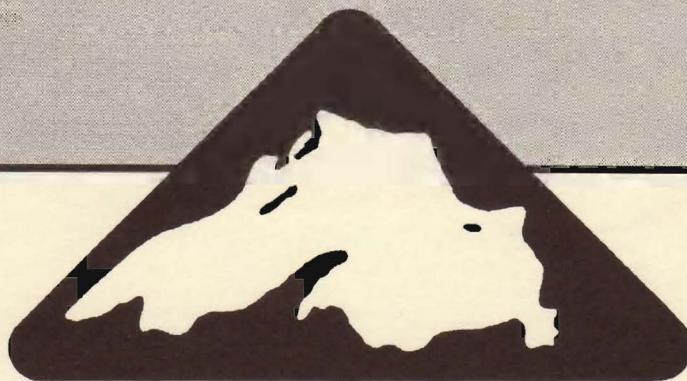


Institute on Lake Superior Geology



Proceedings

40th Annual Meeting May 11-14, 1994

Michigan Technological University
Houghton, Michigan

Volume 40

Part 3—Volcanic geology of eastern Isle Royale, Michigan

By: William I. Rose

40TH ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 40 consists of

Part 1: Program and Abstracts

Part 2: Self-guided geological field trip to the Keweenaw Peninsula, Michigan

Part 3: Volcanic geology of eastern Isle Royale, Michigan

Part 4: Michigan kimberlites and diamond exploration techniques

Part 5: Lessons from mining case histories: West Menominee Range, Michigan

Reference to material in Volume 40, Part 1 should follow the example below:

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Part 3—Volcanic geology of eastern Isle Royale, Michigan

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Preface

(or why people don't go to Isle Royale)

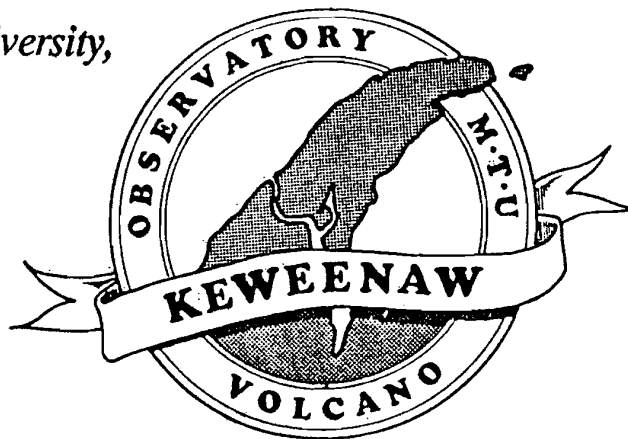
Isle Royale has very few visitors, especially considering that it is a national park and is, for many people, within a couple of days travel. This lack of tourism can be explained partially by the park's island location and by the fact that a trip to Isle Royale seems to require a deeper commitment, of both time and money, than other vacations might require. The very people whom you would most expect to want to visit Isle Royale don't go.

When you compare the popularity of various national parks, the public's avoidance of Isle Royale is obvious, perhaps even more obvious to me because of my position. As a professor at Michigan Technological University for more than 20 years, I have had direct contact with hundreds of students, many of them geology majors, who are committed to the outdoors and to field experiences. However, very few of these students go to the park, even though they live in Houghton, MI, which is the home of the Ranger III, one of the principal transporters of visitors to and from Isle Royale.

Likewise, many of the geologists I have known have visited all of the geological sites around Lake Superior and the other Great Lakes, but only a few of them have been to Isle Royale. This is a remarkable contradiction, something I'm at a loss to explain. It seems to attest to America's addiction to the automobile; maybe people just can't stomach the thought of being separated from their car for a few days!

At any rate, I hope that this guidebook will encourage more geologists, as well as other people, to visit the park. Besides the fact that Isle Royale has outstanding geological sites, a trip there can be made at moderate expense, and the park offers comfortable facilities and logistics that most geologists would find agreeable. I recommend taking a week to visit (September is the very best time) and renting a motor boat from the park concession to allow access to the many wave-washed outcrops.

*Prepared in cooperation with the
Keweenaw Volcano Observatory,
Michigan Technological University,
Houghton, Michigan*



Introduction

This guidebook is meant to be used with *The Geologic Story of Isle Royale National Park* by N. King Huber (1983) and does not try to duplicate what occurs in that volume. Instead, the goal is to focus on the volcanic geology that can be observed in the wave-washed shorelines of the Rock Harbor area, emphasizing the physical volcanology of basaltic lava flows. The field trip described here offers the participant a chance to see excellent exposures of large and thick, tholeiitic lavas and to observe the combination of physical features that are associated with slow solidification and segregation.

Background and Key References

Huber's work offers a complete background to this trip. It includes a bedrock geological map (Huber 1973) and United States Geological Survey (USGS) Professional Papers on the Portage Lake Volcanics (PLV) (Huber 1973a), the Copper Harbor Conglomerate (CHC) (Wolff and Huber 1973), and the glacial and postglacial geology (Huber 1973b).

Since 1973, when Huber's work was published by the USGS, there have been a number of further studies published that are important to the context of Isle Royale. Here, I will cite those that pertain to the Keweenaw section of the Midcontinent rift and to solidification of lavas in particular for those who wish to read more of the current literature.

