D. L. Southwick

FIELD TRIP GUIDEBOOK FOR SELECTED AREAS IN PRECAMBRIAN GEOLOGY OF NORTHEASTERN MINNESOTA

PREPARED FOR THE 21ST ANNUAL MEETING OF
THE GEOLOGICAL SOCIETY OF AMERICA,
NORTH-CENTRAL SECTION
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STRUCTURAL GEOLOGY OF THE BOUNDARY BETWEEN ARCHEAN TERRANES OF LOW-GRADE AND HIGH-GRADE ROCKS, NORTHERN MINNESOTA

By

P.J. Hudleston[1], R.L. Bauer[2], D.L. Southwick[3]
D.D. Schultz-Ela[4], and M.E. Bidwell[2]

[1]Department of Geology and Geophysics, University of Minnesota
Minneapolis, MN 55455

[2]Department of Geology, University of Missouri
Columbia, MO 65211

[3]Minnesota Geological Survey, 2462 University Avenue
St. Paul, MN 55114

[4]Geology Department, Colorado College
Colorado Springs, CO 80903

INTRODUCTION

The Vermilion district of northeastern Minnesota is the best example in the United States of an Archean greenstone belt. Although the district is small, and the rocks are not very well exposed in comparison to many greenstone belts in Canada, it contains the characteristic lithologic, stratigraphic, and structural attributes of larger greenstone belts within a relatively accessible small area. This guide describes 16 stops, all easily reached from highways 169 and 1 and subsidiary roads, that collectively illustrate the major lithologies and structures on either side of the boundary between the low-grade terrane of the Vermilion district and the high-grade terrane of the Vermilion Granitic Complex (Fig. 1).

Archean greenstone belts throughout the world share the following characteristics:

1. The rocks are dominantly supracrustal, consisting of volcanic flows, pyroclastic deposits, and assorted sedimentary rocks derived chiefly from volcanic sources.

2. The stratigraphic succession includes rocks of one or more volcanic cycles. Typically the earliest rocks of a cycle are komatiitic to tholeiitic basalt; these pass upward into calc-alkaline basalt and andesite, which in turn give way to late-stage calc-alkaline dacite and, more rarely, to rhyolite. Most of the basalt is in pillowed flows that were erupted under water; repeated eruptions are interpreted to have built up one or more volcanic piles on the seafloor, which in many instances emerged above sea level at about the time that dacite became the principal volcanic product. The dacitic rocks commonly are pyroclastic and pass laterally into sedimentary aprons of reworked tuff and associated volcanogenic graywacke.

3. Laminated, cherty iron-formation may occur almost anywhere in the stratigraphic succession in minor amounts, but typically it is most abundant in the upper parts of a volcanic cycle. It apparently precipitated as a chemical sediment during periods of reduced volcanic activity and relative tectonic stability, probably in close proximity to submarine hot springs and fumaroles.

4. The volcanic and sedimentary rocks of greenstone belts invariably are tightly folded and extensively faulted. Most commonly they have been metamorphosed to mineral assemblages typical of greenschist facies. Cleavage, schistosity, and lineation are widely developed. Multiple deformation, indicated by superimposed fold structures, is very common and is becoming more widely recognized as more detailed mapping is done. Increasingly recognized too are large recumbent folds and thrusts that formed early in the deformational history (e.g. Poulsen and others, 1980; deWit, 1982). Large longitudinal strike-slip faults that record displacements of 20 km or more are prominent late-stage features of most greenstone belts, and seem to be especially characteristic of those in the Superior Province of the Canadian Shield.

5. The supracrustal rocks of greenstone belts have been invaded by granitoid plutons of diverse size and shape. The granitoid intrusions tend to be diapiric in style and to range in composition from tonalite to granodiorite; monzogranite is relatively rare. The wall rocks commonly are metamorphosed to amphibolite grade near large granitoid intrusions.

6. The basement on which the volcanic and sedimentary rocks of greenstone belts were deposited is rarely preserved, and its attributes generally are not well defined. Continental crust has been identified beneath a few greenstone belts; oceanic crust is postulated beneath others. The basement beneath the supracrustal rocks of the Vermilion district is not exposed, and its characteristics therefore are unknown.

The main belt of volcanic and sedimentary rocks in the Vermilion district is flanked on the south by the intrusive Giants Range batholith, and on the north by a complex zone of faulting (Fig. 1). The higher grade rocks of the Vermilion Granitic Complex, north of the Vermilion fault zone, include paragneiss, amphibolite, a variety of migmatites, and major granitoid intrusions. The Vermilion Granitic Complex is within the Quetico metasedimentary subprovince of the Superior Province, whereas the Vermilion district proper is within the Wawa volcano-plutonic subprovince (Fig. 2). Therefore, the Vermilion fault zone (Figs. 1, 3, 4) marks a subprovince boundary.

The intrusive rocks of the Giants Range batholith and the Vermilion Granitic Complex yield Rb-Sr radiometric ages of about 2700 Ma, and so do dacitic metavolcanic rocks within the Vermilion district proper (Jahn and Murthy, 1975; Arth and Hanson, 1975). Various lines of geochemical and isotopic evidence have been interpreted to show that the entire cycle of volcanic, sedimentary, plutonic, and tectonic activity that formed these rocks took place within a span of time no greater than about 50 Ma (e.g. Arth and Hanson, 1975). This is generally in agreement with the evolutionary life spans of about 35-45 Ma determined by high-precision zircon-

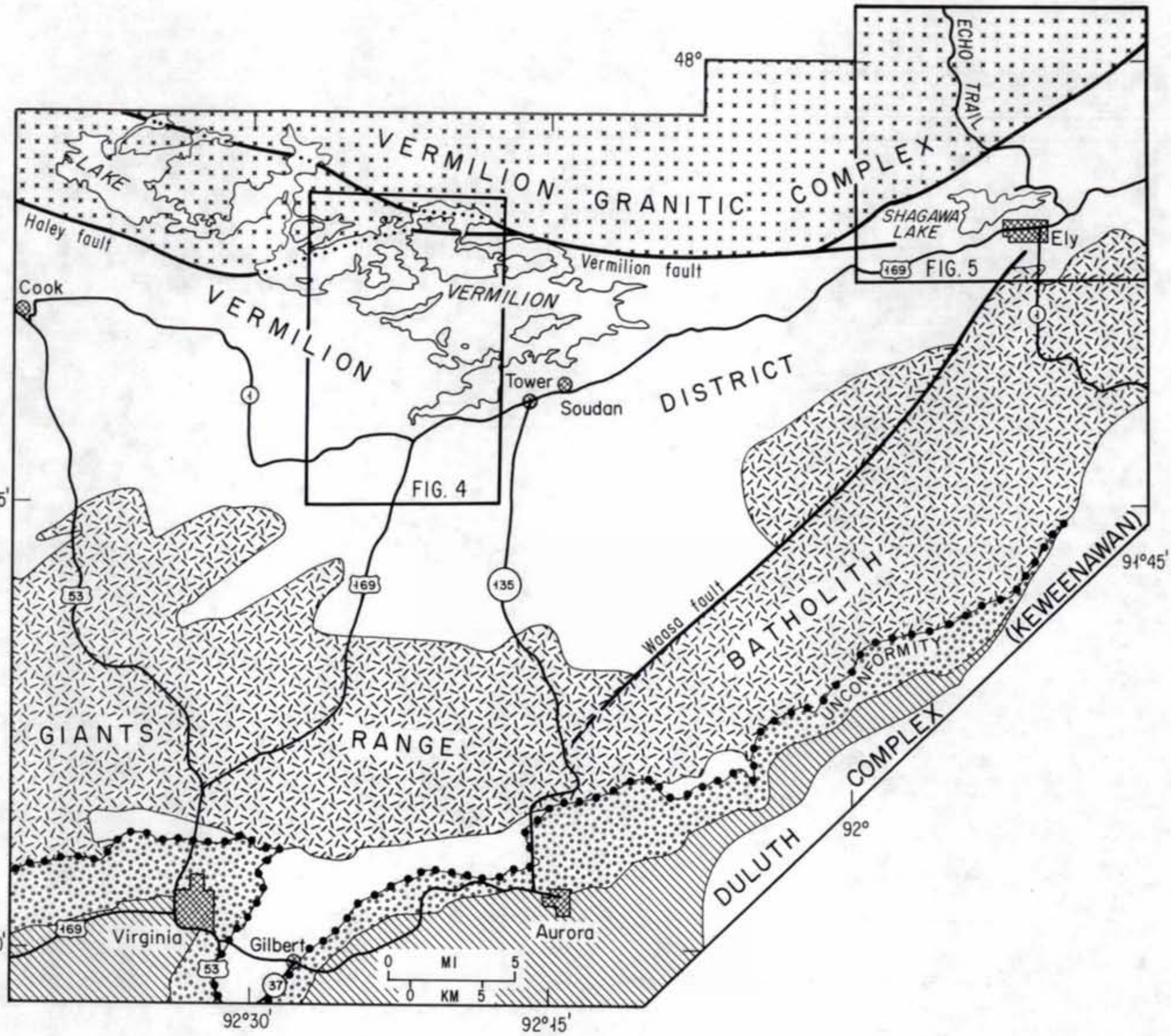


Figure 1. Regional map of the field trip area showing the geologic framework and the major roads. The dotted contact is a major unconformity separating gently dipping Proterozoic strata of the Animikie Group (on the south) from deformed Archean rocks. The Animikie Group, consisting of the Pokegama Quartzite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

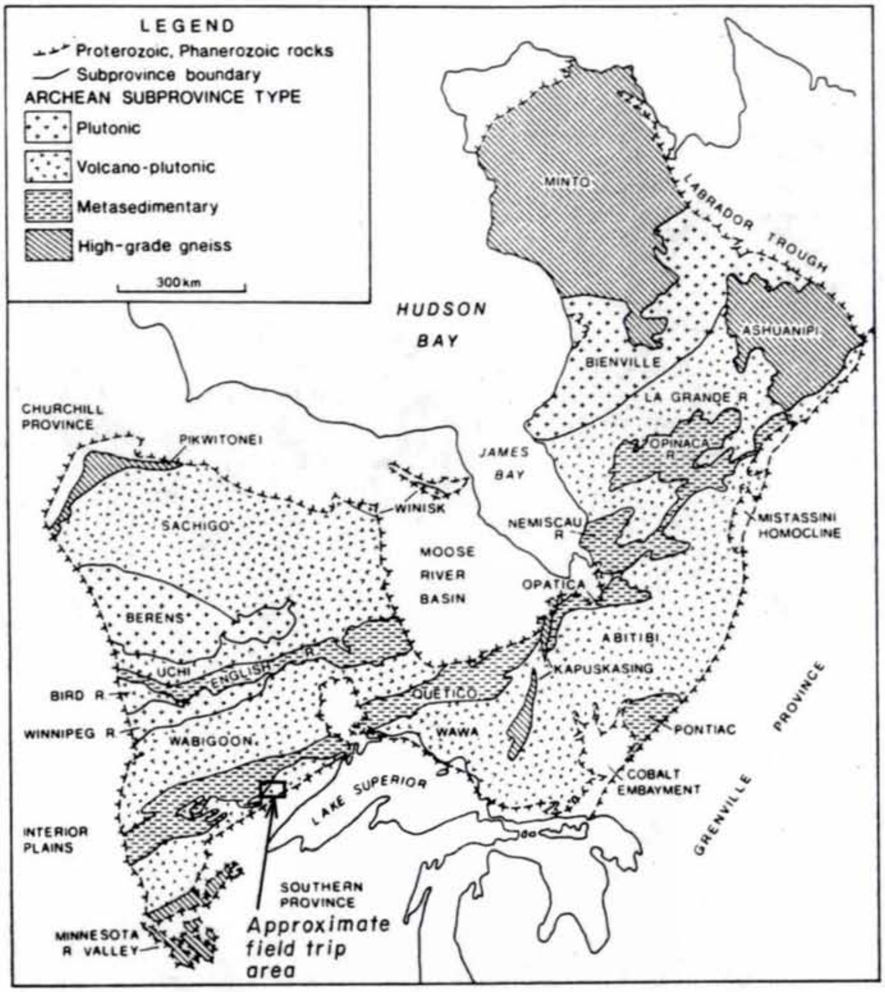


Figure 2. Location of the field trip area relative to the major subdivisions of the Superior Province. From Card and Ciesielski (1986).

dating techniques for single-cycle greenstone belts elsewhere in the Superior Province (e.g. Davis and Edwards, 1986). However, it is clear from the Canadian high-precision zircon work that some greenstone belts are multicyclic (e.g. Nunes and Thurston, 1980), and these have had evolutionary histories as long as 220 Ma.

The principal map-determining structure in the western part of the Vermilion district is the Tower-Soudan anticline (Fig. 3). This regional-scale fold closes to the west, is overturned to the southwest, and plunges steeply east; its form in three dimensions is difficult to ascertain, but is likely to be strongly noncylindrical. The core of the anticline is occupied by basaltic rocks belonging to the lower member of the Ely Greenstone. The lower member of the Ely is overlain by the Soudan Iron-Formation Member of the Ely, which is a key marker unit for defining both stratigraphic order and regional structural patterns in the district. The Soudan Member is overlain to the east by a second sequence of basaltic volcanic rocks, assigned to the upper member of the Ely Greenstone, and to the west by a sequence of dacite tuff, dacite porphyry, and closely associated volcaniclastic sedimentary rocks assigned to the Lake Vermilion Formation (Morey and others, 1970). The Knife Lake Group, composed principally of volcaniclastic sedimentary rocks, is stratigraphically interdigitated with volcanic rocks assigned to the upper member of the Ely Greenstone, and thickens greatly to the east. Thus it is approximately in the same stratigraphic position as the Lake Vermilion Formation at the opposite end of the Vermilion district. The stratigraphically youngest unit in the district is the Newton Lake Formation, which overlies both the upper Ely and the Knife Lake north and northeast of Shagawa Lake.

The upper member of the Ely and the Newton Lake Formation are both primarily mafic volcanic units (Sims and Mudrey, 1978; Green and Schulz, 1982), although both contain minor amounts of other lithologies. They differ fundamentally in composition, the upper Ely being predominantly tholeiitic, and the Newton Lake being predominantly tholeiitic to komatiitic (Schulz, 1980). In addition, the upper Ely consists primarily of pillowed flows, whereas the Newton Lake contains a great many massive to variolitic pillowed flows and also a number of layered, differentiated sills (Green and Schulz, 1977; Schulz, 1980).

In the central part of the Vermilion district, near Ely, the north limb of the Tower-Soudan anticline is greatly disrupted by a multitude of wrench faults and shear zones. These have divided the terrane into a complex assemblage of fault slices and greatly complicated the problem of correlating rock units.

The Shagawa Lake area (Fig. 5) includes this fault-dismembered north limb of the Tower-Soudan anticline in the low-grade terrane south of the Burntside Lake fault (Figs. 3, 5) and the amphibolite-grade metamorphic rocks and granitoid intrusive rocks of the southern margin of the Vermilion Granitic Complex north of the fault. The Burntside Lake fault is dip-slip and is interpreted to have been colineal with the Haley fault in the western part of the district prior to dextral offset on the Vermilion fault zone (Sims, 1976; Fig. 3). The Vermilion district is at its narrowest in this region, constricted between the Giants Range batholith on the south

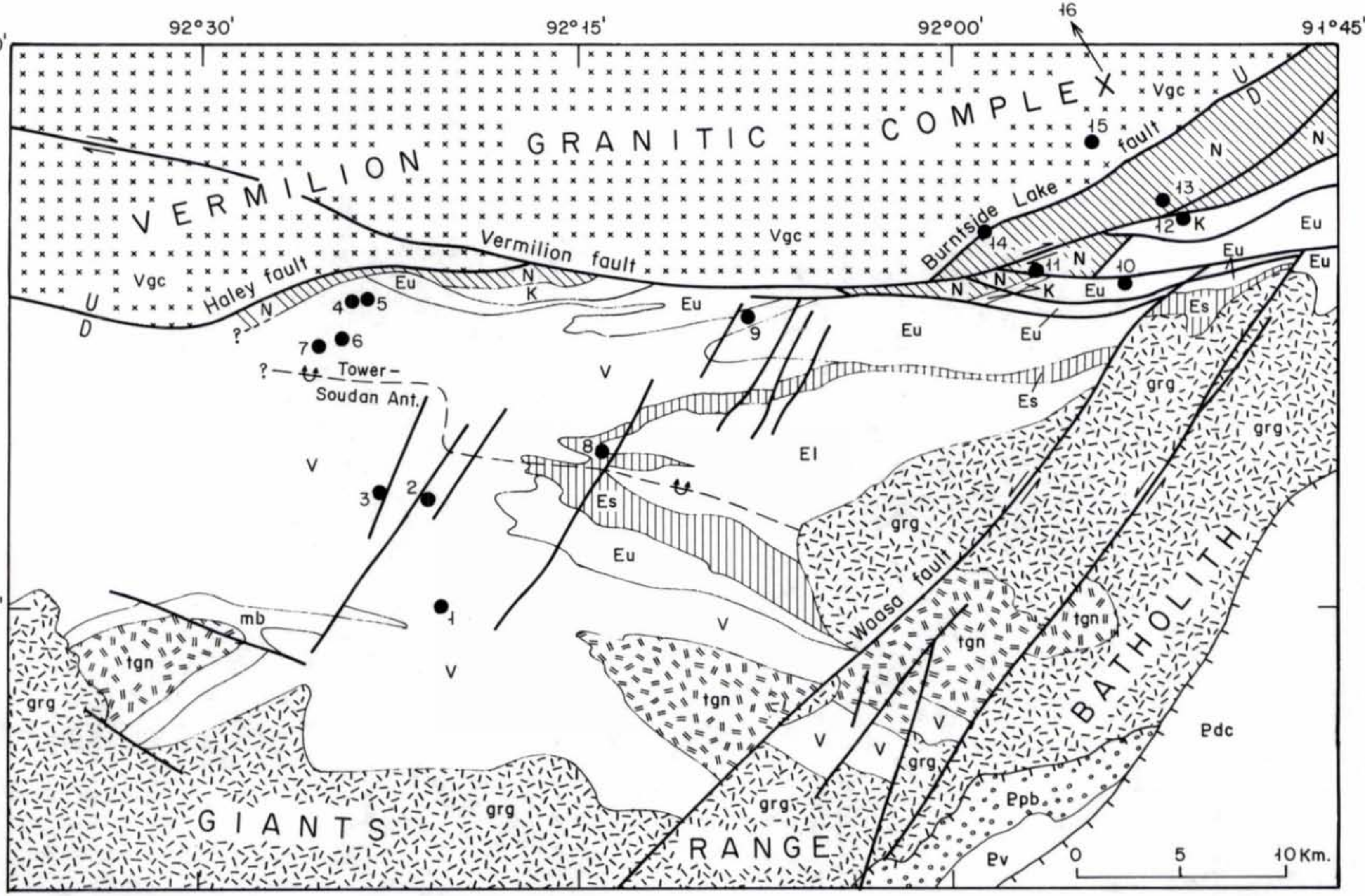
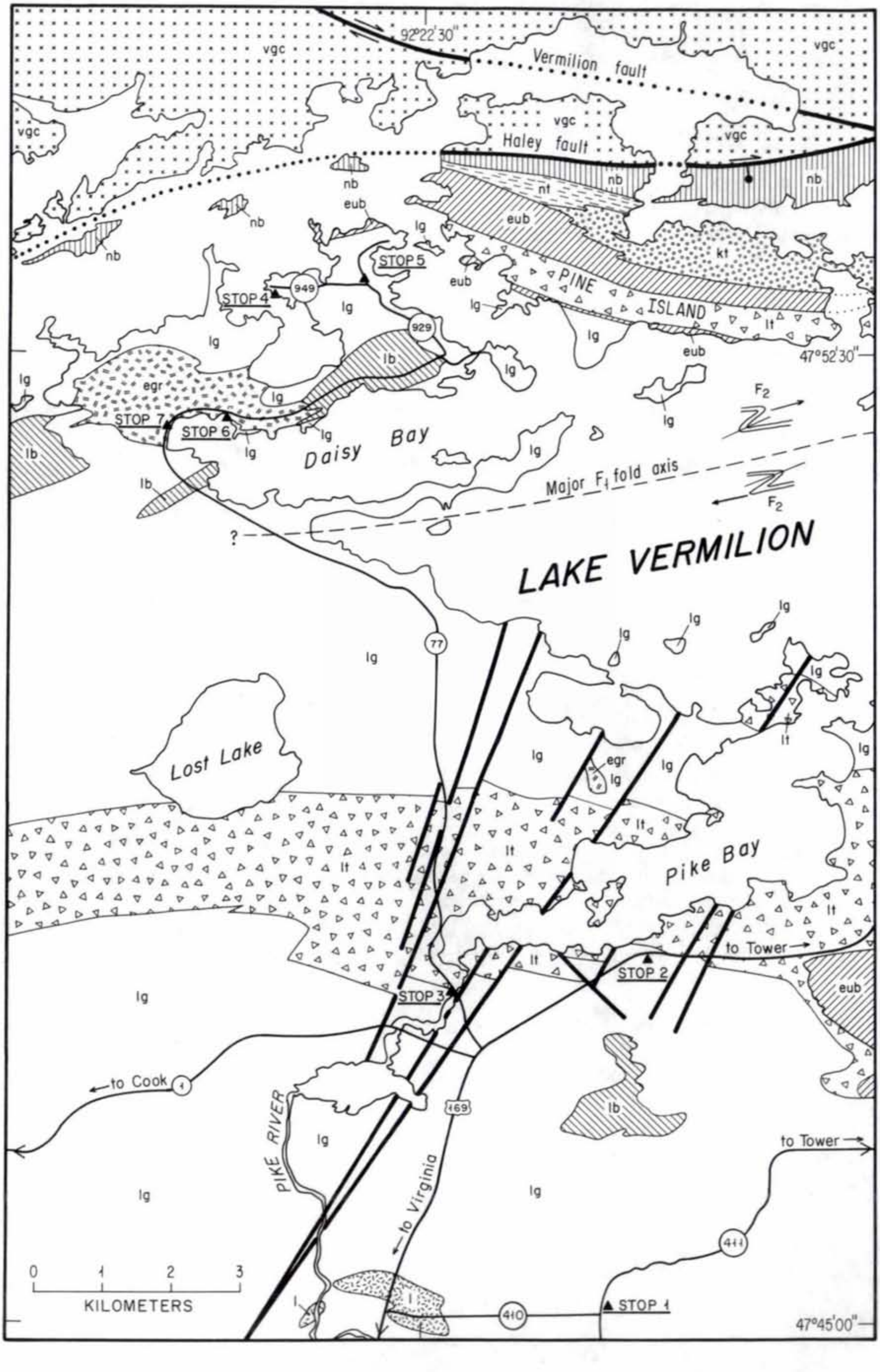


Figure 3. Geologic sketch map of the field trip area showing approximate stop locations. Modified from Green and Schulz (1982) and Sims and Southwick (1985). Map explanation is on the facing page.

