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FIELD TRIP GUIDEBOOK FOR PRECAMBRIAN ROCKS OF THE NORTH SHORE VOLCANIC GROUP, NORTHEASTERN MINNESOTA

PREPARED FOR THE ANNUAL MEETING OF
THE GEOLOGICAL SOCIETY OF AMERICA
AND ASSOCIATED SOCIETIES
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PRECAMBRIAN NORTH SHORE VOLCANIC GROUP NORTHEASTERN MINNESOTA

Leader

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INTRODUCTION

Previous Work and Acknowledgments

Detailed mapping of the Minnesota shore of Lake Superior began with A. E. Sandberg's study (1938) of the section between Duluth and Two Harbors. Grout and Schwartz (1939) and Gehman (1957) studied the intrusions and flows in eastern Lake County; Grogan (1940) mapped the lakeshore between Two Harbors and Split Rock River; Schwartz (1949) studied the Duluth area; and Grout and others (1959) mapped most of Cook County. James Kilburg (1972) has recently mapped the wedge of lavas just west of Duluth. Most of the data reported in this account derive from studies by the writer who, starting in 1965, has mapped the shoreline between Silver Bay and Grand Portage, with considerable reconnaissance inland and to the southwest (Green, 1966; 1968a; 1968b; 1970). The report does, however, also lean considerably on Grout and others (1959) and, for the Duluth-Two Harbors area, on Sandberg (1938). The field studies have been supported by the Minnesota Geological Survey, and most of the laboratory studies have been supported by the National Science Foundation (Grant No's GP-5865 and GA-13411). Sincere gratitude for this support is extended to both agencies. The writer's ideas have benefited from discussions with many other geologists concerned with Keweenawan rocks, especially including Bill Bonnichsen, D. M. Davidson, Jr., H. Hubbard, G. B. Morey, W. C. Phinney, P. W. Weiblen, and W. S. White.

Regional Setting

The name "North Shore Volcanic Group" has been used by Goldich and others (1961) for the lavas and interbedded sediments of Late Precambrian age in northeastern Minnesota (see figure 1). These rocks, as well as all other Upper Precambrian volcanic and sedimentary rocks in the Lake Superior district, have traditionally been called "Keweenawan" by general lithic and structural correlation with rocks exposed on the Keweenaw Peninsula of Michigan, but recent radiometric and paleomagnetic investigations as well as geologic mapping indicate that a more precise stratigraphic framework is needed to adequately describe the complex series of Late Precambrian events and deposits in this area.

In the northeast corner of Minnesota (Grand Portage area) the lowest Upper Precambrian flows disconformably overlie a thin quartzite (Puckwunge Formation) which in turn overlies, apparently disconformably, the shales and graywackes of the Middle Precambrian Rove Formation; here both sequences strike nearly east-west and dip at approximately 10° to the south. At the southwest end of the basin immediately west of Duluth (155 miles away), the lowest Upper Precambrian flows also conformably overlie a thin quartzite ("Nopeming") which there overlies the

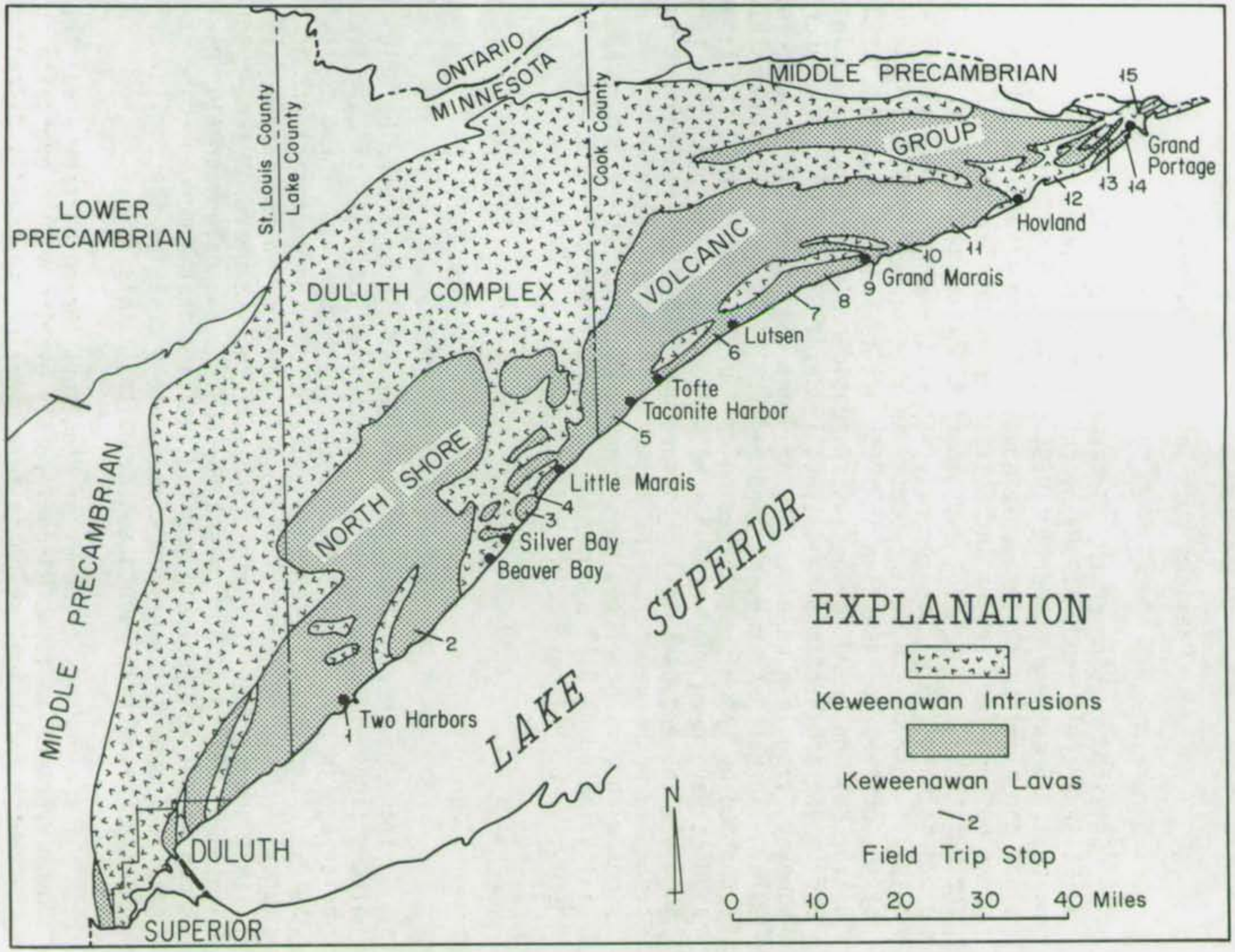

Figure 1. Generalized geologic map of Keweenawan extrusive and intrusive rocks in northeastern Minnesota, excluding "Logan sills."

vertically folded slates and metagraywackes of the Middle Precambrian Thomson Formation, which is correlated with the Rove. Here the flows strike north and dip at about 10° to 25° to the east. The angular unconformity here reflects the diastrophism and subsequent erosion associated with the Penokean orogeny, which evidently did not affect the northeastern corner of the state. Across the axis of the Lake Superior Syncline in northern Wisconsin and Michigan the lowest flows conformably overlie a similar quartzite (Bessemer) that in turn overlies Middle Precambrian shale and graywacke with only minor discordance. These quartzites have always been referred to as Lower Keweenawan, but no radiometric age determinations are available and they may be much older than the volcanic rocks of the Keweenaw Peninsula.

The North Shore Volcanic Group is cut by a great variety of intrusive rocks that are also of Late Precambrian age. These range from the great Duluth Complex, dominated by anorthositic and troctolitic rocks, to smaller sills, stocks, dikes, and irregular plutons of diabase, ferrogabbro, troctolite, syenogabbro, trachybasalt, granodiorite, and granophyric adamellite. Some of these bodies also cut the older rocks to the north, northwest and west of the main Upper Precambrian outcrop area (e.g. the Logan intrusives of Cook County and the Thunder Bay District in Ontario).

Paleomagnetism and Age

Recent paleomagnetic studies (Dubois, 1962; Beck and Lindsley, 1969; Books, 1968; Palmer, 1970) have shown that two reversals of magnetic polarity occur within the Upper Precambrian volcanic rocks of the Lake Superior district. The lowest strata show "normal" (north-seeking) polarity similar to orientations in the underlying Middle Precambrian rocks, but this group of rocks has not yet been recognized in Minnesota. Books (1968) has proposed that the Lower - Middle Keweenawan boundary be redefined at the second magnetic reversal where rocks of reversed polarity are succeeded by rocks of normal polarity. The North Shore Volcanic Group contains at the base of the section at Grand Portage about 9,000 feet of lavas that show reversed polarity, and are thus Lower Keweenawan as magnetically defined (Green and Books, 1972). The thick wedge of flows west of Duluth that underlie the Duluth Complex but overlie the "Nopeming" quartzite show reversed polarity in reconnaissance studies (Green and Books, 1972), and on regional magnetic maps give a negative magnetic anomaly which also implies reversed polarization. Furthermore, they are lithically very similar to the reversed-polarity lavas of Grand Portage. The remainder of the North Shore Volcanic Group has normal magnetic polarity, similar to the bulk of the associated intrusive rocks and to the volcanic rocks of the Keweenaw Peninsula.