A detailed study of the composition of the lavas of the PLV, as determined by study of a complete section on the Keweenaw Peninsula, was completed by Paces (1988). In this study, Paces provides a general description of the flows with respect to texture and thickness (Figure 1); chemical composition (Table 1); mineral chemistry (Figure 2); and petrography (Table 2), which is described in the following:

PLV lava flows display a relatively limited number of textures based on the relationships between dominant mineralogical constituents. These components originally included groundmass plagioclase, olivine, clinopyroxene, iron-titanium oxide, volcanic glass or mesostasis, occasional

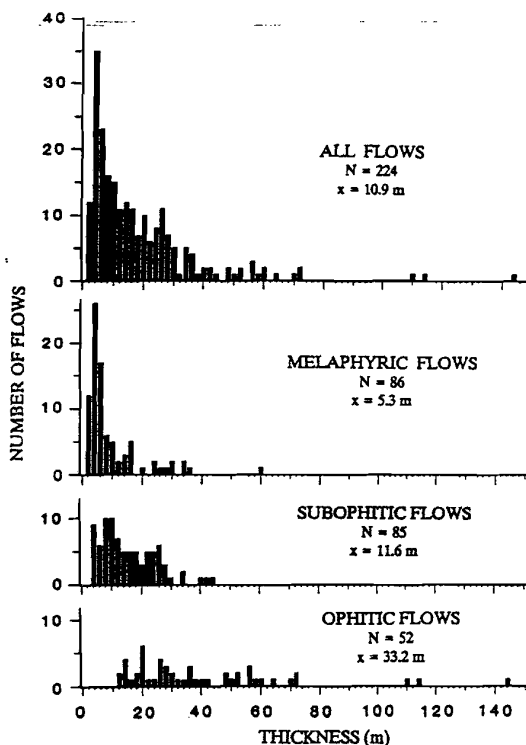


Figure 1: Histograms of PLV lava flow thickness (Paces 1988). N=number of lava flows; X=geometric mean thickness in meters. The coarsely-ophitic Greenstone flow is not shown. Textural categories are based on macroscopic observations.

phenocrysts or microphenocrysts of plagioclase, and sometimes olivine. Textures that developed within the coarsest portion of different lava flows range from fine-grained intergranular through subophitic and ophitic. This same range in textures can be observed in individual, thick lava flows which grade from intergranular chilled flow margins to a coarsely ophitic flow interior. True quench textures (Lofgren 1980), including skeletal, dendritic or spherulitic olivine and pyroxene, have not been observed in PLV basalts.

PLV lava flows do not preserve evidence of an extensive pre-eruptive crystallization history. Chilled margins are generally aphanite. Occasionally, lavas contain minor amounts (usually less than 1%) of small euhedral phenocrysts of plagioclase (often with melt inclusion-rich cores) and sometimes olivine. When present, both of these phases commonly exhibit glomeroporphyritic tendencies. Neither the plagioclase nor olivine phenocrysts show obvious evidence of disequilibrium with the

	POT	OT1	OT2	IOT	FOT	AND	DAC	RHY
Ni(ppm)	400-300 n=5	300-250 n=9	250-200 n=14	200-100 n=8	100-15 n=6	058- 1297	83JP-7	85MH-1
SiO ₂	47.82	47.34	48.03	48.55	49.94	56.39	68.44	77.89
Al ₂ O ₃	15.89	15.27	15.32	15.12	13.28	13.78	15.17	12.77
FeO _t	9.77	11.82	12.32	12.86	14.91	9.87	4.46	1.11
MgO	12.44	11.69	9.85	9.06	7.78	5.52	1.14	0.17
CaO	10.58	10.24	10.16	9.65	6.64	5.10	1.40	0.01
Na ₂ O	2.04	2.10	2.25	2.31	2.91	3.94	4.74	3.67
K ₂ O	0.19	0.22	0.33	0.42	1.43	2.27	3.86	4.28
TiO ₂	0.98	1.13	1.35	1.60	2.34	1.83	0.51	0.08
P ₂ O ₅	0.16	0.19	0.22	0.25	0.36	1.00	0.19	0.01
MnO	0.14	0.16	0.16	0.18	0.24	0.30	0.08	0.01
V	189	230	255	305	431	263	59	0
Cr	286	260	213	203	113	16	6	5
Mn	1090	1316	1250	1365	1804	2282	627	105
Ni	326	279	231	172	54	10	7	5
Cu	37	51	73	86	126	5	13	61
Zn	64	80	79	85	106	146	81	25
Rb	12	6	5	8	30	51	62	129
Sr	358	253	267	283	245	335	88	36
Y	20	20	20	23	31	47	45	35
Zr	78	85	101	126	212	430	573	145
Nb	4	6	7	8	14	28	55	68
Ba	108	154	200	265	514	757	879	1127
La	6.7	8.2	10.5	13.4	25.8	48.6	54.4	39.9
Ce	15.0	18.4	23.7	30.6	58.7	117.2	139.0	96.2
Sm	2.49	3.13	3.74	4.50	7.91	13.78	14.00	8.57
Eu	0.96	1.14	1.33	1.51	2.12	3.84	3.44	0.95
Tb	0.46	0.61	0.71	0.88	1.58	2.51	2.77	1.97
Yb	1.47	1.79	2.00	2.46	4.43	6.94	9.41	6.70
Lu	0.21	0.27	0.30	0.38	0.64	1.04	1.39	1.00
Ta	0.43	0.48	0.55	0.66	1.14	1.77	2.64	3.52
Hf	1.74	2.09	2.57	3.11	5.72	10.44	16.13	7.29
Th	0.55	0.77	0.97	1.31	3.39	5.94	10.32	16.30
Sc	24.86	28.19	28.25	30.62	34.61	21.06	11.43	2.73

Table 1: Average major and trace element compositions for eight groups of PLV lavas (Paces 1988). Tholeiites were grouped by their Ni concentrations with criteria listed in the first row and the number of samples in each group in the second row. POT=primitive olivine tholeiite; OT1=olivine tholeiite 1; OT2=olivine tholeiite 2; IOT=intermediate olivine tholeiite; FOT=Fe-rich olivine tholeiite; AND=andesite; DAC=dacite; and RHY=rhyolite. The last three columns are individual analyses. Oxides are given in weight percent, trace elements in ppm.