EXPLANATION FOR FIGURE 3

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


92°22'30"
vgc
Vermilion fault
Haley fault
nb
nt
eub
kt
PINE ISLAND
lt
lg
lb
egr
STOP 4
STOP 5
STOP 6
STOP 7
949
929
47°52'30"
F2
Daisy Bay
Major F1 fold axis
LAKE VERMILION
77
Lost Lake
Pike Bay
to Tower
STOP 2
STOP 3
to Cook
1
169
PIKE RIVER
to Virginia
411
410
STOP 1
0 1 2 3
KILOMETERS
47°45'00"

EXPLANATION FOR FIGURE 4

Vermilion Granitic Complex (Quetico Subprovince)

VERMILION GRANITIC COMPLEX

vgc — Biotite schist, amphibolite, migmatite, various granitoid rocks, undivided.

TECTONIC CONTACT AND SUBPROVINCE BOUNDARY

Vermilion district (Wawa Subprovince)

STRATIFIED ROCKS

NEWTON LAKE FORMATION

nb — Metabasalt, pillowed, strongly deformed.

nt — Mafic tuff (?); in part, and perhaps mainly, mylonitic.

KNIFE LAKE GROUP

kt — Felsic tuff and closely allied tuffaceous wacke and arenite.

LAKE VERMILION FORMATION

lg — Metagraywacke and slate of volcanic provenance. Chiefly rhythmite; locally includes massive metagraywacke, arenite, breccia.

lb — Metabasalt, typically pillowed.

lt — Dacitic tuff and tuff breccia; local dacite porphyry.

ELY GREENSTONE

eub — Metabasalt, pillowed, strongly deformed near Haley fault. Assigned strotigraphically to upper member of formation.

INTRUSIVE ROCKS

l — Lamprophyre.

egr — Epizonal granite, syenite, granodiorite; largest body is Daisy Bay pluton.

Figure 4. Simplified geologic map of an area southwest of Lake Vermilion including portions of the Vermilion Dam, Lost Lake, Sioux Pine Island, and Tower 7.5-minute quadrangles. Modified from Sims and Southwick (1985).

and the Vermilion Granitic Complex on the north.

Stratigraphic younging is regionally to the north in the rocks SE of the Burntside Lake fault, but local reversals occur in several north-northeast-trending folds that swing to more eastward trends (e.g. the Ely trough; Fig. 5) near major shear zones. Northeast of Shagawa Lake, the sills and metavolcanic rocks of the Newton Lake Formation have been folded isoclinally (Green and Schulz, 1982); these folds have been disrupted by numerous northeast-trending sinistral faults that post-date the folding.

The rocks north of the Burntside Lake fault include biotite schist, biotite paragneiss, migmatite, and several kinds of granitoid intrusives, all within the Vermilion Granitic Complex (VGC). The biotite schist is interpreted to be the higher grade equivalent of the volcanogenic graywacke and tuffaceous rocks of the Knife Lake Group and the Lake Vermilion Formation (Southwick and Sims, 1980). Local staurolite- and sillimanite-bearing mineral assemblages from relatively sparse pelitic layers indicate metamorphic conditions in the middle amphibolite facies. Along the southeastern margin of the VGC, adjacent to the Burntside Lake fault, metagabbroic rocks and metamorphosed variolitic pillow basalts, similar to those of the Newton Lake Formation in the adjacent Vermilion district, occur interlayered with biotite schist (Fig. 5, stop 14). More highly migmatized amphibolite derived in part from gabbro and pillow basalt occurs farther to the north, in and around a large doubly plunging overturned synform mapped by Sims and Mudrey (1978) and referred to here as the Twin Lakes synform (Fig. 5).

Three plutonic rock units, including mafic diorite, trondhjemite, and granite, intrude the supracrustal rocks in this part of the VGC. The diorite plutons are the oldest; they consist of hornblende diorite and locally associated pyroxene-bearing hornblendite that constitute an appinite suite (French, 1966; Pitcher and Berger, 1972). The appinites have chemical characteristics similar to calc-alkaline lamprophyres, which occur locally in both the VGC and adjoining low-grade terrane (Geldon, 1972, and McCall, 1987), and they are interpreted to be the plutonic equivalents of lamprophyres. Such appinites also form a locally important component of the amphibolite mapped by Sims and Mudrey (1978) in and around the Twin Lakes synform.

The Burnstide trondhjemite forms a lenticular intrusive body parallel to the Burntside Lake fault between the fault and the Twin Lakes synform (Fig. 5). Veins of this unit have intruded the supracrustal rocks to form locally complex intrusion migmatites (stop 15). Layers of a pink, massive to foliated granite to granodiorite, as thick as tens of meters, intrude the biotite schist and amphibolite and are folded along with these units around the Twin Lakes synform. Veins of this granitic phase cut the Burntside trondhjemite and are an increasingly significant component of the schist-rich migmatite to the northeast toward the contact with the Lac La Croix batholith (stop 16).

A composite dike with variable proportions of tonalite and diabase crops out intermittently along the southern margin of the Twin Lakes synform and is exposed at stop 15. This unit is generally no more than a few

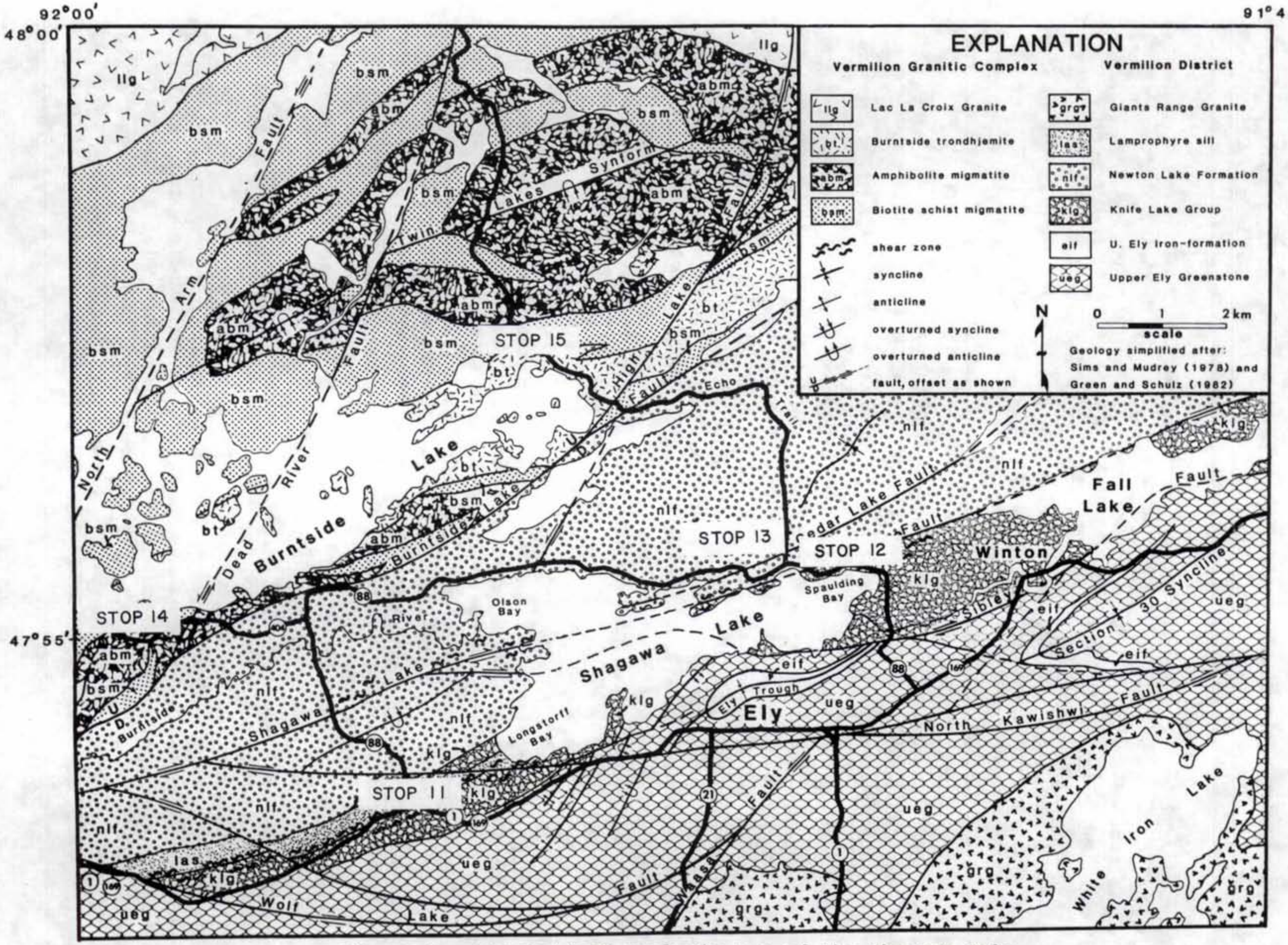


Figure 5. Generalized geologic map of the Shagawa Lake area showing locations of stops 11-15. Geology modified from Sims and Mudrey (1978) and Green and Schulz (1982).

meters thick and varies from predominantly diabase with net veins of tonalite to predominantly tonalite with pillow-shaped inclusions of diabase.

STRUCTURAL GEOLOGY OF THE LAKE VERMILION AREA (WESTERN VERMILION DISTRICT)

Structural analyses of folding in the district have been conducted in metasedimentary rocks of the Lake Vermilion Formation in the Tower-Soudan area (Fig. 3; Hooper and Ojakangas, 1971; Sims, 1972, 1976; Hudleston, 1976) and in metasedimentary rocks of the Vermilion Granitic Complex in the area from the Haley fault northward and across the Vermilion fault (Bauer, 1985a, b). Hooper and Ojakangas (1971) identified three periods of folding in the Tower-Soudan area, which they designated F_1, F_2, and F_3, respectively, and subsequent workers reported similar findings.

Major early folds are tight to isoclinal and were mapped on the basis of reversals of facing direction in graded metagraywackes. Both F_1 and F_2 folds cause changes in facing direction, and the presence of the earlier folds can be established only by determining facing within the axial-planar cleavage, S_2, associated with the F_2 folds. On this basis, Hooper and Ojakangas (1971) and Sims (1976) recognized a number of kilometer-scale folds north and west of Tower, but Bauer and Hudleston (1981) and Bauer (1985b, 1986) considered the evidence more consistent with one very large structure, locally recumbent and thus possibly nappe-like, and a number of much smaller folds. The Tower-Soudan anticline may be an eastward continuation of this major fold (Fig. 3). It is shown to be an F_1 structure by the fact that the symmetry of the F_2 folds does not change across the axial surface trace.

There is poor control on the hinge directions of the early folds, and minor folds are typically isoclinal and often "intrafolial." Interference patterns are common; some are the result of $F_1 \wedge F_2$ superimposition but many are thought to be wholly the result of the D_1 deformation. The three dimensional shapes of folds are hard to determine from glaciated outcrops, but many of the dome-and-basin or "eye" interference patterns are clearly sheath-like in form (stops 2 and 8). This feature, together with the fact that an associated axial-planar fabric is very weak or absent, is evidence that the D_1 event involved a large component of nearly bedding-parallel shear (necessary to produce the sheath folds) in non-lithified strata. However, on the north side of the Haley and Vermilion faults, on which several kilometers of dip-slip, north-side-up movement is indicated by an increase in metamorphic grade, an S_1 foliation is observed (Bauer, 1986). This led Bauer (1985b) to suggest that the D_1 nappe formed under non-metamorphic conditions in its upper parts preserved south of the faults, and under metamorphic conditions in its lower part preserved north of the fault, resulting in good foliation.

Minor F_2 folds and associated S_2 axial planar schistosity are well developed throughout the area. In most of this area (Fig. 4), the hinges plunge moderately to steeply to the east or west, depending on the orientation of the bedding, and the axial planes are steeply dipping with roughly east-west trends. Nearly all the folds have a pronounced Z symmetry. The intersection of the S_2 cleavage and bedding forms a lineation parallel to the fold axes, with subparallel mineral lineation. Both are designated L_2. The change in symmetry of F_2 folds across the Haley fault indicates the presence of a major east-west trending F_2 antiform across the faulted boundary between the two subprovinces (Figs. 3 and 4; Bauer 1985b, 1986).

There is a close relationship between the intensity and symmetry of S_2 metamorphic fabric and the magnitude and symmetry of cumulative strain measured from deformed clasts (Hudleston, 1976; Schultz-Ela, 1986). Fabric symmetry changes from that of a planar ('S') tectonite to that of a linear ('L') tectonite (e.g. Turner and Weiss, 1963, p. 91-104), corresponding to a change in strain symmetry from "flattening" to "constrictional." Also, the mineral lineation is parallel to X and the schistosity is parallel to the XY plane of the strain ellipsoid (designated by axes $X > Y > Z$). This is clear by comparing Figure 6 with Figure 7. These changes appear to occur from outcrop to regional scales in lenses or bands that are subparallel to the trace of the Vermilion fault. In general, flattening strains predominate close to the fault, and constrictional strains predominate southwest of Tower. The strain and fabric pattern indicate a significant component of north-south shortening across the Vermilion district.

On the mesoscopic to map scales, there are a number of structural features to indicate that ductile dextral shear was also an important component of the D_2 deformation. An east-west zone of highly foliated rocks just north and east of Tower coincides with a dextral offset of part of the nose of the Tower-Soudan anticline (Fig. 3), and is clearly a ductile shear zone. Such zones of highly foliated rock increase in frequency northwards towards the Vermilion fault. Another good example is situated in Mud Creek (Fig. 3, stop 9); this ductile shear zone joins the Vermilion fault obliquely. There are also fairly common outcrop-scale zones of highly foliated rock, commonly with the classic sigmoidal pattern of foliation.

A second striking feature of the D_2 deformation is the preponderance of folds of Z-symmetry. Although a number of 'S' folds exist, no consistent pattern of distribution was noted. They appear to be local parasitic folds on the short limbs of Z folds at outcrop scale or just larger. Folding in any case is not abundant and many outcrops show no signs of folding.

Abundant microstructural evidence for dextral shear can be found in the highly foliated rocks within the shear zones just referred to and in other places where strain is not so clearly localized. Shear bands or C' structures (White and others, 1980; Berthe and others, 1979) are common; many grains of feldspar and quartz, lithic fragments, or pyrite cubes have asymmetric pressure shadows (Simpson and Schmid, 1983), and a few porphyroblasts contain a foliation that indicates rotation. This evidence for dextral shear, combined with evidence for north-south shortening, leads to the conclusion that the D_2 deformation across the Vermilion district was a transpression. This was clearly not developed homogeneously but involved locally variable components of compression and dextral shear. The juxtaposition of zones of constrictional and flattening strains is explicable in a deformational regime of this type.

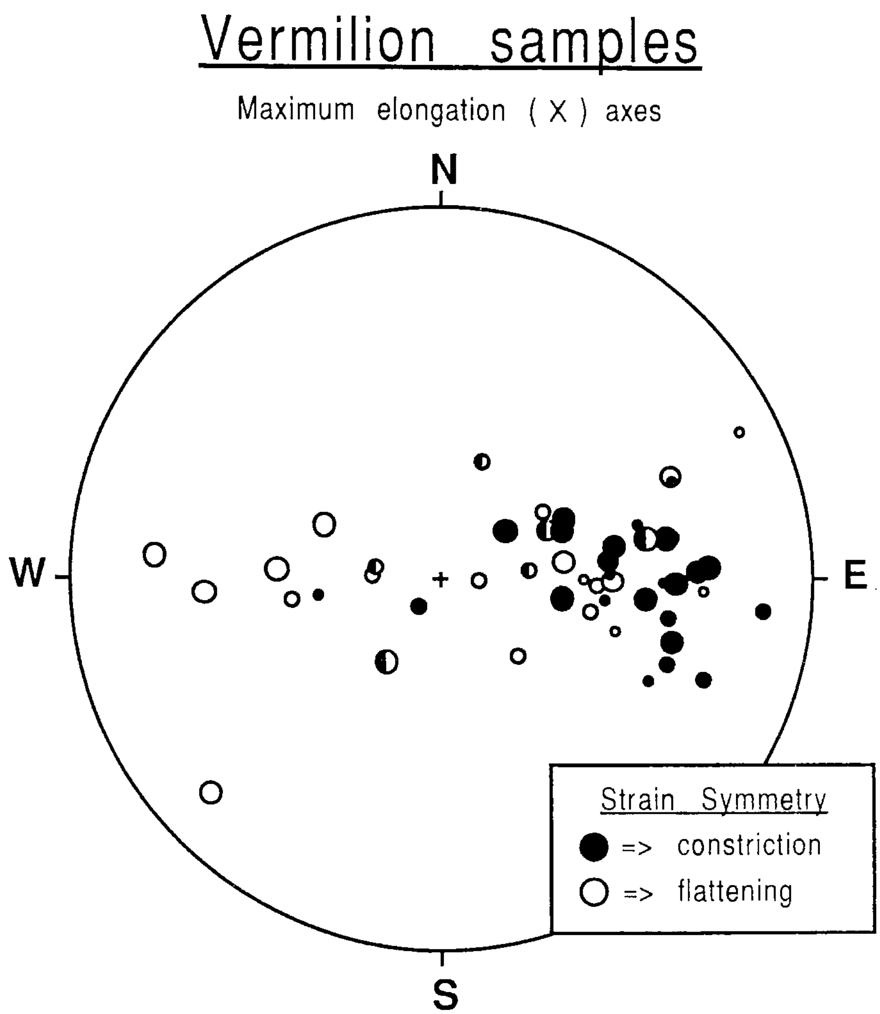


Figure 6. Equal-area projection of maximum extension direction, X, of the measured strain in the western Vermilion district. The larger the dot, the more reliable the data. Half-black circles indicate nearly plane strain.

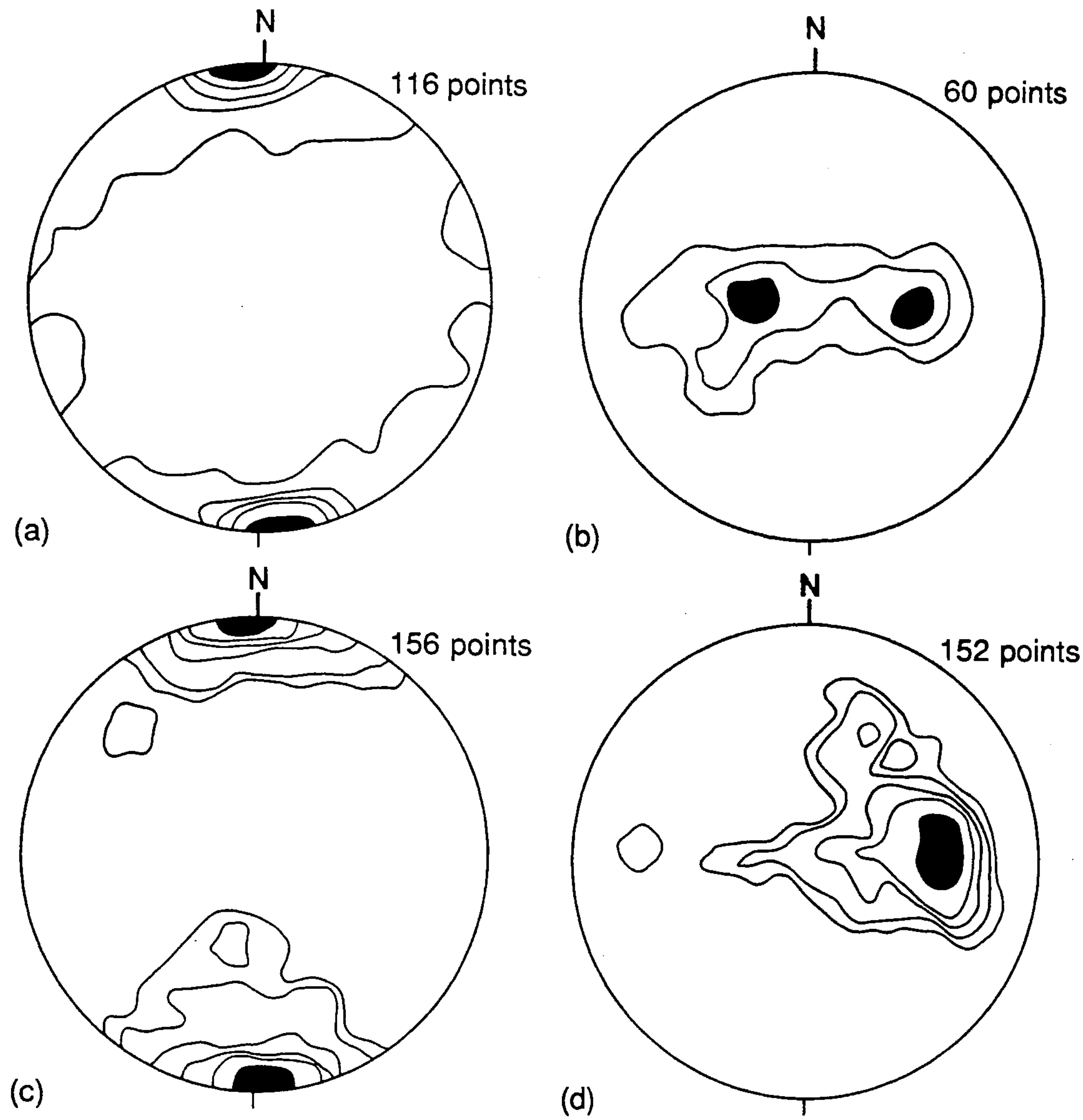


Figure 7. Structural data for rocks of the Lake Vermilion Formation. (a) and (b) west of Tower, south of F_1 axial surface trace (see Fig. 4); (c) and (d) west of Tower, north of F_1 axial surface trace.

The D_3 deformation produced nearly vertical kink bands (F_3), joints, shears, and faults that have little or no effect on the map pattern of the units. The D_3 kinks and shears produced both dextral and sinistral offsets (stop 3). The displacements on the Haley and Vermilion faults probably preceded most of the structures referred to D_3. The Haley fault and Burntside Lake fault are major dip-slip faults that Sims (1976) interpreted as having been contiguous prior to the right-lateral strike-slip displacement of about 19 km across the Vermilion fault. All these faults occur in rocks that underwent large ductile strains during D_2.

STRUCTURAL GEOLOGY OF THE SHAGAWA LAKE AREA (CENTRAL VERMILION DISTRICT)

Shear Zone Development in the Low-Grade Rocks

Distribution and Geometry

Major shear zones affecting the central Vermilion district form a bifurcating, wishbone-shaped trace that roughly corresponds to the outline of Shagawa Lake (Fig. 5). These zones are collectively referred to here as the Shagawa Lake shear zones. The three arms of this shear zone system are informally referred to by the respective bays of Shagawa Lake that they transect: The Olson Bay shear zone and the Longstorff Bay shear zone in western Shagawa Lake and the Spaulding Bay shear zone in eastern Shagawa Lake. The Olson Bay and Spaulding Bay shear zones follow the trace of the Shagawa Lake fault, which is inferred to be a tectonically long-lived structural feature. This family of shear zones is equivalent to the D_2 structures, such as the Mud Creek and Tower-Soudan shear zones of the western Vermilion district.

The Longstorff Bay shear zone, which is the best exposed of the three, deforms felsic tuff, agglomerate, and graywacke of the Knife Lake Group and a lamprophyre sill along the contact between the Knife Lake Group and the Newton Lake Formation (stop 11). Lens-shaped islands of unsheared, mildly deformed lamprophyre occur locally within the shear zone. The zone terminates to the west against the Wolf Lake fault.

The Spaulding Bay shear zone occurs primarily in the Knife Lake Group, although it affects adjacent variolitic pillow basalts of the Newton Lake Formation to the north (stop 12) and units of the Ely Greenstone to the south. This shear zone presumably extends toward Fall Lake, farther to the east, but this has not been verified.

