FIELD TRIP GUIDEBOOK FOR THE KEWEENAWAN (UPPER PRECAMBRIAN) NORTH SHORE VOLCANIC GROUP, MINNESOTA

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

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Leader

John C. Green

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REGIONAL RELATIONS

The Upper Precambrian plateau lavas of the Lake Superior region were produced in response to tensional rifting of North America roughly 1200-1120 x 10^6 years ago (White, 1972a). Geological and geophysical evidence shows that they consist of a group of about eight separate volcanic accumulations which partly overlap in time and space as the locus and activity of rifting changed along what is now the Midcontinent Gravity High (Green, 1977). Nearly all of these lava accumulations ("plateaus") contain preserved sections which range in thickness from 2.5 to 7 km and are made of hundreds of individual flows. They have subsided centrally during and/or after eruption. Basalt of various compositions predominates; the most common type is nonporphyritic olivine tholeiite with unusually high Al content and ophitic texture. Transitional to weakly alkaline basalt is also common. Quartz tholeiite, basaltic andesite and rhyolite are moderately abundant in most of the plateaus, and icelandite (intermediate quartz latite) is found in some.

Recent geologic mapping and petrologic study have been carried out in most of the plateaus, providing a good basis for regional analysis. These studies include, for Ontario--McIlwaine and Wallace, 1976 (Osler Group) and Annells, 1973, 1974 (Michipicoten Island and Mamainse Point); for Michigan --White, 1960, 1968; Huber, 1973 (Portage Lake Volcanics) and Hubbard, 1975 (Kallander Creek and Siemens Creek formations); and for Minnesota--Green, 1972b, Green and others, 1977b (North Shore Volcanic Group).

Each of these plateaus consists almost entirely of subaerial lavas; pillowed basalt is found at the very base of the section in some localities and rarely elsewhere, and pyroclastic rocks are very rare. Flow thicknesses are variable; averages for different plateaus range from about 5 to 25 m. Individual flows range from units less than a meter thick to the Greenstone Flow of the Portage Lake Volcanics which attains a maximum thickness of 450 m. Some of the largest flows can be traced for 40-90 km along strike and contain over 200 km^3 of lava (White, 1960). Red sandstone and conglomerates of fluvial origin are interbedded with the lavas, but constitute only a few percent of any section. Several dike sets are present in different parts of the region (Green, 1977) and the general interpretation for each plateau is a broad, flat lava surface fed by fissure eruptions and slowly subsiding as magma was brought to the surface from the underlying mantle. Two large intermediate to silicic central volcanoes have been identified at the top of the sequence (Annells, 1974; White, 1972b); more may be present in Minnesota at lower horizons.

Paleomagnetic sampling and studies in nearly all the major exposure areas of Keweenawan igneous rocks have helped to establish the regional stratigraphic framework (fig. 1; see Green, 1977). All of these rocks appear to have crystallized during a series of three paleomagnetic intervals known as the lower normal (represented only by the basal flows of the Siemens Creek plateau in Michigan), reversed, and upper normal intervals according to the orientation of the magnetic poles relative to today's; the north pole position traced out a large loop (the "Logan Loop") in the North Pacific area during this time (e.g., Robertson, 1973).

Age determinations on Keweenawan igneous rocks have been carried out by several radiometric methods (summarized in Green, 1977). U/Pb studies on zircons appear to suffer the least from the widespread low-grade hydrothermal alteration of these rocks, and also give the narrowest range in ages. Sampling over nearly the entire stratigraphic range shows a narrow age span of between 1120-1140 x 10^6 years for all of the upper normal polarity rocks and at least the younger reversed polarity rocks,

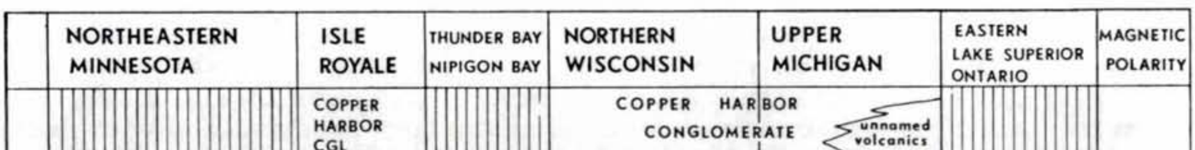


Figure 1. Stratigraphic correlations for Keweenawan volcanic rocks, Lake Superior area. After Green (1977).

thus fixing the time of field reversal (Silver and Green, 1972). These studies are continuing.

In early regional syntheses of the Lake Superior region (e.g., Van Hise and Leith, 1911) the term "Keweenawan" (after Keweenaw Point, Michigan, where the famous native copper deposits occur in the Portage Lake Volcanics) was used for all rocks of post-Penokean or post-Animikie (and pre-Paleozoic) age: that is, approximately equivalent to the later part of the Late Precambrian or Precambrian Y. The Keweenawan rocks were subdivided into the tripartite sequence: Upper Keweenawan (clastic sedimentary strata overlying the volcanic rocks); Middle Keweenawan (volcanic and intrusive rocks and their clastic interbeds); and Lower Keweenawan (thin quartzarenites beneath the lavas) (see Craddock, 1972). More recently it has been recognized that some of the widespread quartzarenites of Minnesota and Wisconsin and possibly Ontario are several hundred million years older than any Keweenawan igneous rocks and these are now generally excluded from the Keweenawan (Craddock, 1972). Other quartzarenite units in Minnesota (Nopeming sandstone) and Michigan (Bessemer sandstone) show soft-sediment deformation by the overlying basal lavas and may be interbedded with the first one or two flows; these were obviously contemporary though unrelated to volcanism.