Only limited radiometric age determinations are yet available on rocks of the North Shore Volcanic Group. Goldich and others (1961)

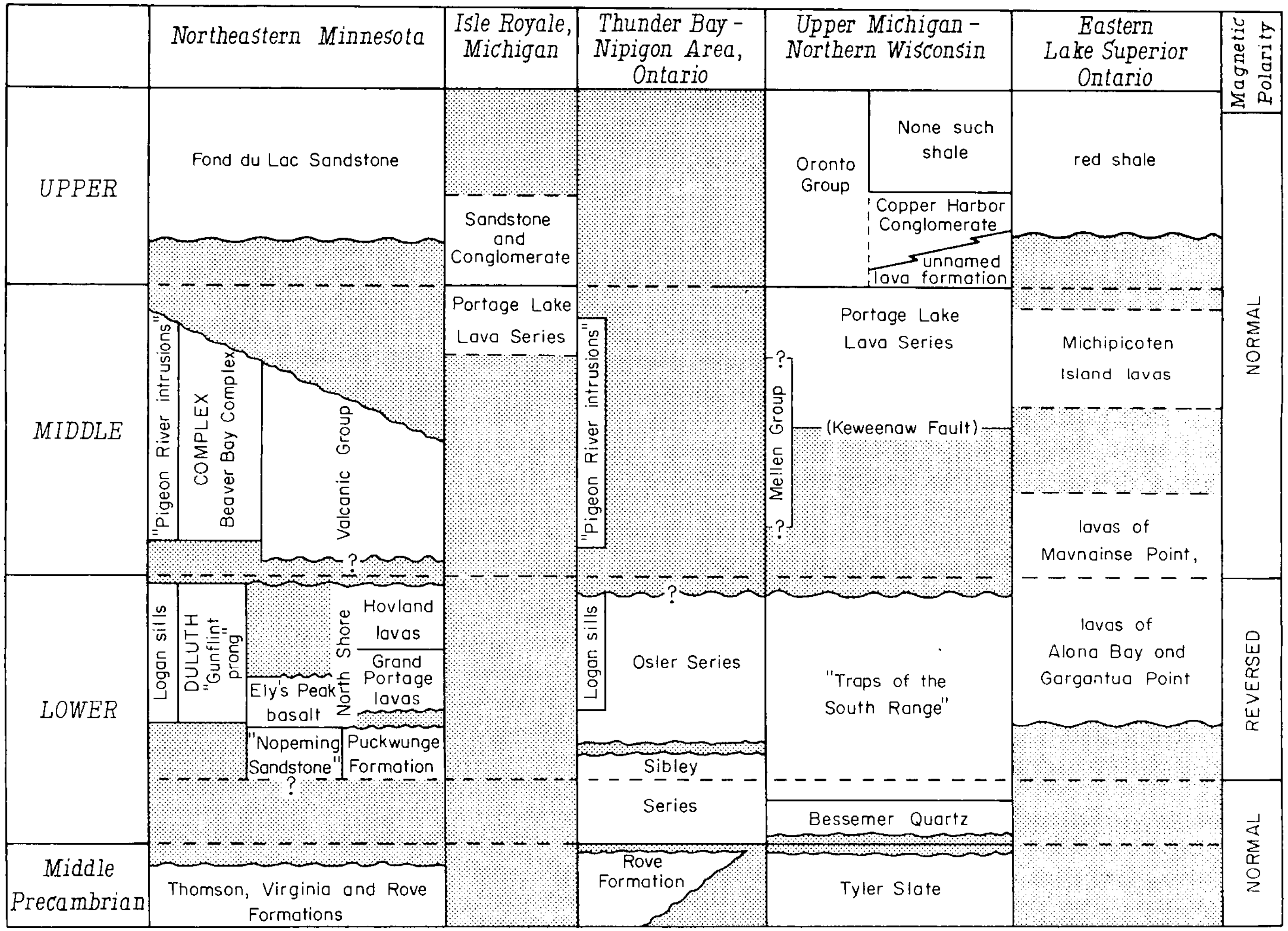

Figure 2. Proposed correlations for the Keweenawan rocks of northeastern Minnesota. Toned area indicates section missing or not exposed.

found a 1.1 ± 0.1 b. y. age for associated intrusive rocks of the Duluth Complex by Rb/Sr and K/Ar methods, and Silver and Green (1963) found an isotopic age of 1.125 b.y. by U/Pb isotopes in zircons of both lavas and intrusive rocks from the Duluth and Mellen, Wisconsin areas. Faure and others (1969) determined the age of the Endion sill, which cuts the flows at Duluth, as 1.092 b.y., and that of the Duluth Complex at Duluth as 1.115 b.y. by the Rb/Sr method. However, all of these sampled rocks are in areas of normal magnetic polarity, so no data are available as to the age of the older, magnetically reversed Keweenawan lavas of, for instance, the Grand Portage area. Hanson and Malhotra (1970) have recently found a 1.380 b.y. age (K/Ar) of a "Logan Intrusive" in southern Ontario, which may indicate the possible age span of the Lower Keweenawan. Isotopic U/Pb studies over the range of Upper Precambrian igneous rocks in the district are currently in progress.

Proposed correlations are shown in Figure 2.

STRUCTURE

The general structure of the North Shore Volcanic Group is that of a great nest of dishes tilted gently to the southeast into Lake Superior. At the northeast end the strata at the base strike slightly north of west and dip about 10-12° south, whereas at the southwest end, 155 miles away, they strike north and dip about 10-12° east. In between, the strikes gradually converge along the shore of Lake Superior as higher stratigraphic levels are reached, until the flows strike parallel to the shore in the vicinity of Schroeder, Tofte, and Lutsen in southwestern Cook County. Here the highest stratigraphic units are exposed, and the dip is approximately 12° to the southeast.

The lavas are intruded by a great variety and bulk of intrusive rocks, including several large diabasic sills at Duluth, the Beaver Bay Complex, the Hovland and Reservation River diabase complexes and the Logan intrusions. Where these intrusions are discordant and abundant they have deformed the lavas considerably, with local strongly divergent strikes and steep to overturned dips. Along with the thick glacial cover inland, they have also made difficult to impossible the long-distance tracing of stratigraphic units in the lava series. Several major flows or groups of similar flows, however, can be traced inland from the lakeshore for at least 15 to 25 miles (see figure 3). Faulting is common in the flows near the areas of abundant intrusions (such as from Silver Bay to Little Marais). These faults appear to be of minor displacement and are mostly transverse and steeply dipping with no strongly preferred strike or displacement, but a few longer strike-faults have been found, one of which probably extends for at least five miles.

The thickness of the lava succession has been measured and estimated by Sandberg (1938) and Grogan (1940) as 23,148 feet between Duluth and