The exact position of the Olson Bay shear zone is poorly constrained. It appears to form an anastomosing network in Olson Bay and along Hoodoo Point, just south of the bay. Its western extension is largely conjectural, partly on the assumption that it would coincide with the topographic low just north of and parallel to the Shagawa Lake fault.

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

Shear-Related Fabrics and Structures

A pervasive mylonitic C-foliation occurs in each of the major shear zones. There are, however, locally less strained areas within the shear zones that contain small-scale S-C fabrics and shear bands that indicate a dextral sense of shearing. Porphyroblastic "fish" structures, such as those described by Lister and Snoke (1984) in quartz-mica schists, occur locally at a microscopic scale as calcic amphibole fish in some samples from the Longstorff Bay shear zone. These are also consistent with dextral shear.

The mylonitic C-foliation in the shear zones has a relatively consistent orientation of approximately N. 70° E., 70° S. (Fig. 8), except in the northward deflection of the Longstorff Bay shear zone as it enters Shagawa Lake (Fig. 5). Mineral lineations on C are not ubiquitous but occur in local concentrations where they are defined by elongate chlorite, amphibole, or quartz. The lineation orientations concentrate along a segment of the C-foliation great circle with moderate plunges to the south and southwest (Fig. 9), but they also have a smaller dispersed concentration along the same great circle to the northeast. Small symmetric crenulations of the C-foliation with open interlimb angles occur in localized zones within the shear zones. They are best developed in felsic tuff of the Knife Lake Group and in sheared lamprophyre, and they are believed to have formed in areas of local perturbation during the latter stages of shearing. Kink bands are also locally well developed in the shear zones and are considered to be younger structures analogous to those assigned to D_3 in the western Vermilion district by Hooper and Ojakangas (1971).

Strain Analyses

Strain data were obtained from 15 oriented samples of deformed lamprophyre, agglomerate, and variolitic pillow basalt from the Longstorff Bay and Spaulding Bay shear zones. These rocks record strains that range from near plane strains (Flinn parameter, k=0.94) to large apparent flattening strains (k values as low as 0.06) (Fig. 10) with r values (= X/Y + Y/Z + 1) locally greater than 15. This range in strain is reflected in the steroplot of X- and Z-axis orientations (Fig. 11). The X areas plot along a great circle that is oriented roughly parallel to the average C foliation, and the Z axes cluster in the same area as the poles to C. The X axes of the three samples with the highest k values plot in a small cluster with an average orientation that is close to the orientation of one of the lineation concentrations. As k decreases, the X axes disperse along the great circle, although not in a strictly uniform distribution. However, the highest concentration of the low-k-value X axes plot in the same field as another lineation concentration. The finite strain pattern is complex and cannot be the result of a single strain mechanism such as simple shear. Models for the strain path illustrated in Figure 11 are considered by Bidwell and Bauer (1987, in press.)

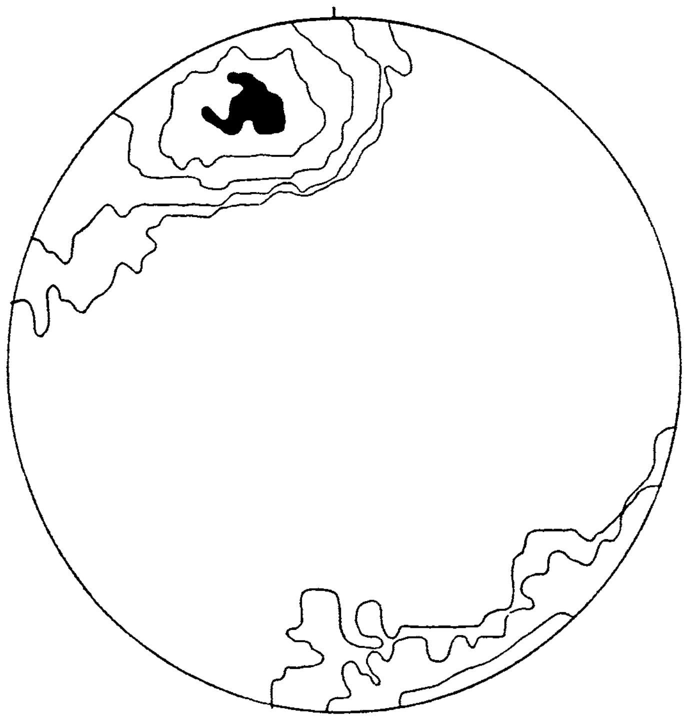


Figure 8. Contoured equal-area projection of poles to the C-foliation in the Shagawa Lake shear zones. Contours at 20, 9, 4, 1, and 0.5 percent per unit area of the hemisphere, 194 points.

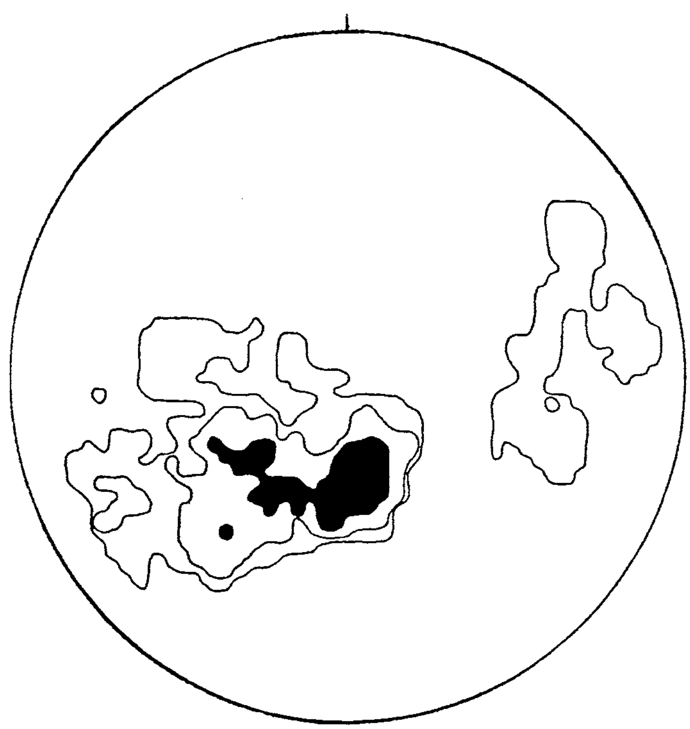


Figure 9. Contoured equal-area projection of mineral lineation orientations on the C-foliation. Contours at 9, 4, and 1 percent per unit area of the hemisphere, 76 points.

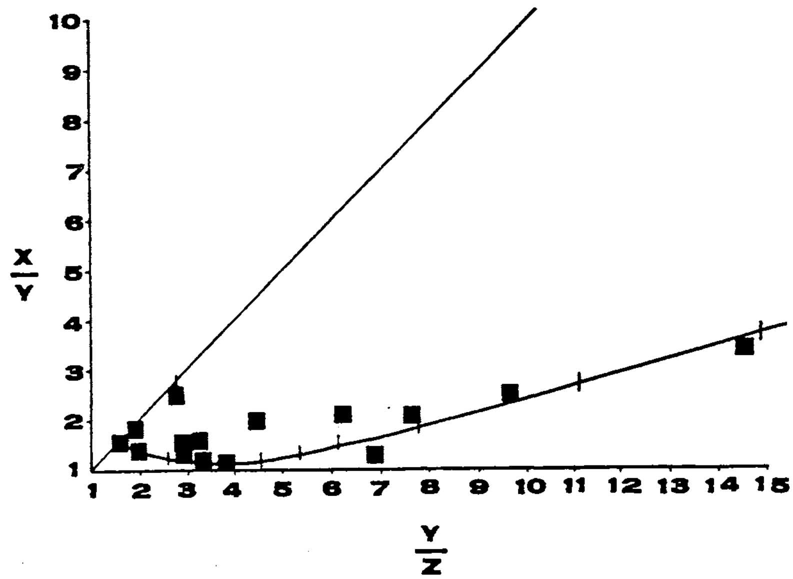


Figure 10. Flinn diagram of finite strain analyses from rocks in the Shagawa Lake shear zones. The curve through the points is a strain path model from Bidwell and Bauer (1987).

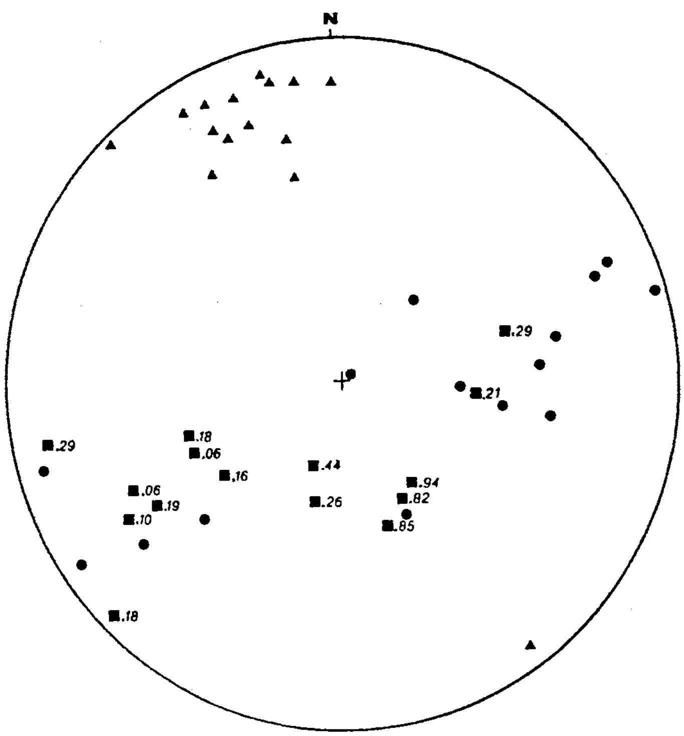


Figure 11. Equal-area projection of the orientations of minor (triangles), intermediate (circles), and major (squares) axes of the finite strain ellipsoids corresponding to the strains plotted in Figure 10. Numbers are k values.

Dextral Transpression Tectonics

The folds and shear zones in the south-central part of Figure 5 possess several characteristics suggesting their concomitant development. The inferred tectonic regime for their formation involves a dextral transpression within an east-west zone of shearing--oblique movement during compression directed northwest-southeast. Two characteristics of the folds are significant: their en echelon pattern and the progressive rotation of their axial traces from a northward to a more eastward direction. In the transpressive regime described above, folds would form perpendicular to the maximum principal stress acting from the northwest and southeast on the translation direction. However, because these folds occur within a zone of oblique covergence, they would occur as en echelon structures (Harland, 1971). Continued shortening along this oblique zone would cause the fold axes to rotate progressively toward the zone of displacement, similar to the rotation shown by the north-trending folds in Figure 5 into the Ely trough. Harland (1971) notes that such a process would concentrate an incompetent material into elongate, steeply dipping zones that would tend to take up the shear displacement as the system evolved. This is apparently the role assumed by the tuffaceous and volcanogenic sedimentary rocks of the Knife Lake Group, where most of the shear zones in the Ely area are concentrated.

North-striking sinistral faults and the dip-slip displacement on the Haley-Burntside Lake fault system apparently pre-dated the displacement on the east-striking dextral faults in the Vermilion district. However, these dextral faults may be the final manifestation of a long-lived dextral tectonic regime that affected the Vermilion district and possibly much of the Superior Province of the Canadian Shield (Card, 1987).

STRUCTURAL CORRELATIONS BETWEEN THE VERMILION DISTRICT AND THE VGC

General Correlations

The rocks of the southern VGC have undergone three phases of deformation (Bauer, 1985a, b, 1986); the first two have been correlated with D_1 and D_2 deformation in the adjacent Vermilion district. The earliest phase produced a well-developed S_1 foliation parallel to bedding in the biotite schist. Recumbent folding associated with this deformation has been inferred across the boundary between the VGC and the Vermilion district (Bauer and Hudleston, 1981; Bauer, 1985b); however, the exact nature of this deformation remains uncertain.

The D_2 deformation produced west-plunging F_2 folds with steeply dipping east-striking axial planes in the biotite schist along the southern boundary of the VGC. These folds are invariably of S-symmetry and have a locally well-developed S_2 axial plane schistosity that forms an intersection lineation parallel to the F_2 fold hinges and local L_2 mineral lineations. Bauer (1985b) has correlated these folds with F_2 folds of Z-symmetry in the western Vermilion district and has inferred the presence of a large F_2 antiform across the boundary between the VGC and the Vermilion district in this area. This D_2 deformation is therefore correlated with the D_2 dextral transpression inferred for the western and central Vermilion district (Hudleston and others, in review).

Structural Contrasts with the Vermilion District

Despite the structural correlations just mentioned, there are two important structural contrasts between the Vermilion district and VGC that are attributed to differences in crustal level during deformation (Bauer and others, 1986; Bauer, 1987a).

One important contrast is in the relative effect of shearing. As a rule, with local exceptions as discussed below, shear zones are uncommon in the VGC, and deformation directly attributable to shear is much less widespread than in the Vermilion district. Shear strains in the more ductile rocks of the VGC may have been accommodated over a larger area rather than in narrow shear zones such as those in the Vermilion district. The exceptional case is illustrated by stop 15, located in biotite schist along the northern margin of the Burntside trondhjemite. Locally intense ductile shearing is evident from complex asymmetrical pull-aparts (Hanmer, 1986) and porphyroclast systems of both α and δ types (Passchier and Simpson, 1986) that occur in trondhjemite veins within folded biotite schist.

Another structural contrast between the two terranes is the development of F_3 folds in the migmatites along the southern margin of the VGC (Bauer, 1986) and their absence from the adjacent Vermilion district. (It is important to note that these F_3 folds come between the F_2 and F_3 events in the Vermilion district. The latter are represented by F_4 structures in the VGC.) Analysis in the VGC suggests that F_2 folds were reoriented during emplacement of granite plutons and were subsequently refolded by non-cylindrical F_3 folds that formed during the latter stages of the regional D_2 transpression event. Since late D_2 plutonism was not significant at the level of exposure of adjacent parts of the Vermilion district, the existing F_2 folds in the Vermilion district were not reoriented and refolded, but continued to flatten in the regional D_2 transpressional regime.

F_3 Folding in the Burntside Lake Area

A similar response, including the generation of F_3 folds, is inferred for the portion of the southern VGC considered on this field trip (Bauer, 1987b). In the southern Crab Lake quadrangle, just west of Figure 5, S-symmetry F_2 folds are reoriented from steep west-plunging axes to moderate to shallow southwest-plunging orientations. These axial orientations become shallower to the north and eventually plunge to the northeast in the vicinity of the Twin Lakes synform. The Twin Lakes synform is interpreted as an F_3 structure that was localized in part by its proximity to the margin of the Lac La Croix batholith and in part by the dense amphibolite unit that occupies its core. Along the southwest closure of the synform (Fig. 5), F_2 folds in the biotite schist have reclined orientations with northeast-dipping axial planes and northeast-plunging hingelines. Small-scale interference patterns occur locally in this area involving F_2 folds of this orientation and upright symmetric F_2 folds that also plunge to the northeast. The F_3 folds in this part of the VGC are interpreted to be a result of local reorientation of the country rocks during emplacement of the Lac La Croix batholith during continued D_2 transpression.

Unfortunately, outcrops illustrating these relationships between F_2 and F_3 folding are accessible only by boat and are not examined on this field trip. However, an important point to be made here is that the folds examined at stop 15 that deform earlier shear-generated structures are probably

ROADLOG AND STOP DESCRIPTIONS

This roadlog begins at the Holiday Inn in Eveleth, Minnesota, and ends at the U.S. Forest Service Voyageur Visitor Center east of Ely. The route follows major highways from Eveleth to the vicinity of Tower and Soudan, where several stops are reached from secondary roads (Figs. 1, 3, and 4). It continues northeastward from the Tower-Soudan area toward Ely on highways 1 and 169, and, northeast of Ely, turns north on the Echo Trail to reach another group of closely spaced stops (Fig. 5).

Mileage, day one of trip

0.0 Intersection of Holiday Inn driveway and frontage road. Turn right on frontage road and proceed to stop sign. Turn left from frontage road and left again into northbound lane of U.S. 53.

1.6 Geologic note: The highway is running more or less along the unconformity that separates strongly deformed Archean greenstone and metagraywacke (on right or east side of road) from overlying, gently dipping metasedimentary rocks of Early Proterozoic age (on left or west side of road). The long roadcut on the southbound lane of the highway is the argillaceous member of the Pokegama Quartzite, the lowermost formation of the Early Proterozoic Animikie Group. Low outcrops of Archean rocks occur in the ditch along the northbound lane.

3.0 Geologic note: The high dumps on the right (northeast) side of the highway are from the Rouchleau mine, one of the largest open-pit iron-ore mines on the Mesabi range. The mine has been inactive for many years. Most of the material mined from the Rouchleau was hematitic "direct-shipping" ore. Such ore was formed from the magnetite-chert-iron silicate rock of the Biwabik Iron-Formation by leaching and oxidation along structurally controlled zones. The composition and origin of the ore-forming fluids are still debated after decades of study. Unenriched magnetite-chert-iron silicate rock, known locally as taconite, is the major commercial source of iron at the present time. The crushing and concentrating plant of the Minntac Taconite Mine (USX Corporation) can be seen on the horizon straight ahead.

5.6 Hazardous intersection controlled by four-way flashing stoplight. Continue straight ahead on combined highways 53 and 169.

8.9 Wayside for Lookout Mountain recreation area.

Geologic note: The crest of this hill marks the Laurentian Divide, which separates south-flowing drainage toward Lake Superior and the Mississippi River from north-flowing drainage toward Rainy Lake, the Rainy River, and, ultimately, Hudson Bay. The large cuts along the highway display a complex migmatitic phase of the Giants Range batholith. The Giants Range batholith is a complex Archean intrusion within the Wawa Subprovince as extended into Minnesota (Fig. 2). It invades and locally metamorphoses the supracrustal rocks of the Vermilion district, which it bounds on the south (Figs. 1, 3).

9.7 Highway 169 bears right (northeast); follow 169 toward Tower and Ely. Continue on Highway 169 for approximately 14.2 miles.

23.9 Cross bridge over Pike River--slow down.

24.1 Intersection (obscure and poorly marked) with County route 410. Turn right (east) and continue on gravel road.

27.0 Intersection with County route 411. Turn left (north) and proceed on blacktop road for about 0.1 mile. Park vehicles north of swampy creek and disembark.

STOP 1. Outcrops of folded, cleaved slate, metagraywacke, and pebbly metagraywacke of Lake Vermilion Formation in brush east of County route 411, sec. 23, T. 61 N., R. 16 W., St. Louis County.

These rocks exhibit meter-scale F_2 folds in sedimentary bedding and the associated S_2 schistosity and lineation. The folds are of Z-symmetry and are predominantly of westward and downward structural facing with respect to the cleavage. Graded bedding is well preserved. One can readily observe that the clasts are flattened in the plane of cleavage, and stretched in the direction of the mineral lineation and the F_2 fold hinges. These linear features plunge at about 30° to the east. The strain is constrictional throughout these outcrops. Only one cleavage (S_2) is present except very locally, where a later crenulation cleavage develops. Although the predominant structural facing is westward in the hinges of folds, there are local zones of eastward-facing fold structures. The alternation of westward- and eastward-facing fold zones implies the presence of earlier folds (F_1) on the scale of tens or hundreds of meters in size; the predominance of westward-facing hinges further suggests, however, that the F_1 folds are relatively minor parasitic structures on the flank of a regional F_1 fold. There is neither cleavage nor measurable clast strain associated with the inferred F_1 folding in this area.

27.0 Return to vehicles; resume traveling north and east on County route 411.

30.5 Junction with Minnesota 135. Turn left (north) toward Tower.

32.9 Intersection of Minnesota 135 with 1 and 169 on western outskirts of Tower. Turn left (southwest) and proceed on 1 and 169.

35.3 Large cut on south side of highway. Pull onto shoulder on north side of highway and disembark. Use caution crossing the road.

STOP 2. Highway cuts and natural outcrop surfaces along U.S. Highway 1 and 169 about 2.5 miles west of Tower, NE1/4NE1/4 sec. 2, T. 61 N., R. 16 W. Spectacularly folded slate and metagraywacke of the Lake Vermilion Formation. NO HAMMERING.

This outcrop was revealed during highway realignment and powerline construction about 20 years ago, and it has become a field-trip classic. It clearly shows the superposition of two generations of folds in thin-bedded, well-graded turbidite. The second folds (F_2) are clearly tectonic inasmuch as they are associated with a regional axial-plane cleavage in which sedimentary clasts are visibly flattened. The earlier folds (F_1) have no associated cleavage or observable clast strain, and tend toward concentric, cuspate, and bulbous morphologies in the more competent layers. These characteristics are consistent with a soft-sediment or partially lithified origin for the F_1 structures (Hudleston, 1976), an interpretation the present leadership endorses. This position has not been accepted universally, however (Hooper and Ojakangas, 1971; Ojakangas and others, 1978).

The evidence for fold superposition includes interference patterns of several sorts ("eye" and "mushroom" forms are well represented) and the transection of F_1 folds by cleavage related to F_2 folding. Most of the "eye" interference structures, however, are wholly of D_1 age (Fig. 12). They represent sheath folds associated with large shear strains. Removing the effects of D_2 strain and F_2 folds would not remove these structures. The magnitude of the D_2 strain is not nearly enough here to produce sheath folds; shear strains of about $\gamma = 10$ would be needed for this (Cobbold and Quinquis, 1980). One can find numerous examples of antiformal synclines and synformal anticlines, indicating local stratigraphic inversion prior to the second folding. As at stop 1, the linear component of the metamorphic fabric is stronger than the planar, and the strain is constrictional. The S_2 cleavage is nearly restricted with an east-west strike, and L_2 plunges at 40°-50° to the east.

35.3 Return to vehicles; resume traveling west-southwest on 1 and 169.

37.1 Intersection with County route 77; turn right (north) on County 77 and proceed slowly.

37.6 Cross bridge over Pike River; pull off into small clearing on left (southwest) of road a few meters beyond north end of bridge; disembark. Watch out for cars and pedestrians--this area is frequently congested.