The coincidence of an apparently major stratigraphic break (locally unconformable) with the horizon where the reversed-to-normal paleomagnetic pole transition is recorded throughout the basin has led several workers to propose a redefinition of the Lower/Middle Keweenawan boundary. Instead of retaining it at the base of the volcanic rocks (which may not be isochronous throughout the basin), they propose to move it to the major depositional break within the volcanic rocks that is marked by the polarity change, thus making the distinction more useful for subdividing the great thicknesses of Keweenawan lavas, as well as retaining ease of determination with simple field equipment (Green, 1972a; Hubbard, 1975, Books, 1972).

White (1972b) has also proposed raising the Middle/Upper Keweenawan boundary from the base to the top of the Copper Harbor Conglomerate of Michigan and Wisconsin, thus including all the of the youngest volcanic rocks in the Middle Keweenawan.

Correlations within the Keweenawan Supergroup of King (1976) around the Lake Superior basin are given in Figure 1.

NORTH SHORE VOLCANIC GROUP

The Keweenawan volcanic and interflow strata that are found in northeastern Minnesota are collectively known as the North Shore Volcanic Group (Goldich and others, 1961). It contains approximately 6100 to 8100 m of strata belonging to the older, reversed-polarity "Ironwood-Grand Portage-Nopeming" plateau and the overlying "North Shore normal" plateau of Green (1977). The rocks are well exposed along the shore of Lake Superior where they are seen to dip gently to moderately (8-20°) toward the lake in a large crescentic structure. Thus dips are easterly in the southwestern (Duluth) part, and southerly in the northeastern (Grand

Portage) part. They are generally underlain and intruded by comagmatic rocks of the Duluth Complex, the Beaver Bay Complex and many smaller intrusive sills, stocks, dikes, and other plutons. A general summary is found in Green (1972b).

Because of the superior exposures, detailed mapping has been confined mostly to the lakeshore (Sandberg, 1938; Grout and Schwartz, 1939; Schwartz, 1949; Grout and others, 1959; Grogan, 1940). More recent remapping by the writer (Green and others, 1977b) and others (e.g., Kilburg, 1972) has so far concentrated on the northeastern two-thirds of the shoreline (Silver Bay to Grand Portage) and has attempted to trace units inland away from the shore exposures. This work is also developing the geochemical and petrologic character of the plateau lavas and associated minor intrusions (Brannon and others, 1979; Green and others, 1977a). Jirsa (1978) is currently studying the interflow sediments.

The North Shore Volcanic Group contains the full range of compositions from primitive Al-rich olivine tholeiite to rhyolite, with rather more of the intermediate and felsic types than in most of the other Keweenawan areas. Many of the physical and chemical characteristics of the main varieties are outlined in Table 1. Nearly all flows have a thin vesicular zone at the base, a massive interior and an increasingly amygdaloidal zone in the upper third or so, with holocrystalline texture. Most intermediate and felsic flows are porphyritic, but most basalts and basaltic andesites are nonporphyritic (aphyric). The entire volcanic pile, which subsided many kilometers during and after eruption, has been affected to varying degrees by hydrothermal alteration (burial metamorphism). Some of the least permeable rocks (generally the massive central parts of flows) are but little altered, but the more permeable rocks are typically strongly altered to mineral assemblages ranging from upper greenschist or prehnite-pumpellyite facies (in the lower parts of the section) to zeolite facies. Where the lavas have been intruded by mafic plutons, contact metamorphism has resulted in higher temperature assemblages.

The recent mapping has allowed subdivisions of the North Shore Volcanic Group into volcanostratigraphic units analogous to those mapped by Walker (1959) in the Tertiary plateau lavas of eastern Iceland. Figure 2 shows the map pattern and lateral continuity along strike for the northeastern half of the area. The units consist of individual major flows or of groups of flows of similar character that can be traced along strike. They were discussed briefly by Green (1972b); see Tables 2 and 3. Mapping and geochemical studies are continuing to refine this stratigraphic framework. So far no single flow has been traced for more than 37 km in Minnesota. Faulting and other structural complications relating to intrusions of the Beaver Bay Complex interrupt the continuity of the section in some areas, particularly between Split Rock River and Little Marais in Lake County, creating serious uncertainties as to the sequence and thickness of units in that area. Thicknesses corresponding to the maximum exposed continuous sequence in each unit for that area are given in the tables. For the rest of the section, thicknesses in the tables are derived either by summing successive flow thicknesses measured along the shore (such as from Sandberg, 1938) or by geometric construction from cross sections using averaged measured dips and strikes for the unit. No deep drilling has been done.