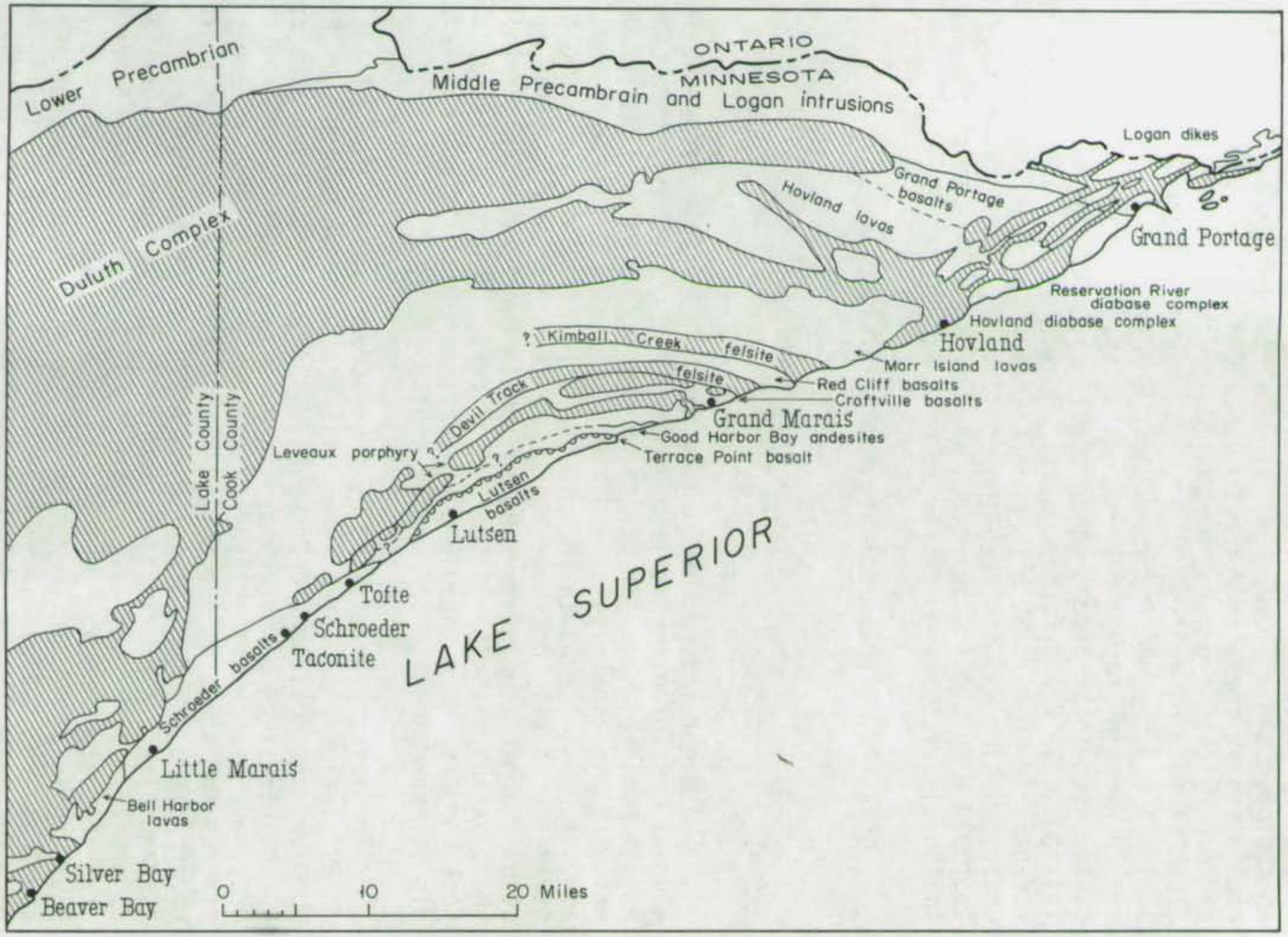

Figure 3. Generalized geologic map of the northeastern part of the North Shore Volcanic Group showing lateral continuity of some of the lava units.

Split Rock River (the beginning of the Beaver Bay intrusive complex) by adding the individual flow thicknesses intersected along the lakeshore. Whether this conforms to the true thickness of the pile at Split Rock River is not known. Northeast of the Beaver Bay Complex about 5,000 feet of lavas are estimated from recent mapping to form the lakeshore section between Silver Bay and the uppermost flows at Tofte. Northeast of Tofte and Lutsen, where the flows are parallel to the shore, lavas totalling about 16,500 feet have been measured down to the Reservation River diabase near Hovland. Below (northeast of) this is an older section of about 5,000 feet of lavas, for a total on this limb of about 21,500 feet.

Estimates of volcanic thicknesses by constructing cross-section profiles give between 11,000 and 18,000 feet at Tofte, above the Duluth Complex, depending on assumed dips between 12° and 20°. Although the average dip at Tofte is about 12°, there is very little control on dips near the base of the section as the few inland outcrops rarely expose flow contacts. Farther northeast at the Cascade River, about 15,000 feet of lavas above the Duluth Complex are calculated with an average dip of 12°; another thick section, possibly as much as 5,000 feet thick, here lies beneath the Complex.

GENERAL DESCRIPTION

The North Shore Volcanic Group bears many resemblances, both physically and chemically, to plateau lava sequences of various geologic ages. Similarities to the Tertiary plateau lavas of eastern Iceland are particularly striking. The lavas are almost entirely subaerial, showing highly vesicular (now amygdaloidal) upper portions and massive interiors, and various types of jointing, surface features, and textures depending on their specific composition. Evidence of submarine extrusion is almost entirely limited to the base of the section both at Grand Portage and at Duluth; at Nopeming, west of Duluth, the lowest flow is pillowed and on Grand Portage Island the lowest flow shows spheroidal forms that could possibly be pillows, but excellent, thick-rinded, vesicular pillows constitute a flow on the lakeward side of the island a few flows above the base of the section (see figure 4). Unequivocal but less well formed pillows and pillow-breccia have been seen only rarely higher in the section. These could have formed in local lakes or stream beds on the lava surface. The flows are in general tabular, and since some individual flows or flow groups can be traced along strike for at least 20 miles, the general impression is that of a broad, rather flat volcanic terrane. In contrast to the situation in eastern Iceland, however (Walker, 1964), no clear evidence of volcanic centers, representing shield or composite volcanoes contemporaneous with the plateau volcanism, has yet been found. White (1960) has drawn attention to the remarkable extent of some Keweenawan flows (especially in Michigan) and with ample justification calls them flood basalts.

Figure 4. Basalt pillows a few flows above base of section, southeast shore of Grand Portage, Island, Cook County.

Figure 5. Scoriaceous rubble of flow-top in the Bell Harbor lavas, in which interstices have been filled with red, laminated sandstone. Near Little Marais, Lake County.

Figure 6. Two smooth, gently billowing flow tops of ophitic olivine basalt (at middle and just above base of falls), Gooseberry River, Lake County.

Figure 7. Porphyritic trachyandesites of the Hovland lavas, from various localities.

Interflow sediments make up a minor part (1-3 percent) of the section. They are principally red, cross-bedded sandstones, that occur sporadically as beds a few inches thick between flows, but a few local accumulations of over 100 feet are found. Conglomerate is rare. Some sand has filtered down into cavities in the upper parts of flows, and also forms a matrix for flow-top breccia in others (see figure 5). These sediments appear to have been deposited by occasional temporary streams winding across the volcanic surface. There is little evidence of erosion. Pyroclastic deposits are extremely scarce, but welded tuff and mixed sand and shards have been reported from the Cascade River in Cook County (Johnson and Foster, 1965) and basaltic to andesitic breccia, other than flow-top breccia, is present in a few localities.

With the exception of a high potassium content in some mafic and intermediate members and the relative abundance of rhyolite, the compositions of the lavas are also very similar to those of plateau lava series in Iceland and elsewhere. Table 1 shows the general characteristics and abundance of the major types; Table 2 summarizes selected analyses.

The most abundant general type is olivine basalt of several varieties; one widespread, important, and distinctive variety is mottled (ophitic), and is similar to what has been called olivine tholeiites in other areas. These typically have ropy surfaces and were very fluid (see figure 6). Rough columnar joints are common. Other olivine basalts are coarser, some with diabasic and some with other characteristic textures. In the Tofte-Lutsen area, high in the section, is a group of olivine basalts with abundant, small (1-3 mm) bytownite phenocrysts or crystal clots. At the base of the section both at Duluth and on Lucille Island east of Grand Portage are distinctive basalts that contain abundant phenocrysts, 2-3 mm across, of augite and (serpentinized) olivine: these are particularly unusual in having ferromagnesian instead of plagioclase phenocrysts. Another moderately abundant and distinctive rock type is the "quartz tholeiite" which is aphanitic or very fine grained and slightly more siliceous and viscous than the olivine basalts. The quartz tholeiites characteristically have a rubbly or brecciated top with the highly vesicular fragments set in a matrix of washed-in red sand (see figure 5) or occasionally calcite and zeolites. They also commonly show narrow oxidation bands, 1-3 mm thick, along subhorizontal flowage planes, and vugs of agate and quartz. This quartz tholeiite grades into more potassium-rich varieties (trachybasalt, trachyandesite) that can be distinguished only by chemical analysis and microscopic study; patches of interstitial K-feldspar are present in these rocks but are invisible in hand specimen.

