Southwick

Objectives and Regional Relationships

The objective of this field excursion is to illustrate the geology of two Archean terranes in northern Minnesota. The first part of the trip, stops 1-10, will focus on the metavolcanic and metasedimentary rocks of the Rainy Lake area (Ojakangas, 1972), which are at the south edge of the Wabigoon subprovince of the Superior province of the Canadian Shield (see Figs. 1 and 2, map A). The second part, stops 11-18, will focus on the transition southward from metagraywacke (biotite schist) into the Vermilion Granitic Complex (see Figs. 1 and 3, map B). The rocks at stops 11-18 are all in the Quetico subprovince.

The trip starts in the metavolcanic-metasedimentary terrane of the Rainy Lake area east of International Falls, Minnesota. Metagraywacke, greenstone, tuffaceous biotite-chlorite schist, felsic tuff, feldspathic quartzite, and conglomerate will be examined. The Rainy Lake-Seine River fault (unexposed in Minnesota) marks the boundary between greenschist facies metamorphic lithologies to the north and somewhat higher-grade metagraywacke (biotite schist) to the south, and also is the boundary between the Wabigoon and Quetico subprovinces. The broad belt of biotite schist south of the fault originally was included in the Coutchiching Series of Lawson (1913). The equivocal relationship of these metasedimentary rocks to metavolcanic rocks on the north was central to the classic debate about the stratigraphy and structure of the Rainy Lake area (Adams and others, 1905; Lawson, 1913), and still has not been firmly resolved. In view of the continuing uncertainty as to the proper stratigraphic position of these rocks, they are now mapped in Minnesota simply as unnamed biotite schist. Similar rocks directly along strike in Canada have recently been termed the Quetico metasediments by Wood (1980), who proposed that the name be used informally.

Two-mica leucogranite of proposed anatectic origin has been emplaced into the biotite schist. The relative abundance of the leucogranite increases southward toward the Vermilion Granitic Complex; the north contact of the complex with biotite schist is gradational and is mapped arbitrarily at the horizon where leucogranite becomes subequal to biotite schist. Within the contact zone the biotite schist is also intruded by tonalite and granodiorite, which in turn are cut across by grayish-pink granite equivalent to the Lac La Croix Granite, the major intrusive phase of Vermilion Granitic Complex (Southwick and Sims, 1980). The nature of these intrusive events and the textures of the migmatites produced will be examined at several stops.

The road log for this trip includes more stops than can be visited on a one-day excursion. The leaders will select among the stops, taking into account road conditions, time of day, and group desires.