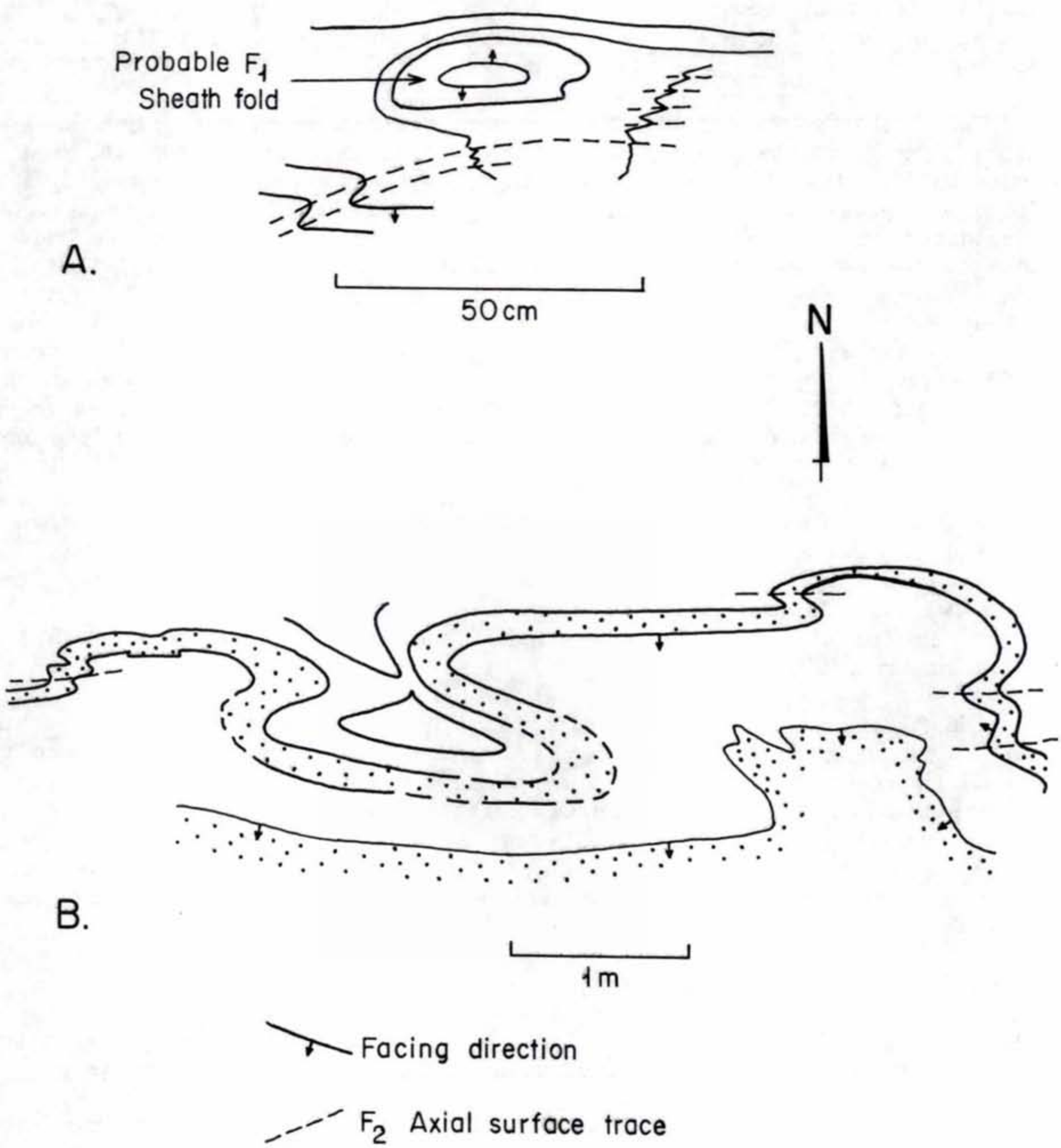


Figure 12. Examples of fold interference patterns in graywacke and slate at stop 2. The "eye" pattern in A and the "mushroom" pattern in B are interpreted as F_1 sheath folds. Note the modification by F_2.

STOP 3. Glacially scoured outcrop west of St. Louis County Highway 77, immediately north of the Pike River bridge, NW1/4SW1/4 sec. 3, T. 61 N., R. 16 W.

This outcrop of graded, thin-bedded, south-topping metagraywacke contains a good cleavage (left of bedding) and lineation (which is hard to appreciate on this flat outcrop), but, in contrast to the previous stops, no folds are present. Graded bedding and other structures characteristic of turbidites are exceptionally well preserved. Of the 201 graywacke beds in this outcrop, 64 percent are graded, and 9 percent of the 100 silt beds are graded (Ojakangas, 1972a). The thin bedding displayed in this outcrop (about 0.1 m) is relatively local; graywacke beds as thick as 3 m occur a short distance to the south, and nearly massive dacite tuff and reworked tuff occur just up the hill to the north. The graded graywacke beds in this thin-bedded section are composed of the same sand-size materials--volcanic quartz, plagioclase, and fine-grained dacitic rock fragments--as the more massively bedded tuffaceous and agglomeratic rocks.

Although F_2 folds are lacking in this outcrop, the relationships among bedding, cleavage, and stratigraphic younging directions are entirely consistent with the D_2 structural geometry of the previous two stops. They imply westward structural facing in the cleavage, and a position on the south limb of a large, south-overturned regional F_1 structure. Strain is still constrictional.

The prominent northeast-trending kink bands and shear zones traversing this outcrop are the result of the latest deformation, D_3, to affect the Vermilion district. These zones contain small-scale features indicative of progressive shear deformation in the brittle and brittle-ductile regime, and are uncommonly photogenic. Good examples of Riedel shears and en echelon extensional fractures may be seen. The shear zones are parallel to a regional left-lateral fault which follows the south side of the Pike River between the bridge and the dam.

37.6 Return to vehicles; proceed north on County route 77.

43.2 Road swings close to Lake Vermilion at head of Daisy Bay; stop 7 on left (west) side of road will be visited on return trip.

45.9 Junction of County route 929 with County route 77; turn left (north) on route 929 and proceed on gravel road.

46.9 Junction of County route 949 with County route 929; turn left (west) on 949 and proceed slowly on narrow gravel road.

47.8 Park vehicles; disembark and walk short distance to outcrops in driveway of private cabin. This is PRIVATE PROPERTY and permission to enter must be obtained from the owner. Drivers should turn vehicles around in nearby driveways.

STOP 4. Outcrops of deformed metasedimentary rocks of Lake Vermilion Formation in private driveway near end of western prominence of Black Duck Point: near center of sec. 5, T. 62 N., R. 16 W.

This and the next stop are about a mile from the trace of the Haley fault (Fig. 4). The rocks here are strongly deformed. The prominent fold and its axial planar crenulation cleavage formed during the D_2 deformation, but they fold the main S_2 foliation, which is nearly parallel to bedding (dips of both are very steep) and can be best seen away from the fold hinge. Thus they are designated F_2' and S_2' respectively. Note that the fold is of "S" symmetry, unusual for either F_2 or F_2' folds. Although not easily seen in this outcrop, the D_2 metamorphic fabric is characterized by being strongly planar ($S_2 >> L_2$), in contrast to the situation at stops 1-3. The relationships among fold symmetry, S_2, and S_2' are in fact somewhat enigmatic here. S_2' is of the typical orientation found in association with Z folds produced by incremental dextral shear in an east-west shear zone. If this fold is a parasitic fold on the middle limb of a larger than outcrop scale Z fold, as we assume, S_2 or S_2' should be right of bedding in the long limbs of the folds. In fact it appears to be left of bedding. If the deformation did involve dextral shear, for which there is so much evidence elsewhere, this relationship implies either transection of the fold limb by the cleavage (Borradaile, 1978) or complete rotation of bedding and S_2 on the central limb of the inferred large Z fold, without greatly changing the angular relationship between them. Note the change in shape of the clasts passing from the limbs to the hinge of the fold. This indicates a change from a strong flattening strain in the limbs toward a plane strain in the hinge. (This is inferred from the appearance here and results elsewhere--strain has not been measured here.)

47.8 Return to vehicles; retrace route to intersection of routes 949 and 929.

48.7 Junction of 949 and 929. Park vehicles and disembark; walk about 100 m north (left) along route 929 to outcrops on west (left) side of road.

STOP 5. Outcrops of Lake Vermilion Formation along County route 929 on Moccasin Point: SE1/4NW1/4 sec. 4, T. 62 N., R. 16 W.

Minor F_2 folds within the hinge of a larger fold of greater than outcrop-scale are well displayed here, with a good axial plane cleavage (S_2), which varies in intensity from limb to limb of some folds. Cleavage refraction from layer to layer is also well displayed, as is fanning of cleavage about some folds. Clasts are flattened in S_2 in the hinges and limbs of the folds, providing strong evidence for lack of clast strain during D_1. The metamorphic fabric is planar and the strain is of flattening symmetry. The lineation formed by the intersection of S_0 and S_2 is very well developed and can be seen to be parallel to F_2 and plunging steeply to the east. This stop and stop 4 are on the north limb of the large D_1 structure, whereas stops 1-3 are on the south limb (Fig. 4). Facing is predominantly east in the cleavage rather than west.

48.7 Return to vehicles; turn right (south) on County route 929.

49.7 Intersection of 929 with County route 77. Turn right (west) on County 77 and proceed on blacktop road. Go slowly and be prepared to stop.

51.8 Entrance to Clover Point Resort on left (south). Turn into resort and park vehicles; disembark. Walk to outcrops on shore of Lake Vermilion at the boundary between the resort and the neighbor's property to the west. This is PRIVATE PROPERTY and permission to enter and to examine outcrops must be obtained from the owner.

STOP 6. Outcrops of Lake Vermilion Formation on grounds of Clover Point Resort on Daisy Bay of Lake Vermilion: NW1/4SW1/4 sec. 8, T. 62 N., R. 16 W.

This outcrop lies a short distance from the contact of the Lake Vermilion Formation with the Daisy Bay pluton (seen at the next stop) to the north. The contact lies between this outcrop and the road. Bedding, S_2, and S_2' are well-developed. S_2' is a good crenulation cleavage, and it has the typical orientation (N. 80° E.) of S_2 elsewhere in the Vermilion district where there is no sign of S_2'. The pluton is inferred to be pre- or syn-D_2 and to have perturbed S_2 from its typical orientation, and thus disposed it in an orientation (now S. 50° E.) favorable for it to have become folded and for S_2' to have formed during dextral transpression (see Hudleston and others, in review). Note the refraction of S_2 across the contacts between schist and graywacke.

51.8 Proceed on foot from resort onto north shoulder of County route 77 and walk west (to left) along the road to cuts at the sharp bend at the head of Daisy Bay (distance approx. 1 km or 0.6 mi). The vehicles will pick up passengers after stop 7 has been examined.

52.4 Roadcuts at head of Daisy Bay.

STOP 7. Hornblende syenite of the Daisy Bay pluton, exposed in roadcuts along County route 77 at head of Daisy Bay: NW1/4SE1/4 sec. 7, T. 62 N., R. 16 W.

The Daisy Bay pluton locally has a weakly developed foliation, consistent in attitude with S_2 (or S_2' where S_2 has been perturbed) in the nearby Lake Vermilion Formation. It also is cut by a number of discrete shear surfaces or fractures, probably of D_3 or later age.

52.4 Return to vehicles; proceed south on County route 77.

58.0 Pike River bridge.

58.5 Intersection of route 77 with 1 and 169. Turn left (northeast) and proceed toward Tower.

62.7 Junction with 135 on outskirts of Tower. Proceed straight ahead (east) into town on 1 and 169.

62.8 Junction with Hoodoo Point road on left (north); turn left (north) and follow signs for Hoodoo Point.

64.1 Picnic area at Hoodoo Point. LUNCH STOP.

Geologic note: Thick-bedded tuff and tuff-breccia composed dominantly of dacitic detritus are exposed in a low, glacially polished outcrop along the lake shore a few paces south of the picnic area. Although this rock is described in volcanic nomenclature, there is considerable evidence that sedimentary processes redistributed the volcanic detritus after its original deposition. Final deposition is thought to have involved the reworking of unlithified volcanic debris by streams and marine processes on the slopes of a partially emerged volcanic island. The rock possesses a strong cleavage (S_2) in which clasts are aligned; the cleavage is at a high angle to bedding at this locality and is axial-planar to some rather photogenic small-scale folds (almost of M symmetry) in a local thin-bedded portion of the outcrop. This lithology is widespread in the Vermilion district; here it is mapped with the tuffaceous member of the Lake Vermilion Formation (unit lt of Fig. 4).

64.1 Return to vehicles; retrace route over Hoodoo Point road to junction with 1 and 169 in Tower.

65.4 Junction with highway 1 and 169. Turn left (east) and continue through Tower on the main street. CULTURAL NOTE: The baked goods and hot pasties (Cornish meat pies) produced by the Tower Bakery are the best to be had in northern Minnesota.

67.1 Large cut in greenstone (metadiabase) on left (north) side of highway; junction with street just east of outcrop. Turn left on street and continue northeast past Soudan School.

67.5 Stop sign. Turn right (southeast). Proceed one block and turn left. Continue more or less straight past the Soudan Fire Station and up the hill toward Tower-Soudan State Park and Stuntz Bay.

68.0 Driveways and mine buildings on left (southwest); park vehicles and disembark. Walk about 100 m north along road to outcrop on right (east).

STOP 8. Folded jaspilite iron-formation of the Soudan Iron-Formation Member of the Ely Greenstone: Tower-Soudan State Park, NE1/4NE1/4 sec. 27, T. 62 N., R. 15 W. NO HAMMERING!

This classical exposure of the Soudan Iron-Formation displays two generations of close folding in delicate laminations of chert (creamy white), chert-hematite (red) and magnetite-chert (black). The second-generation folds are of tectonic origin; their subvertical axial surfaces trend east-west, their axes plunge steeply east, and they are dominantly of Z-symmetry. The first-generation folds have been sharply refolded by the second generation, resulting in fold interference patterns of several types (Fig. 13). Some geologists (e.g. Hooper and Ojakangas, 1971) have interpreted the first folds to be of tectonic origin; others (e.g. Hudleston, 1976) have suggested that they may have formed by soft-sediment processes. Small faults and kink bands of brittle origin cut across the folds.

Lundy (1985) studied the folding in this outcrop in considerable detail, and concluded that some of the first-generation folds are sheath folds and thus appear as interference patterns without the involvement of F_2 (see discussion for stop 2). Moreover, he found that the F_1 structures exhibit a wide variety of style and orientation, and are predominantly intrafolial. These observations suggest a high component of shear strain during D_1, and are consistent with layer-parallel, soft-sediment slumping as a probable mechanism to account for the F_1 structures.

The deep open pits a few meters north of the outcrop are early workings of the Soudan iron mine, the first iron mine in Minnesota. The mine produced about 16 million tons of high-grade hematite lump ore between 1884 and 1962, when high mining costs and changes in steel-making technology forced it to close. The early open-cut method of mining was replaced by underground operations about 1900, and most of the historic production has come from underground mining. The mine was deeded to the state of Minnesota in 1962, and is now operated as a tourist facility featuring guided underground tours.

68.0 Return to vehicles; retrace route to stop sign at the bottom of Soudan Hill.

68.3 Stop sign; turn left (southeast) on residential street.

68.8 Junction with highways 1 and 169; turn left (east) and continue toward Ely.

Geologic Note: The highway follows the outcrop belt of the Soudan Iron-Formation along the north limb of the Tower-Soudan anticline for many miles. Most of the cuts along this stretch are either banded iron-formation or volcanic rocks that are complexly interstratified with banded iron-formation.

76.4 County route 408 (Mud Creek Road) enters from left (north). Turn left; proceed cautiously on narrow, rough, curving road.

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

STOP 9. The Mud Creek shear zone; outcrops near the crossing of Mud Creek Road over Mud Creek: SE1/4SE1/4 sec. 5, T. 62 N., R. 14 W.

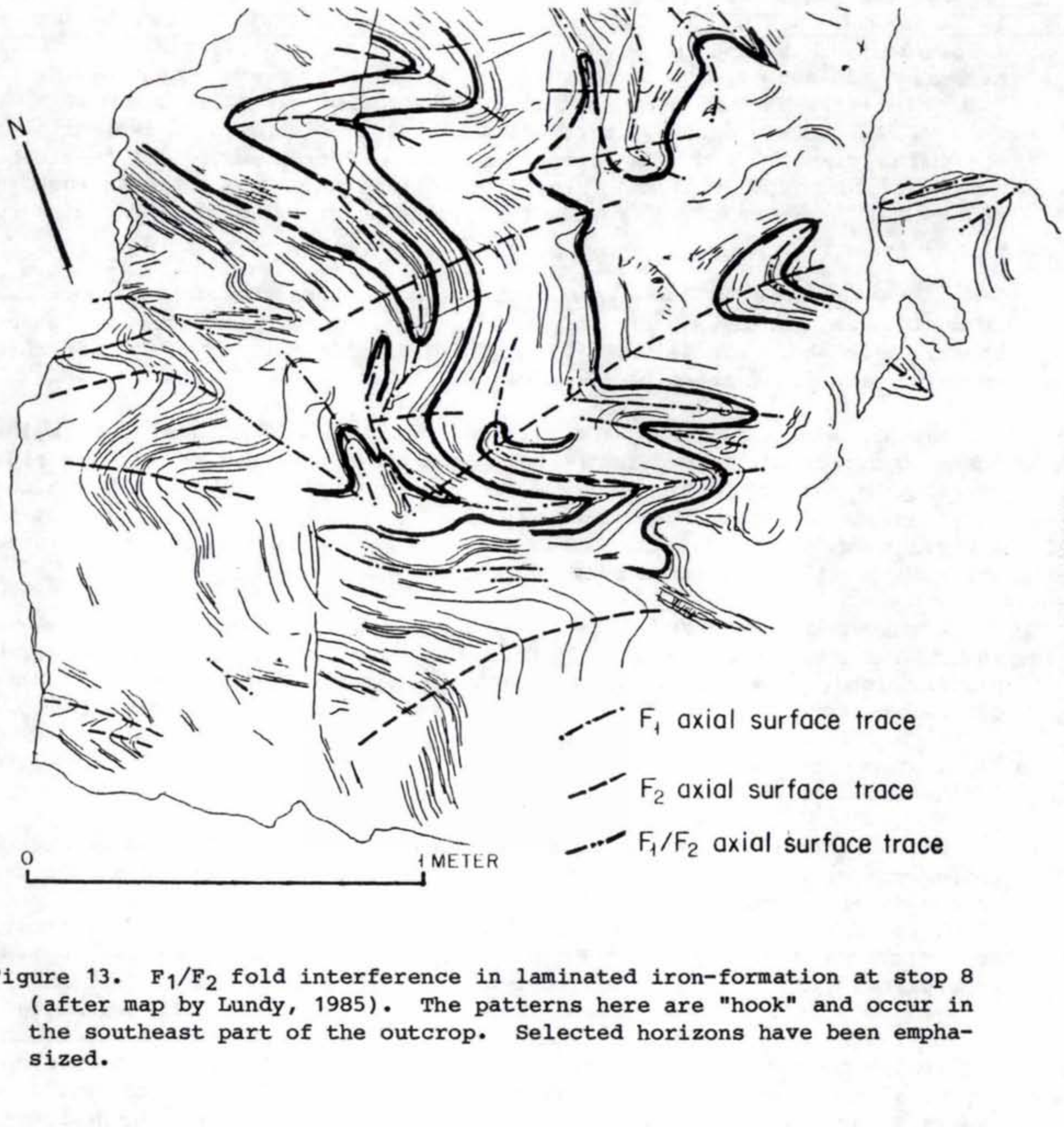


Figure 13. F_1/F_2 fold interference in laminated iron-formation at stop 8 (after map by Lundy, 1985). The patterns here are "hook" and occur in the southeast part of the outcrop. Selected horizons have been emphasized.

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

The best exposures are in scrub just north of the creek and within about 100 m of the road on the east side. The best example of local S_2' and F_2 development in a lens of otherwise uniform S_2 is here (see Fig. 14). In general S_2 is subparallel to the margins of the Mud Creek shear zone (N. 70° E.). Locally, it has been perturbed and rotated clockwise about 40°, to form folds with a secondary crenulation cleavage (S_2') developed parallel to the axial plane. Both cleavages can be traced from within the perturbed zone outward to merge into a single planar fabric, S_2, in the surrounding rock. Good examples of en echelon tension veins can also be found in nearby outcrops.

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

Farther along the road, after it has run some 500 m in a more or less westward direction, turned to the north and begun to climb up onto the ridge overlooking Mud Creek, there is a small quarry off to the right in which a very fissile chlorite schist or mylonite is exposed. This is presumably derived from pillow basalt. This exposure, north of the main Mud Creek shear zone, will be visited only if time permits.

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

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

80.1 Return to vehicles; retrace route along Mud Creek road to high-

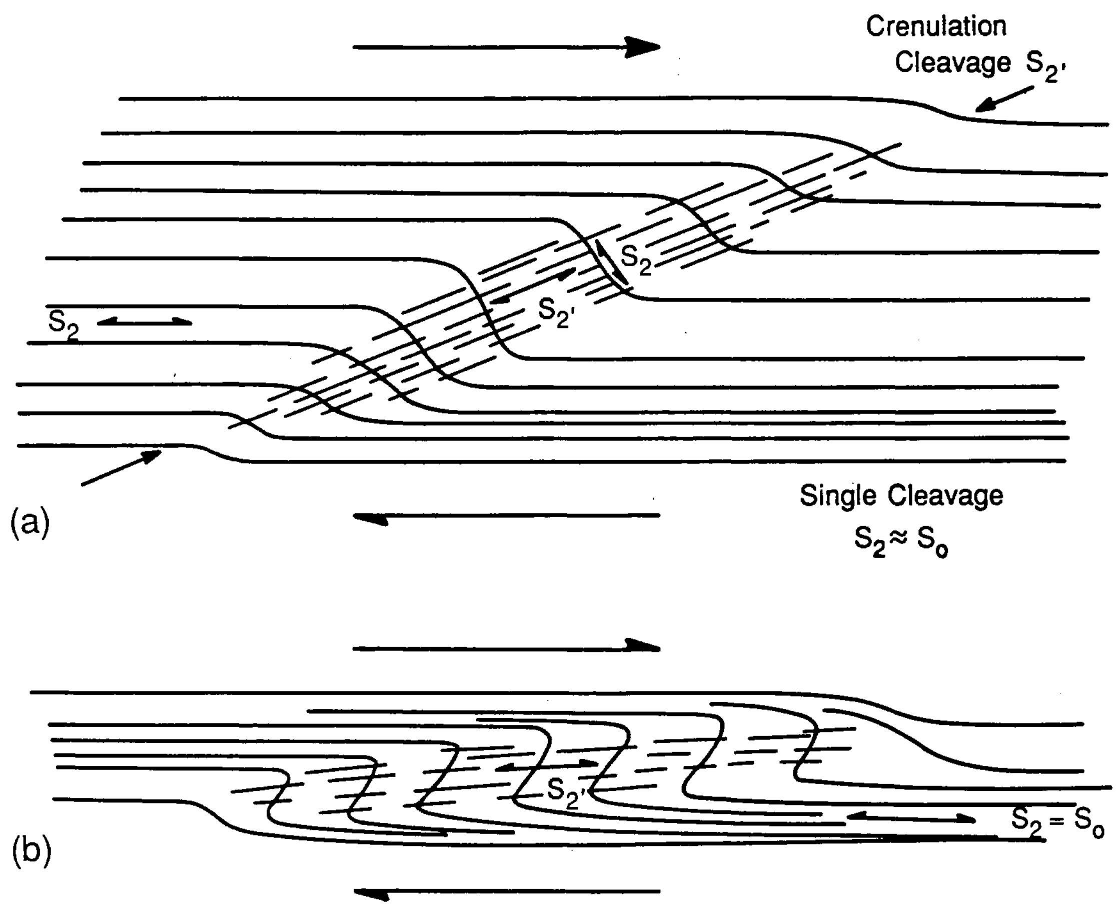


Figure 14. Schematic illustration of the development of F_2' folds and S_2' cleavage during a simple deformation that also produced the foliation (S_2) being folded.

way 1 and 169.

83.8 Highway 1 and 169. Turn left (northeast) toward Ely.

95.0 High roadcuts along 1 and 169 about 0.2 mile west of Ely city limits. Park on shoulder; disembark and cross highway to cut on north side.