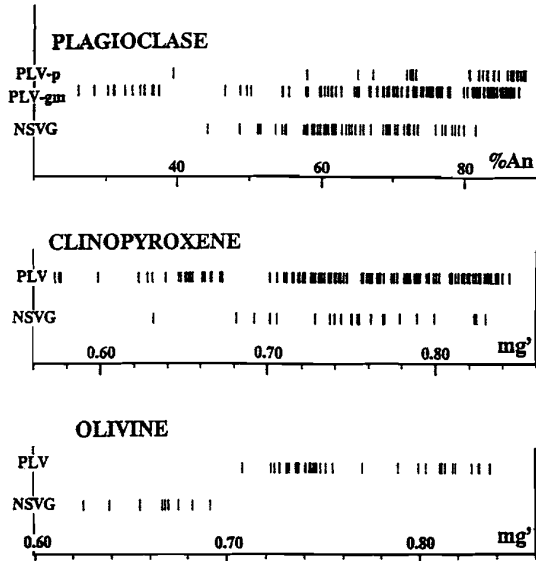


Figure 2: Compositions of minerals in PLV primitive olivine tholeiites compared to those available from North Shore Volcanic Group primitive olivine tholeiites (Paces 1988). Each line represents a single analysis. The North Shore Volcanic Group data was taken from BVSP (1981) and Brannon (1984). PLV plagioclase compositions are sub-divided into groundmass (PLV-gm) and phenocryst (PLV-p) crystals.

liquid. Except for rounded plagioclase cores, both olivine and plagioclase phenocrysts are in apparent textural equilibrium with the liquid. Slightly porphyritic lavas frequently exhibit serrate textures.

The dominant textural element in all lavas is the framework of groundmass plagioclase laths. This framework is a randomly-oriented, felt-like structure of interlocking euhedral to subhedral laths. Rarely, the partial alignment of laths forms crude trachytic fabric, indicating movement of magma after at least partial crystallization.

The second most prominent textural element is defined by clinopyroxene crystals and their relationships to the plagioclase lath framework. In all cases, clinopyroxene has clearly crystallized later than olivine and plagioclase. Clinopyroxene crystals exhibit intergranular to ophitic textures depending both on the size of the clinopyroxene crystals as well as the size of the plagioclase laths. Melaphyric flows and chilled flow margins contain small, blocky clinopyroxene crystals intergranular to the plagioclase framework. In many (but not all) thicker flows, clinopyroxene grains begin to enclose subophitically, and eventually ophitically, plagioclase and olivine crystals as the massive flow interior is approached. The boundary between

	Olivine Basalts N=8		Basaltic-andesites N=3	
	Typical	Range	Typical	Range
Groundmass				
Plagioclase	41	(39-56)	53	(50-55)
Clinopyroxene	23	(19-29)	18	(16-22)
Olivine	18	(11-19)	—	—
Fe-Ti Oxides	4	(2-13)	7	(6-10)
Glass	10	(4-11)	19	(15-25)
Vesicles	4	(1-9)	3	(1-10)
Phenocrysts				
Plag ± Oliv	<1	(<1-9)	<1	<1

Table 2: Petrographic modes, in volume percent, of representative PLV olivine basalts and basaltic andesites (Paces 1988). Model analyses are based on 500-spot point counts on a 0.6 x 1.2 mm grid.

subophitic and ophitic textures is gradational and is exceeded when a significant number of plagioclase laths are completely enclosed by the surrounding clinopyroxene oikocrysts. Absolute size of the oikocryst is not definitive: a large clinopyroxene grain may only subophitically enclose large groundmass plagioclase laths, however the same sized grain may ophitically enclose plagioclase laths of smaller dimensions.

Thus, over half, 60-70% (volume basis), of most PLV lava flows are typically composed of a plagioclase lath framework with loosely packed clinopyroxene oikocrysts. The remaining interstitial space within the plagioclase framework and between oikocrysts is filled with variable proportions of intergranular olivine, iron-titanium oxides, and interstitial volcanic "glass." Evidence of gas exsolution is preserved in some flow interiors as vesicular cavities of ellipsoidal to highly irregular shapes. Diktytaxitic textures, however, are not apparent.

Vesicles are particularly well preserved in thinner flows which quenched rapidly; however, they are observable in some thicker flow interiors as well.

--Paces 1988

Two conclusions emerge from Paces work: (1) the lavas are compositionally similar throughout the section and generally are high magnesium, olivine tholeiites; and (2) the flows range from less than 10 m (33 ft.) to more than 100 m (330 ft.) thick, and the thicker ones are more likely to have ophitic textures. Paces and Miller (1993) have recently published a summary of age information on the igneous rocks of the Midcontinent rift (Figures 3 and 4), which shows that the PLV represents one of the last events of the approximately 25 million year period of rift magmatism.

Lane (1911) describes the first recognition of the mirror image geology and lithological similarity