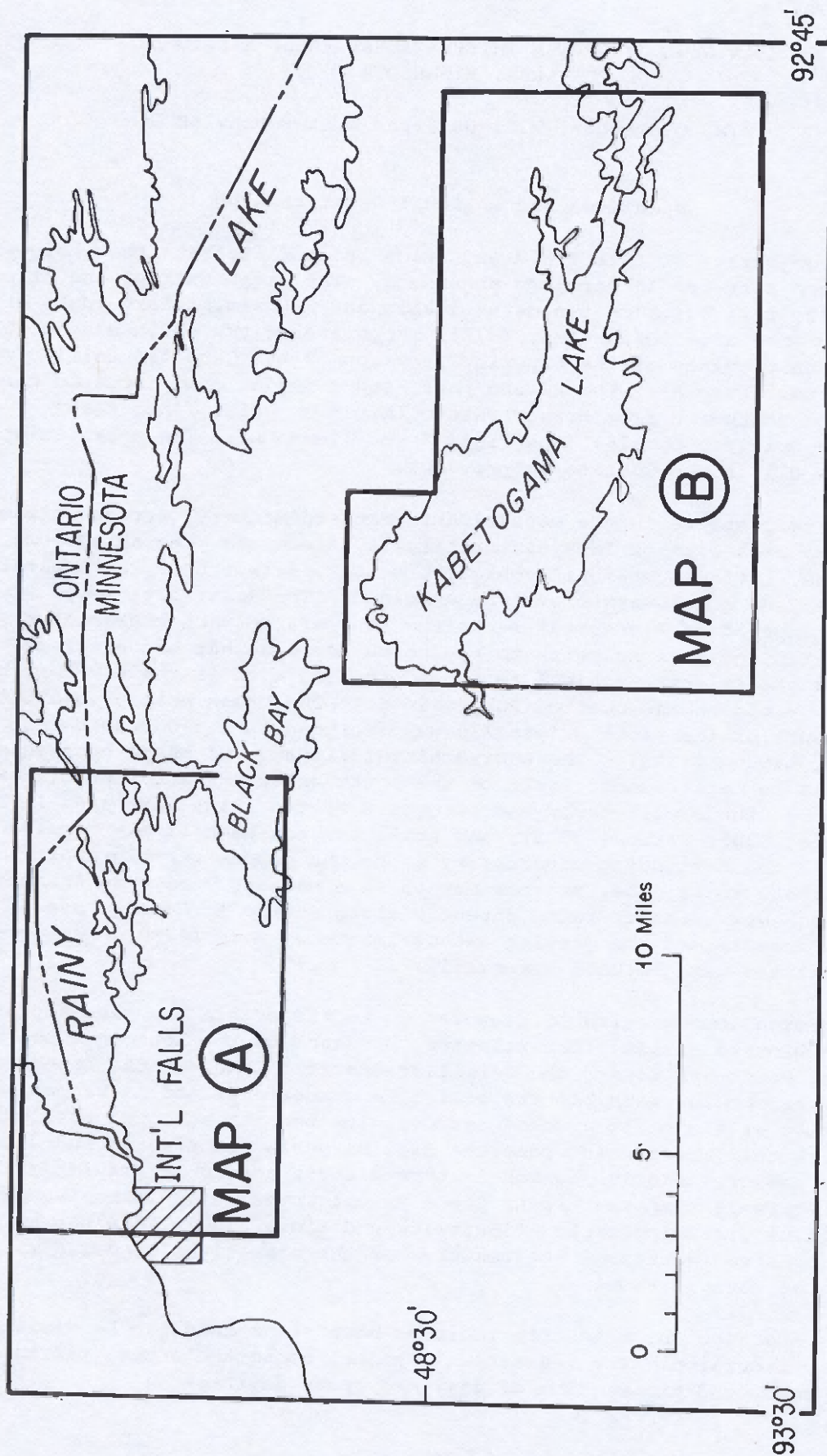


Figure 1. General location map showing the areas covered by detailed maps A and B.

ROAD LOG

This road log starts at the intersection of U.S. Highway 53 and Minnesota Highway 11 near the center of International Falls, Minnesota (3rd Ave. and 4th St.) and terminates at Ash River. Part of the trip duplicates stops in an earlier guidebook by Southwick and Ojakangas (1979b); the regional geology of the area to be covered is shown at scale 1:250,000 on the geologic map of Minnesota, International Falls sheet (Southwick and Ojakangas, 1979a). Stops 1 to 11 are plotted on Fig. 2, map A; stops 12-18 are on Fig. 3, map B.

Approximate

Mileage [accumulated mileage in brackets]

- 0.0 Junction with U.S. 53 and Minnesota Highway 11. Proceed east on
[0.0] Highway 11.
- 1.4 Bridge.
[1.4]
- 1.2 Junction with Koochiching County Highway 20; turn left (north)
[2.6] to Ranier.
- 0.35 STOP 1. Metasedimentary rocks which Lawson (1913) called the
[2.95] Couthiching in the Rainy Lake area are present near both Fort
 Frances and International Falls. This exposure of
 metagraywacke (fine-grained biotite schist) is representative
 of the least metamorphosed parts of this unit. The best expo-
 sure has been a small knob just south of the municipal liquor
 establishment, but lichen growth, sodding and concrete have in
 recent years partially obscured the original sedimentary
 structures. The beds have an attitude of N. 45° E./80° NW. and
 display excellent grading with tops to the northwest.
 Lineations plunge to the north-northeast at 45-50°. Small-
 scale cross-bedding occurs locally in interbedded silty laminae
 and flame structures are visible in a few places.