STOP 10. Deformed, pillowed metabasalt of the upper member of the Ely Greenstone; roadcut about 0.2 mile west of Ely near center of NW1/4 sec. 33, T. 63 N., R. 12 W.

Outcrops showing more than a two-dimensional view of pillowed greenstone are rare in the flat terrain of northern Minnesota. One sees deformed pillows in three dimensions in this exposure, and can get a sense of the bulk strain which the rock has undergone. The pillows are flattened in the plane of cleavage (essentially the main face of the cut); the Z direction is normal to cleavage and the X and Y axes lie in the cleavage and are subequal in length. Thus these rocks occupy a zone of flattening strain. Cleavage strikes northeast and dips steeply south; the X axes of deformed pillows and a weak to pronounced mineral lineation both plunge steeply northeast.

95.0 Return to vehicles; continue eastward on 1 and 169 through downtown Ely.

96.4 Entrance to Kosir's Motel on the east side of Ely. END OF FIRST DAY.

<u>Mileage, day two of trip</u>

96.4 Kosir's Motel. Turn left (west) onto 1 and 169 and proceed through downtown Ely and out of town to the southwest.

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

STOP 11. Longstorff Bay shear zone; quarry and natural exposures in the SE1/4 sec. 36, T. 63 N., R. 13 W., west of Ely.

At this stop the Longstorff Bay shear zone has deformed metasedimentary rocks of the Knife Lake Group and a lamprophyre/appinite sill that occurs along the contact between the Newton Lake Formation and the Knife Lake Group.

Locality 11a: Sheared lamprophyre in quarry pit.

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

Locality 11b: Sheared tuff of the Knife Lake Group.

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

100.5 Return to vehicles; retrace route to 1 and 169 and then to left (east) back through Ely.

104.6 Minnesota route 1 turns south toward Illgen City; continue east on U.S. highway 169 toward Winton.

105.6 County route 88 (signs for Echo Trail) enters from left (north); turn left onto route 88.

107.6 Prominent roadcuts on either side of road; park on shoulder and disembark.

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

Locality 12a: Sheared tuff of the Knife Lake Group.

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

Locality 12b: Sheared Newton Lake basalt.

Variolitic pillow basalt and more massive flows of the Newton Lake Formation are cut by discontinuous shear zones at this outcrop. Strain analyses using varioles from this unit indicate high flattening strains (k=0.06 and 0.10) with X plunging moderately to the southwest (Fig. 11). Weak shear bands with spacings on the order of 5 cm are visible on some of the vertical outcrop faces at a high angle to the shear zones.

107.6 Return to vehicles; continue on route 88 to junction with Echo Trail.

107.9 Echo Trail enters from right (north); turn right and proceed slowly for about 1/4 mile.

108.2 Park on shoulder and disembark; cross road to west side and walk up trail through woods.

STOP 13: Undeformed variolitic pillow basalt of the Newton Lake Formation on prominent ridge in the NW1/4 sec. 22, T. 63 N., R. 12 W.

This exposure overlooking Shagawa Lake is north of the zones of intense shearing; the variolitic pillow basalt is relatively undeformed. This is the type C Newton Lake Formation basalt of Schulz (1980) and is the most common basalt type in the formation. These rocks have higher MgO and incompatible element contents than the Ely Greenstone basalts.

108.2 Return to vehicles; turn around and go south to County road 88; turn right (west) on 88.

113.5 County road 404 (Van Vac Road) enters from right (west); turn right on 404.

114.9 Park vehicles on shoulder; disembark and walk to outcrops.

STOP 14: Deformed pillow basalt (amphibolite facies) in the southern part of the Vermilion Granitic Complex located along County road 404 (Van Vac Road) in the NW1/4 sec. 27, T. 63 N., R. 13 W.

This outcrop area is in the high-grade rocks of the southern Vermilion Granitic Complex north of the Burntside Lake fault. Deformed pillow basalts in this area are locally variolitic and are interpreted to be the higher grade equivalents of the Newton Lake basalts in the adjacent Vermilion district. The low-lying outcrop off the south side of the road contains basalt with indistinct pillows that have been flattened and then folded into S-symmetry folds that are typical of F_2 in this area. The pillow rinds locally take on a strong linear fabric parallel to the fold hinges. North of the road, low-lying outcrops in the woods contain poorly exposed variolitic pillow basalts that have been flattened and folded and contain stretch varioles parallel to the local F_2 hinges.

114.9 Return to vehicles; retrace route back to Echo Trail.

121.3 Junction of Echo Trail with County road 88. Turn left (north) on Echo Trail.

125.8 County route 803 (Passi road) enters from left (southwest). This intersection is obscure and easily missed; it is at the top of a steep pitch rising from the northeast end of Burntside Lake. Turn left on 803 and left again into gravel track in low brush. Park vehicles and disembark.

STOP 15: Folded and sheared migmatite: SW1/4NW1/4 sec. 8, T. 63 N., R. 12 W.

Low-lying biotite schist outcrops are exposed on both sides of the road at this stop which lies just north of the contact between the schist and the Burntside trondhjemite. The schist contains numerous veins of trondhjemite forming a complex intrusion migmatite. Numerous kinematic shear indicators including asymmetric pull-apart structures and both α and δ porphyroclast systems in the deformed veins indicate a dextral sense of vorticity. However, sinistral-shear sense indicators also occur, and both the schist and the veins have been folded by probable F_3 folds. Fold axes in the schist plunge gently to the east or less commonly to the west.

A composite net-veined diabase dike about 2 m wide crops out intermittently with an east-west trend along the outcrop ridge east of the road.

125.8 Return to vehicles; proceed back to Echo Trail and turn left (north).

131.6 Huge, flat outcrops of granite on left (west); pull into dirt track, park, and disembark. Walk onto outcrop. HISTORICAL NOTE: This area was used by the Hercules Powder Company as a testing ground for blasting compounds when mining was still active in the Vermilion district.

STOP 16: Border phase of the Lac La Croix Granite, NE1/4SE1/4 sec. 13, T. 64 N., R. 13 W.

This extensive outcrop occurs along the southeastern margin of the Lac La Croix batholith. The oldest granitic phase exposed here is a porphyritic biotite granite with centimeter-size K-spar phenocrysts aligned in an east to northeast-trending foliation that parallels the local batholith margin. This granitic phase is not characteristic of the Lac La Croix batholith, but it is intruded by veins of pink massive granite to granodiorite and younger pegmatite and aplite veins that are more typical of the main part of the batholith. The porphyritic granite contains small local inclusions of partially digested biotite schist and one large inclusion of folded migmatite with a meter-scale Z-symmetry fold plunging gently to the west.

131.6 Return to vehicles; turn around and retrace route down Echo Trail toward Ely.

144.2 Junction of route 88 with U.S. 169; turn right (west).

144.5 U.S. Forest Service Voyageur Visitor Center. Pull into parking area (if open); REST STOP prior to long trip home.

This ends the formal road log for field trip 9.

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GEOLOGY OF THE KEWEENAWAN (UPPER PRECAMBRIAN) BEAVER BAY COMPLEX IN THE VICINITY OF SILVER BAY, MINNESOTA

by

James D. Miller, Jr.
Minnesota Geological Survey
University of Minnesota
St. Paul, MN 55114

INTRODUCTION

A thick (2.5-7 km) sequence of dominantly basaltic plateau lavas, mafic intrusions, and minor interflow sedimentary rocks of the Keweenawan Supergroup (Morey and Green, 1982) underlies most of Minnesota's Lake Superior shoreline (Fig. 1). These and related rocks around western Lake Superior were formed during the development of the Midcontinent rift about 1.1 b.y. ago (Van Schmus and others, 1982). The volcanic rocks, which are referred to as the North Shore Volcanic Group (NSVG) (Goldich and others, 1961), are typical continental tholeiites (Green, 1977).

Concomitant with the accumulation of the lavas, large volumes of magma were repeatedly emplaced within and beneath the volcanic edifice. The multiple intrusions of troctolitic, gabbroic, anorthositic, and granitic rocks which underlie the NSVG (Fig. 1) comprise the Duluth Complex (Weiblen and Morey, 1980). Although fewer large intrusions occur in the upper portion of the volcanic pile, a significant concentration occurs along the lakeshore in the vicinity of Silver Bay, approximately midway between Duluth and the Canadian border (Figs. 1 and 2). Because this group of hypabyssal to plutonic gabbroic intrusions are stratigraphically, structurally, and compositionally different from most Duluth Complex intrusions, it is distinguished as the Beaver Bay Complex (Grout and Schwartz, 1939). From the lakeshore, the Beaver Bay Complex extends approximately 30 km to the north-northeast where it becomes covered by thick glacial till (Fig. 1). Aeromagnetic and gravity anomalies over this covered area indicate a high ratio of intrusions to volcanic host rocks (Chandler, 1986) and imply that the Beaver Bay Complex is gradational into the Duluth Complex.

Geologic mapping in the Silver Bay, Split Rock Point NE and the Illgen City 7.5' quadrangles (Fig. 2) was initiated 2 years ago by the Minnesota Geological Survey in conjunction with the U.S. Geological Survey's COGEOMAP program. This ongoing project has elucidated much of the volcanic and intrusive history of this unique part of the Keweenawan section. The field trip is designed to show examples of the rock types which make up the Beaver Bay Complex and show evidence of their intrusive history and mode of emplacement.

GENERAL GEOLOGY

The NSVG units which host the Beaver Bay Complex are dominantly flows of tholeiitic basalt to basaltic andesite, but also include arkosic interflow units and several thick (≤100 m) rhyolite flows (Green, 1972, 1982a). Though skewed toward basalt, the volcanic rocks define a bimodal compositional range characteristic of rift environments. The typical shallow lakeward dip of most NSVG units is disrupted in this area due to faulting coeval with intrusion of the Beaver Bay Complex, which recent mapping shows was emplaced in three major events (Fig. 2). Each event produced a unique suite of rock types reflecting different parent magmas and modes of emplacement. In order of decreasing age, these intrusive suites are the Lax Lake gabbro, the Beaver River diabase, and the Beaver Bay gabbro (Fig. 2). The Beaver Bay Complex also includes several minor diabase intrusions whose genetic relationship with the major suites is unclear.

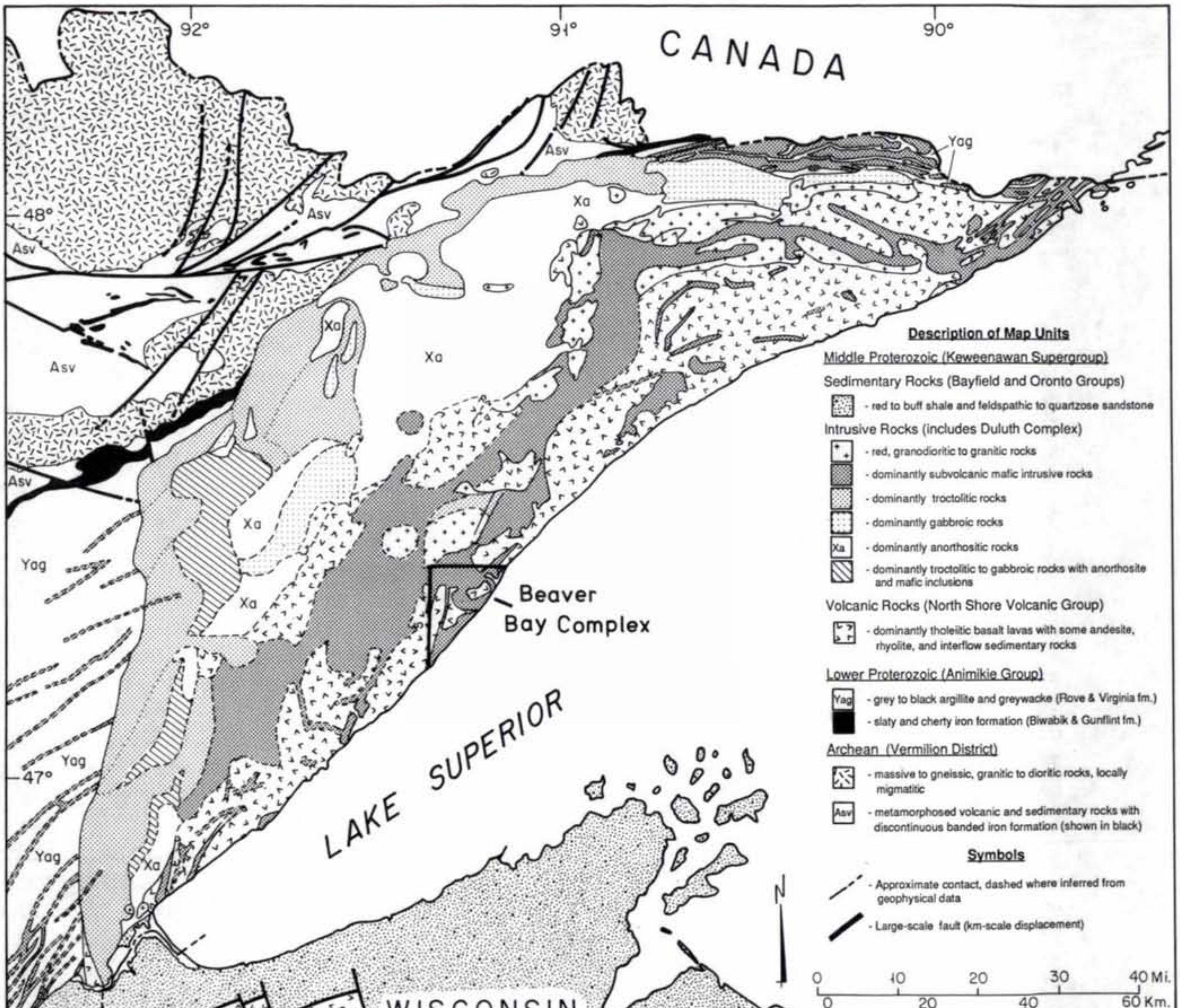

Figure 1. Generalized geology of northeastern Minnesota. Outline shows area of Figure 2. Compiled from Minnesota Geological Survey 1:250,000-scale map atlases of East-central Minnesota (Morey and others, 1981), the Two Harbors sheet (Green, 1982b), the Hibbing sheet (Sims and others, 1970), and the International Falls sheet (Southwick and Ojakangas, 1979). The geology of the glacial till-covered, southern half of the Duluth Complex is based on new interpretations of high-resolution aeromagnetic data (Chandler, 1986, and in preparation).

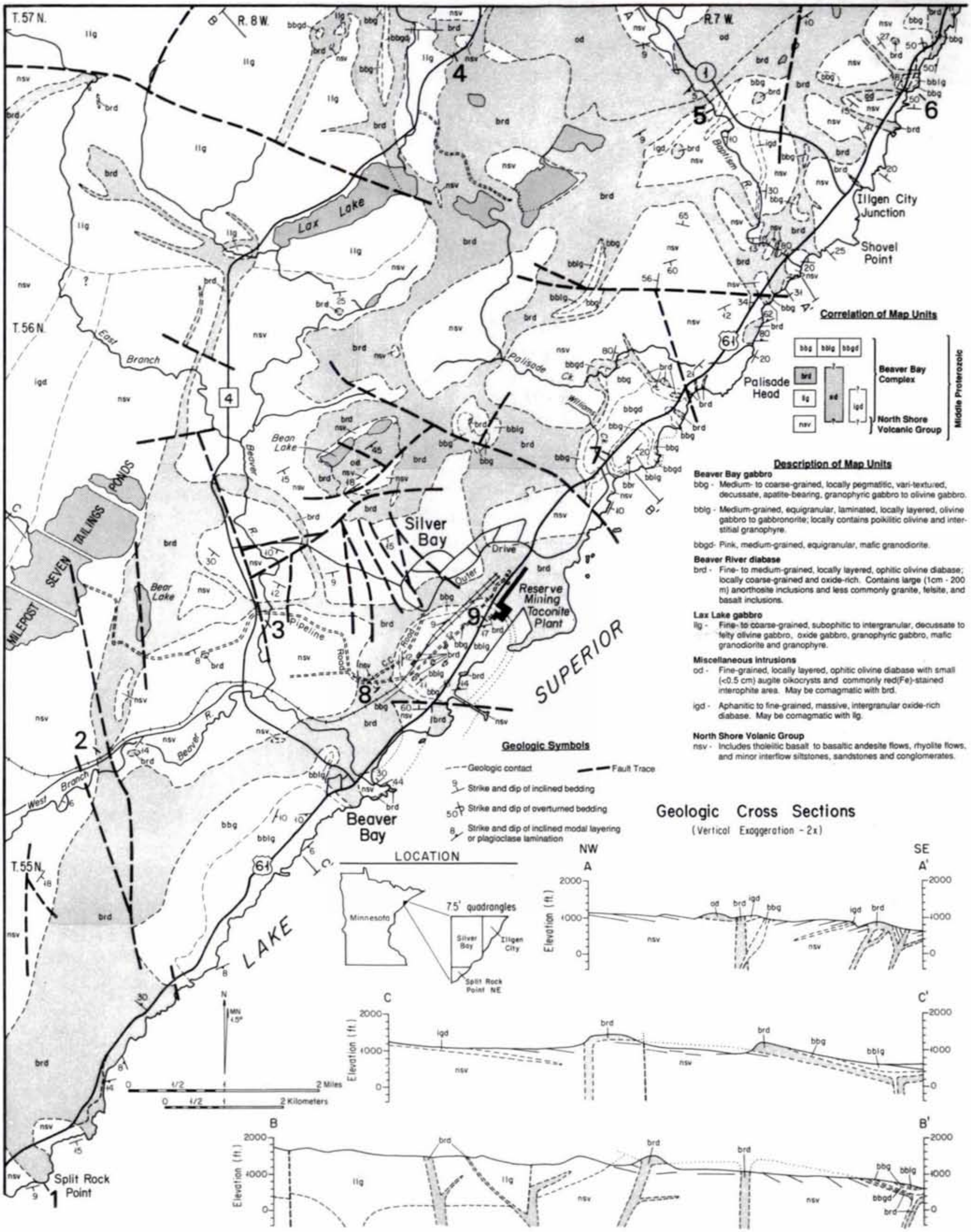

Figure 2. Geology of the Beaver Bay Complex in the vicinity of Silver Bay, Minnesota showing field trip stop locations (1-9). The geology is compiled from mapping in 1985 and 1986 by Jim Miller, Colin Reichhoff, Jayne Reichhoff, Steve Shank, Bernhardt Saini-Eidukat, Terry Boerboom, Dusty Early, and Daniel Holm and also from maps by Green (1982a and unpublished maps), Gehman (1957), and Grout and Schwartz (1939).

Lax Lake Gabbro

Subophitic olivine gabbro, oxide-rich gabbro, granophyric gabbro, and mafic granodiorite of the Lax Lake gabbro are the oldest intrusive rocks in the area (Stop 4). Intrusive contacts with the volcanic rocks have not been found, but dikes of Beaver River diabase chilled against the Lax Lake are commonly observed. The Lax Lake gabbro underlies a subdued topography northwest of Lax Lake (Fig. 2). Aeromagnetic data imply that these rocks are the southeastern portion of a larger gabbroic intrusion centered within an area of thick glacial cover (Chandler, 1986).

Most gabbroic rocks of the Lax Lake suite are noncumulates displaying a fine- to coarse-grained, decussate, intergranular to subophitic texture. Subophitic to prismatic augite (En43-34:Fs17-25:Wo35-41) and lath-shaped, strongly zoned plagioclase (An75-30) are ubiquitous. They are joined by extensively altered olivine (≤Fo59) in relatively magnesian rocks and by apatite and abundant titanomagnetite and ilmenite in more iron-rich rocks. Low-Ca pyroxene is rare in Lax Lake gabbro rocks. Interstitial granophyre ranges in mode from 5% to 20% in most gabbroic rocks to more than 80% in granodiorite which may also contain hornblende and prismatic ferrohedenbergite (En5:Fs49:Wo46).

Beaver River Diabase

Dikes and sills of Beaver River diabase are the most pervasive intrusions in the Beaver Bay Complex and underlie most of the high ground in the area (Fig. 2; Stops 1-6, 8). Where steep diabase dikes intrude volcanic rocks, they tend to occur in an orthogonal set oriented north-northeast and east-southeast. Dikes emplaced in the Lax Lake gabbro typically have irregular shapes and orientations. The dikes commonly pass into thick (≤ 100 m) sills (Stop 2) which form prominent flat-topped hills.

The Beaver River diabase is typically fine- to medium-grained, locally layered, ophitic olivine gabbro but grades to coarse-grained, oxide-rich subophitic gabbro in the interiors of thick dikes and sills. Plagioclase in the groundmass and as locally common phenocrysts (Stop 2) is typically labradoritic (An75-50). Olivine (Fo60-30), which comprises 5% to 25% of the diabase, is typically granular but locally has a poikilitic habit (Stops 8 and 9). Near the margins of Beaver River intrusions olivine isomodal layering is commonly developed. Oikocrysts of augite (En47-35:Fs15-27:Wo37-41) are ubiquitous and are commonly 2-5 cm across. Anhedral granular iron oxides and some pigeonite (En38:Fs53:Wo9) become abundant in more iron-rich rocks.

The diabase intrusions are unique in that they contain abundant inclusions of anorthosite, some as much as 100 m in diameter. The inclusions tend to be concentrated in the lower parts of sills (Stops 1 and 2). Typically, they are coarse-grained, consist almost entirely of calcic plagioclase (An 54-80; Morrison and others, 1983), and are commonly tectonized. Inclusions of partially assimilated, medium-grained granite and aphanitic felsite occur along with anorthosite in a less common phase of the Beaver River diabase that appears to have been intruded before the main emplacement event (Stops 2 and 3). The basal portions of the diabase sills and the underlying volcanic rocks are commonly intruded by granophyre dikes, which may have been generated by partial melting of the volcanics (Stop 2).

Beaver Bay Gabbro

The iron-rich Beaver Bay gabbro, the youngest intrusive unit in the area, occurs as numerous, concentrically zoned bodies and as irregularly shaped masses (Fig. 2; Stops 5-9). Because all Beaver Bay gabbro intrusions occur within or adjacent to Beaver River diabase dikes and sills, both they and the Beaver River intrusions were apparently emplaced through the same crustal conduits. The abundance of Beaver River diabase inclusions, which are especially common in the intrusion centered south of Silver Bay (Stops 8 and 9), and the lack of any chill at the margins of the Beaver Bay gabbro intrusions (Stops 6 and 8) indicate that the gabbroic magmas intruded soon after the diabase had crystallized.

Zoned intrusions of Beaver Bay gabbro are particularly common along the lake shore (Fig. 2). Most grade abruptly from a margin of coarse-grained, vari-textured granophyric gabbro to an interior of medium-grained, laminated, locally layered olivine gabbro and less common gabbronorite (Stops 6-8). Mineral compositions tend to be most magnesian in the marginal gabbro (Fo36; En41-36:Fs21-27:Wo38-37) and become progressively iron-rich upsection and inward through the laminated gabbro (Fo35-2; En40-4:Fs23-53:Wo37-43). The intrusion northeast of Silver Bay (Williams Creek body, Fig. 2) also contains a signi- ficant amount of medium-grained, mafic granodiorite to quartz monzodiorite (gd, Table 1), which is gradational with the marginal gabbro but transgresses the zoned structure of the body (Fig. 2; Stop 7). Several irregularly shaped Beaver Bay gabbro intrusions are composed of medium- to coarse-grained, granophyric olivine gabbro, which locally grades into mafic granodiorite and resembles the marginal gabbro of zoned intrusions in mineralogy and texture (Stop 5).