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

Characteristic	Olivine Tholeiite	Transitional Basalt	Quartz Tholeiite	Andesite and Trachyandesite	Intermediate Quartz Latite (Icelandite)	Rhyolite and Quartz Latite
Wt. % SiO_2	46-50	47-51	50	51-56	60-65	69-75
Wt. % Al_2O_3	15.2-18.4	14.1-15.3	15	13.1-16.6	10.6-14.6	11.0-12.8
Wt. % MgO	5.3-8.6	4.2-6.5	5.9	2.6-4.5	0.8-1.9	0.1-0.7
Wt. % K_2O	0.1-0.5	0.8-1.9	0.6	1.1-2.4	2.8-5.0	3.4-6.2
Thickness, meters						
Range	1-50	5-100	10-45	15-170	25-160	15-300
Common	3-25	8-20	25	20-50	30-50	50-90
Textures	Ophitic, Occas. plagioclase-porphyritic	Subophitic to intergranular, occ. plag.-porphyritic	Intergranular, pilotaxitic, fine banding	Very fine-grained Intergranular, some porphyritic (plag., augite, olivine)	Aphanitic, porphyritic (plag., augite, olivine, mag.)	Aphanitic, felsitic, most porphyritic (feldspars, quartz, augite, mag. ± ol.)
Structures						
Flow tops	smooth, ropy	smooth, ropy	scoriaceous rubble	scoriaceous rubble or smooth	scoriaceous	vesicular, banded, wrinkled
Jointing	sheeted tops, columnar centers	sheeted tops columnar to irregular centers	massive to columnar; small, irregular blocks	small, irregular blocks	irregular to sub-horizontal, platy	platy, subhorizontal; big columns in thick flows
Vesicles	round or irregular	irregular	stretched	stretched or round	stretched or round	stretched, round
Others	pipe vesicles at base, vesicle cylinders common: very fluid	vesicle cylinders in some	quartz, agate common in amygdules		contacts rarely exposed	
Color	black, gray, brown	black, brown	black, brown	brown-weathering	brown to red-brown	pink, red, light gray

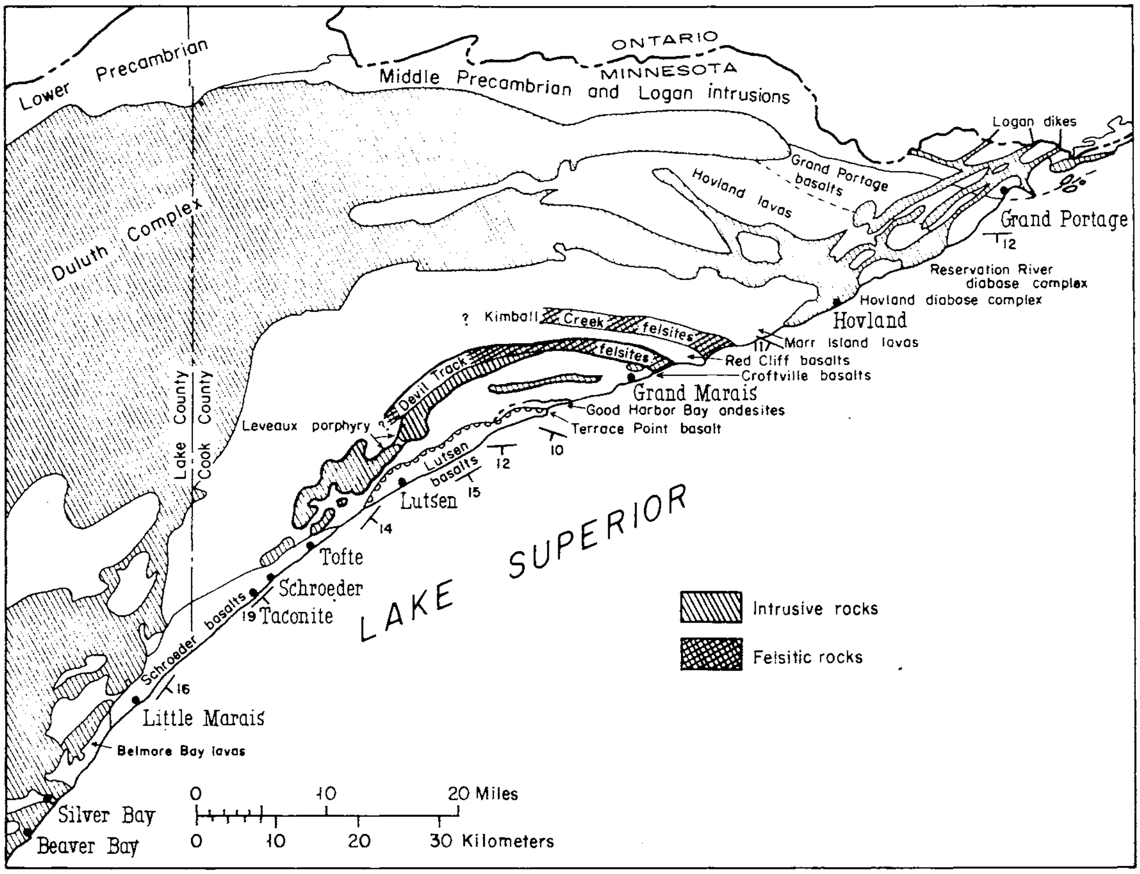


Figure 2. Generalized geologic map of the northeastern tip of Minnesota showing known continuity along strike of some of the major units of the North Shore Volcanic Group.

Table 2. Generalized volcanic stratigraphy of southwest limb (Duluth-Tofte), North Shore Volcanic Group (interflow sedimentary rocks not included)

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

Table 3. Volcanic stratigraphy of northeast limb (Lutsen-Grand Portage), North Shore Volcanic Group. (Interflow sedimentary rocks not included)

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

ROAD LOG--KEWEENAWAN NORTH SHORE VOLCANIC GROUP

Leader: John C. Green

This trip is designed to show examples of as wide a variety of stratigraphic and petrographic units, as well as structural relations, as practicable in a single day. A generalized map is presented in Figure 3, and for each stop the appropriate U.S. Geological Survey topographic quadrangle is indicated in the log. Stops are keyed to the stratigraphic units of Tables 2 and 3, and chemical analyses of rocks at most of the stops are given in Table 4.