Although a few large detrital grains of quartz and plagioclase are present, these exposures consist dominantly of finely recrystallized plagioclase, with lesser amounts of quartz and biotite; garnet is rare. In general the rocks resemble coarser grained garnet- and staurolite-bearing biotite schists that crop out south of the greenstone belt, some of which will be seen in the last several stops on this field trip.

Return over some route to Highway 11.

- 0.35 Junction with Highway 11; turn left (east).
[3.3]
- 2.5 Junction with Koochiching County Highways 20 and 109. Turn
[5.8] right (south) and follow Highway 109.

1.2 STOP 2. This exposure of feldspathic-lithic quartzite is one
[7.0] of a number that form a discontinuous easterly-trending belt 16 km long and 0.8 km wide. The beds strike east-northeast, are vertical to slightly overturned, and plunge to the east at 3°-55°. Abundant cross-beds indicate that the unit dips to the south. The cross-bedding (trough-type) is partially obscured by shearing; it is best seen on the south side of the exposure about 30 m east of the road. The original clastic texture is commonly well preserved in spite of pervasive shearing. Quartz comprises 50 percent of the rock; other grains in the abundant sericitic matrix include felsic to intermediate volcanic rock fragments, plagioclase, K-feldspar, felsic plutonic rock fragments, carbonate and pyrite. This quartzite and the conglomerate of stop 8 are equivalent to the Seine Series (Seine Conglomerate) to the east-northeast in Ontario in the same greenstone belt. Lawson (1913) called these units Huronian, noted that they clearly overlie an unconformity in Ontario, and placed them at the core of a syncline. Grout (1925a) said the structure was an anticline. Ojakangas (1972), partly on the basis of the consistent southerly topping direction of the cross-beds, interpreted them to be part of a southward-facing fault block. (See accompanying text in this volume.) The quartzites are interpreted as braided stream deposits with the source to the north. (See abstract by Ojakangas and Olson, this volume.)

Turn around and return to Highway 11.

1.2 Turn right (east) and proceed to low rock outcrop on left
[8.2] (north) side of highway just west of Bohman Airways.

0.9 STOP 3. This outcrop consists of two lithologies: (1) a mixed
[9.1] schist (thin alternating laminae of chloritic and biotitic fine-grained schist) which is in part ankeritic or sideritic and (2) massive greenstone (metamorphosed mafic hypabyssal intrusive rocks) on the northwest part of the outcrop. Eastward along strike are greenschists. The mixed schist is interpreted as a sheared tuffaceous rock. (This locality is about 2.5 km north of the Rainy Lake-Seine River fault.)

0.1 Continue east on Highway 11 across bridge over Jackfish Creek.
[9.2]

0.2 Turn left (north) on Koochiching County Highway 103.
[9.4]

0.4 STOP 4. Greenschist outcrops by driveways J-10, J-11 and J-12.
[9.8] Some traces of sheared pillows may be present. About 10 m west of driveways in woods is a very coarse-grained, massive greenstone containing long pyroxene crystals with a "branching" habit (quench textures, rapid crystallization?) resembling spinifex texture.

Proceed eastward.

0.8
[10.6]
(1.2 mi
in from
Hwy 11)
STOP 5. Greenschist with granitic stringers from the west end of Grassy Island "tonalite", a 4 km long by 0.3 km wide intrusion. To the south of the road and to the north on the lakeshore is a 30 meter-wide diabase dike which trends NNW and has been dated at about 2200 m.y. by Hanson and Malhotra (1971). This dike is the western dike of a closely spaced pair of dikes which lines up with dike exposures near Kabetogama Lake 22 km to the south and with other dike exposures as far as 40 km to the southeast and as far as 25 km to the northwest near the Quetico Fault.

0.2
[10.8]
(1.4 mi
in from
Hwy 11)
STOP 6. Large roadcut on hilltop of greenschist and "mixed schist" with minor boudinaged quartz and granite. Disseminated pyrite and minor chalcopyrite are present in this cut.
Continue south past other outcrops of biotite schist and sericite schist (metamorphosed felsic tuffs and metasediments?).

0.4
[11.2]
Junction with Highway 11. Turn left (east).