Gehman (1957) observed dikes of coarse-grained gabbro intruding laminated gabbro in the two large shoreline intrusions southwest of Silver Bay. He concluded that dike rock was correlative with the coarse marginal gabbro (his Black Bay gabbro) surrounding the laminated gabbro (his Beaver Bay ferrogabbro), and interpreted the marginal rock as a younger ring-like intrusion emplaced between the Beaver River diabase and the laminated gabbro. However, the consistent concentric spatial relationships of the two rock types (Fig. 2), their typically gradational contact relationships (Stops 6-8), and their nearly continuous, differentiated, compositional range (Figs. 3 and 4; see below) suggest that the coarse marginal gabbro is comagmatic with the laminated internal gabbro. We suggest that the marginal gabbro formed in a stagnant boundary layer around (flow-?)laminated cumulates (Shank, 1987). The gabbro dikes noted by Gehman (1957; Stops 6 and 8) may have formed from late, minor intrusions or from remobilization of magma from within the intrusion.

Other Minor Intrusions

The Beaver Bay Complex also contains several minor diabase intrusions, of which there are three major types. One type is an aphanitic to fine-grained, massive, locally pyritic, intergranular diabase (igd; Fig.2, Table 1). This rock type occurs in a 15- to 20-m-thick, gently east-southeast-dipping sill west of the Milepost Seven Tailings Basin (Fig. 2) and in two 10- to 15-m-thick, gently northwest-dipping sills exposed in the Baptism River (Fig. 6, Stop 5C). Another type is a fine-grained, iron-stained, slightly plagioclase-porphyritic ophitic diabase (od; Fig. 2,

Table 1) occurring in an extensive 55- to 65-m-thick near-horizontal sill (Stop 5A). The weathered inter-ophite groundmass of this diabase commonly displays a distinctive red color. A third diabase type is olivine-bearing and of a glomeroporphyritic, intergranular texture (gpd; Fig. 6, Table 1). It occurs in a 5-m-wide dike emplaced in the ophitic diabase sill just mentioned (Stop 5A).

PETROLOGY

Petrochemical and mineral chemical analyses of Beaver Bay Complex rock types have only recently been obtained and therefore only a cursory evaluation of their significance is presented here. Major element variations are represented by an AFM plot (Fig. 3) and minor and incompatible trace element variations are denoted by a TiO_2-Zr plot (Fig. 4). Also shown in Figures 3 and 4 are the composition fields of Keweenawan volcanic rocks. Representative whole rock analyses of Beaver Bay Complex rocks are listed in Table 1.

The mineralogy and whole rock chemistry of Lax Lake gabbro rocks define a broad range of compositions which overlap those of younger Beaver Bay Complex rocks (Figs. 3 and 4). Overall, Lax Lake gabbro rock types have compositions similar to low mg' tholeiitic basalt (transitional basalt of Green (1983)). Two notable exceptions to this are the Zr-rich, felsic composition of a mafic granodiorite/granophyre sample (C281, Table 1) and the titanium-rich composition of a hornblende alkali gabbro sample (C489, Table 1). Both samples are from the interior of the Lax Lake body and appear to be late siliceous differentiates. It is not clear whether the broad compositional range of the Lax Lake gabbro suite resulted from fractional crystallization within the Lax Lake magma chambers or from multiple intrusions of different composition magma. This is because the spatial relationships between various rock types and the overall shape of the Lax Lake body are obscured by generally poor exposure, a lack of internal structures, and post-crystallization faulting and diabase intrusion. The observance of abrupt and gradational changes in rock type suggest that the Lax Lake gabbro magmas were emplaced in multiple intrusive episodes but also experienced some post-intrusion fractionation.

Ophitic olivine diabase of the Beaver River suite is an olivine tholeiite characterized by mg' values (Mg/Mg+Fe+MnO in mole%) between 46-60% (Fig. 3) and low to intermediate incompatible element abundances (Fig. 4) similar to high mg' tholeiitic basalts . Oxide-rich diabase has mg' values as low as 39% (B319, Table 1). Although the Beaver River diabase is the most primitive of all Beaver Bay Complex intrusions , it is more evolved than many olivine tholeiite basalt flows in the NSVG (Figs. 3 and 4). Mineralogic and compositional variations within the larger Beaver River intrusions are indicative of tholeiitic (iron enrichment) differentiation (Fig. 3, Table 1).

The Beaver Bay gabbro suite is more iron-rich than the other Beaver Bay Complex rocks and most volcanic rocks of the NSVG (Figs. 3 and 4). The comagmatic relationship of the coarse marginal gabbro and the internal medium laminated gabbro is supported by the overlapping compositions of these rock types (Table 1, Figs. 3 and 4). Moreover, the chemistry of the marginal gabbro is suitable as a parent magma to cumulates represented by the laminated gabbros. Clearly, however, the marginal gabbro is itself an evolved rock and was probably derived from the fractionation of a more primitive magma at depth. Given the close temporal and spatial relationships between the Beaver Bay gabbro and Beaver River diabase suites (Fig. 2) and their somewhat colinear fractionation trends (Fig. 3), it seems plausible that the Beaver Bay gabbro parent magmas are later differentiates of the same magmas which produced the Beaver River diabase. Presumably, however, this differentiation occurred at a deeper crustal level than is presently exposed.

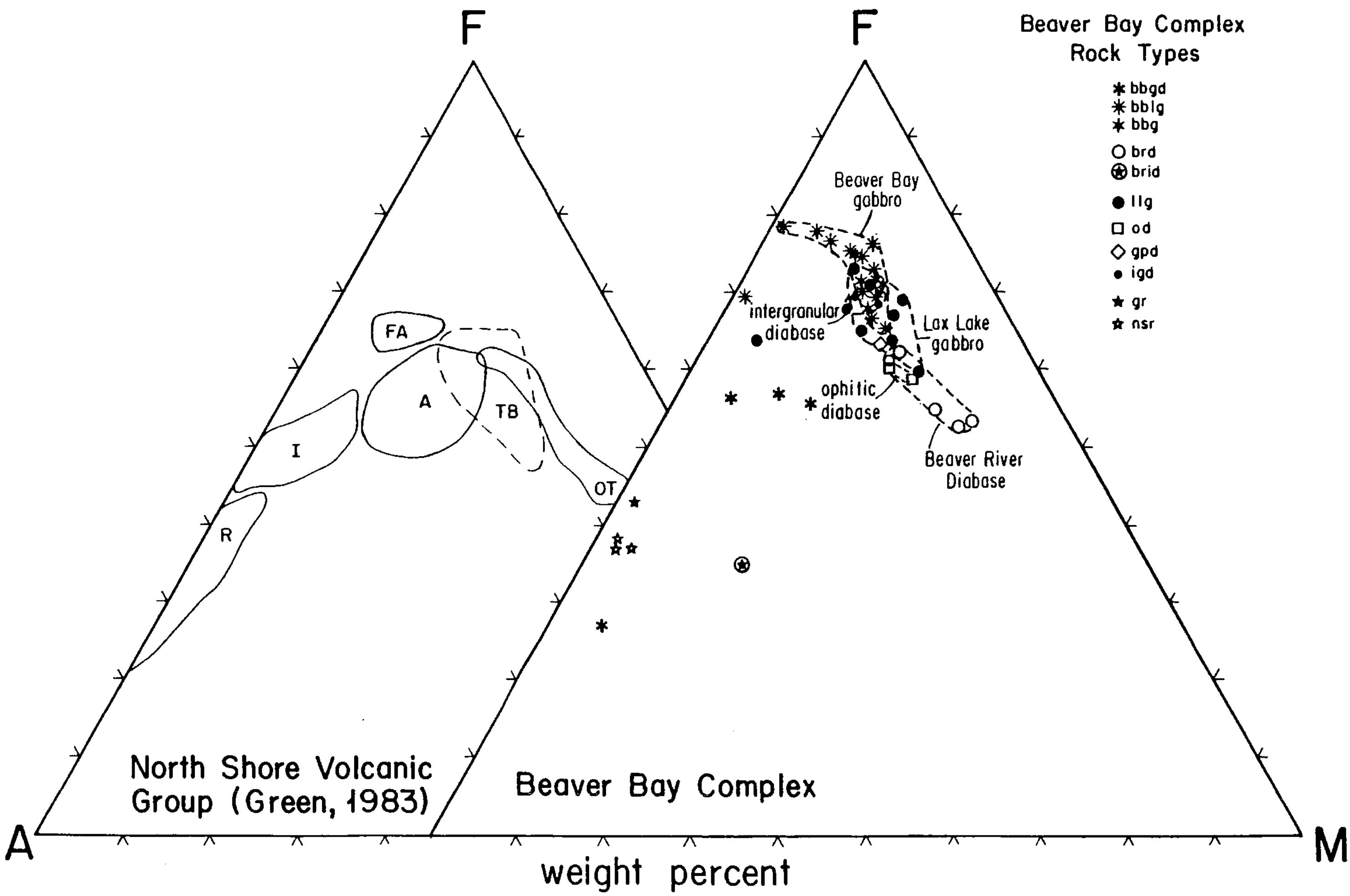

Figure 3. AFM (Na_2O+K2O - Fe_2O_3+MnO - MgO) diagrams comparing the compositional fields of NSVG volcanic rocks and Beaver Bay Complex rocks. Volcanic rock data from Green (1983); OT-olivine tholeiite, TB-transitional (Fe-Ti) basalt, A-andesite, FA-ferroandesite, I-icelandite, R-rhyolite. Beaver Bay Complex data from this study, Shank (unpublished data), Green (1982a and unpublished data), and Gehman (1957); bbg,bblg,bbgd-Beaver Bay gabbro, laminated gabbro, and granodiorite to quartz monzodiorite, respectively; brd,brid-Beaver River ophitic olivine diabase and inclusion-rich diabase, respectively; llg-Lax Lake gabbro; od-ophitic diabase; igd-intergranualar diabase; gpd-glomeroporphyritic diabase; gr-granite inclusion in brid; nsr-NSVG rhyolite flows. Composition fields of gabbroic compositions of each rock suite are outlined.

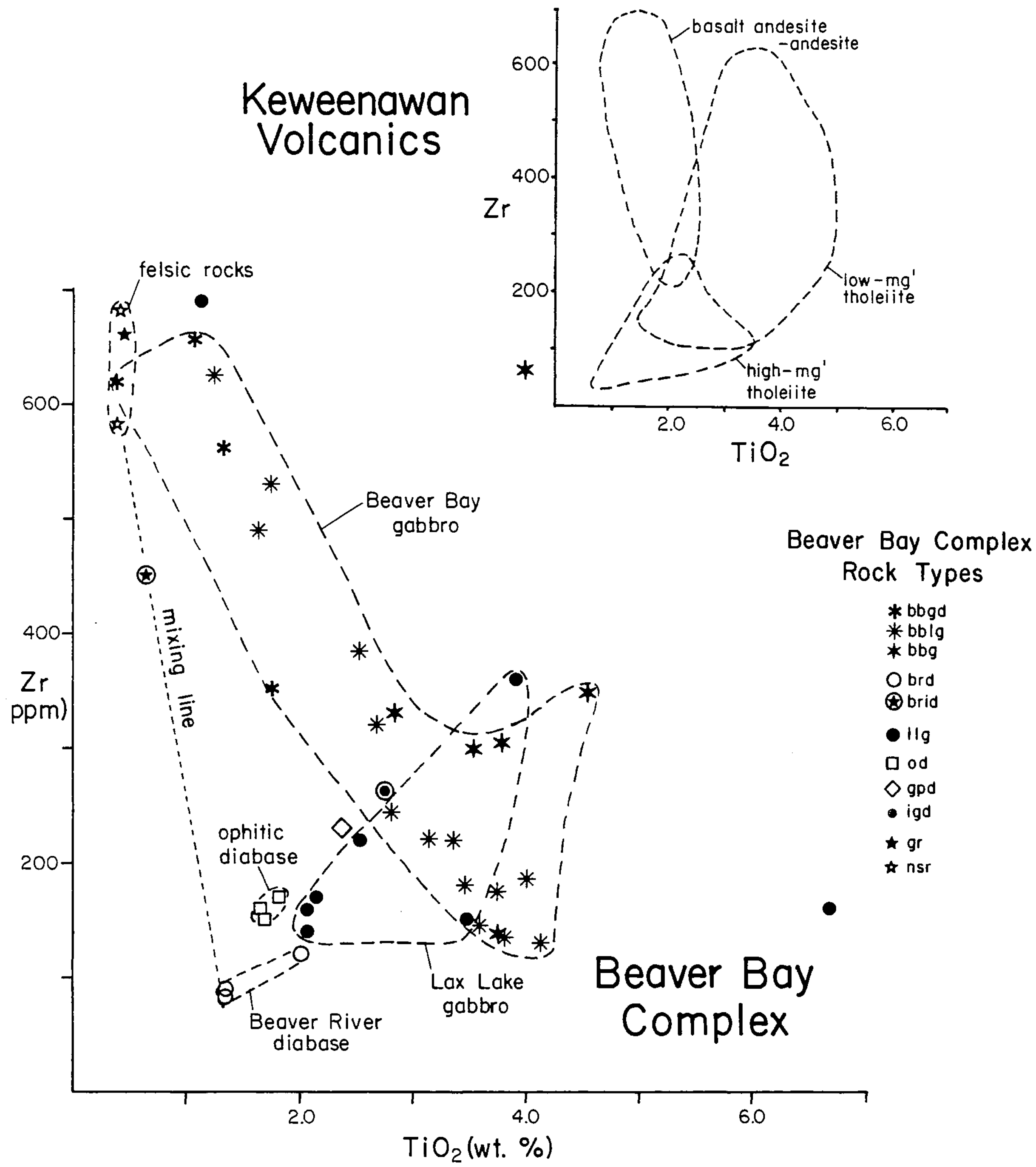

Figure 4. Plot of Zr and TiO_2 abundances in Beaver Bay Complex rocks and comparison to composition fields of Keweenawan volcanic rocks. Beaver Bay Complex data from this study, Shank (unpublished data) and Green (unpublished data). Composition fields are outlined for each rock suite except for some anomalous compositions which are labeled. Mixing line shows possible mixing relationship between felsic rocks and primitive Beaver River diabase to give felsic inclusion-rich diabase composition (brid; A275C, Table 1). Volcanic composition fields are distinguished for high mg' (>45%) tholeiitic basalt (SiO_2<52%), low mg' (<45%) tholeiitic basalt, and basaltic andesite to andesite (SiO_2=52-65%) and are defined by over 500 analyses from various published sources.

TABLE 1: CHEMICAL ANALYSES OF SELECTED ROCKS FROM THE BEAVER BAY COMPLEX

	Lax Lake Gabbro			Beaver River Diabase			Beaver Bay Gabbro						Miscellaneous Intrusions		
Rock Type *-	gp/gd	hag	g	od	oxd	ird	g	g	gp	lpg	lg	gd	od	igd	gpd
Sample # -	C281	C489	C491	B326	B319	A275C	B309B	SB28†	SS 1B°	A386F	F237†	C484	F256†	B301A	F257†
SiO_2	60.6	43.5	48.0	47.8	48.9	67.4	51.3	47.4	65.7	47.2	53.5	57.2	50.2	49.7	50.9
TiO_2	1.12	6.71	2.06	1.32	2.01	0.65	2.83	3.99	1.33	3.14	1.64	1.74	1.81	2.67	2.38
Al_2O_3	11.2	12.0	15.0	15.7	15.4	12.0	12.1	12.8	12.1	13.2	10.6	13.0	16.0	12.4	15.1
$Fe_2O_3{}^t$	13.7	21.0	14.8	11.9	13.7	5.19	16.4	18.2	10.22	19.0	18.7	10.8	12.6	17.0	13.6
MnO	0.16	0.28	0.19	0.17	0.19	0.07	0.21	0.21	0.11	0.27	0.34	0.18	0.13	0.23	0.21
MgO	1.25	4.58	5.00	7.99	5.03	2.84	3.97	3.96	1.21	3.73	0.44	3.14	4.94	4.42	4.28
CaO	3.33	6.62	9.37	10.2	10.4	2.51	7.35	8.11	3.17	7.14	6.58	5.82	9.70	8.63	9.90
Na2O	3.87	3.10	2.76	2.09	2.62	4.09	2.60	2.40	3.23	2.97	3.19	3.01	2.62	2.55	2.74
K2O	2.77	1.42	0.74	0.36	0.61	2.96	1.31	0.92	3.47	0.71	1.78	2.53	0.71	0.97	0.81
P2O5	0.20	0.19	0.23	0.14	0.18	0.08	0.28	0.16	0.32	0.41	0.27	0.29	0.27	0.30	0.28
LOI	1.54	1.08	1.00	1.85	0.47	1.93	1.39	1.54	—	2.08	3.08	1.54	1.31	0.62	—
Total	100.0	100.6	99.3	99.6	99.6	99.9	99.9	98.2	100.9	99.9	98.6	99.4	98.0	99.7	99.1
mg'(mole%)	15.1	29.8	39.7	56.7	41.7	51.6	32.1	29.0	18.8	27.7	4.4	36.1	43.4	33.6	38.1
Trace Elements (ppm)															
Cr	30	20	110	170	120	70	30	24	<5	20	10	30	100	100	59
Co	30	70	70	70	60	20	60	56	15	70	8	40	45	60	46
Ni	10	10	80	170	50	60	90	43	1	10	440	20	110	50	43
Rb	<10	40	30	10	20	90	40	30	87	30	60	70	30	40	20
Ba	790	270	240	130	180	720	380	160	894	270	620	670	360	290	239
Sr	120	250	200	200	210	140	150	360	180	170	190	260	260	150	245
Y	110	20	30	30	30	90	50	80	73	50	80	50	30	50	47
Zr	690	160	160	80	120	450	330	490	562	220	490	350	170	260	230
Nb	60	50	30	20	30	40	40	50		30	50	30	20	30	
Location T.N.S or **stop**	57.8.34	57.8.35	**4**	**5B**	56.7.9	**3**	**5E**	**7**	55.8.13	**6**	**7**	56.8.1	**5A**	**5C**	**5A**

* Rock types: gp-granophyre, gd-granodiorite, hag-hornblende alkali gabbro, g-gabbro, od-ophitic diabase, oxd-iron oxide-rich diabase, ird-felsic inclusion-rich diabase, lpg-laminated poikilitic olivine gabbro, lg-laminated gabbro, igd-intergranular diabase, gpd-glomeroporphyritic diabase.

†-Miscellaneous XRF and INA analyses by Green (unpublished data); °- DCP analyses (UofMn) by Shank (unpublished data); all others recent XRF analyses by XRAL(Don Mills, Ont.).

Because ilmenite and Ti-magnetite are cumulus phases in the Beaver Bay laminated gabbros, the strong negative correlation of Zr and Ti defined by these rocks (Fig. 4) would appear to be a differentiation trend resulting from oxide fractionation. However, the projection of the trend toward felsic rock compositions and textural evidence of silicate liquid immiscibility (Stops 5E,F and 8) suggest that this trend may reflect liquid "unmixing". Both processes are probably involved. Shank (pers. comm. 1987) and Olmsted and Yuchniewicz (1986) have noted that the major element compositions of the Beaver Bay gabbro plot near the silicate liquid immiscibility gap (Roedder and Weiblen, 1971). Although either processe can explain local granophryric segreations in the Beaver Bay gabbro, it does not seem possible to generate the great abundance of granodiorite in the Williams Creek body (Fig. 2, Stop 7) from a gabbroic magma by either crystal fractionation or liquid unmixing. The petrogenetic relationships of the minor diabase bodies with major Beaver Bay Complex intrusions are unclear. The intergranular diabase sill is mineralogically, texturally and compositionally similar to some Lax Lake gabbro rock types (Figs. 3 and 4) and therefore may be an offshoot of that intrusion. The glomeroporphyritic diabase dike (Stop 5A) also has compositional affinities to the Lax Lake gabbro (Figs. 3 and 4), but it is texturally distinct from this all other Beaver Bay Complex rock types. However, the very fine grain size of the intergranular diabase sills suggests that they were emplaced at shallower depths than the Lax Lake gabbro. Perhaps the intergranular diabase sills are comagmatic with high-Ti basalt flows, in which case they would be considerably older than the major Beaver Bay Complex intrusions.

The oxidized ophitic diabase sill in the northeastern portion of the field area (Fig. 2) is texturally and mineralogically identical to finer-grained portions of Beaver River diabase suggesting that they are comagmatic. However, for similarly textured diabase samples, the composition of ophitic diabase is considerably more evolved (Ni=40-110, TiO_2=1.65-1.8, Zr=150-170) than Beaver River diabase (Ni=170-200, TiO_2=1.32-1.36, Zr=80-90). Instead, the chemistry of the ophitic diabase is more similar to the coarse-grained oxide-rich gabbro found in the interiors of thick Beaver River intrusions (e.g., B319, Table 1). Because of such compositional differences and the unique alteration and consistently fine-grained texture of the ophitic diabase, we suggest that it is a distinct intrusion from the Beaver River dikes and sills. Perhaps it is comagmatic with one of the ophitic basalt flows occurring in the NSVG sequence.

STRUCTURE

The rocks of the Silver Bay area have been tilted slightly southeastward toward the axis of the Lake Superior syncline (White, 1966), and also have been deformed by faulting. This faulting was both coeval with and later than the emplacement of the Beaver Bay Complex. Faulting that accompanied the intrusion of the Beaver River diabase dikes and sills produced the greatest disruption of the volcanic sequence. The deformation caused by the emplacement of the Lax Lake gabbro is unclear because the surrounding volcanic rocks are poorly exposed. Negligible deformation accompanied the intrusion of the Beaver Bay gabbro bodies because they were emplaced along previously formed Beaver River diabase conduits.

Fault traces (Fig. 2) are recognized by (1) apparent offsets of geologic units, particularly flows, (2) changes in strike of tilted volcanic units, (3) extensive, narrow topographic depressions, and (4) rare sheared exposures along the lakeshore. Except for the steep fault exposed along the lakeshore just south of Palisade Head (Fig. 2), the dip of the various faults can not be determined. Throw on most faults appears to be minor (< 50 m). Where slip sense can be inferred, it is typically left lateral. Two dominant directions of faulting are recognized in the area - a north-south to north-northwest set and a less common east-west to east-southeast group. Both sets cut and are truncated by Beaver River diabase indicating that a similar stress regime existed during and after its emplacement. The NE to NNE trend of most diabase dikes, indicative of NW extension, and the dominant NNE and ESE fault orientations, perhaps indicative of shear, are consistent with rift models where the maximum tension is oriented NE-SW (Weiblen and Morey, 1980).

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ROADLOG AND STOP DESCRIPTIONS

Field Trip Leaders: Jim Miller, Paul Weiblen, and John Green

Nine field stops (Fig. 2), which display the salient features of the Beaver Bay Complex, are described below. Permission for access is required for stops situated on private and some mining company property (Stops 5, 8 and 9). The stops are organized for a 1.5-day field trip, but a small group could visit most localities in a single day.

-DAY 1-

The field trip starts at Split Rock Lighthouse State Park, 45 miles north of Duluth on U.S. Highway 61. A state park permit is required. Park at the history center lot and head east toward lake overlook, north of the lighthouse.