Road mileages are given for elapsed miles since the previous landmark underlined in the narrative. Cumulative mileage, mostly along Highway 61, is given in brackets.

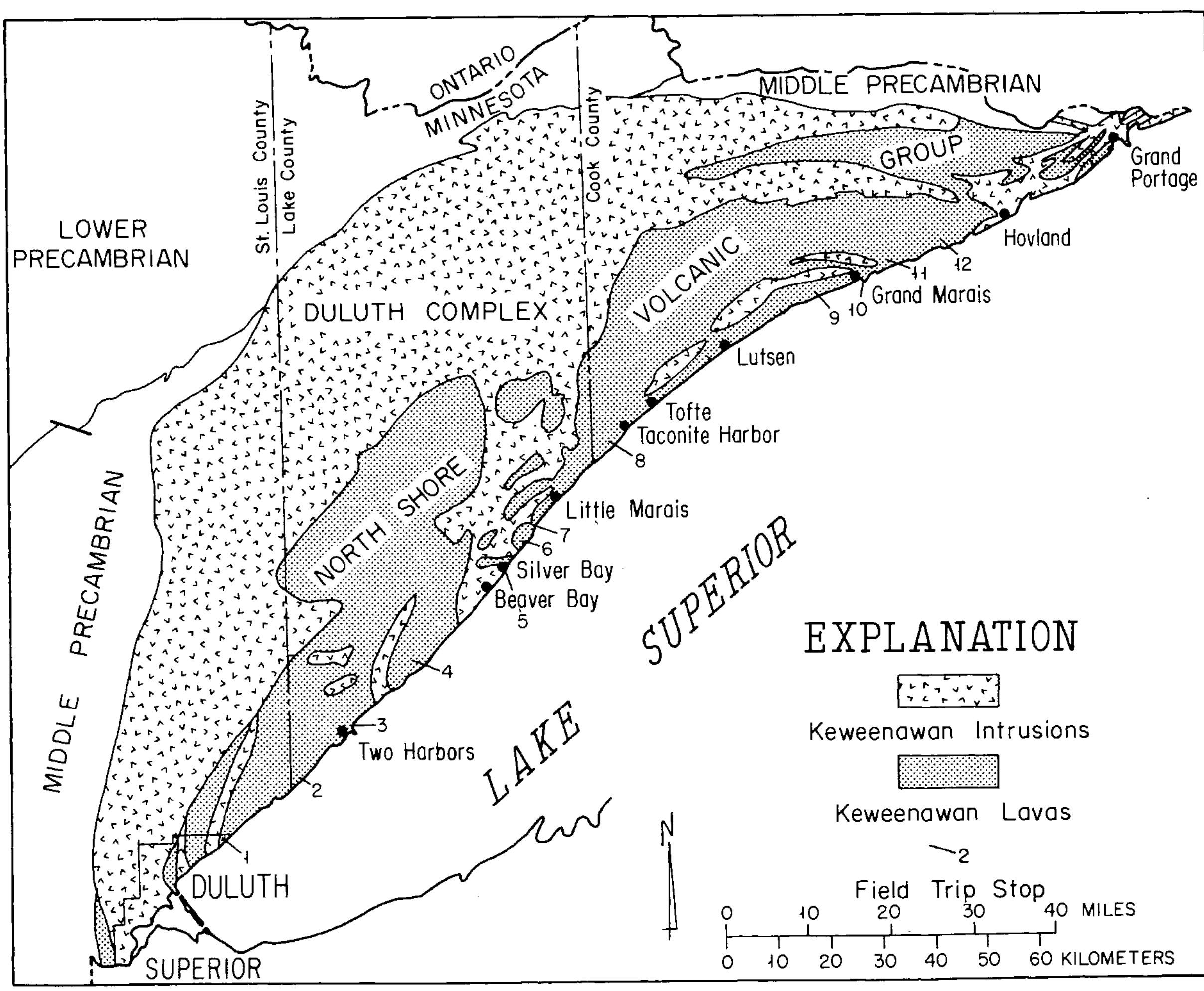


Figure 3. Map of Minnesota shore of Lake Superior showing field trip stop locations.

Table 4. Chemical analyses (wt.%) of selected samples of North Shore Volcanic Group

	LW-21	KR-20	TH-2	GEH-1	GEH-12	F-201	F-54	T-45	GH-25	GH-2b	S&G-5-9	GM-14	MI-2
SiO_2	49.54	48.52	50.19	49.16	49.83	74.41	53.08	45.71	47.19	55.42	52.70	72.23	62.60
TiO_2	2.14	0.72	1.51	1.36	2.21	0.24	1.99	1.28	0.95	2.15	1.76	0.45	1.09
Al_2O_3	15.05	17.57	15.15	17.09	11.59	10.95	13.25	17.47	17.04	12.29	14.47	11.38	12.01
Fe_2O_3	10.05	2.18	5.51	2.28	4.51	1.64	8.73	7.80	2.63	9.00	7.44	4.08	8.18
FeO	3.23	6.10	5.82	7.99	17.19	2.91	3.74	3.41	7.69	3.32	5.55	0.24	2.02
MnO	0.17	0.13	0.15	0.19	0.37	0.05	0.15	0.15	0.14	0.23	0.24	0.04	0.12
MgO	5.05	8.65	5.91	7.43	1.06	0.30	4.34	6.80	8.11	2.89	3.70	0.44	1.40
CaO	8.38	10.83	9.13	10.89	7.34	0.50	5.78	10.53	10.76	3.25	8.01	1.07	2.22
Na_2O	2.67	2.23	2.71	2.35	2.93	1.93	3.37	2.61	2.23	4.47	3.19	2.62	4.04
K_2O	1.29	0.17	0.62	0.45	1.15	5.64	1.91	0.31	0.35	2.72	1.14	5.50	4.15
H_2O^+	2.53	2.25	1.92	0.60	0.53	0.79	2.11	1.77	2.55	2.86	0.68	1.54	1.72
H_2O^-			1.76	0.39	0.48		1.98	1.78		1.71	0.48	0.50	0.93
P_2O_5	0.29	0.03	0.17	0.13	0.54	0.04	0.38	0.14	0.13	0.42	0.25	0.03	0.28
CO_2	n.d.	n.d.	0.13	0.02	0.01	0.26	0.07	0.12	0.07	0.15	n.d.	0.45	0.04
Cr_2O_3	0.03	0.05	n.d.	n.d.	n.d.	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.43	99.44	100.68	100.33	99.74	99.66	100.88	99.88	99.84	100.88	99.68*	100.57	100.80