1.6
[12.8]
Junction Highway 11 and Koochiching County Highway 138. Turn left (north).

0.3
[13.1]
Crossing topographic low along Rainy Lake-Seine River Fault.

0.45
[13.55]
STOP 7. Gravel pit in wood just to the left (west) of highway near top of hill. Sheared greenschist in the Rainy Lake-Seine River Fault zone is visible here. Quartz and rusty carbonate pods are abundant in phyllitic greenschist.

The only productive gold mine in Minnesota was located on Little America Island just 2.5 km east of this point. The Little America mine, in a 2 meter-wide composite quartz vein with intermixed schist, produced \$4600 worth of gold in 1894-1895. Several other prospects were located farther east. On Bushyhead Island 6 km to the east, a prominent gossan is exposed in an old adit.

Continue north.

0.1
[13.65]
Fork in road - bear right here and at next junction as well.

0.55
[14.2]
STOP 8. "Neil Point conglomerate" by garage and by house overlooking fault zone. This unit, a large lens 180 m thick and at least 4.5 km long, overlies the feldspathic-lithic quartzite of stop 2. The massive conglomerate, largely clast-supported with a biotitic and feldspathic sandy matrix, contains well-rounded clasts of "granite," volcanic rocks, chert,

white quartzite and biotite schist. Clasts are as large as 25 cm. The conglomerate is interpreted as an alluvial fan deposit which prograded over the sandstones (quartzite) of related braided streams. (See abstract by Ojakangas and Olson, this volume.)

Follow road (which is one-way) around loop on Neil Point, past stop 7 to Highway 11.

- 0.0 Reset Mileage; turn right (west) on Highway 11 and drive toward International Falls, past stop 3.
- 4.6 Junction with Koochiching County Highway 332 (truck by-pass
[4.6] around International Falls). Turn left and follow Highway 332 south.
- 0.6 Stop sign; junction with 13th Street; turn left (east) con-
[5.2] tinuing on Highway 332.
- 0.3 STOP 9. Metagraywacke outcrops. These are located on a 1.2 km
[5.5] wide metagraywacke belt, within the broader greenstone belt, that extends another 40 km to the northeast to Swell Bay of Rainy Lake in Ontario. Graded beds to the northeast of this outcrop face both northwest and southeast, indicating the presence of isoclinal folds.
- 0.4 Additional outcrops of metagraywacke as at stop 9.
[5.9]
- 0.1 Right angle bend in road to south.
[6.0]
- 0.8 STOP 10. Large roadcut of greenschist containing both chlorite
[6.8] and amphibole. Minor magnetic iron-formation is also present. This outcrop exhibits considerable shearing, for the Rainy Lake-Seine River fault zone is just 0.3 mi to the south.
- 0.3 Broad topographic low is the Rainy Lake-Seine River fault zone.
[7.1]
- 0.7 Junction of Highway 332 with Koochiching County Highway 24.
[7.8] Turn right (west).
- 0.8 Junction of Highway 24 with U.S. Highway 53. Turn left
[8.6] (south).
- 1.1 STOP 11. Low outcrops on both sides of U. S. Highway 53.
[9.7] TRAFFIC IS HEAVY--BE CAREFUL!

The biotite schist (metagraywacke) at this locality is approximately one mile south of the Rainy Lake-Seine River fault and therefore is within the Quetico superbelt.

Petrographically the rock is quartzofeldspathic biotite schist. It has a fine-grained, equigranular texture with foliation defined by biotite and muscovite and contains accessory amounts of fine-grained poikiloblastic garnet. Dikes of porphyritic felsite and dark green lamprophyre cut across schistosity and bedding (strike about N90°E), and are parallel to a second cleavage (strike N70°E); the dikes and the second cleavage are best seen on top of the east outcrop. These dikes may be related to the volcanism within the Rainy Lake greenstone belt to the north.