STOP 1. Split Rock Lighthouse State Park; Beaver River diabase sill with anorthosite inclusions. Exposures around the base of the lighthouse (Area A) and to the southwest along the shoreline (Area B) will be investigated.

AREA A. Outcrops of fine-grained, ophitic olivine diabase typical of much of the Beaver River diabase are exposed just northeast of the lighthouse atop a sheer 30-m-high sea cliff. The centimeter-wide augite oikocrysts obvious here are typical of the lower portion of this diabase sill, which dips gently (<15°) into the lake. The prominent point just to the northeast (Rusty Point) is held up by a very large (>200 m) inclusion of medium-grained granite lying at the base of the sill. Split Rock Point is held up by a smaller (≥30 m) anorthosite inclusion, which is exposed around the base of the lighthouse.

The anorthosite inclusion displays meter-scale modal layering of coarse-grained granular, noritic anorthosite (20% Hyp + 80% Pl) and anorthosite (>99% Pl). The steeply dipping layers are cut by thin dikes of medium-grained, granular noritic anorthosite. Layering and mineralogy of this and other anorthosite inclusions are similar to anorthositic units of many layered mafic intrusions (e.g., Stillwater and Bushveld Complexes) but differ from Duluth Complex anorthosites which are rarely layered, are compositionally evolved, and rarely contain cumulus hypersthene. Isotopic and trace element compositions of these crustal xenoliths are ambiguous as to whether they are syn- or pre-Keweenawan in age (Morrison and others, 1983).

AREA B. Follow the footpath south to the pumphouse on the lakeshore. Here, black, massive basalt is exposed in wavewashed outcrops. The brecciated, amygdaloidal top of this basalt flow is exposed in the rubbly bluff to the northeast in the direction of the lighthouse. Laminated siltstone in the matrix of the flowtop dips gently toward the lake.

Carefully continue northeast over some large boulders of ophitic diabase to observe the base of the Beaver River sill conformably overlying the basalt flow top. The amygdaloidal basalt and siltstone are clearly metamorphosed by the diabase, and many inclusions of anorthosite are obvious in the sill. Note that the diabase is chilled against the basalt but not against the anorthosite inclusions. The abundance of inclusions causes irregular columnar jointing in the diabase. Numerous boulders along the base of the cliff display the textural and mineralogical varieties of anorthosite inclusions present. Looking to the northeast, one can see that the vertically layered inclusion beneath the lighthouse extends to lake level.

Return to U.S. 61 and head about 5 miles northeast to the town of Beaver Bay. Turn left on Lake County Road 4 (Lax Lake Road). Immediately after crossing Beaver River (1.5 miles) turn left (west) on airport road. Proceed about 1.8 miles to clearing between road and railroad tracks to the north (right). Head north to railroad cut.

STOP 2. Reserve Mining RR tracks; Beaver River diabase dike passing into a sill which contains inclusions of felsic inclusion-rich diabase.

The fanning pattern of columnar jointing exposed in this railroad cut through Bear Lake Ridge reflects the transition from a dike flanking the west side of the ridge to a sill holding up its eastern slope. The north-northeast-trending, near-vertical dike, which is over 20 km long and averages about 150 m wide, defines the western margin of the Beaver River diabase dike and sill network in this part of the Beaver Bay Complex (Fig. 2). The rock type here is a fine-grained ophitic olivine diabase noticeably lacking anorthosite inclusions.

The larger railroad cut 150 m to the east reveals the irregular, well-jointed base of the diabase sill overlying the amygdaloidal flow-top breccia of a deeply weathered ophitic basalt. (CAUTION, OUTCROP FACE IS UNSTABLE) Abundant weathered anorthosite inclusions are evident in the diabase. Several granophyre dikes observed in the footwall of the sill were probably generated by partial melting of the basalt. This sill holds up the extensive 120-m cliff visible south of the Beaver River.

Two types of diabase are exposed in the upper ledge of the railroad cut which is accessible from the east. The more common type is the same fine-grained ophitic olivine diabase observed in the dike, but it contains scattered anorthosite inclusions and locally is plagioclase porphyritic. Exposed in the center of the cut is a dense, black, aphanitic, intersertal diabase charged with quartz and feldspar (xeno?)crysts and numerous large anorthosite, granite, felsite, and basalt inclusions. The inclusion-rich intersertal diabase appears to be a large (≈ 40 m) inclusion within the ophitic diabase. Along the eastern margin of the inclusion, columnar jointing and a chilled margin are developed in the ophitic diabase adjacent to a sharp, steep contact with the inclusion-rich diabase. A more ambiguous relationship is observed along the western contact.

The inclusion-rich diabase, which is locally observed near the margins of ophitic olivine diabase intrusions, probably represents early intrusions of anorthosite- (and granite-)bearing Beaver River magmas which locally incorporated and partially assimilated numerous volcanic inclusions during the brittle development of conduits. We will inspect the inclusion-rich diabase more thoroughly at Stop 3.

Return east to Lax Lake Road and turn left. Proceed 1.1 miles to pipeline road, turn right and park at gate. About 100 m east of gate, head south to clearing below road.

STOP 3. Pipeline road over the Beaver River. Inclusion-rich, contaminated phase of Beaver River diabase.

Three interconnected dikes of aphanitic to fine-grained, inclusion-rich diabase, intrusive into amygdaloidal ophitic basalt, are exposed in low outcrops in the bulldozed clearing (Fig. 5). The diabase has distinct marginal and interior phases in terms of their texture and inclusion content.

The thin southwest dike and the margins of the two wider masses (ipd, Fig. 5) are composed of black, aphanitic to fine-grained, slightly amygdaloidal, intergranular diabase with felty plagioclase and anhedral granular pyroxene and oxide. The marginal diabase is slightly Pl-porphyritic and locally contains meter-sized blocks of anorthosite and basalt, but it is distinctly free of granite or felsite inclusions. The marginal diabase is chilled against the basalt inclusions.

Typically within 1.5 m of the diabase-basalt contact, this marginal intergranular diabase abruptly becomes lighter in color, more amygdaloidal, and enriched in quartz and K-feldspar megacrysts (ird, Fig. 5). Inclusions of pink, medium-grained granite and red, aphanitic felsite, in addition to basalt and anorthosite, are very common in the interior of both wide dikes. The interior diabase is chilled against all but the anorthosite inclusions. In outcrop and in thin section, the interior diabase appears to have partially assimilated many of the granite and felsite inclusions. The diabase matrix has a variolitic intersertal texture composed of acicular, commonly radiating plagioclase, microgranular oxide and mafic minerals, and a cryptocrystalline matrix. Quartz and K-feldspar (xeno?)crysts and granite and felsite xenoliths are typically rounded to amoeboidal and mantled by cryptocrystalline material.

Do the marginal and interior phases of the diabase represent flow differentiation of inclusions and subsequent assimilation or do they represent composite intrusions? If flow differentiation, why does anorthosite occur in the margins? In either case, the lack of olivine and ophitic texture in even the least contaminated marginal diabase questions whether the parent magma of this early intrusive phase was comagmatic (albeit contaminated) with the younger and more abundant ophitic olivine diabase. As illustrated in Figures 3 and 4, the whole rock composition of an inclusion-rich diabase sample from this area (brid, Figs. 3 and 4; A275C, Table 1) is compatible with its being derived from a primitive (low-mg') Beaver River diabase magma which assimilated and included felsic material.

Go approximately 6.2 miles north and east on Lax Lake Road. Service road on right provides inland access to Tettegouche State Park. (Hiking trails off the service road pass over very hilly terrain underlain by Beaver River diabase. Several overlooks on large anorthosite knobs (e.g., Mt. Baldy) provide spectacular vistas of the Tettegouche lakes, the Baptism River valley, and Lake Superior.) Continue 0.7 mile to first road cut on northwest side of road.

Figure 5. Outcrop geology map of Field Stop 3. Shows outcrop areas of inclusion-rich Beaver River diabase (ird, dark shade), inclusion-poor Beaver River diabase (ipd, light shade), and ophitic basalt (nsob, outlined). Large (>1 m) inclusions of anorthosite (black areas), basalt (outlined, no flag), felsite (outlined, f-flag), and granite (outlined, g-flag) in the diabase are also shown.

STOP 4. Lax Lake Road; Lax Lake gabbro, Beaver River diabase, and hornfels basalt exposures.

The southwesternmost roadcut displays a common variety of Lax Lake gabbro, a medium coarse-grained, moderately granophyric, equigranular, subophitic gabbro. It consists of 70% plagioclase laths (An67-31), 20% augite oikocrysts (En40:Fs20:Wo40), 5% subpoikilitic oxy-exsolved Ti-magnetite and some ilmenite, and 5% granophyric, apatite-bearing mesostasis. Its whole rock chemistry (C491,Table 1) is equivalent to moderately-evolved (mg'= 39.7%) tholeiitic basalt, but it is one of the more primitive compositions of the Lax Lake gabbro suite (mg'= 46%-15%).

The Lax Lake gabbro is intruded by Beaver River diabase along a moderately northeast-dipping contact passing between this and the next roadcut to the northeast. The contact is exposed on the ridge behind the swamp and on the hillslope south of the road. A more accessible exposure of anorthosite-bearing diabase chilled against medium-grained gabbro can be observed in a low roadcut on the north side of Lax Lake Road, 2.9 miles west of this roadcut.

The next roadcut 250 m to the northeast shows the diabase to be medium fine-grained, subophitic, olivine-rich, and slightly plagioclase-porphyritic. Locally, it displays olivine-layering dipping 30°-40° NNE. Such layering is common in the margins of Beaver River dikes. The olivine diabase contains several inclusions, the most common and interesting of which is a plagioclase- porphyritic, subophitic, leucocratic olivine gabbro of obscure origin. Rocks of this type have not been observed in the Lax Lake gabbro.

Massive, sparsely amygdaloidal, very fine grained granoblastic basalt is exposed in the next roadcut, 210 m to the northeast. A thin diabase dikelet, probably an offshoot of the Beaver River intrusion, cuts the basalt at the southwest end of the roadcut. A similar-looking rock is exposed in a low, long roadcut on the opposite (SE) side of the highway, but closer inspection reveals that it is slightly plagioclase-porphyritic, nonamygdaloidal, and displays a primary subophitic texture in thin section. This is a basal chill zone of Beaver River diabase that also crops out on the hillslope to the south.

Continue about 2 miles northeast on Lax Lake Road to Minnesota Highway 1 and turn right. After crossing the Baptism River, continue 0.8 mile to Valley Drive on right (SW). Stop at Y in road. Walk west (right fork) past a woodpile to log cabin (Bergin's) on bluff above Baptism River.

Stop 5 is on private property. Because this one area contains excellent exposures of several Beaver Bay Complex rock types, special permission for access was granted for this field trip, but will probably not be granted at other times. Therefore, other areas where these rock types can be observed are noted below.

STOP 5. Baptism River; Miscellaneous intrusions: ophitic diabase, glomeropor- phyritic diabase, ophitic olivine diabase with anorthosite inclusions (Beaver River diabase), intergranular diabase, and granophyric gabbro (Beaver Bay gabbro). Figure 6 shows the detailed geology of the stop and the six areas (A-F) which will be investigated. PLEASE USE CAUTION! The river often runs high and fast, especially during spring flooding.

AREA A. A foot trail from the Bergin cabin to the river's edge leads to a wall-like outcrop of a vertical, 5-m-wide diabase dike displaying exceptional columnar jointing (gpd, Fig. 6). The diabase is texturally and compositionally distinct from other Beaver Bay Complex rocks and therefore may have a unique petrogenesis. It consists of plagioclase, augite, ilmenite and altered olivine in a fine-grained, intergranular texture with glomerophenocrysts of medium-grained plagioclase, some olivine, and rare pigeonite. It has an intermediate mg' value (mg'=38.1%, F257, Table 1; gpd, Fig. 3) and is moderately enriched in incompatible elements (gpd, Fig. 4). The glomeroporphyritic diabase is more evolved than most Beaver River ophitic diabase and less evolved than most Beaver Bay gabbro compositions (Figs. 3 and 4).

The dike intrudes fine-grained, ophitic diabase which is exposed in outcrops just northwest of the columnar-jointed dike (od, Fig. 6; F256, Table 1). The diabase contains augite ophites that are consistently less than 0.5 mm across and are surrounded by a reddish matrix. The matrix is composed of plagioclase, iron oxide, altered (iddingsite) olivine, biotite altering to chlorite, and an amorphous brown mesostasis, and is apparently stained with cryptocrystalline iron oxide. Except for the reddish staining and more intense alteration of olivine, the texture and mineralogy of this diabase is very similar to the Beaver River diabase seen at Stop 1.

The ophitic diabase here is 25 to 30 m above the base of a shallow southeast-dipping sill (Fig. 6). In exposures 120 m upstream, the ophitic diabase displays a subtle layering dipping 5°SE which is manifested by variations in the amount of plagioclase enclosed in augite oikocrysts. The red staining and small ophite size of this diabase is pervasive throughout the sill, which can be traced to Bean Lake, 8.5 km to the southwest (Fig. 2) and to Victor Head, 7.5 km to the northeast. The high bluff south of Bean Lake and exposures east of Lax Lake Road near Stop 4 (Fig. 2) are good alternate locations for observing this red-stained ophitic diabase.

AREA B. Hiking downstream around a southward curve in the river and past a small tributary stream, one finds outcrops of Beaver River ophitic olivine diabase containing several anorthosite inclusions on both sides of the river. Again, note the sharp, unchilled contacts between diabase and anorthosite. The diabase displays the same mineralogy and ophitic texture as observed in area A and in the steep cutbank exposure just upstream, but the interophite mineralogy is much less altered and is not stained. Moreover, the composition of this diabase (B326, Table 1; mg'=56.7%, Zr=80ppm) is much more primitive than ophitic diabase sampled near Area A (F256, Table 1; mg'=43.4%, Zr=170ppm). As stated above, we interpret these observations as indicating that the ophitic diabase is an older intrusion than the Beaver River diabase. The contact between the ophitic diabase and this anorthosite inclusion-bearing Beaver River diabase is inferred to project through the break in exposure just upstream of this outcrop.

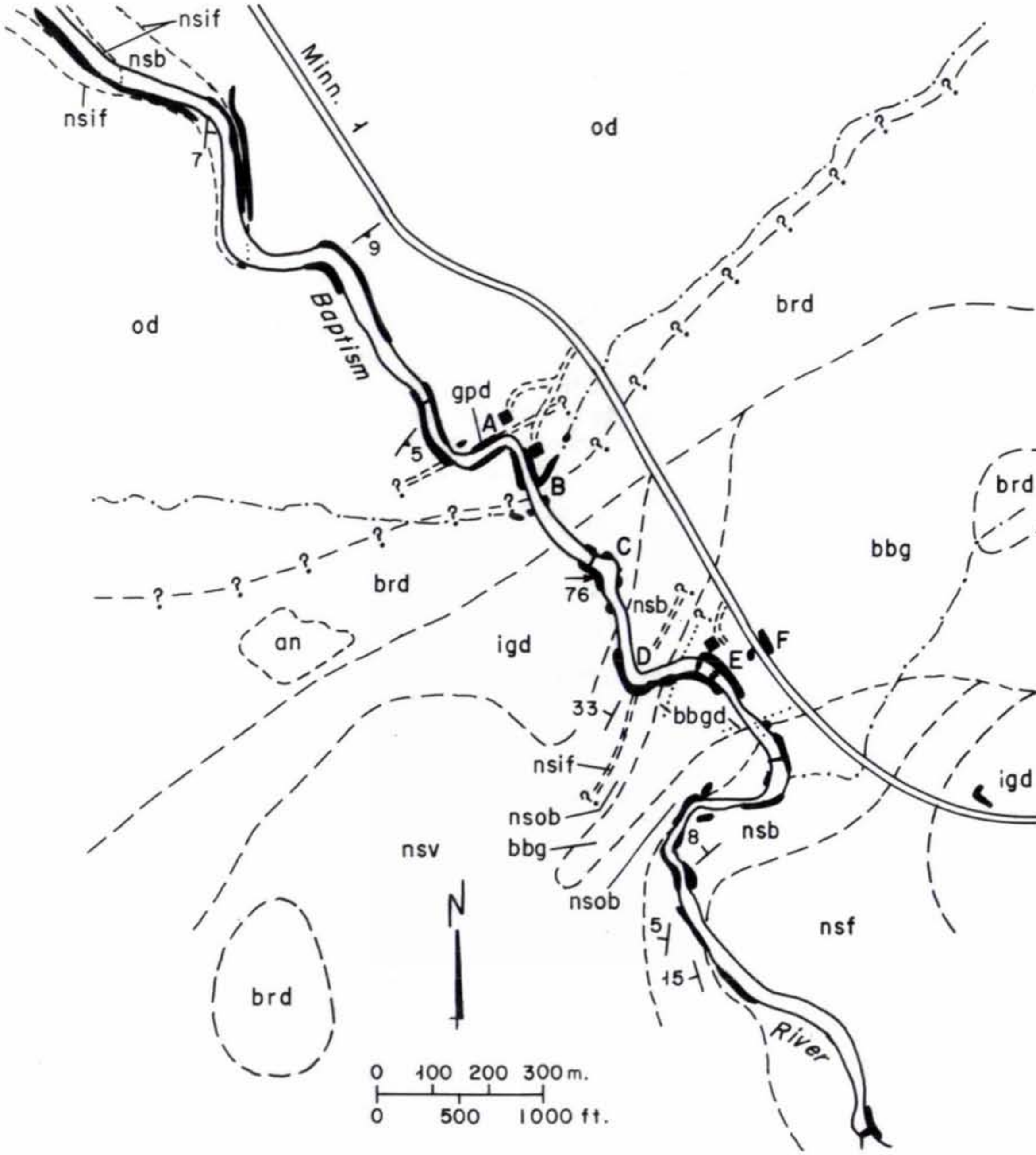

Figure 6. Detailed geology of Stop 5. Outcrop areas along the Baptism River and Highway 1 shown in black. Stop locations A through F are also denoted. Map unit abbreviations are: od-ophitic diabase, brd-Beaver River diabase, an-anorthosite, igd-intergranular diabase, nsb-intergranular to intersertal basalt, nsob-ophitic basalt, nsif-interflow sedimentary rock, nsv-undifferentiated NSVG rocks, bbgd-granodioritic phase of Beaver Bay, bbg-coarse-grained gabbro phase of Beaver Bay gabbro. Geologic symbols as in Figure 2; dotted line - gradational contact; question mark line - reflects uncertainty as to whether od and brd are distinct units.

AREA C. The well-jointed outcrops 120 m downstream from Area B consist of black (weathered brown), dense, fine-grained, intergranular oxide-rich diabase (igd, Fig. 6). The columnar jointing displayed here and plunging about 75° to the east is developed near the top of a westward-dipping sill that is 20-30 m thick. Downstream, downsection through the sill, the diabase coarsens to a medium grain size before being hidden beneath alluvium. The mineralogy, texture, and major element chemistry of this iron-rich diabase (B301A, Table 1; mg'=33.6%) are similar to the intergranular diabase sill west of the Milepost Seven tailings basin (Fig. 2; ferrodiorite of Green, 1982a) and some fine-grained phases of the Lax Lake gabbro implying a common petrogenesis. Another intergranular diabase sill downsection from this one can be observed in a roadcut on Highway 1 southeast of Area F (Fig. 6).

AREA D. Exposed in the high cutbank on the opposite (SW) shore is a sequence of five west-northwest-dipping basalt flows which underlie the intergranular diabase sill. The four uppermost flows are intergranular to intersertal basalts with smooth, amygdaloidal flow tops (nsb, Fig.6). Note the thinning of flow 3 over a thickened flow 4 and the nonamygdaloidal area in the upper part of flow 4. Between flow 4 and the billowing amygdaloidal top of flow 5 is a 2-m-thick red to buff, laminated, interflow siltstone dipping 30°-35°WNW (nsif, Fig. 6). Around the bend in the river, a narrow gap in the outcrop marks the intrusive contact between the hornfelsed ophitic basalt of flow 5 (nsob, Fig. 6) and the granophyric margin of a Beaver Bay gabbro dike (bbgd, Fig. 6). The fine-grained mafic granophyre gradually coarsens in grain size and becomes less granophyric away from the contact.

AREA E. Outcrops of Beaver Bay gabbro on the northeast bank of the river above Illgen Falls (bbg, Fig. 6) contain medium-grained, intergranular, granophyric (5-10%), apatite-(0.5-1%) and olivine-bearing (<5%) gabbro. This rock type is typical of dike-like and irregularly shaped Beaver Bay gabbro intrusions (Fig. 2). The gabbro consists mostly of decussate laths of intermediate plagioclase (commonly bleached), subprismatic augite (note bronze sheen on uralitized cleavage faces), subequant and commonly skeletal iron oxides, subpoikilitic to prismatic olivine (weathered pits), and a mesostasis of micrographic quartz and K-feldspar, myrmekitic plagioclase, prismatic apatite, iron oxide, biotite, and an amorphous brown grunge. Its whole rock composition (B309B, Table 1) is that of an iron-rich (mg'=32.1%) quartz monzogabbro to quartz diorite and is similar to marginal gabbro of the zoned Beaver Bay gabbro intrusions.

Toward the lip of Illgen Falls (PLEASE BE CAREFUL), the gabbro irregularly grades from medium to coarse grained and local granophyre-rich segregations appear which contain coarse, prismatic mafic minerals (mostly ferroaugite/ hedenbergite and iron-rich olivine). Zeolite-lined miarolitic cavities also occur within these granophyric segregations. The whole rock chemistry of a similar granophyric segregation sampled from the zoned intrusion near Beaver Bay (SS 1B, Table 1) has a mafic granite normative composition and is similar to icelandites of the NSVG (Fig. 4). As suggested above, these textural, mineralogical, and chemical characteristics may be indicative of silicate liquid immiscibility.

AREA F. The roadcut on Highway. 1 is an easily accessible outcrop of the same coarse-grained Beaver Bay gabbro as exposed at Illgen Falls. Note the long (≤10 cm) prismatic fayalitic olivine crystals which are commonly oriented in a trellis pattern.

Continue southeast on Highway 1 to the junction with U.S. Highway 61. Turn left, proceed 1.25 miles to Y-junction with old Highway 61 which branches to the right, and park.

Stop 6. U.S. Highway 61; Beaver Bay gabbro, Beaver River diabase, and NSVG basalts. Two areas (A & B, Fig. 7) will be investigated.

AREA A. The roadcut on U.S. 61 displays a nearly complete cross section through a small, zoned intrusion of Beaver Bay gabbro (Fig. 7). The intrusion has the form of a broad, shallow asymmetric synform which plunges about 15° to the east and measures about 450 m north to south. It is intrusive into the axial portion of a Beaver River diabase dike about 500-600 m wide, which dips steeply to the north.