Intermediate varieties are nearly all porphyritic, with plagioclase, augite, magnetite, and in some specimens iron-rich olivine phenocrysts; they have the compositions of andesites, trachyandesites, and intermediate quartz latites. Most are aphanitic, but one unusual flow, here called the Manitou trachybasalt, is exceptionally thick (at least 300 feet) and granular, and can be traced for 5 miles although it originally continued for an unknown distance in both directions. These flows are commonly brown or red and irregularly jointed or with platy, subhorizon-

Table 1 -- Generalized characteristics of major lava types of North Shore Volcanic Group

Characteristic	Olivine Tholeiite	Quartz Tholeiite	Andesite Trachyandesite	Intermediate Quartz Latite	Quartz Latite Rhyolite
Wt % SiO_2	46-49	50-51	52-57	62-65	72-75
Wt % K_2O	0.1-0.5	0.6-0.9	1.9-2.7	2.8-5.0	3.9-6.2
Wt % MgO	5.9-6.8	4.3-5.9	1.9-4.5	0.9-1.9	0.0-0.4
Textures	Ophitic Occasionally porphyritic (plagioclase)	Very fine-grained, intergranular, some flow structure, fine oxidation-banding	Very fine-grained commonly porphyritic (plag., augite)	Aphanitic, mostly porphyritic (plag., augite, ol.)	aphanitic to felsitic; aphyric or porphyritic (plag., orthoclase, quartz, mag., pyrox.) occas. spherulitic
Thickness, feet					
Range	1 to 100	30-150	50-240	80-200	50-1300 perhaps 3500
Common	10-40	80	Variable	120	50-500
Structures					
flow tops	smooth, ropy	scoriaceous rubble	scoriaceous, rubbly	vesicular wrinkled	vesicular, rolled, flow-banded
jointing	sheeted tops, columnar centers	small, irregular	small, irregular	irregular to sub-horizontal, platy	platy, sub-horizontal; big columns in thick flows
vesicles	round or irregular	stretched	stretched or round	stretched or round	stretched, round
Other Characteristics	very fluid pipe amygdules at base segregation veins, vesicle cylinders	more viscous some contain more K_2O, Kspar; quartz, agate common in cavities	brown-weathering somewhat variable	few flow contacts exposed	pink, red, or light gray

Table 2 Chemical analysis, in weight percent, of selected Keweenawan igneous rocks from North Shore Volcanic Group

	TH-2	F-201	F-54	F-108	T-45	T-56	DY-6b	GH-25	GH-2b	S&G-5-9
SiO_2	50.19	74.41	53.08	51.08	45.71	46.87	47.69	47.19	55.42	52.70
TiO_2	1.51	0.24	1.99	2.20	1.28	0.81	1.28	0.95	2.15	1.76
Al_2O_3	15.15	10.95	13.25	14.17	17.47	19.20	18.36	17.04	12.29	14.47
Fe_2O_3	5.51	1.64	8.73	10.25	7.80	5.42	6.47	2.63	9.00	7.44
FeO	5.82	2.91	3.74	3.69	3.41	2.97	4.74	7.69	3.32	5.55
MnO	0.15	0.05	0.15	0.19	0.15	0.12	0.17	0.14	0.23	0.24
MgO	5.91	0.30	4.34	4.73	6.80	5.86	5.27	8.11	2.89	3.70
CaO	9.13	0.50	5.78	8.08	10.53	12.41	11.21	10.76	3.25	8.01
Na_2O	2.71	1.93	3.37	2.98	2.61	2.27	2.35	2.23	4.47	3.19
K_2O	0.62	5.64	1.91	0.87	0.31	0.12	0.46	0.35	2.72	1.14
H_2O+	1.92	0.79	2.11	1.20	1.77	1.55	1.62	2.55	2.86	0.68
H_2O-	1.76		1.98	0.77	1.78	2.08			1.71	0.48
P_2O_5	0.17	0.04	0.38	0.38	0.14	0.08	0.15	0.13	0.42	0.25
CO_2	0.13	0.26	0.07	0.18	0.12	0.10	0.00	0.07	0.15	
Total	100.68	99.66	100.88	100.77	99.88	99.86	99.77	99.84	100.88	99.68*

* includes 0.02% S and 0.05% BaO

Table 2 Continued

	GM-14	MI-2	H-5b	H-4	GP-27	GP-26	GP-4a
SiO_2	72.23	62.60	53.22	57.31	54.88	53.60	50.90
TiO_2	0.45	1.09	2.05	1.62	1.69	3.16	1.05
Al_2O_3	11.38	12.01	17.55	13.39	15.36	11.94	14.50
Fe_2O_3	4.08	8.18	4.63	4.23	4.91	4.08	1.28
FeO	0.24	2.02	6.18	8.05	6.50	9.28	9.63
MnO	0.04	0.12	0.13	0.17	0.19	0.16	0.18
MgO	0.44	1.40	2.33	1.89	3.27	3.32	6.49
CaO	1.07	2.22	4.79	3.61	3.03	6.21	8.41
Na_2O	2.62	4.04	5.35	3.88	4.84	2.93	2.80
K_2O	5.50	4.15	1.76	2.66	2.40	1.66	0.85
H_2O+	1.54	1.72	1.32	2.05	1.97	1.99	3.47
H_2O-	0.50	0.93		0.61			
P_2O_5	0.03	0.28	0.51	0.59	0.65	0.45	0.17
CO_2	0.45	0.04	0.11		0.06	0.85	0.08
Total	100.57	100.80	99.93	100.06	97.75	99.63	99.81

Table 2 Continued

TH-2	fine-gr., dk gray basalt, L. Superior shore at Town Part, Burlington Bay, Two Harbors; SE 1/4 NW 1/4 Sec. 6, T. 52 N., R. 10 W., Lake Co.; anal. M. Kumanomido
F-201	aphanitic, pink felsite with plagioclase, orthoclase, quartz, and altered fayalite (?) phenocrysts, NE cliff of Palisade Head, NE/NW 1/4 Sec. 22, T. 56 N., R. 7 W., Lake Co.; anal. K Ohta
F-54	fine-gr., brown trachybasalt, Highway 61 cut N of Kennedy Landing, E 1/2 NE 1/4 Sec. 36, T. 57 N., R. 7 W., Lake Co.; anal. Shiro Imai
F-108	fine-gr. black basalt, L. Superior shore NE of Kennedy Ck., SE 1/4 SW 1/4 Sec. 36, T. 57 N., R. 7 W., Lake Co.; anal. Shiro Imai
T-45	black, ophitic basalt, Cross River at 1090 ft.; NW 1/4 NW 1/4 Sec. 36, T. 59 N., R. 5 W., Cook Co.; anal. M. Kumanomido
T-56	ophitic olivine basalt with small plagioclase phenocrysts, L. Superior shore E. of Onion R., range line T. 59 N., R. 3/4 W., Cook Co.; anal. M. Kumanomido
DY-6b	coarse, brown, ophitic olivine basalt, L. Superior shore W. of Cascade R., SE 1/4 SE 1/4 Sec. 2, T. 60 N., R. 2 W., Cook Co.; anal. K Ohta
GH-25	black, fine gr. ophitic basalt, Highway 61 cut at Good Harbor Bay, NW 1/4 NW 1/4 Sec. 34, T. 61 N., R. 1 W.; Cook Co.; anal. K. Ohta
GH-2b	fine-gr., red-brown trachyandesite with small plagioclase, augite, and magnetite phenocrysts, L. Superior shore ENE of Good Harbor Bay, NW 1/4 SE 1.4 Sec. 26, T. 61 N., R. 1 W., Cook Co.; anal. S. Imai
S&G-5-9	granular, brown trachybasalt of columnar flow, Grand Marais harbor, Sec. 14, T. 61 N., R. 1 E., Cook Co., anal. E. D. Burr (Sandell and Goldich, 1943, Table 5, No. 9)
GM-14	fine-grained, gray felsite, L. Superior shore approx. 1/2 mi. E. of Devil Tract R., NW 1/4 NW 1/4 Sec. 18, T. 61 N., R. 1 E., Cook Co.; anal. Tadashi Asara
MI-2	aphanitic, red-brown quartz latite with small plagioclase, ferroaugite, olivine and magnetite phenocrysts, Highway 61 cut at W. edge of Sec. 6, T. 61 N., R. 3 E., Cook Co.; anal. Tadashi Asari
H-5b	fine-gr. trachybasalt with large plagioclase phenocrysts, NW of Highway 61 W. of Reservation R.; NE 1/4 NW 1/4 Sec. 12, T. 62 N.,

Table 2 Continued

	R. 4 E., Cook Co.; anal. K. Ohta
H-4	aphanitic, brown trachyandesite dike, Highway 61 at old road jct., NE 1/4 NW 1/4 Sec. 12, T. 62 N., R. 4 E., Cook Co., anal. T. Konda
GP-27	fine-gr., black basalt, Highway 61 cut NE of Deronda Bay, SE 1/4 NW 1/4 Sec. 25, T. 63 N., R. 5 E., Cook Co.; anal. K. Ohta
GP-26	granular gray porphyritic trachybasalt dike with plagioclase phenocrysts, Hwy. 61. NW 1/4 of NE 1/4 Sec. 25, T. 63 N., R. 5 E., Cook Co.; anal. K. Ramlal
GP-4a	diabasic gray basalt, 1st road cut Highway 61 SW of Grand Portage, NE 1.4 NE 1.4 Sec. 17, T. 63 N., R. 6 E., Cook Co.; anal. K. Ohta

tal joints. The "Hovland lavas" contain a very distinctive group of platy plagioclase-porphyritic trachybasalts and trachyandesites (see figure 7).