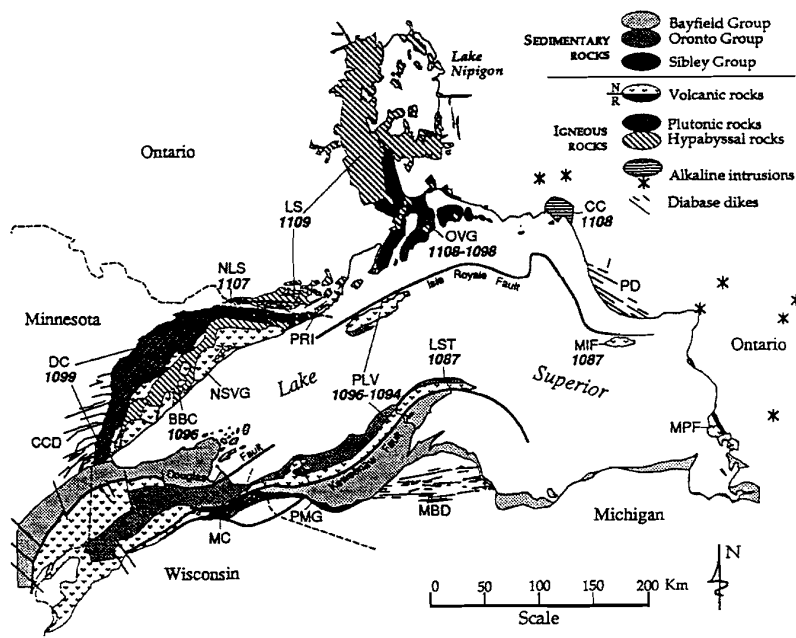


Figure 3: Generalized middle Proterozoic geology of the Lake Superior region (Paces and Miller 1993). Major igneous units are abbreviated as follows: DC=Duluth Complex; NLS=Nathan's layered series; BBC=Beaver Bay Complex; NSVG=North Shore Volcanic Group; CCD=Carlton County dikes; PRI=Pigeon River intrusions; LS=Logan sills; OVG=Osler Group; CC=Coldwell Complex; PD=Pukaskwa dikes; MIF=Michipicoten Island Formation; MPF=Mamainse Point Formation; MBD=Marquette-Baraga dikes; PLV=Portage Lake Volcanics; LST=Lake Shore traps; PMG=Powder Mill Group; MC=Mellen Intrusive Complex. Volcanic units are differentiated on the basis of remnant magnetic polarity (N=normally polarized; R=reversely polarized). Major graben-bounding faults are shown as heavy, labeled lines.

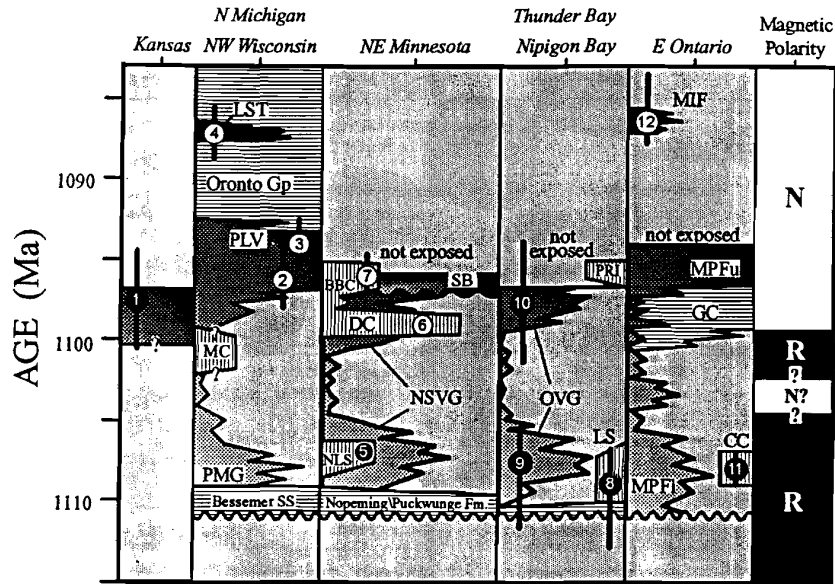


Figure 4: Generalized stratigraphic correlations and absolute age determinations for Midcontinent rift rocks exposed in the Lake Superior region and subsurface Kansas (Paces and Miller 1993, modified after Green 1982). Unit abbreviations are the same as in Figure 3, with additions: SB=Schroeder basalts, and GC=Great Conglomerate. Episodicity of volcanism is schematically portrayed by the amplitude of jagged curves, implying eruptive frequency and volume increasing toward the right. Major intrusive events are indicated by vertically ruled polygons, and major episodes of clastic sedimentation are denoted by horizontally ruled areas. The boundary of the major reverse-to-normal magnetic polarity switch is placed between 1099 and 1100 Ma, but it is uncertain at a level of 2-3 million years.

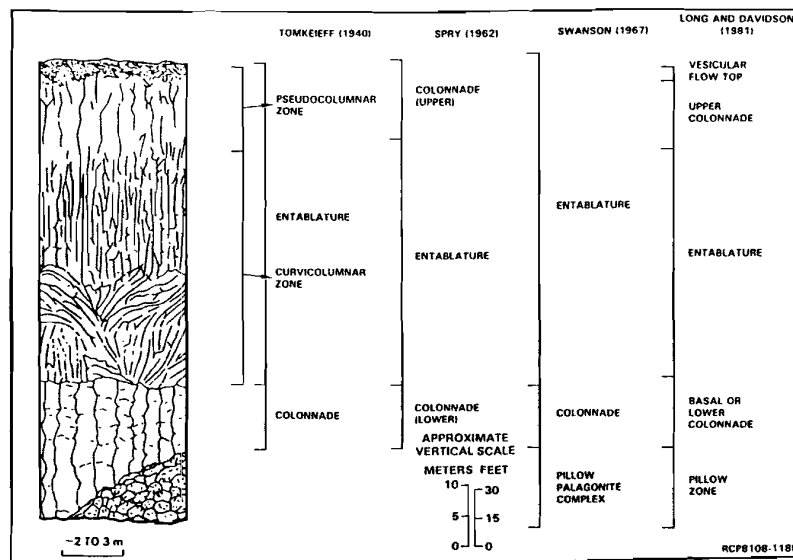


Figure 5: Typical intraflow structures present in Grande Ronde Basalt flows (Long and Wood 1986). Fractures are represented in a stylized manner, and fracture widths are not to scale.