*Includes 0.02% S and 0.05% BaO

LW-21: transitional olivine basalt, L. Superior shore, SW 1/4 SW 1/4 Sec. 34, T. 51N; R. 13W. J. Brannon, analyst: new analysis (XRF).
KR-20: high-Al olivine tholeiite, U.S. Hwy. 61, SW 1/4 SE 1/4 Sec. 20, T. 52N, R. 11W. J. Brannon, analyst; new analysis (XRF).
TH-2: quartz tholeiite, Two Harbors tourist park, SE 1/4 NW 1/4 Sec. 6, T52N; R. 10W. (Green, 1972, p. 309).
GEH-1: fine-grained border of Beaver River gabbro, Reserve Mining Co., Silver Bay, SE 1/4 Sec. 31 T. 56N, R. 7W, (Gehman, 1957, Table 1, no. 1; see Green, 1972, p. 323).
GEH-12: foliated ferrogabbro, L. Superior Shore, NW 1/4 NW 1/4 Sec. 13, T. 55N, R. 8W, (Gehman, 1957, Table 6, no. 12; see Green, 1972, p. 323).
F-201: pink porphyritic rhyolite, Palisade Head, NE/NW 1/4 Sec. 22, T. 56N, R. 7W (Green, 1972, p. 312).
F-54: brown basaltic andesite, Hwy 61, E 1/2 NE 1/4, Sec. 36, T. 57N, R. 7W (Green, 1972, p. 310).
T-45: black ophitic olivine tholeiite, 1090 ft. elev. in Cross R., NW 1/4 NW 1/4, Sec. 36, T. 59N, R. 5W (Green, 1972, p. 309).
GH-25: black, ophitic olivine tholeiite, Hwy. 61, W. of Good Harbor Bay, NW 1/4 NW 1/4 Sec. 34, T. 61N, R. 1W (Green, 1972, p. 309).
GH-2b: porphyritic trachyandesite, L. Superior Shore E. of Good Harbor Bay, NW 1/4 SE1/4 Sec. 26, T.61N., R. 1W. (Green, 1972, p. 310).
S&G-5-9: brown transitional basalt of columnar unit, Grand Marais harbor, Sec. 14, T.61N, R. 1E (Sandell and Goldich, 1943, Table 5, No. 9).
GM-14: gray felsite, L. Superior shore E of Devil Track R., NW 1/4 NW 1/4 Sec. 18, T. 61N., R. 1E (Green, 1972, p. 312).
MI-2: red-brown, porphyritic icelandite (quartz latite), Hwy. 61 at W edge of Sec. 6, T. 61N, R. 3E (Green, 1972, p. 311).

Mileage

Downtown Duluth is situated on the lower part of the Leif Erickson Park lavas, the lowest magnetically normal unit of the North Shore Volcanic Group. Just to the southwest and west, the Point of Rocks and hilltop are held up by the upper part of the immense Duluth Complex of gabbroic and anorthositic rocks which are intruded into the base of the section.

Drive northeast on Superior Street (U.S. Highway 61) through down-town Duluth to junction with London Road. Keep right on London Road (Highway 61). Gentle rise is held up by the 300-m-thick Endion sill intruding the lavas. Continue northeast through
0.0 Lakeside residential district to Lester River, where road log
[0.0] mileage begins. At start of freeway just beyond, road cuts are in
diabase of Lester River sill. Here keep right at Scenic North
1.7 Shore Drive (County 61), past low cuts of diabase; park in
[1.7] parking area just before first significant right bend.

STOP 1. Lakewood quadrangle. Granular, weakly alkaline subophitic basalts and rhyolite of the Lakewood series. Walk 300 yards southwest from parking area and go down over clays of Glacial Lake Duluth to the lakeshore. The first accessible outcrop on the shore consists of weakly alkaline or "transitional" olivine basalt (see LW-21, tbl. 4) which directly overlies an uneven, vesicular top of a red rhyolite flow. As is characteristic of the lakeshore exposures in general, the massive basal portion of the basalt forms a small point because it is more resistant to wave erosion than its amygdaloidal, more altered top. Vesicle cylinders 3-5 cm in diameter occur in its center. Well-preserved ropy and "rhino-skin" pahoehoe surfaces are found on the top of this flow, whereas the succeeeding basalts to the northeast show flatter, smoother pahoehoe surfaces. The second (overlying) flow is thinner (about 5 m), shows pipe vesicles at its base, and two thin flow units at its top. Large vesicle cylinders are developed in the third flow. Three or four more basalt flows succeed each other in this sequence past the parking area.