The felsic lavas are anomalously abundant for a simple differentiation series from a basaltic parent magma. They are red, pink, or light gray, and have the composition of quartz latites. These flows tend to be much thicker than the other types: the thickest is 1,300 feet, a few miles east of Grand Marais; the 3,500-foot Brule River rhyolite west of Hovland may be a lava dome. Their top surfaces are mostly strongly flow-banded, vesicular, and contorted, but not brecciated, and their bases are commonly flow-banded and locally brecciated. Spherulites are occasionally present. Jointing ranges from large columns 4 feet across in the thickest flows (see figure 8) to subhorizontal platy joints; small tectonically-produced parallel fracture sets a few mm apart commonly break up the cooling joint fragments into small pieces. Most of the felsites are porphyritic, with quartz and feldspar phenocrysts (oligoclase-andesine and/or orthoclase) but some are only weakly porphyritic or aphyric. Poikilitic quartz surrounding stout alkali-feldspar laths ("snowflake texture") is a common microscopic texture in the thicker flows. Even these siliceous lavas have evidently flowed a great distance; one lava or flow group can be traced for at least 23 miles west from the Devil Track River, Grand Marais (see map, figure 3).

ALTERATION

The lavas have been strongly but irregularly affected by secondary solutions that have deposited low-temperature minerals in vesicles, fractures, and other cavities, and altered some of the minerals of the lavas themselves. For instance, no fresh olivine has been detected in any of the lavas, although it is common in the intrusive diabases. A broad zonation of this alteration is apparent; at Duluth and at Grand Portage (in the lower parts of the lava section) much of the groundmass pyroxene has been converted to actinolite (although many larger augites are unaffected) and some plagioclase has been saussuritized. Here also the amygdule minerals are characteristically quartz, prehnite, calcite, epidote, and chlorite, basically the same assemblage as is found in the Portage Lake Lava Series on the Keweenaw Peninsula (Stoiber and Davidson, 1959). The high-temperature zeolite wairakite has also been found in the lavas west of Duluth (Kilburg, 1972). In and northeast of Duluth K-feldspar is also occasionally found, and laumontite becomes abundant. Higher in the section various zeolites, along with calcite, are dominant except in the quartz tholeiites and similar lavas where agate, crystalline quartz and chlorite are common. The most abundant zeolites are laumontite, stilbite, heulandite, thomsonite and scolecite, but analcite, natrolite, mesolite, mordenite, datolite, and apophyllite have also been found. Saponite is common in olivine basalts. Andradite garnets have been discovered in several localities in amygdules and veins from a wide range of lava types (basalts to rhyolites) and levels in the sequence, and traces of native

Figure 8. Palisade rhyolite flow, exposed in Palisade Head (foreground) and Shovel Point (Little Palisades, 2 miles away in distance). Cliffs are about 200 feet high. Northeast of Silver Bay, Lake County.

copper have been found in several localities. Thus the secondary zonation in the North Shore Volcanic Group spans both the deeper-level, higher-temperature type of the Keweenaw Peninsula and the higher-level, cooler type characteristic of the lower parts of the Tertiary plateau lavas of eastern Iceland as described by Walker (1960). Walker's upper, zeolite-free zone is apparently not represented in Minnesota. According to his estimates, the presently exposed top of the section on the Lake Superior shore could have been approximately 5,000 feet below the surface during mineralization. Although detailed work has not yet been done, no clear cross-cutting relations of zeolite zones to stratigraphy within the lavas have been recognized, but the evident Upper Precambrian, postvolcanic unconformity which probably follows the north shore must have postdated the mineralization, since it does crosscut the zeolite zones.

It should be stressed, however, that none of the flows has been entirely converted to secondary minerals. In fact, the plagioclase and augite are typically unaltered or only locally altered in most mafic and intermediate rocks, although no fresh olivine has been discovered. There has typically been some oxidation of the opaque minerals, especially of magnetite, and pigeonite is commonly oxidized at its borders. In many intermediate and felsic lavas, plagioclase phenocrysts have been albitized and/or zeolitized; some of this alteration could be deuteric. Fresh, undevitrified volcanic glass is still present in occasional samples, notably in a basaltic andesite from about two miles west of the mouth of the Brule River.

STRATIGRAPHY

The lavas of the North Shore Volcanic Group can be conveniently divided into several lithostratigraphic units of coherent petrographic character primarily on the basis of exposures at or near the Lake Superior shore. Many of these units can be traced for a considerable distance inland, but interruptions and structural complications by intrusive bodies, as well as glacial and lacustrine deposits prevent the reconstruction of a complete, continuous sequence. No clear trend of compositional change is evident from base to top; in fact, although the most ferromagnesian lavas occur at the base, the uppermost flows, in the Tofte-Lutsen area, are entirely olivine basalts. It should be kept in mind also that a major stratigraphic break may occur between the Grand Portage-Hovland lava section (showing reversed magnetic polarity) and the higher strata.

Table 3 lists the informal stratigraphic units proposed for the northeast limb (Tofte to Grand Portage) of the North Shore Volcanic Group, with their estimated thicknesses and general lithic characters, and Table 4 gives similar data for the southwest limb. This latter table depends largely on the work of Sandberg (1938) and Grogan (1940), pending restudy; the informal names are new.

Table 3 Stratigraphy of northeast limb (Tofte-Grand Portage) North Shore Volcanic Group (exclusive of interflow sediments and intrusions)

Approx. Thickness (ft.)		Lithostratigraphic unit	Lithic Character
Top			
1020	Normal magnetic polarity	Lutsen basalts	olivine basalts, olivine tholeiites
160		Terrace Point basalt flow	thomsonite-bearing ophitic basalt
310		Good Harbor Bay andesites	brown, porphyritic andesite, trachyandesite
360		Breakwater trachybasalt flow	brown, columnar, granular trachybasalt
500		Grand Marais rhyolite flow	pink, red, gray porphyritic rhyolite
600		Croftville basalts	various fine-grained basalts
1020		Devil Track felsites	aphyric and porphyritic rhyolite flow
400-900		Red cliff basalts	amygdaloidal, ophitic olivine basalt
1300		Kimball Creek felsite	pink to tan, porphyritic felsite
1800		Marr Island lavas	mixed tholeiitic basalt, intermediate felsic lavas
1000		Brule River basalts	granular-diabasic basalts
3500		Brule River rhyolite flow	pink to gray porphyritic rhyolite

Table 3 Continued

Approx. Thickness (ft.)		Lithostratigraphic unit	Lithic Character
4000 (est.)	Reversed magnetic polarity	Hovland lavas	mixed porphyritic basalt, trachybasalt rhyolite
200		Red Rock rhyolite flow	red, porphyritic rhyolite
260		Deronda Bay andesite flow	gray-brown, aphyric andesite
4500		Grand Portage basalts	mixed tholeiitic to diabasic basalts pyroxene-porphyritic basalts locally at base
Base		Disconformity	
		Puckwunge Sandstone	cross-bedded quartz sandstone and conglomerate

Table 4 Generalized stratigraphy of southwest limb (Tofte-Nopeming) North Shore Volcanic Group (exclusive of interflow sediments)

Approx. Thickness (ft.)	Lithostratigraphic Unit	Lithic Character
Top		
4000	Schroeder basalts	amygdaloidal ophitic olivine tholeiites
300	Manitou trachybasalt flow	red-brown granular trachybasalt to basalt
	(more of the Schroeder basalts)	
280	Bell Harbor lavas	mostly quartz tholeiites, other basalts
300	Palisade rhyolite flow	gray to pink, porphyritic rhyolite
few 100's	Baptism River lavas	mixed lavas, mostly basalts
- - -	Beaver Bay Intrusive complex	- - - - - -
3200	Gooseberry River basalts	mixed basalts, one felsite
- - -	LaFayette Bluff, Silver Creek Cliff intrusions	- -
1025	Two Harbors fine-grained basalts	"melaphyres", some quartz tholeiites
1615	Larsmont ophitic basalts	amygdaloidal ophitic olivine basalts
- - -	Knife River diabase intrusion	- - - - - -
4930	Sucker River basalts	mixed basalts, mostly ophitic
4400	Lakewood basalts	mixed basalts, mostly non-ophitic

Normal Magnetic Polarity

Table 4 Continued

Approx. Thickness (ft.)		Lithostratigraphic Unit	Lithic Character
- - -		Lester River diabase sill	- - - - - - -
3600		Lakeside lavas	mixed basalts, andesites, felsites
- - -		Endion diabase sill	- - - - - -
2560		Leif Erickson Park lavas	mixed basalts, andesites
- - -		Duluth Complex	- - - - - - - - -
2300	Reversed Magnetic Polarity	Ely's Peak basalts	augite-porphyritic basalts, diabasic basalts
Base		"Nopeming Sandstone"	quartz sandstone and conglomerate

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ROAD LOG AND STOP DESCRIPTIONS

FIRST DAY: Trip will leave Duluth and head up-section in the southwestern limb of the basin. At Two Harbors a thick quartz tholeiite flow will be examined, followed by columnar-jointed ophitic olivine basalts at Gooseberry Falls State Park. Continuing northeastward, the trip will examine a thick rhyolite flow and dramatic wave-cut shoreline features near Illgen City, followed by a sequence of basalts which have been overturned as a result of adjacent intrusions of gabbro with a great anorthosite block, which will also be seen; this is a part of the Beaver Bay Complex. At the next stop, approaching the highest level of the section, some excellent exposures of thin-bedded, ropy-surfaced, ophitic olivine tholeiite will be seen at Sugarloaf Point.