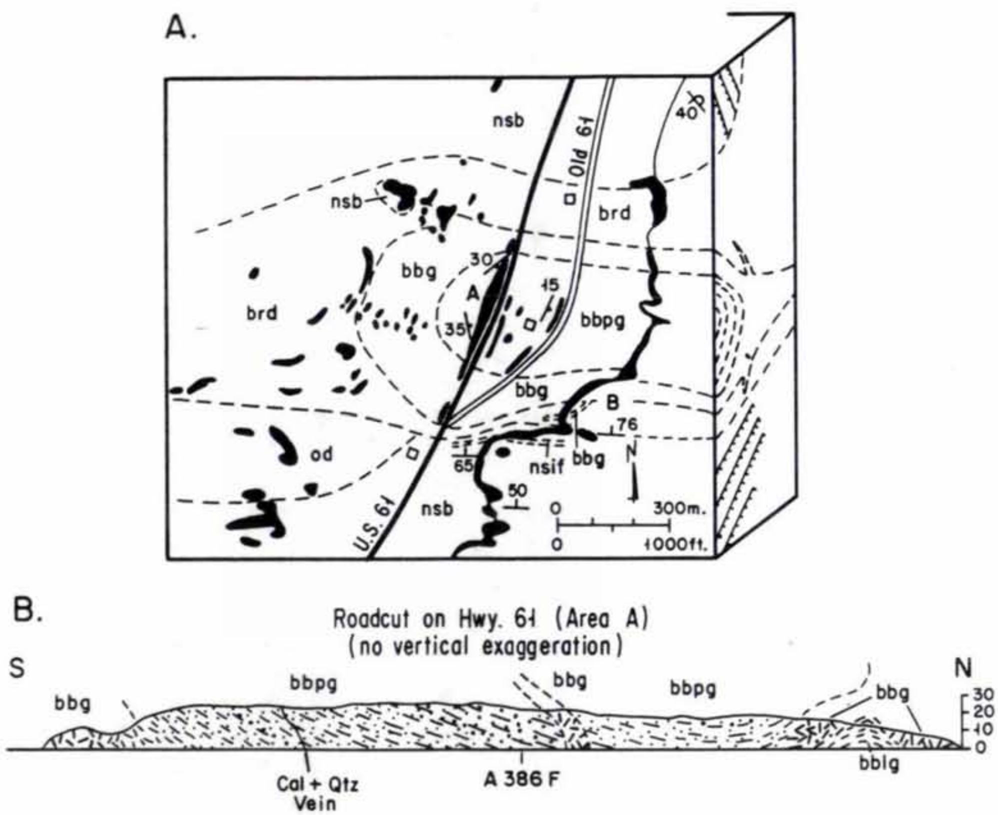

Figure 7. (A) Detailed geology of the vicinity of Stop 6 and (B) sketch of the roadcut on U.S. Highway 61 (area A).

A) Outcrop areas shown in black. Stop locations A and B are noted. bbpg-laminated, poikilitic olivine gabbro phase of the Beaver Bay gabbro; all other map units as in Figure 6. All geologic symbols as in Figure 2. Interpretive cross section illustrates possible three-dimensional structure of intrusive units and attitude of volcanic flows (dots indicate flow tops).

B) Tick marks represent the relative size and orientation of plagioclase. Dots represent the relative size and concentration of pseudomorphic olivine oikocrysts. bblg-nonpoikilitic laminated gabbro. Location of sample A386F (Table 1) is denoted.

On either side of the roadcut, a deeply weathered, coarse-grained, decussate, apatite-bearing, granophyric gabbro, similar to the vari-textured gabbro observed at Stop 5E, grades into a medium-grained, well-laminated, subprismatic, poikilitic olivine gabbro (Fig. 7B). Although the whole rock chemistry of this laminated poikilitic olivine gabbro (A386F, Table 1, Fig.7B) is slightly more iron-rich (mg'=27.7%) than the coarse-grained gabbro at Illgen Falls (B309B, Table 1; mg'=32.1%), the generally similar compositions of these texturally distinct rock types is remarkable. In larger Beaver Bay intrusions to the southwest, the laminated olivine gabbro is more commonly equigranular (nonpoikilitic) and becomes very enriched in iron and incompatible elements (Figs. 3 and 4).

The laminated gabbro typically consists of about 50-55% prismatic to lath-shaped plagioclase; 15-20% subprismatic and partially uralitized augite; 5-10% subequant to bladed iron oxide; 5-15% subpoikilitic to poikilitic, completely altered olivine; and 5-15% granophryic mesostasis also containing prismatic apatite and brown amorphous alumino-silicate material. In thin section, the glassy black alteration product of the once iron-rich olivine, commonly termed hisingerite, appears to be mostly dark greenish-brown biotite, partially altered to chlorite, with some serpentine and iron oxide. The oxidation of iron oxide, which is especially common around the outer margin of the oikocrysts, produces purplish coronas around the black clots.

Variations in the abundance and size of olivine oikocrysts (1.5 to 5 cm across) impart a layering to the gabbro which is parallel to plagioclase lamination. This internal structure defines an asymmetric synform whose axial plane projects throught the northern half of the intrusion (Fig. 7A). Note that plagioclase crystals within the oikocrysts are not aligned. This implies that the oikocrysts crystallized before plagioclase lamination developed. Although flow alignment of accumulating crystals in a convecting magma seems to be the most straightforward explanation for this lamination, would such a mechanism produce (and preserve) such slender plagioclase crystals (some have length:width ratios greater than 40:1!)? Perhaps in situ crystallization in a convecting magma or compaction played a role in the development of this lamination.

A 1.5-m-wide dike of coarse-grained, decussate gabbro, similar to the marginal rocks, cross cuts the internal structure of the laminated gabbro about midway through the roadcut (Fig. 7B). Gehman (1957) interpreted a similar relationship in the intrusion near Silver Bay (Fig. 2) to indicate that the coarse gabbro (his Black Bay gabbro) was younger than the laminated gabbro (his Beaver Bay ferrogabbro). However, the typically concentric zonation and gradational contact relationship of these rock types and their overlapping compositions (Figs. 3 and 4, Table 1) suggest that they are comagmatic and coeval. The occasional dikes of coarse-grained, decussate gabbro internal to the zoned intrusion may represent late, minor intrusions of similar magma.

AREA B. Heading to the lakeshore, due east of the road junction, a steeply (>60°) northward-dipping sequence of basalt flows and interflow sediments is exposed. Exposed at the north end of the cove is an interflow siltstone of irregular thickness (<1 m) which is cross-bedded and is partially incorporated into the flow above it. Layered and stretched amygdules are evident in the base of this flow.

On the north side of the point, the flow top of this steeply dipping (75°-80°N) basalt is found in conformable intrusive contact with fine-grained, ophitic olivine-rich Beaver River diabase. Just north of the contact, bifurcating dikes of coarse-grained to pegmatitic, prismatic mafic granodiorite cut the diabase. The dikes range from 15 cm to 1.5 m across and are mineralogically zoned with mafic margins and granophyric interiors. Prismatic pyroxene crystals as long as 5 cm are commonly aligned normal to the margins of the dikes. The diabase adjacent to the dikes is strongly chloritized. In exposures to the northeast, accessible only by boat, these and similar dikes can be traced in outcrop to the margin of the Beaver Bay gabbro intrusion, about 40 m from this point (Fig. 7A).

Coarse- to medium-grained, granophyric, apatite-bearing, equigranular gabbro of the Beaver Bay suite is exposed along the top of the steep lake bluff extending north to the next point. The upper outcrop surface of this point displays a decussate coarse-grained gabbro which is more equigranular than vari-textured gabbros observed in the roadcut (area A) and at Stops 5E and F. Also, moderate plagioclase lamination is locally observed. To the north and downsection, the gabbro gradually becomes increasingly well-laminated, medium-grained, and eventually olivine poikilitic. Looking to the lake cliff exposures to the north, one sees laminated poikilitic olivine gabbro with layering similar to that observed at the roadcut.

The spatial relationships between the coarse, decussate gabbro and the medium, laminated gabbro give the impression that the decussate gabbro forms an envelope around the laminated rocks. A plausible interpretation of the two rock types is that the decussate gabbro formed in the stagnant margin of an internally convecting intrusion.

Note that a thin (0.5 m), medium-grained, equigranular mafic granodiorite dike cuts across the gradational contact between the decussate and laminated gabbros on the northern cliff face of the point. (DO NOT ATTEMPT TO CLIMB THE CLIFF FACE.) This relationship has implications for the origin of a much more extensive granodiorite body that comprises a major portion of the Beaver Bay intrusion centered on Williams Creek (Fig. 2), which will be observed at Stop 7.

Overnight in Silver Bay.

-DAY 2-

From the stoplight at the junction with Outer Drive, go 1.35 miles northeast on U.S. 61, turn right on Old Town Road, and park.

STOP 7. Williams Creek; various rock types of the Beaver Bay gabbro and felsic volcanics. Roadcuts on U.S. 61 and Old Town Road (Area A) and outcrops in Williams Creek (Area B) will be investigated.

AREA A. The roadcuts on both sides of U.S. 61 display a variety of Beaver Bay gabbro types. The outcrop on the southeast side of the highway is dominantly medium-grained, granophyric, equigranular gabbro displaying poor to well- developed lamination. A whole rock analysis of a similar rock type sampled 120 m southeast of this roadcut, indicates a very fractionated, iron- and incompatible element-rich composition (mg'= 4.4%, Zr=490; F237, Table 1).

A similar medium-grained, laminated gabbro occurs at the northeast end of the opposite roadcut, but it is conformably underlain by a deeply weathered, medium- to coarse-grained, decussate, granophyric, apatite-bearing, vari-textured gabbro along an abrupt irregular contact. A similar coarse- grained gabbro, exposed in a U.S. 61 roadcut 500 m west of Williams Creek, has a less evolved composition than the laminated gabbro (mg' = 27.0%; SB28, Table 1), but it is very similar to the laminated poikilitic olivine observed at Stop 7. However, the Zr content of this coarse gabbro (620 ppm) is anomalously high compared to other Beaver Bay rock types with comparable major element chemistries (130-350 ppm, Fig. 4).

Exposed at the southwest end of this roadcut and on the northeast side of Rieder Memorial Drive is a medium-grained, equigranular mafic granodiorite similar to that seen yesterday at Stop 6. Its relationship to the decussate gabbro is not obvious here, but elsewhere this rock grades into the decussate granophyric gabbro as seen at Stop 5D. We will get a better look at this rock type in Williams Creek.

About 275 m south on Old Town Road, iron-stained, medium coarse-grained, granophyric, equigranular gabbro occurs in weathered outcrops on the slope north of the road. The gabbro is decussate to moderately laminated. These textural characteristics appear to represent a more transitional contact between the coarse, decussate marginal gabbro and the medium, laminated interior gabbro of this zoned Beaver Bay intrusion (Fig. 2).

AREA B. Exposed downhill (SE) from the road in the narrow gully of Williams Creek is pink (locally weathered green), massive, fine- to medium-grained, equigranular, mafic granodiorite. This rock type composes about 50% of the exposed area of this Beaver Bay gabbro intrusion (Fig. 2). The granodiorite is typically composed of about 45% micrographic quartz and perthitic K-feldspar, 35% altered (sericitized and albitized) plagioclase phenocrysts, 15% uralitized, subprismatic to prismatic ferroaugite/hedenbergite, 5% granular iron oxides, and minor amounts of apatite, hornblende and biotite. A chemical analysis of a similar rock type sampled northeast of Lax Lake (C484, Table 1) indicates a moderately iron-rich (mg'=36.1%) mafic granodiorite normative composition which is similar to NSVG andesite lavas (Figs. 3 and 4).

A contact between the granodiorite and a pinkish-gray, aphanitic felsite is exposed on the southwest slope of a gully made by a small tributary flowing into Williams Creek from the west. Although the granodiorite becomes fine-grained at the contact, it is not chilled. Rather, the contact seems somewhat gradational.

In the stream bed of Williams Creek, about 50 m upstream from the felsite contact, the granodiorite contains a large (≈35 m) inclusion(?) of medium fine-grained Beaver River diabase. Locally, the diabase contains vesicles, plagioclase-phenocrysts, and anorthosite and granite inclusions. Granodiorite outcrops continue upstream to U.S. 61, locally becoming coarse-grained and cut by thin dikes of fine-grained granophyre. A characteristic green (malachite) color on weathered surfaces is obvious in many exposures.

The petrogenesis of the granodiorite is unclear. The cross-cutting relationship observed at Stop 6B and the larger scale trangressive relationship of the granodiorite to the gabbroic rocks of this intrusion (Fig. 2) imply that the granodiorite is younger. Yet, in many places, granodiorite definitely grades into coarse-grained, vari-textured, granophyric gabbro. Was a distinct granitic melt emplaced into a partially solidified gabbroic crystal mush, or could the granodiorite represent a siliceous (immiscible?) differentiate? Also problematic is why so much granitic melt was emplaced in this particular intrusion and not in the other Beaver Bay gabbro intrusions. Does the contact relationship observed here give evidence that the granitic melt might have been derived by partial melting of felsic volcanic rocks, which are particularly abundant in this area?

Return to Silver Bay, following Outer Drive through town. About 0.4 mile past the high school, after a right curve, turn left on the dirt road to the Silver Bay Country Club. Proceed 1.0 mile to the point where the road begins to parallel the pipeline road and park.

STOP 8. Reserve Mining pipeline road and railroad track; hornfelsic basalt, Beaver River diabase with anorthosite inclusions, zoned Beaver Bay gabbro. The detailed geology of the stop and the locations of five outcrop areas (A-E) described below are shown in Figure 8A. The stop is located on Reserve Mining property and permission should be sought at the security gate on U.S. 61 before entering the area.

The geology displayed here consists of a zoned Beaver Bay intrusion emplaced in Beaver River diabase, as observed at Stop 6. However, this circular Beaver Bay intrusion is about 10 times larger than the intrusion at Stop 6 (Fig. 2) and contains slightly different rock types.

AREA A. Roadcuts on both sides of the country club road expose a well-jointed, dense, black, aphanitic, massive hornfelsic basalt. This basalt is surrounded by exposures of anorthosite inclusion-bearing Beaver River diabase (Fig. 8A; note anorthosite in roadcut to the west) but it is not clear whether the basalt is an inclusion or is part of the irregular footwall of a southeast-dipping diabase sill.

AREA B. Low outcrops north of the pipeline road, about 200 m east of Area A, contain fine- to medium fine-grained, ophitic, granular olivine-rich diabase with abundant meter-scale anorthosite inclusions. Progressing from west to east over the diabase exposures, one notes that olivine abundance decreases and that a medium ophitic texture develops (oikocrysts ≤ 5mm).

AREA C. In the next roadcut east, the diabase is much coarser grained with augite ophites 3-4 cm across (locally as large as 10 cm), and olivine occurs as subpoikilitic to poikilitic oikocrysts 1-4 cm in diameter. This variety of Beaver River diabase locally occurs in gradational to sharp contact with more common granular olivine diabase. The sharp contacts are typically marked by centimeter-thick layers of gabbro pegmatite.

The diabase is cut by a 3-m-wide dike of very coarse-grained, prismatic, granophyre-rich gabbro about midway across the roadcut. This coarse gabbro dike is apparently an offshoot of the Beaver Bay gabbro intrusion immediately to the east, similar to the dike observed at Stop 6B.

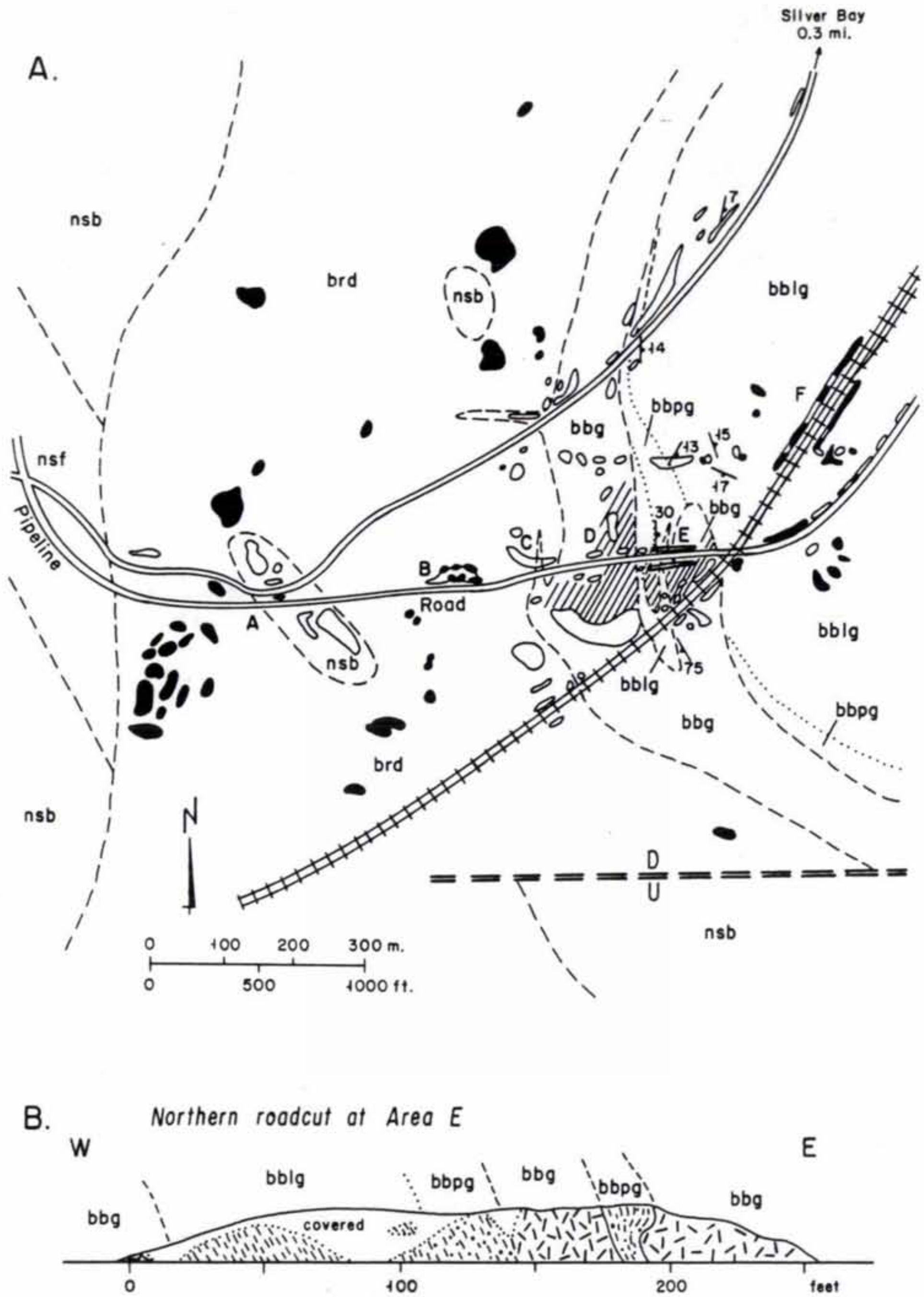

Figure 9. (A) Detailed geology in the vicinity of Stop 8 (Areas A-F) and (B) sketch of roadcut on pipeline road (area E).

A) Outcrop areas of major map units outlined; outcrop areas of anorthosite inclusions in Beaver River diabase (brd) and diabase inclusions in Beaver Bay laminated gabbro (bblg) are shown in black. Diagonal stripes denote areas of grus. Dashed lines - sharp contacts; dotted lines - gradational contacts; double dashed lines - fault. Geologic symbols and map units as Figures 2, 7 and 8.

B) Tick marks represent the relative size and orientation of plagioclase. Dots represent the relative size and concentration of pseudomorphic olivine oikocrysts.

AREA D. Low, deeply weathered outcrops of medium coarse- to very coarse grained, vari-textured, granophyric, apatite-bearing gabbro, typical of Beaver Bay intrusion margins, occur north of the pipeline about 37 m east of the Area C roadcut. As at Illgen Falls (Stop 5E and F), the local granophyric segregations apparent in this rock may reflect silicate liquid immiscibility. Here and in the clearing on the south side of the road, a distinctive grus is developed on this rock type (Fig. 8A).

AREA E. Another 75 m east at the west end of a large roadcut, the coarse, vari-textured gabbro abruptly grades to a medium-grained, well-laminated, equigranular, subprismatic, gabbro with 1- to 2-mm, anhedral granular olivine (Fig. 8B). Lamination dips about 30°E. Farther east along this roadcut, the laminated gabbro becomes slightly finer grained. Beyond a narrow break in the exposure, it is again medium grained, plagioclase is moderately laminated and still dipping 30°E, but olivine develops a subpoikilitic habit (1-2 cm oikocrysts). Over a poorly exposed portion of the roadcut, the laminated poikilitic gabbro abruptly grades back to a coarse-grained to pegmatitic, prismatic, vari-textured, granophyric gabbro. Coarse-grained, granophyric gabbro persists over most of the eastern half of the roadcut except for a 5-m interval of subpoikilitic olivine gabbro with steep, east-dipping lamination (Fig. 8B). The sharp, irregular contacts between the two gabbro types and the convoluted, but generally contact-parallel lamination in the olivine gabbro may indicate flow alignment of plagioclase in a crystal mush which intruded the coarse, granophyric gabbro. Alternatively, the contorted but conformable lamination in the medium gabbro may have resulted from the intrusion of the granophyric gabbro magma into partially solidified, laminated gabbro. In either case, the relationships observed here and at earlier stops indicate that the two phases are roughly coeval.

A similar mixture of medium-grained, laminated olivine gabbro and coarse-grained, vari-textured granophyric gabbro also occurs in the roadcut and low outcrops south of the pipeline road (Fig. 8A).

AREA F. Exposed in the railroad cuts northeast of the pipeline road is medium-grained, well-laminated, equigranular subprismatic gabbro with abundant large inclusions of Beaver River diabase. In fact, the inclusions, which are the medium coarse-grained, poikilitic olivine variety, compose most of the exposure and are common throughout this particular Beaver Bay intrusion Fig. 2). Contacts between the diabase and gabbro are sharp, but not chilled. In many places, the lamination in the gabbro is strongly parallel to the contact with the diabase. This nonpoikilitic, equigranular gabbro is the dominant rock type in the interior of this intrusion and the larger body to the south (Fig. 2).

Return to Silver Bay and Outer Drive. At U.S. 61, turn right, proceed 0.4 mile, then left at the Reserve Mining plant gate. (Because the plant shut down indefinitely in the summer of 1986, it may not be possible to get access to the plant area, but check with security guard at the gate.) Turn right after checking in at the plant gate and continue 0.5 mile on the service road to a three-way junction.

STOP 9. Reserve Mining Taconite Processing Plant; layered Beaver Bay gabbro and Beaver River diabase inclusions.

The outcrops of medium-grained, well-laminated, equigranular gabbro in roadcuts near the junction display excellent rhythmic modal layering manifested by alternating mafic-rich and plagioclase-rich layers. Some slight grain-size variations may also be associated with the modal changes. Modal layering in the laminated gabbro interiors of the zoned Beaver Bay intrusions is not rare, but it is typically more subtle than displayed here. Inclusions of Beaver River diabase are locally abundant and appear to cause much of the irregular attitude of the layering. One particularly large inclusion with layering draped over it is exposed in a 7-m-high roadcut along the lower road.

Three types of layering occur in the area. The type displayed at the road junction is centimeter-scale, rhythmic, laterally continous, and isomodal. Exposures northeast of the junction show modal layering on a scale of centimeters to meters, which is typically graded upsection from mafic-rich to plagioclase-rich laminated gabbro. Roadcuts along the lower road that curves back to the north display a modal and textural layering where meter-thick layers grade from granular olivine-rich bases to plagioclase-rich, subpoikilitic olivine-bearing tops. The latter two layering types are typically lenticular and discontinuous, and commonly display trough banding and channel-scour features indicative of fluid flow.