11.9 Continue northeast up Scenic Highway 61 through Knife River
2.1 village to a connecting road to the freeway (U.S. 61) visible to
[15.7] the left. Take it across the freeway and turn left again heading
uphill back toward Duluth.

0.3 Stop at road cut on right, near top of rise at milepost 320.
[16.0]

STOP 2. Knife River quadrangle. Fine-grained olivine tholeiite of the Larsmont ophitic basalts. This fine-grained, fresh basalt has the most primitive composition (highest Mg, Cr, Ni, lowest Fe/Mg, incompatible elements) of any rock yet analyzed from the North Shore Volcanic Group or its associated intrusions (KR-20, tbl. 4). It is unusually fresh and retains much of the original olivine. All of the other olivine tholeiites appear to be related to this composition, by some magmatic process not yet clearly deciphered (Brannon and others, 1979). Examination of the entire

0.1-mile road cut shows that this fine-grained basalt is part of a thick, banded ophitic flow. The banded structure, expressed as uneven layers a few centimeters thick of variable vesicularity and/or different sized ophitic pyroxenes, is of problematic origin and found in only some of the many ophitic olivine tholeiites of the North Shore volcanics. Neither the base nor the top of this flow is exposed here, but exposure on the shore is essentially continuous.

0.7 [16.7] Continue southwest 0.7 miles to the first chance to reverse direction, and resume travel to northeast on freeway. Drive northeast (all road cuts are in Larsmont basalts) to Two Harbors, a shipping port for some of U.S. Steel Co.'s taconite iron ore from the Mesabi range. Continue east through Two Harbors to left bend after third traffic light.

7.2 [23.9] 0.4 [24.3] Soon turn right opposite golf course at "Burlington Bay Campsite" sign, drive past beach and up hill. Park at corner of First Street and 3rd Avenue at Two Harbors Tourist Park; walk down to shore.

STOP 3. 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 limmit of Sandberg's (1938) mapping (fig. 4a). 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 (29 m according to Sandberg) "melaphyre" which has the typical structures, textures, and composition of quartz tholeiite (sample TH-2, tbl. 4). 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 both augite and pigeonite are present. The rock shows thin (1-3 mm) lensing and 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 centimeters 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 the top of the bank to the south.

8.0 [32.3] Return north to Highway 61, turn right. Proceed northeast along Highway 61 past Flood Bay, Silver Creek Cliff, Lafayette Bluff, and Crow Creek. These bluffs are composed of gabbro and diabase of two large, slightly discordant sills (Pope, 1976). The base of one can be seen at highway level at Silver Creek Cliff. Note the deep weathering at the exposures of the Lafayette Bluff sill.

Continue through the settlement of Castle Danger to Gooseberry
5.1 Falls State Park. Park here before the bridge over Gooseberry
[37.4] River.

STOP 4. Split Rock Point quadrangle. Smooth-surfaced ophitic olivine basalts of "Gooseberry River basalts." The Falls below the highway (see fig. 4b) expose three basalt flows that are characterized by smooth, gently billowing surfaces typical of very fluid lava. The billows have apparent wave lengths of 2 to 5 m and relief of a few centimeters. 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 flow in the middle of this waterfall. The middle flow is about 3 m thick and overlies another smooth, gently billowing flow top; the contact between the middle and lower flows 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.

4.2 Continue northeast on Highway 61 across Split Rock River into the
[41.6] rugged topography held up by the gabbros of the Beaver Bay
Complex, through Beaver Bay, across Beaver River to Reserve Mining
10.3 Company's large taconite plant. Stop at road cut on left side
[51.9] opposite plant.

STOP 5. Silver Bay quadrangle. Diabase, anorthosite and ferrogabbro of Beaver Bay Complex. The large road cut opposite the parking area is made in black, medium-grained diabase which contains many large, angular xenoliths of pale anorthosite of somewhat variable character. Contacts are sharp but not chilled. Some of the anorthosite blocks contain large blotches of poikilitic, interstitial olivine. Anorthosite inclusions like these are abundant in many of the diabase intrusions of the Beaver Bay Complex (Grout and Schwartz, 1939; Phinney, 1969), but their origin is problematic--perhaps they represent samples of ancient lower crust (Phinney and others, 1979). They are considerably more plagioclase-rich and pyroxene-poor than the gabbroic anorthosite which makes up such a large proportion of the Duluth Complex. The chilled margin of the diabase is exposed across the highway within the plant area; it has the composition of an olivine tholeiite (GEH-1, tbl. 4).

Small veins and dikes of red granitic rock can be seen cutting across both diabase and anorthosite. These could be either a residual liquid from diabase differentiation or a melt produced by the diabase from rhyolitic lavas. Along the highway to the southwest just past the new taconite tailings slurry pipeline is a lower road cut which is made in dark-brown olivine ferrogabbro. Called the Beaver Bay Ferrogabbro by Gehman (1957), this rock is at the edge of a circular plug or stock about 1.3 km in diameter which exhibits cumulate textures (including the primary foliation shown in this cut) and Skaergaard-type iron enrichment. The plug or stock intrudes the olivine diabase that makes up the bulk of the Beaver Bay Complex. See GEH-12, Table 4 for similar composition, another locality.

The Reserve Mining Company produces about 11 million tons per year of taconite pellets in this plant from the metamorphosed Middle Precambrian Biwabik Iron Formation in its mine at Babbitt, 43 miles (69 km) to the northwest on the Mesabi range. Reserve is constructing a large on-land disposal facility at the Milepost 7 site about 5 miles to the west of Silver Bay for the tailings, and is scheduled to cease disposal in Lake Superior in 1980.