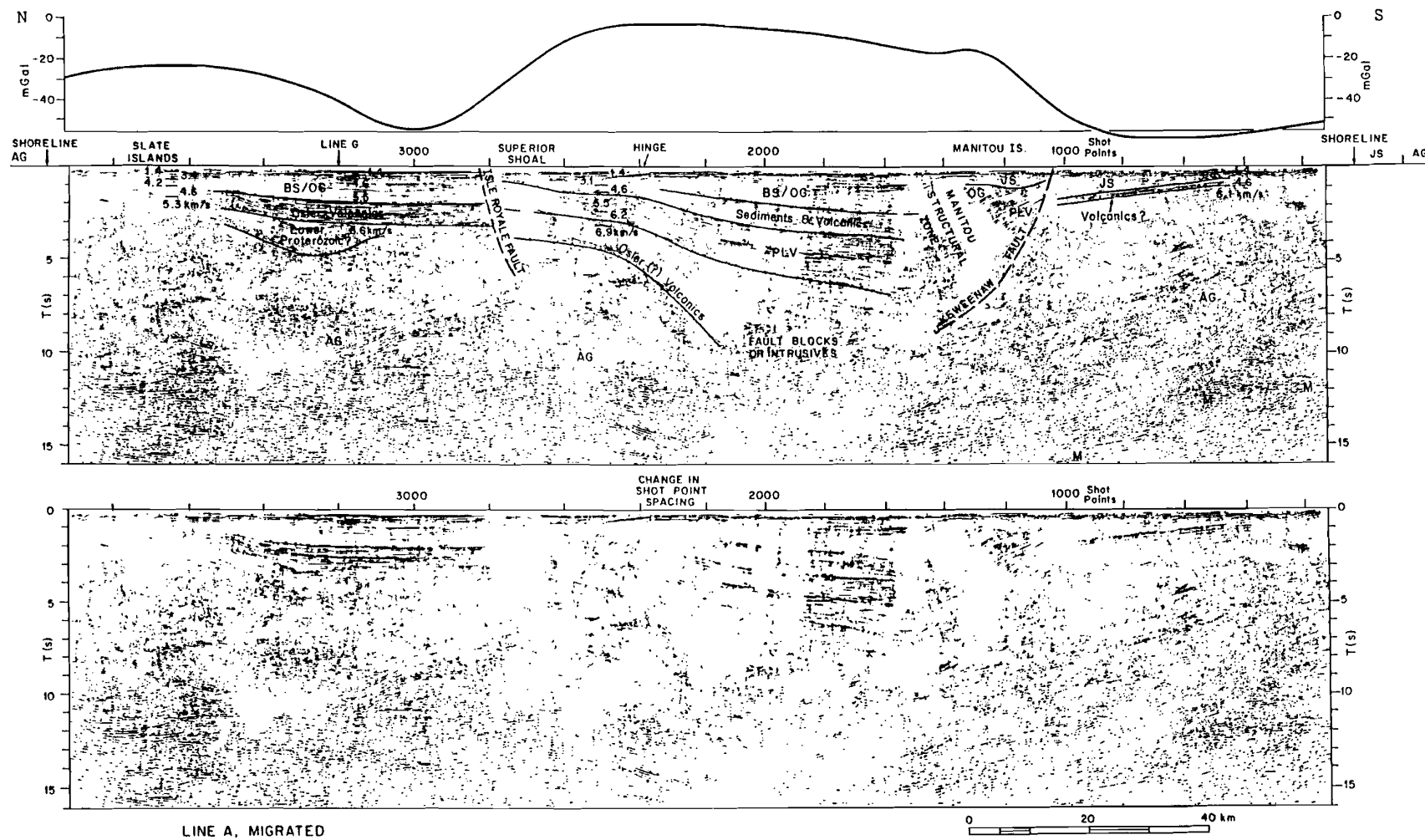


Figure 6: **Top:** Interpreted reflection profile along line A showing the subsurface geology beneath central Lake Superior (Cannon et al. 1989). **Bottom:** Migrated seismic reflection profile along line A (Cannon et al. 1989). Vertical scale is seconds of two-way travel time. Vertical exaggeration is 1:1 for average velocity of 6 km/s.