In the afternoon the trip will examine "primitive" olivine basalts near Lutsen and a thick, coarse-grained olivine basalt flow near Cascade, followed by a large road cut at Good Harbor Bay where a complex thomsonite-bearing basalt can be seen overlying the thickest interflow sediment unit on the north shore, as well as a porphyritic andesite flow which underlies the sediment farther east across Cutface Creek. After this a stop will be made at the cuesta-forming "Breakwater trachyandesite" in Grand Marais, and the day's geological expedition will end at an abandoned wave-cut cliff of felsite near Five Mile Rock. Return to Grand Marais for the night.

On the following log, the appropriate U. S. Geological Survey 7-1/2 minute topographic quadrangle is indicated for each stop.

Mileage

0.0 0.0 Radisson-Duluth Hotel, Superior Street at 6th Ave. W. We are close to the upper contact of the Duluth Complex (see bluffs to west at Point of Rocks) against the Leif Erikson Park lavas, the lowest magnetically normal unit of the North Shore Volcanic Group. Drive NE on Superior Street (U. S. Hwy. 61) through downtown Duluth to junction with London Road. Keep right on London Road (U. S. Hwy. 61) through the Endion district. Slight rise is held up by the 1,000-foot thick Endion sill, intruding the lavas. Continue NE through

6.2 Lakeside district, cross Lester River, and take freeway to Two Harbors. Road cuts at start of freeway are in diabase of Lester River sill, which trends north to hold up the ridge, soon visible to the left of the highway. Several road cuts on the way to Two Harbors in basaltic lavas.

27.2 At Two Harbors (a shipping port for some of U. S. Steel's taconite from the Mesabi Range) proceed E through town on U. S. Hwy. 61 to L bend shortly beyond; turn R at "Two Harbors Tourist Park" sign, drive S past Burlington Bay. Park at top of next rise at City Tourist Park.

27.6 STOP I. Two Harbors quadrangle. Quartz tholeiite of "Two Harbors fine-grained basalts." In the wave-cut outcrops here are exposed a series of fine-grained basalts at the limit of Sandberg's (1938) mapping. The amygdaloidal upper zones of the flows are rich in laumontite (now leonhardite) and have been more effectively attacked by the waves than the massive lower parts of the flows. Of particular interest here is a large (95 feet according to Sandberg) "melaphyre" which has the typical structures, textures, and composition of quartz tholeiite (Sample TH-2; see Table 2). It is a fine-grained, black basalt with traces of interstitial quartz and altered glass in a pilotaxitic, intergranular to locally subophitic texture. The plagioclase is zoned from An$_{70}$ cores to andesine rims, and the pyroxene is about En$_{42}$, Wo$_{38}$, Fs$_{20}$. No olivine was detected. The rock shows thin (1-3 mm), lensing, slightly coarser laminae where the pyroxenes are oxidized; these laminae are roughly parallel to the base of the flow and give a rough pin-striped appearance to the lower part. A few amygdules are also present in the lower part of the flow; they are filled principally with chlorite or agate. Where the flow rests directly on the highly amygdular and slabby top of the flow beneath, small pockets and lenses of sandstone are locally present, and a few small pipe amygdules occur in the lowest few inches of the flow. The upper zone of this tholeiite becomes rubbly, vesicular, and brecciated, with most open spaces filled with laumontite, or locally, calcite; it can be examined by walking along with top of the bank to the south.

28.0 Return N to Highway 61, turn R. Proceed NE along
35.8 Highway 61 past Flood Bay, Silver Creek Cliff, Lafay-
ette Bluff, and Crow Creek. These bluffs are composed
of gabbro and diabase of a large, slightly discordant
sill, the base of which can be seen at highway level
at Silver Creek Cliff. Note the deep weathering at
some exposures, especially at Lafayette Bluff. Con-
tinue through the settlement of Castle Danger to
Gooseberry Falls State Park. Park here before the
bridge over Gooseberry River:

13.1 41.1 STOP 2. Split Rock Point quadrangle. Smooth-surfaced ophitic olivine basalts of "Gooseberry River basalts." The Falls below the highway (see figure 6) expose three basalt flows that are characterized by smooth, gently billowing surfaces typical of very fluid lava. The billows have apparent wave lengths of 5 to 15 feet and relief of a few inches to a foot. The upper flow has a characteristic columnar, amygdaloidal to massive, ophitic central zone that forms the falls above the bridge as well as the top part of the first falls below the bridge, and it overlies the billowy top of the next in the middle of this waterfall. The flow beneath is about 10 feet thick and overlies another smooth, gently billowing flow top; this flow contact can be followed downstream (and down dip) where a natural arch has been eroded through it in an island in the center of the river. The next falls are in the columnar portion of this lower flow. These flow surfaces strongly resemble those on some Quaternary Icelandic flood basalts. Note the lack of ropy structures and of pipe vesicles in these lavas.

Continue NE on Highway 61 into the rugged topography
52.7 held up by the gabbros of the Beaver Bay Complex,
55.4 through Beaver Bay, past Reserve Mining Co.'s taconite
plant (diabase and anorthosite of Beaver Bay Complex),
where about 100,000 T of taconite ore from the eastern
Mesabi Range are processed per day; past Palisade Head
(rhyolite) and across the Baptism River. About 0.45

miles past the Baptism, stop at roadside on rise and look for trail along low ridge on lake side.

19.3 60.4 STOP 3. Illgen City quadrangle. Palisade Head porphyritic rhyolite at Shovel Point. Follow the trail, in Baptism River State Park, toward lakeshore; at trail junction go to left uphill to top of cliff of "Little Palisades." Be Careful. Here is the upper-middle part of the thick (greater than 300 feet) porphyritic rhyolite (quartz latite) that also forms Palisade Head to the SW and the highway cuts to the NE just before Illgen City. This flow can be traced for at least 6 miles and possibly as far as 10. View along shore to SW over underlying lavas ("Baptism River lavas") and some phases of the Beaver Bay diabase complex to Palisade Head (with radio beacon). Follow trail down dipslope to end of Shovel Point and around to NE corner: view NE up shore toward overlying quartz tholeiite flows of "Bell Harbor lavas".

The phenocrysts in this flow are of quartz, plagioclase, and K-feldspar. The base of the flow shows contorted banding, and the top ten feet are vesicular but not pumiceous and are vaguely banded parallel to the top surface (which is not exposed). There is no suggestion in any outcrop or thin section of pyroclastic origin, including hot ash flow eruption; it appears to have been a lava. For chemical analysis see Table 2, No. F-201.

60.8 Continue NE on Highway 61 through Illgen City at junction with Minnesota Route 1, past cuts in tholeiitic basalts and layered gabbro to a low cut in a rising bend to the R. before a very high road cut.

2.1 62.5 STOP 4. Illgen City quadrangle. Overturned lavas of Bell Harbor group. In this low cut are exposed 17 flows and flow units, all striking about N. 10° W. with a 45° dip to the SW. (The regional altitude here is about N. 60° E., 8° SE.) Volcanic structures within the flows (vesicular zones, rubbly tops, lobes and toes, etc.) and relations with interflow sediments clearly indicate that the sequence is overturned. This overturning is most likely the result of either forceful intrusion by, or foundering in, adjacent mafic intrusions of the Beaver Bay Complex. The high cut just to the NE is in a great anorthosite block (An_{68}) included in ophitic gabbro, and the next cut to the SW is in layered gabbro or syenogabbro.

The lavas include both granular, felty-textured amygdaloidal basalts with crusty, lobate tops, and fine-grained, quartz-tholeiitic basalts with vesicular-rubble tops. The characteristic fine texture of the quartz tholeiites, the thin oxidation banding in the lower-middle, massive portion of the flows, large quartz vugs and occasional vesicular autoliths in the upper-middle parts, and the vesicular-rubble tops, here filled in with red sand, are well displayed. Although these flows have vesicular, rubbly, aa-like surfaces, they do not show the clinkery basal zones typical of the Hawaiian aa basalts. Two chemical analyses of flows from this group, but not from this outcrop, are given in Table 2 (F-54, F-108). Minute, golden crystals of andradite have been found on joint surfaces in one of the interflow sandstones; laumontite and calcite are abundant amygdules. A basaltic dike cuts the lavas at the SW end of the exposure.