- 0.0 RESET MILEAGE and continue south on U.S. 53.
- 6.1 Village of Ericsburg; continue south on U.S. 53.
[6.1]
- 5.8 Minnesota Department of Natural Resources fire tower on right
[11.9] (west).
- 0.7 Railroad overpass.
[12.6]
- 1.6 Village of Ray; sharp corner at junction with Koochiching
[14.2] County Highway 217; continue east on U.S. 53.
- 7.1 "Gateway Store" and junction with St. Louis County Highway 122.
[21.3] Typical northern Minnesota walleye on left. Turn left (north)
 and follow Highway 122 toward Kabetogama Lake.
- 2.3 Junction with St. Louis County 123 (straight ahead): turn left
[23.6] (west) and stay on Highway 122.
- 3.3 "Y" in road at junction with St. Louis County Highway 902; con-
[26.9] tinue straight ahead on Highway 902.
- 0.3 Paved road ends; continue on gravel road.
[27.2]
- 0.3 Highway 902 ends at junction with St. Louis County Highways 673
[27.5] and 675; turn right and follow Highway 675 to Rocky Point
 Resort.
- 0.3 Follow driveway on left to Rocky Point Resort. Obtain per-
[27.8] mission from resort owners before examining outcrops.

STOP 12. This outcrop on the south shore of Kabetogama Lake is in the transition zone between the relatively granite-free biotite schist to the north, and schist-rich migmatite mapped with the Vermilion Granitic Complex to the south. The amount of leucogranite within the biotite schist increases from north to south in this transition zone. Metamorphic recrystallization has obscured original textures here, but across the lake to the north the graded bedding indicates northward stratigraphic younging.