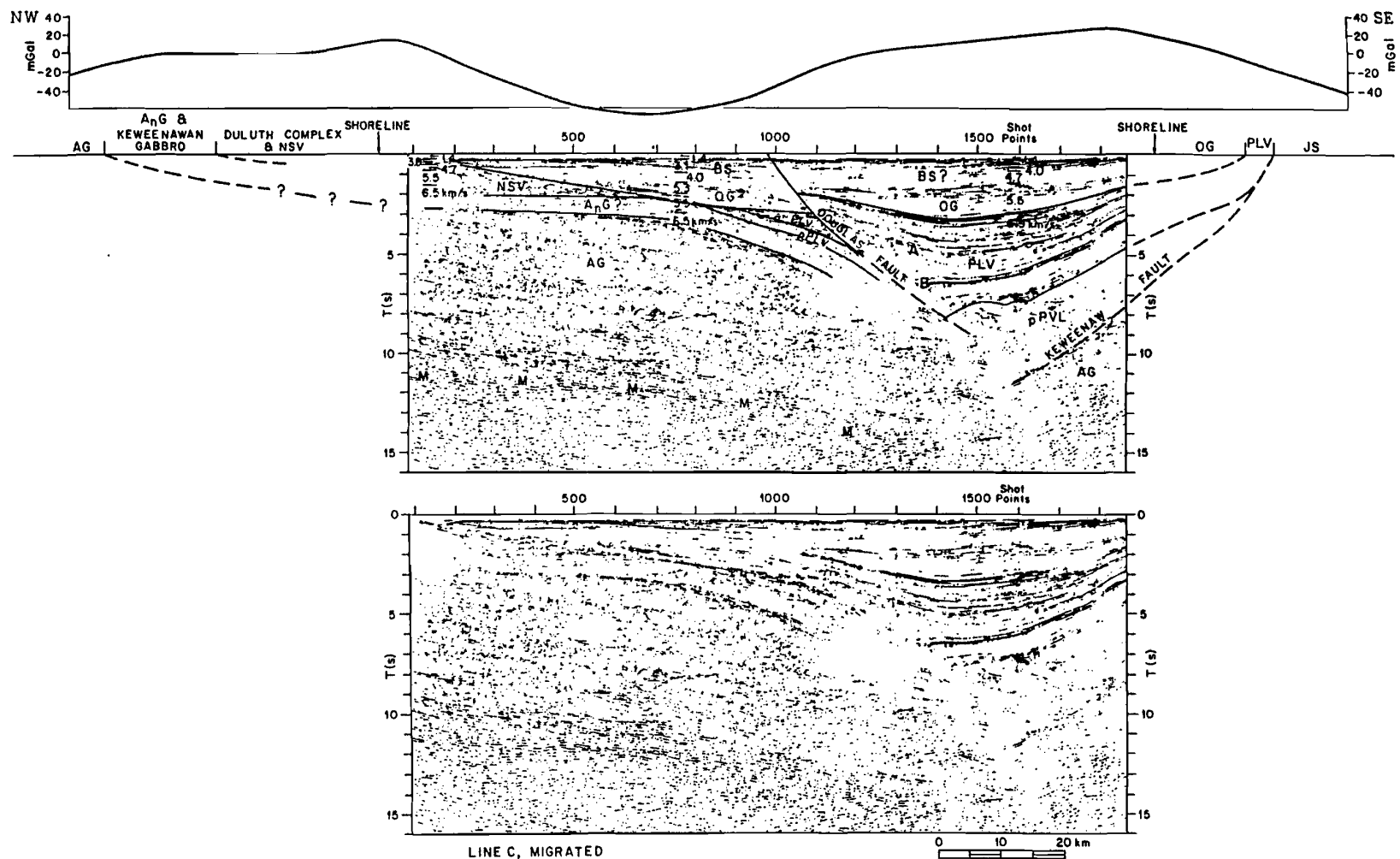


Figure 7: *Top*: Interpreted reflection profile along line C, showing subsurface structure beneath W Lake Superior (Cannon et al. 1989). Inferred subsurface units are projected updip to their exposed extensions on land in N Michigan and Minnesota. *Bottom*: Migrated seismic reflection profile along line C (Cannon et al. 1989). Velocity/depth profiles determined from refraction surveys were used to calculate depths to reflectors. M=approximate location of Moho; AG=Archean Gneiss; PLV=Portage Lake Volcanics; pPLV=pre-Portage Lake Volcanics; NSV=North Shore Volcanics Group; OG=Oronto Group; BS=Bayfield Group; and AnG=Animikie Group. Vertical scale is seconds of two-way travel time. Vertical exaggeration is 1:1 for average velocity of 6 km/s.

of the PLV and the CHC on both sides of the syncline and further suggests that the great lava flow of the Keweenaw Peninsula and the large flow of Isle Royale are the same. Huber (1973a) strongly supports Lane's correlations. Longo (1984), after extensive field mapping and sampling at Isle Royale and the Keweenaw, gives field observations and geochemical data that strongly confirmed the correlation of the Greenstone flow.

This correlation means that the Greenstone flow is one of the earth's largest lava flows; according to Longo (1984), it has an aggregate volume of 1650 km³ (396 mi³), comparable to the Roza flow of the Columbia River Flood basalts, which is estimated to be 1500 km³ (360 mi³) by Swanson et al. (1975). The areal extent of the Roza, 40,000 km² (15,450 mi²), is much larger than the Greenstone flow, 5000 km² (1930 mi²), a comparison which results from the ponding of the Greenstone within the rift basin. Thus, the solidification of the Greenstone flow is a kind of magma ocean experiment, the likes of which is rare on this planet.

Studies of the formation of columns in lavas are also important to the appreciation of the Isle Royale occurrences. The recognition of the role of water infiltration in the formation of certain kinds of entablature jointing (Figure 5) in the Columbia River Flood basalts by Long and Wood (1986) was an important insight, as was the detailed work on column formation by DeGraff and Aydin (1993) and DeGraff et al. (1989). The work by Goff (1977) provides information on vesicle cylinders in lavas for the Isle Royale occurrences. Green's (1989) paper on the physical volcanology of the North Shore Volcanics gives a valuable comparison with rocks associated closely in time and space with the Isle Royale PLV.

The GLIMPCE results (Cannon et al. 1989) provide confirmation of the rift basin synclinal geometry and allow a more accurate picture of the rift to be developed (Figures 6 and 7). The discussion by Cannon (1994) of evidence that suggests a relationship between the Grenville event and the closing of the Keweenaw rift contributes to the understanding of the rift episode (Figure 8). The consideration of implied tilting of ancient shore-

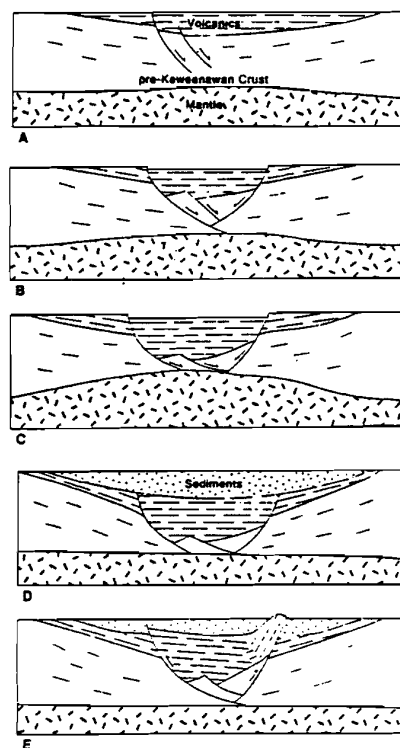


Figure 8: (a-e) Schematic depiction of development of the Midcontinent rift (Cannon 1994). (a) Lower Keweenaw, broad crustal sag and eruption of wide-spread plateau basalts. Low-angle normal faults and shear zones develop in Archean crust, producing some crustal thinning. Some normal faulting occurs near rift axis but is subordinate to sagging. (b) Middle Keweenaw, early rift valley stage. Continued extension and thinning of crust results in development of a central graben and rift valley by a combination of normal faulting and continued sagging. Volcanism is mostly confined to the rift valley. (c) Middle Keweenaw, late rift valley stage. Central graben expands and deepens. Rotation of basement blocks causes asymmetrical shape. Very thick volcanic accumulations are in the graben, and little or no volcanic flows spread outside the graben. The Archean crust nearly separates by extension on low-angle faults. (d) Upper Keweenaw, thermal collapse and sedimentation stage. Extension and volcanism end. Both the central graben and surrounding areas subside by thermal collapse, and a thick (as much as 10 km) basin develops and is filled with clastic sediments. (e) Upper Keweenaw, tectonic inversion stage. The central graben is uplifted. Original graben-bounding normal faults are transposed to high-angle reverse faults. Rocks of the central graben are thrust up several km or more. Thin sequences (up to 2 km thick) of clastic rocks (not shown) are deposited unconformably on deformed volcanic and sedimentary rocks.