Continue NE on Highway 61, through high cut in anor-
thosite in gabbro; then drive through diabase, grano-
phyre, and basalts, across Kennedy Creek and past Ken-
nedy Landing cove. The high bluff on the left is made
of a thick quartz tholeiite or trachybasalt flow, and
several more are well exposed in cuts along the next
63.7 1/4 mile.

74.5 Continue NE on Highway 61 through Little Marais, across the Manitou River and Caribou River into Cook County. Turn off highway to R at the mailbox of Consolidated Paper Company's pulpwood storage and shipping operation; drive down road to Sugarloaf Cove.

12.25 74.75 STOP 5. Little Marais quadrangle. Thin-bedded ophitic olivine tholeiite of Schroeder basalts, Sugarloaf Point. Private Property. Walk around shore ledges of the point at the end of the beach. (Beach developed mainly from glacial drift of Superior Lobe; note variety of Keweenawan volcanic rocks, gabbros, and granophyres, and occasional Canadian granites and gneisses.) Exposed here are excellent examples of thin flow units (few inches to a few feet thick) and two thicker flows of rather typical "olivine tholeiite." The highly fluid nature of these lavas is shown in the flat flow surfaces, the thinness of the flow units, the well developed, small ropy surfaces, the abundant pipe amygdules, the granularity and pea-sized ophitic texture of the thicker flows, and the vesicle cylinders in the thicker flows, particularly the one that forms the "sugarloaf" near the end of the point. Please do not remove or destroy these structures! Also seen here are several clastic dikes, both discordant to and following columnar joints, and small, vesicular basalt dikes that also follow columnar joints. The shoreline visible to the NE to and well past Erie Mining Co.'s power plant and taconite dock (Taconite Harbor) is composed entirely of similar ophitic olivine basalts of the Schroeder basalt group. For a chemical analysis of a similar rock see T-45, Table 2.

Continue NE on Highway 61 through Taconite Harbor and
81.9 Schroeder, across Temperance River (excellent erosional potholes in ophitic basalts) to Tofte, and on across Onion River NE to Poplar River, at entrance road to Lutsen Resort.

16.75 91.5 STOP 6. Lutsen quadrangle. Porphyritic olivine basalts of Lutsen series, Poplar River. Private Property. These lavas, near the highest in the North Shore Volcanic Group, are notable for their "primitive" composition (lowest K, highest Mg) compared to all others analyzed (see T-56, Table 2). Abundant small, blocky bytownite (An_{78-88}) phenocrysts lie in a well crystallized ophitic groundmass of magnesian augite (En_{45}, Wo_{43}, Fs_{12}), plagioclase, and altered olivine. Phinney (1970) has calculated that most of the other basalts and basaltic andesites of the North Shore lavas analyzed at that time could have been produced from a parent magma very close to this composition, by subtraction of the minerals that constitute the gabbroic anorthosite that forms the bulk of the Duluth Complex.

This basalt can be examined in the west bank of the river above the bridge. Around the sharp L bend in the river upstream it is underlain by vesicular rubble, with cross-bedded red sand matrix, of the top of a large andesitic flow.

Continue up Highway 61 to the NE, through Lutsen. Road and shoreline are nearly parallel to strike of Lutsen basalts. Stop just past slight R bend where Cascade Lodge comes into view.

9.1 100.6 STOP 7. Deer Yard Lake quadrangle. Thick, medium-grained olivine basalt of Lutsen basalts, Cascade. Lakeshore ledges here and as far as can be seen in both directions are made of a thick, medium-grained olivine basalt flow with local, coarse, ophitic mottling. In this area the flow contains may large, cylindrical "segregation veins", about 4 to 6 inches in diameter, that cut vertically through the massive basalt. One can be seen in longitudinal section. These segregation cylinders are slightly coarser in texture and are amygdaloidal, in contrast to the enclosing basalt. These cylinders, and thin sill-like bodies elsewhere in these thick Lutsen basalts, are thought to be residual liquids of the flow that have auto-intruded the mostly-solidified mush of the remainder of the lava. See Table 2 for a chemical analysis of this flow (DY-6b).

101.25 102.95 Continue NE on Highway 61 past Cascade River. Beginning at the junction with County Route 7, the highway descends onto the upper portion of the thick Terrace Point basalt, and follows it until the next big L bend and road cut overlooking Good Harbor Bay.

4.65 105.25 STOP 8. Good Harbor Bay quadrangle. Thomsonite-bearing basalt and interflow sediments, Good Harbor Bay. In this large road cut, one of the major cliff-formers of the "Sawtooth Range", the Terrace Point basalt, overlies a thick (130 feet) section of interflow sediments. The Terrace Point basalt is predominantly a massive, fine-grained, black, ophitic basalt that characteristically contains thomsonite in amygdules, but in its lengthy exposure (including in this cut) several flow units and breccia zones of various character show complex relations with the major, massive, basal part of the flow. Traces of native copper have been found here. The thomsonite in this locality is concentrically banded in pink, green, and white, and is much sought after as a semi-precious gem. However, it is easily damaged in breaking it out of hard basalt. A chemical analysis of the ophitic basalt is given in Table 2 (GH-25).

The shoal out in the lake to the east (Gull Rock) is probably an extension of the massive basal part of the Terrace Point basalt. The flow is about 160 feet thick in this area.

The interflow sediments in this cut are mainly thin-bedded siltstone and silty shale, but by walking up the bed of Cutface Creek at the bottom of this hill one passes outcrops of the base of the sediments resting on the amygdaloidal-rubbly top of an andesite flow of the Good Harbor Bay andesites. The lower parts of this large lens of sediment (it extends for at least 7 miles along strike) are well bedded medium sandstone showing abundant ripple marks. The sediments appear to have been deposited in a large depression on the irregular andesite terrane.

105.8 Up the grade NE of the R bend at Cutface Creek and Thomsonite Beach, exposures of the Good Harbor Bay andesites can be seen on the L (N) side of the highway. These fine-grained, brown or gray-brown, weakly porphyritic andesites and trachyandesites containing scattered small plagioclase and rarer augite phenocrysts (for analysis see Table 2, GH-2b). The upper parts of the two flows exposed here are vesicular and the top zones rubbly.

110.5 Continue E on Highway 61 into Grand Marais. At harborside keep straight (do not bear left on Route 61) to second stop sign; turn R and drive out to Coast Guard station.

5.8 111.05 STOP 9. Good Harbor Bay quadrangle. Breakwater trachybasalt flow. Tombol here is made by gravel bar connecting mainland to resistant island and breakwater ledges of a massive, locally columnar-jointed, weakly porphyritic trachybasalt or basalt with small phenocrysts of plagioclase, augite, and rare olivine. For chemical analysis, see S & G-5-9, Table 2. This unit is about 360 feet thick. It is not known with certainty whether this is a big flow or a sill; to the west it has a sharp, chilled basal contact against felsite, but its tip surface is covered. It does become amygdaloidal and zeolitized near its top and is assumed to be a flow. As can be seen from this vantage point, it forms one of the major strike-ridges of the "Sawtooth Range" to the west. The harbor here is probably eroded from the small-jointed rhyolite that underlies the Breakwater trachybasalt. The big ridge to the north behind Grand Marais is held up by thick basalt flows and diabase intrusions.

111.45 Return to last (nearest) stop sign; keep straight N to rejoin Highway 61. Turn R and continue eastward on Highway 61 past Croftville settlement (on Nipissing-stage terrace), across Devil Track River and eastward on well developed abandoned beach terrace of Nipissing stage (about 3,500 yr. b.p.), with wave-cut slope and cliffs on the left. About opposite Five-Mile (Guano) Rock, stop at a promontory in this abandoned cliff.

5.2 116.25 STOP 10. Kadunce Creek quadrangle. Rhyolitic felsite of Devil Track series. This series, about 1,020 feet thick, is composed at the shoreline of two rhyolitic flows. The upper, thicker one (exposed here) is non-porphyritic (with only rare, small quartz phenocrysts) and felsitic with poikilitic ("snowflake") texture, and shows slabby jointing and vague flow-banding. Its upper portion has been cut into by the Devil Track River to form a deep, inaccessible canyon to the west. One-fourth mile to the east of this stop the base of this flow rests on the vesicular, locally spherulitic and flow-banded top of a porphyritic flow of similar composition. This felsite group has been traced 23 miles along strike to the west (figure 3). A chemical analysis of this flow from another locality (GM-14) is given in Table 2.