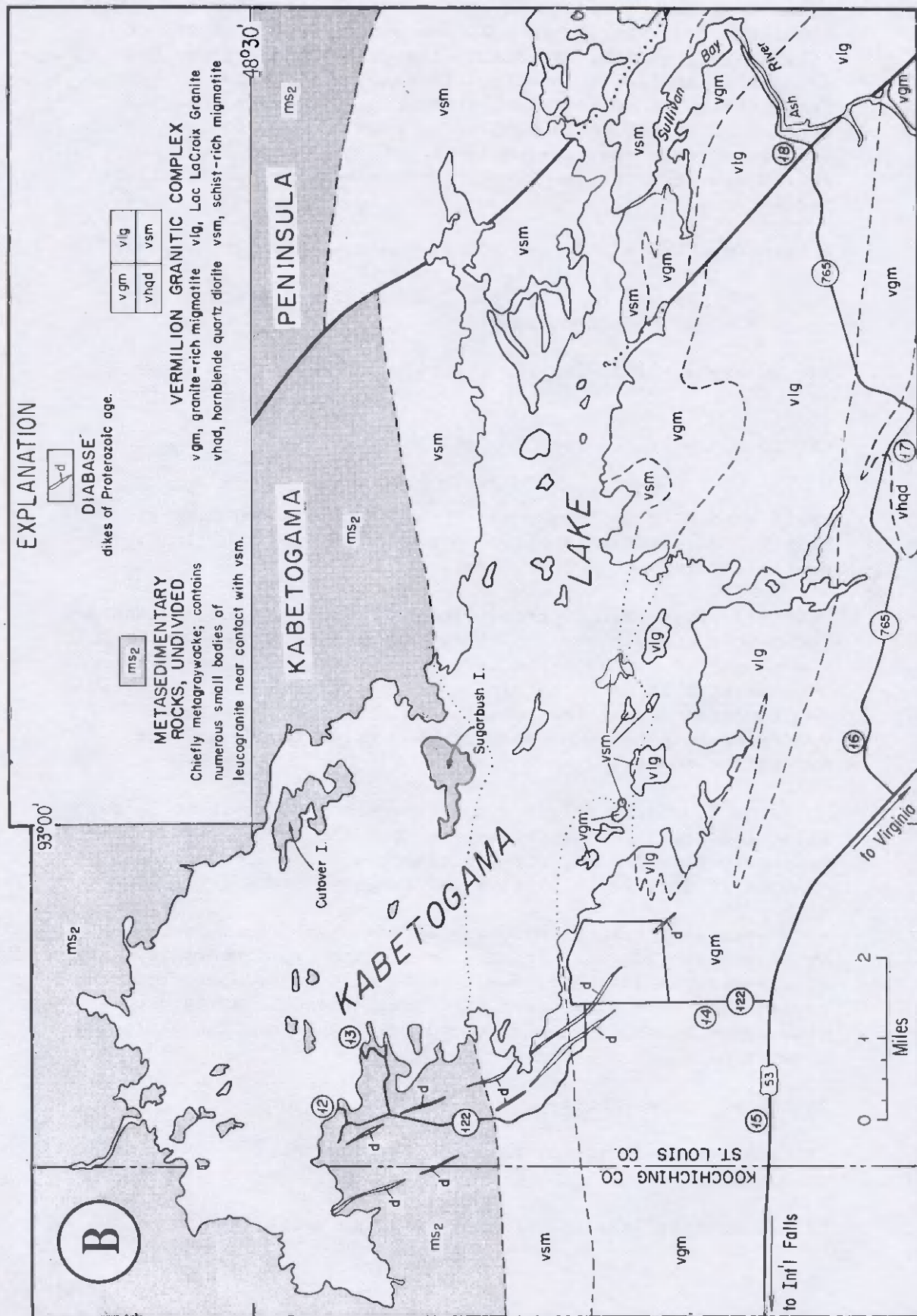


Figure 3. Simplified geologic map of the Lake Kabetogama area showing locations of stops 12 through 18.

The biotite schist of the Kabetogama Lake region has a fine- to medium-grained, equigranular schistose texture. Local aluminous beds within the schist contain porphyroblasts of sillimanite, garnet, and staurolite. Schistosity, which is generally parallel to bedding, is isoclinally folded. Pegmatite and coarse-grained leucogranite are enfolded and boudinaged concordantly within the host biotite schist. Dikes of granite that are physically indistinguishable from the folded leucogranite cut across the schistosity and isoclinal folds.

Return over routes 675 and 902 to junction with Highway 122.

- 0.0 RESET MILEAGE. Turn left (east) onto 122 and proceed toward Chief Wooden Frog Campground.
- 0.4 "Y" in Highway 122, stay to right.
[0.4]
- 0.4 "Y" in Highway 122; stay to left on 122.
[0.8]
- 0.5 Chief Wooden Frog Campground. Proceed to camping area B-3
[1.3] (outcrop description applies to any of the numerous low lying granitic outcrops in this area).

STOP 13. This area is transitional between the metasedimentary rocks to the north and schist-rich migmatite to the south, with the amount of leucogranite here greater than at Stop 12. Leucogranite forms thin veins that are syntectonically enfolded and boudinaged with the schist, and also forms lenticular bodies up to a few hundred feet long which invade and cut across the folds.

The leucogranite has a coarse-grained gneissic to pegmatitic texture. The mineralogy is dominated by quartz, microcline and sodic plagioclase, with accessory garnet. The gneissic texture is defined by biotite and primary muscovite.

Separate textural subunits of the leucogranite suite can be delineated (pegmatitic, medium-grained hypidiomorphic, coarse-grained gneissic, etc.), which can be seen crosscutting and grading into each other. Although these subunits have a wide range in major element abundances, they are thought to be cogenetic.

Return over same route.

- 0.5 "Y" in Highway 122; stay to right heading west.
[1.8]
- 0.4 "Y" in Highway 122; stay to left heading west.
[2.2]

- 0.4 Stop sign, junction Highway 122 with Highway 902. Turn left
[2.6] (south) and continue on Highway 122.
- 3.3 Stop sign, turn right (south) and continue on Highway 122. At
[5.9] top of hill south of junction is an excellent outcrop of a composite diabase dike. This dike belongs to a swarm of Proterozoic dikes (age about 2 b.y.) that extends from the Mesabi Range, Minnesota to the vicinity of Kenora, Ontario; another dike in the swarm was seen at stop 5.
- 1.1 Junction with Highway 123. Kay's Bar on left; continue south
[7.0] on 122.
- 0.4 Barney and Oscar's Bar on left, continue south, slow down.
[7.4]
- 0.2 Outcrops on both sides of Highway 122. Pull vehicle onto
[7.6] shoulder of road.