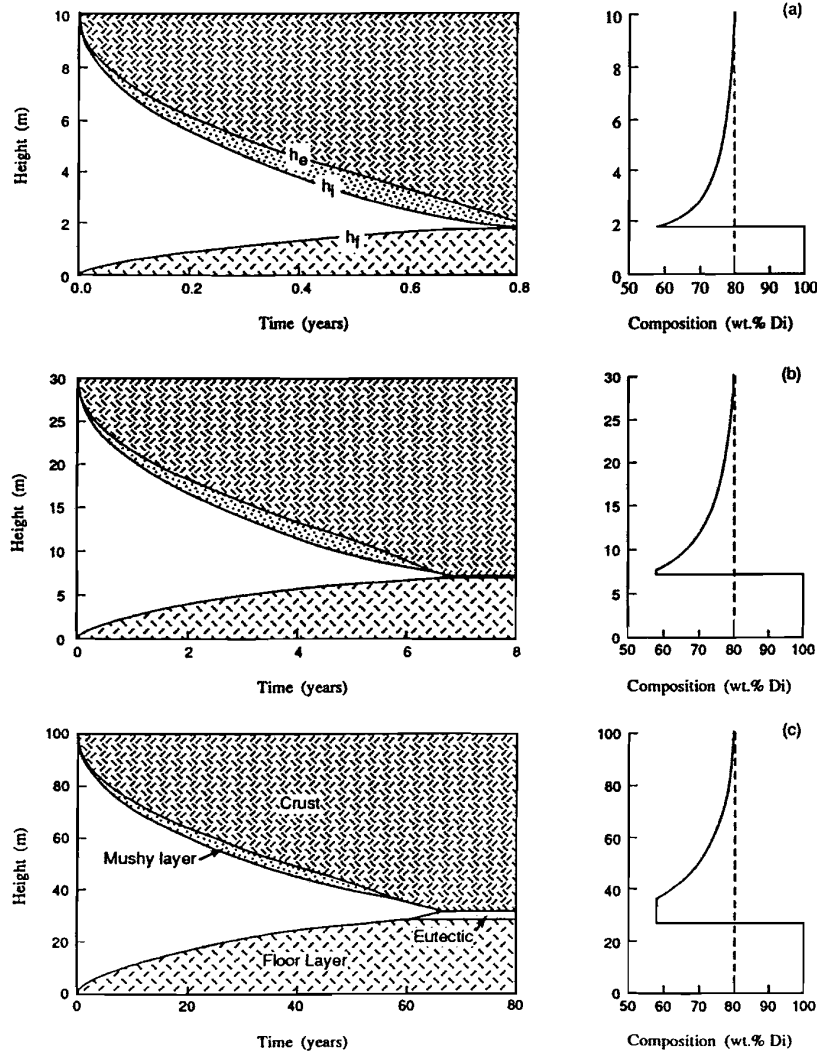


Figure 9: History of solidification and final compositional profile in lava lakes of initial composition $\text{Di}_{80}\text{An}_{20}$ and initial temperature equal to the liquidus temperature of 1352°C (Worster and Huppert 1993). The curves labelled h_e , h_i , and h_f show the interfaces between the crust and the mushy layer, the mushy layer and the melt, and the melt and the floor layer, respectively.

lines around the Great Lakes by Clark et al. (1994) is clearly important to understanding Isle Royale, with its abundant evidence of tilted shorelines.

The processes that operate during the solidification of tabular magma bodies are reviewed by Marsh et al. (1991). Worster and Huppert (1993) present models developed to predict the patterns of solidification in time and space (Figures 9 and 10); fundamental work to understand solidification in other kinds of materials has been done and is pre-

sented by Hellawell et al. (1993).

The literature lacks lucid explanations about ophitic texture and its origin. Longo (1984) infers the following:

An ophitic texture is produced by large augite crystals enclosing, either partially or totally, unoriented laths of plagioclase. A qualitative explanation for ophitic texture, as with all igneous textures, involves fusion entropy relationships coupled with growth rates and nucleation rates (Carmichael et

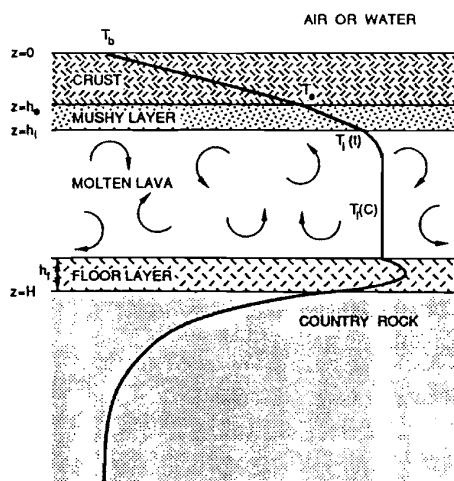


Figure 10: Schematic diagram of a lava lake that is being cooled at its surface by contact with the cold air or water above it and also cooled by conductive heat transfer to the country rock beneath (Worster and Huppert 1993). A crust of composite solid grows downward from the roof where the temperature, T_b , is constant. A mushy layer separates the composite solid from the molten lava, which is convecting vigorously. Internal crystallization, which occurs as a result of the interaction of convection with the kinetic undercooling at the interface with the mushy layer, forms a solid layer near the floor of the lake. A sketch of the temperature field is indicated on the diagram.

al. 1974). While the magma was cooling slowly, initially abundant plagioclase nuclei grew relatively slowly and were enveloped by faster growing, but less abundant clinopyroxene nuclei. The slower cooling rates of flow interiors typically allow clinopyroxenes (in this study augite $\pm$ pigeonite) to grow to larger diameters. In other words, crystals tend to increase in size away from the flow margins. The crystal network formed by the simultaneous crystallization of augite and plagioclase inhibits crystal settling in the flow after extrusion. The ophitic texture imparts a mottled and knobby surface to the weathered outcrop. On the freshly broken surface, clinopyroxene cleavage faces are clearly visible.