0.5 Continue northeast past traffic lights (village of Silver Bay to
[52.4] the left) past another ridge of ferrogabbro, and on until opposite
a large hill with a tower on it on right (Palisade Head).

2.8 Turn off Highway 61 to right at Palisade Head wayside rest sign.
[55.2] Careful: road is very steep, narrow, and twisting. Park at
0.4 overlook.
[55.6]

STOP 6. Illgen City quadrangle. Palisade Head porphyritic rhyolite. Be careful: some columnar joints at cliff edge are widening and could collapse. This hill is made of an aphanitic rhyolite flow with quartz, plagioclase, and K-feldspar phenocrysts. For chemical analysis see F-201, Table 4. The flow is at least 90 m thick, and shows contorted banding at the base and a vesicular but not pumiceous top. It appears to have been a lava and not an ash flow. It overlies another thick, but nonporhyritic rhyolite that occurs slightly below it in the local section. The porphyritic rhyolite can be traced for 10 and possibly 16 km before being lost under the lake, glacial deposits, or intrusive rocks. Up the shore to the northeast, the main feature is Shovel Point, 3 km away, which is made of this same columnar-jointed rhyolite showing the same general dip as the lavas here (fig. 4c).

1.4 Return to Highway 61, continue northeast across Baptism River,
[57.0] through Illgen City at junction with Minn. Route 1, past a cut
2.9 in basaltic andesite and a cut in layered gabbro to a low cut on
[59.9] the left in a rising bend to the right before a very deep road cut.

STOP 7. Illgen City quadrangle. Overturned lavas of Belmore Bay group(?). In this cut are exposed 17 flows and flow units, all striking about N. 10° W., with a dip of 45° SW. (The regional attitude here is about N. 30° E., 15° 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 northeast is in a great anorthosite block included in ophitic gabbro, and the next cut to the southwest 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, rubbly 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, rubbly tops, here filled in with red sand, are well displayed (see fig. 4d). Although these flows have vesicular, rubbly, aa-like surfaces, they do not show the clinkery basal zones typical of the Hawaiian aa basalts. A chemical analysis of a similar flow from this group, but not from this outcrop, is given in Table 4 (F-54). Minute, golden crystals of andradite have been found on joint surfaces in one of the interflow sandstones; laumontite and calcite are abundant in amygdules. A basaltic dike cuts the lavas at the southwestern end of the exposure.

Continue northeast on Highway 61, through high cut in anorthosite in gabbro; then drive through diabase, granophyre and basalts, across Kennedy Creek and past Kennedy Landing cove. The high bluff on the left is made of a thick quartz tholeiite or trachyba-
1.2 salt flow, and several more are well exposed in cuts along the
[61.1] next 1/4 mile.

Weathered, ophitic olivine tholeiite lavas of the Schroeder basalts are exposed occasionally from here to the northeast
5.9 through Little Marais, across the Manitou River and Caribou River
[67.0] into Cook County.

5.0 At the mailbox of Consolidated Paper Company office, turn off
[72.0] highway to right; drive downhill to Sugarloaf Cove, where log
0.3 rafts were formerly assembled to be towed across the lake to
[72.3] Ashland, Wisconsin mills.

STOP 8. Little Marais quadrangle. Thin-bedded ophitic olivine tholeiite of Schroeder basalts, Sugarloaf Point. Private property. Walk clockwise around shore ledges of the point at the end of the beach. (Beach developed mainly from Superior lobe glacial drift, containing a variety of Keweenewan volcanic rocks, gabbros, granophyres, and scattered Archean granites and gneisses from Canada.) Exposed here are excellent examples of thin flow units (some less than a meter 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 (see fig. 5a), 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 northeast (to and well past Erie Mining Co.'s power plant and taconite dock at 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 4.

Drive back up to Highway 61 and continue northeast through
Taconite Harbor and Schroeder, across Temperance River (excellent
9.5 erosional potholes in ophitic basalts) to Tofte. In this area the
[81.8] highest flows in the North Shore Volcanic Group section are
exposed; to the northeast the shoreline intersects successively
3.8 lower flows as far as the Onion River, where the erosional level
[85.6] again begins to rise in more olivine tholeiites that are probably
related to the Schroeder basalts, but are known here as the Lutsen
basalts. These basalts, many of which are rather thick and coarse
grained, continue past the village of Lutsen and the Cascade
13.5 River.
[99.1]

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 left bend and road cut
4.0 overlooking Good Harbor Bay.
[103.1]

STOP 9. Good Harbor Bay quadrangle. Thomsonite-bearing basalt and interflow sediments, Good Harbor Bay (fig. 5b). In this large road cut, the Terrace Point basalt flow, one of the major cliff-formers of the "Sawtooth Range", overlies a thick (40 m) 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 4 (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 50 m thick in this area.

The interflow sediments in this cut are mainly thin-bedded siltstone and silty shale. Their basal contact is exposed in the bed of Cutface Creek at the bottom of the hill. The sediments overlie 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 11 km along strike) are well-bedded, medium-grained sandstone showing abundant ripple marks. The sediments appear to have been deposited in a large depression on the irregular andesite terrane.

Up the grade northeast of the right bend at Cutface Creek and Thomsonite Beach, exposures of the Good Harbor Bay andesites can be seen on the left (north) side of the highway. These fine-grained, brown or grayish-brown, weakly porphyritic andesites and trachyandesites contain scattered small phenocrysts of plagioclase and rarer augite; for analysis see Table 4, GH-2b. The upper parts of the two flows exposed here are vesicular and the top zones are rubbly.