STOP 14. Outcrops on both sides of the road are of granite-rich migmatite. Regionally this rock type has 5 to 25 percent inclusions in a granitic neosome; the inclusions are biotite schist, amphibolite, trondhjemite, and granodiorite. At this locality most of the inclusions are trondhjemite.

On the west side of the road is a glacially polished outcrop of migmatite with vague grayish inclusions that are partially digested by the enclosing granite neosome. Ductile shearing of the inclusions is evident and probably was associated with the emplacement of the granitic core of the complex to the south. Plagioclase diffusion "halos" can be seen surrounding trondhjemitic inclusions on the fresh roadcut on the east side of the road.

Continue south on 122.

- 0.7 Stop sign, junction with U.S. 53. Turn right onto U.S. 53 and
[8.3] proceed west.
- 1.5 Large roadcuts on both sides of U.S. 53. Pull off highway onto
[9.8] shoulder. TRAFFIC IS HEAVY-PLEASE BE CAREFUL.

STOP 15. These roadcuts encapsulate the structural and intrusive history of the granite-rich migmatite in the Vermilion Granitic Complex. The neosome is light gray to pink granite with a coarse-grained, weakly gneissic texture. Blocks of biotite schist, amphibolite, tonalite, and early migmatite are rafted within the granite and display varying degrees of assimilation and deformation. Faint outlines of digested country rock inclusions are abundant.

The included blocks of early migmatite have paleosomes of amphibolite and biotite schist, or amphibolite alone, and

neosomes of gray tonalite or granodiorite. Much of the amphibolite is coarse grained and foliated, with a "spotted" appearance caused by clusters of biotite. Early migmatite blocks that consist dominantly of amphibolite paleosome and tonalite neosome typically show agmatic structure, wherein the amphibolite has been split into distinct pieces that could be fit back together like a jigsaw puzzle.

These east-trending cuts are oriented nearly parallel to the planar fabric of the migmatite, and therefore the faces of the cuts appear to contain a larger fraction of inclusions than is really the case for the rock as a whole. A closer estimate of the inclusion-to-granite ratio can be made from the natural subhorizontal surface on the top of the north cut.

0.0 RESET MILEAGE. Turn around and proceed back east on U.S. 53.

1.5 Junction with Highway 122; continue southeast on U.S. 53.
[1.5]

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

0.8 STOP 16. Granite-rich migmatite, consisting of 5 to 10 percent
[5.2] inclusions in modally uniform, faintly gneissic granite, crops out just north of the Ash River Trail. Numerous indefinitely bounded lenses and layers of pegmatite occur here, and are typical of granite-rich migmatite in the Vermilion Granitic Complex.

Continue east on Highway 765.

0.8 Cross over Daley Brook in marshy area.
[6.0]

3.7 Outcrop on right (south).
[9.7]

STOP 17. This outcrop is dominantly a gray biotite-hornblende quartz diorite, an early plutonic body within the Vermilion Granitic Complex. It is cut across by numerous veins of biotite granite and pegmatite believed to be related to the Lac La Croix Granite. The quartz diorite is massive with a uniform mineralogic composition, and has a medium- to coarse-grained hypidiomorphic granular texture. In thin section one sees that iron oxides are exsolved from the interior of the amphibole along cleavage traces.

Continue eastward toward the village of Ash River.

0.2 Sharp turn to the left (north); continue on Highway 765.
[9.9]

0.6 Paved road starts.
[10.5]

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

STOP 18. This large knob of Lac La Croix Granite (Vermilion Granite of Grout, 1923) is part of a crescent-shaped body that occupies the hinge area of a large, east-plunging fold. It contains no more than 5 percent inclusions, several of which are well displayed near the microwave tower, and also has pegmatitic lenses. This is about as homogeneous as the Lac La Croix Granite gets in the northwest part of the Vermilion Granitic Complex. Almost perfectly uniform granite crops out some 50 km to the southeast, well beyond the itinerary of this field trip. The hilly vista to the southeast is typical of terrain underlain by the Vermilion Granitic Complex.

Turn around and return over Ash River Trail to U.S. 53.

9.3 Junction with U.S. 53.
[23.2]

END OF FIELD TRIP II.
RETURN TO INTERNATIONAL FALLS.

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