Five Mile (Guano) Rock, a mile out in Lake Superior, is made of diabase that is probably continuous with intrusions that crop out in Grand Marais.

Return to Grand Marais for the night.

SECOND DAY: Leaving Grand Marais, the trip will continue down-section in the northeastern limb of the North Shore Volcanic Group. The first stop will be at an intermediate quartz latite of the Marr Island lava group east of Kadunce Creek; then, after crossing the Hovland diabase complex, an exposure of highly porphyritic trachybasalt of the reversely polarized Hovland lavas will be examined. The Reservation River diabase complex will be traversed and the next stop will be at a banded trachyandesite of the Grand Portage lavas and a large, porphyritic trachybasalt dike near Deronda Bay. The next-to-last stop of the trip will be at the basal basaltic flows of the Grand Portage lavas near Grand Portage, where their metamorphic alteration can be seen. The final stop, where Middle Precambrian sedimentary rocks are cut by Keweenawan dikes, also has a panoramic view over the lakeshore scenery in the Pigeon Point area. Return to Grand Marais for lunch, and on to Duluth and Minneapolis.

In the morning continue ENE on Highway 61 from last stop, past Durfee Creek, around big L bend in Red Cliff basalts, across Cliff, Kimball, and Kadunce Creeks that are cut in the Kimball Creek felsite group, and stop at a large road cut on the L side.

5.75 122.0 STOP 11. Kadunce Creek quadrangle (east edge). Porphyritic intermediate quartz latite of Marr Island lavas. Two large road cuts here at the east edge of the quadrangle expose a thick (approx. 150 feet) intermediate quartz latite that contains small phenocrysts of andesine (but many are albitized or zeolitized), ferroaugite (En_{15}, Wo_{42}, Fs_{43}), olivine (completely altered) and magnetite, in a groundmass that contains abundant alkali feldspar. Neither top nor base of this flow is exposed, but jointing gives an impression of its attitude. In the western cut the upper part of the flow contains occasional round amygdules of laumontite, prehnite, Fe-rich montmorillonite, and rarely quartz.

Flows of very similar composition have been collected and analyzed from several horizons in the North Shore Volcanic Group. A chemical analysis of this flow (MI-2) is given in Table 2.

Drive E on Highway 61 past Paradise Beach, over
125.8 a low ridge held up by the Brule River basalts,
129.8 across the Brule (Arrowhead) River, through the
Hovland diabase complex and the village of Hovland and past Big Bay. This topographic basin is rimmed by hills held up by intrusive rocks of the Hovland complex (to W. and N.) and the Reservation River diabase complex (to NE.). After next rise and L bend in highway, stop at driveway on R.

12.7 134.7 STOP 12. Hovland quadrangle (east edge). Trachyandesite dike cutting porphyritic trachyandesite lava flow of Hovland series. The Hovland lavas, which show reversed magnetic polarity, are a heterogeneous group of widely varying composition, but include a large number of distinctive trachyandesite to trachybasalt flows that display platy plagioclase phenocrysts. These rocks have not been found in any other part of the stratigraphic section, and many are strikingly similar to the reversely magnetized "turkey-track" porphyries of the "Traps of the South Range" in Michigan and Wisconsin. The flow exposed in an abandoned lake cliff to the north of the highway is especially remarkable for the unusual size of the plagioclase phenocrysts, which here attain lengths of up to 10 cm. They are calcic andesine, An$_{46}$, where not altered. This flow is obviously a few tens of feet thick, but its top is not exposed. Its base (to the east; private property) rests on the wrinkled, crusty, amygdaloidal surface of another similar flow, probably a flow unit of the same eruptive event. Epidote and quartz are common in amygdules here.

The outcrop on the S. side of the highway is in the fine-grained trachyandesite dike, which can be traced for at least 2 miles to the west. It is also magnetically reversed. It contains small phenocrysts of altered plagioclase, clinopyroxene (En$_{32}$, Wo$_{34}$, Fs$_{34}$) and titaniferous magnetite.

Chemical analyses of both the lava (H-5) and the dike (H-4) are given in Table 2.

135.7 Continue NE on Highway 61 up rise onto Reservation
River diabase complex; pass many outcrops
and road cuts in ophitic gabbro for about 4 1/2
140.0 miles. At ENE edge of the Complex, descend onto
lowland underlain by the oldest lava group of
the northeast limb of the North Shore Volcanic
Group, the Grand Portage lavas; these also show
reversed magnetic polarity. Cross the Red Rock
140.9 rhyolite flow (road cut), then at Deronda Bay,
an andesite. Shortly past the next road cut (a
trachyandesite) stop at an inconspicuous and unmaintained side road to R.

7.0 141.7 STOP 13. Grand Portage quadrangle (W. edge). Porphyritic trachybasalt dike and tholeiitic trachyandesite lava of Grand Portage series. Walking S on the old road, one crosses a dike of the E-trending Grand Portage dike swarm, and in 1/8 mile comes to a small cove on the lakeshore by an old cabin site. On the R(SW) is the lower, massive portion of a fine-grained, oxidation-banded, tholeiitic trachyandesite (the same one that crops out in the highway cut just passed). The long point on the L (NE) is made of a large, compound dike typical of the Grand Portage swarm. The concentration of plagioclase phenocrysts varies with distance from the contact, probably as a result of flowage phenomena. The rock is a trachybasalt with iron-rich clinopyroxenes and abundant alkali feldspar in the groundmass. Paleomagnetic sampling of this dike by Books (1968) shows it to have reversed polarity; it may have been a feeder for some of the Hovland lavas. The entire swarm is basaltic or trachybasaltic, and most of the dikes contain sizeable plagioclase phenocrysts.

See Table 2 for chemical analysis of the trachyandesite (GP-27) and of a similar dike (GP-26) of the same swarm but another locality.

Continue E on Highway 61, travelling over basalts of the Grand Portage series cut by E-trending dikes. Several large, abandoned beach ridges to the L were mined out for the highway construction. Stop on rise at junction of Cook County Route 17.

2.9 144.6 STOP 14. Grand Portage quadrangle. Basal basalts of North Shore Volcanic Group. These road cuts constitute the lowest easily accessible exposures in the Keweenawan lava succession in this area; the Lower Keweenawan Puckwunge sandstone underlies the gentle slope down which the highway continues to the north, around Grand Portage village. Five flows can be distinguished in these cuts. It is not known how many more underlie these above the Puckwunge, since they are covered, but the number is thought to be small (one to five); the Puckwunge and the directly overlying basalts are well exposed 1/4 mile to the NNW in a steeper slope, and also on Grand Portage Island 2 miles to the east. These flows, and one sampled 4 miles to the northwest, show reversed magnetic polarity, as does the Puckwunge beneath. This Grand Portage basalt series trends nearly E-W, though its strike swings somewhat more northeasterly a few miles east of Grand Portage. This is in marked contrast to the uniform NE strike of the upper Middle Keweenawan lavas of Isle Royale, just 25 miles to the east, and suggests a discordance between the Lower Keweenawan and Upper-Middle Keweenawan series that may be the result of either faulting or a more complex depositional and/or erosional history than has generally been assumed for this area.

The basalts in this cut are generally fine to medium grained with a somewhat diabasic texture. Low-grade hydrothermal (burial?) metamorphism has strongly altered much of the rock to a low greenschist facies assemblage of actinolite, chlorite, epidote, and prehnite. Amygdules contain prehnite, epidote, and weathered agate. Pumpellyite has been looked for but not found, although it is present ("Isle Royale Greenstone") on Isle Royale to the east.

Table 2 gives a chemical analysis of a basalt (GP-4a) from this cut.

Continue NE on U. S. 61 across Grand Portage
basin, underlain by shales and graywackes of the
Middle Precambrian Rove Formation. The sur-
rounding ridges are held up by large Keweenawan
diabase dikes ("Logan dikes") and on the SW side
by the Lower Keweenawan basalts. Continue up-
146.9 slope past the old voyageurs' Grand Portage
Trail, past cuts in Rove Formation and basalt
dikes, through great cut in Mount Josephine dia-
base dike, past Teal Lake on left, and down to
an overlook on the right opposite a road cut.

4.7 149.3 STOP 15. Grand Portage quadrangle. Rove shale and graywacke cut by basalt dikes, and view over Lake Superior. View over Wauswaugoning Bay of Susie Islands (Rove Formation, Puckwunge Sandstone, and basal Keweenawan flows), Hat Point and Mount Josephine (Logan diabase, "Pigeon River intrusions") and Isle Royale in distance (upper Middle Keweenawan flows). Pigeon Point (differentiated Keweenawan sill cutting Rove Formation) is to E of the Bay. This stop is at the limit of the trip; return down the Lake Superior shore via U. S. 61.

(Stop for lunch at Grand Marais)

Continue SW through Duluth to Minneapolis.