5.3 Continue east on Highway 61 into Grand Marais. At harborside keep
[108.4] straight (do not bear left on Route 61) to second stop sign (Broadway).

0.4 Turn right on Broadway and drive out to Coast Guard station.
[108.8]

STOP 10. Good Harbor Bay quadrangle. Breakwater trachybasalt flow. Tombolo 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 in Table 4. This unit is about 110 m 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 top surface is covered. As can be seen from this vantage point, it forms one of the major strike ridges of the "Sawtooth Range" to the west (fig. 5c). The harbor here is probably eroded from the small-jointed rhyolite and soft basalts that underlie the breakwater trachybasalt. The big ridge to the north behind Grand Marais is held up by thick basalt flows and diabase intrusions.

Return to last (nearest) stop sign; keep straight north to rejoin
0.3 Highway 61. Turn right and continue eastward on Highway 61 past
[109.1] Croftville settlement (on Nipissing-stage terrace), across
3.6 Devil Track River and eastward on well-developed abandoned beach
[112.7] terrace of Nipissing stage (about 3,500 yr. b.p.), with wave-cut slope and cliffs on the left.

1.0 About opposite Five-Mile (Guano) Rock, stop at a promontory in
[113.7] this abandoned cliff.

STOP 11. Kadunce River quadrangle. Rhyolitic felsite of Devil Track series. This series, about 310 m thick, is composed at the shoreline of two rhyolitic flows. The upper, thicker one (exposed here) is nonporphyritic (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. The felsite group has been traced for 37 km along strike to the west (fig. 3). A chemical analysis of this flow from another locality (GM-14) is given in Table 4.

Five-mile (Guano) Rock, a mile out in Lake Superior, is made of fine-grained basalt that is probably continuous with the Croftville basalts to the west in Grand Marais.

Continue east-northeast on Highway 61 past Durfee Creek, around
1.8 big left bend in Red Cliff basalts. Proceed across Cliff and
[115.5] Kimball Creeks and Kadunce River that are cut in the Kimball
4.0 Creek felsite group, and stop at a large road cut on the left
[119.5] side.

STOP 12. Kadunce River quandrangle (east edge). Porphyritic intermediate quartz latite of Kimball Creek felsites. Two large road cuts here at the east edge of the quadrangle expose a thick (approx. 45 m) intermediate quartz latite (icelandite) that contains small phenocrysts of andesine, ferroaugite, olivine (completely altered) and magnetite, in a groundmass that contains abundant alkali feldspar (fig. 5d). 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 rare quartz.

Flows of very similar composition have been sampled and analyzed from several levels in the North Shore Volcanic Group. A chemical analysis of this flow (MI-2) is given in Table 4.

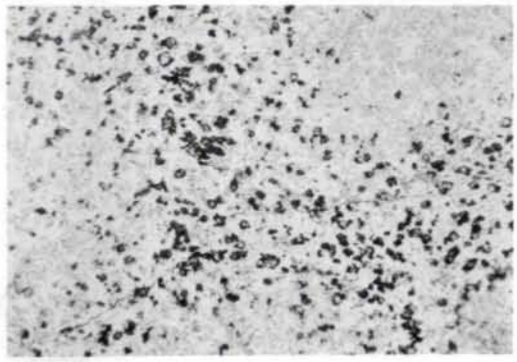
This is the last stop in this one-day trip. Four additional stops, visiting units lower in the northeastern section of the North Shore Volcanic Group, are described in Green (1972c). Return to Duluth.

End of Day.

Figure 4. Photographs of volcanic features of North Shore Volcanic Group. (a) flow contact in quartz tholeiite basalts, Two Harbors Tourist Park (Stop 3); (b) flow contact in olivine tholeiites, Gooseberry Falls (Stop 4); (c) view northeast to Shovel Point (rhyolite flow) from Palisade Head (Stop 6); (d) sand-infilled rubbly flow top of basaltic andesite, near Little Marais, Lake County.

Figure 5. Photographs of volcanic features of North Shore Volcanic Group. (a) photomicrograph of ophitic olivine tholeiite. Large roundish pale areas are augite, small dark grains are altered olivine and oxides, small clear laths are plagioclase; (b) olivine tholeiite flow (Terrace Point basalt) resting on interflow silty sandstone, Highway 61 at Good Harbor Bay (Stop 9); (c) view to west-southwest from Grand Marais Coast Guard station (Stop 10) showing cuestas and dipslopes on flows and sills higher in section; (d) photomicrograph of porphyritic quartz latite (Stop 12) showing phenocrysts of ferroaugite, altered olivine and plagioclase in groundmass rich in K feldspar.

4a



5a

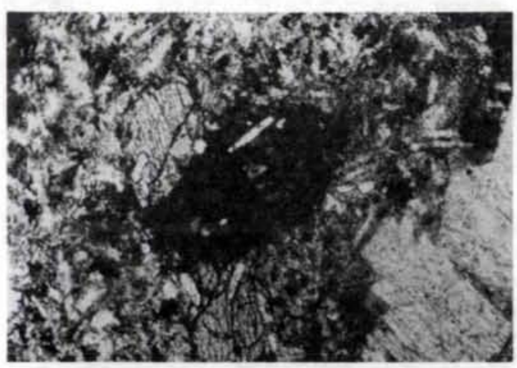
4b

5b

4c

5c

4d



5d

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