--Longo 1984

The full environmental significance of ophitic texture is important for understanding the Isle Royale exposures. We need to know how the rates of crystallization and heat loss work together to produce the jointing, segregation, and textural patterns that are observed.

The works cited above, along with others referenced in this guide, contribute more information to our understanding of the geology of Isle Royale. All of these works are valuable as supplements to this field guide.

The First Day

Grand Portage, MN

Our trip begins at Grand Portage, a national monument and reconstructed fort that commemorates the fur trade era, which began in the sixteenth century and reached a peak in the later part of the eighteenth century. The fort was built in 1778 and abandoned in 1803. Figure 11, from the National Monument, describes the geography of the fur trade and the significance of this site.

From Grand Portage we will travel E and eventually go all the way around Isle Royale in a clockwise fashion (Figure 12).

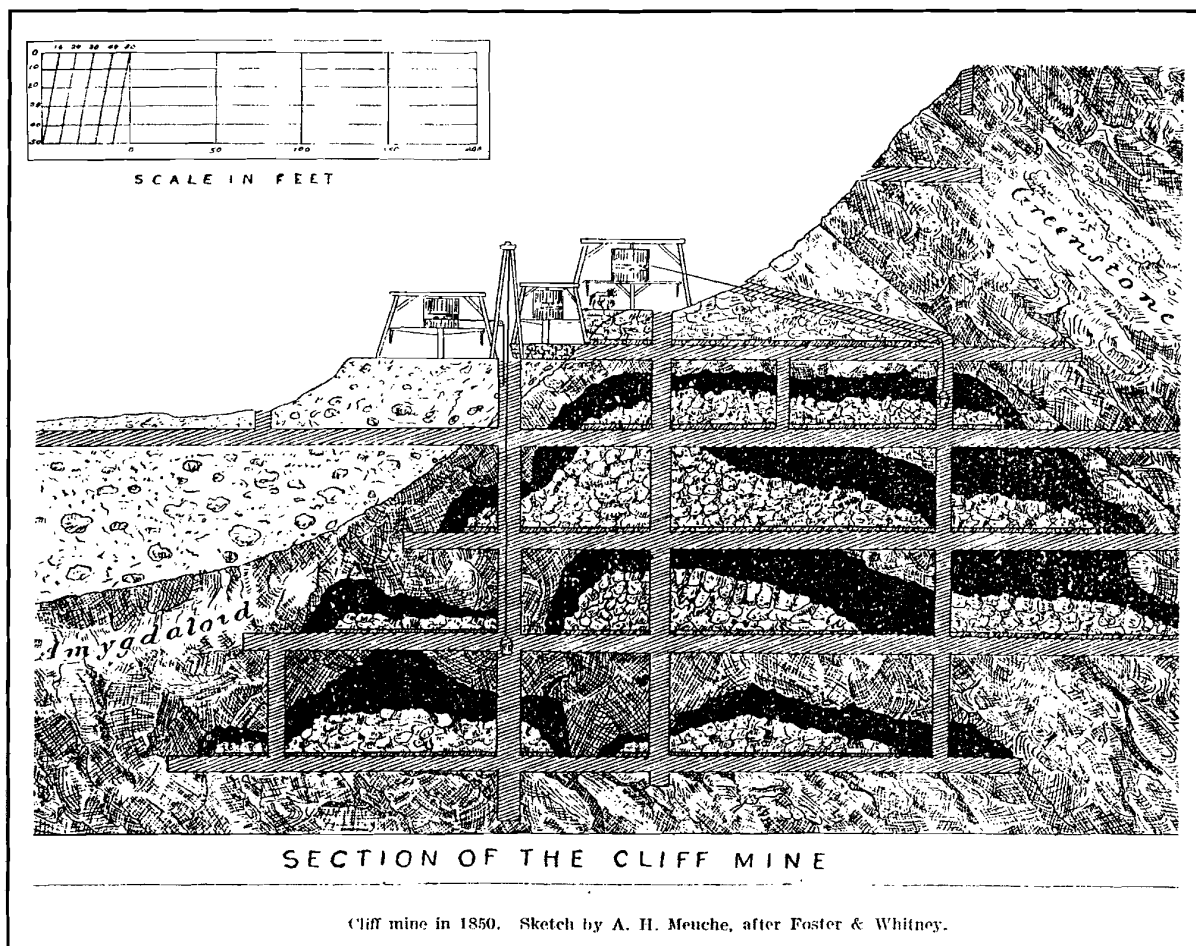
The Isle Royale Fault

Between the Minnesota shoreline and Isle Royale, the strike of Keweenaw rocks, known as the

North Shore Volcanics in Minnesota (1109-1100 Ma), changes from E-W to about N 55° E, where the PLV formation (1096-1094 Ma; Figure 13) at Isle Royale begins. This discontinuity could be partially related to the Isle Royale Fault (Figure 6), which the Voyageur crosses between Grand Portage and Isle Royale. This is a thrust fault, apparently associated with the inversion of the Midcontinent rift and was detected in the GLIMPCE profile collected on a N-S line E of the Keweenaw Peninsula (Figures 6 and 7). It is thought to extend W to at least the SW end of Isle Royale, where Isle Royale is mantled with a much thicker portion of glacial till and the glacial features are much more prominent (Huber 1983; see pp. 20-21 and 41-54).

Washington Harbor

From Grand Portage, we will take the Voy-



The Great Carrying Place

Only three water passages to the Northwest are scored into the broad rock face of the Laurentian Shield which forms the western shore of Lake Superior. They are the rivers known today as the St. Louis, the Kaministiquia, and the Pigeon. The last of these is navigable except for a few kilometers at its mouth, but a narrow, muddy trail links the lake with the navigable waters of the Pigeon. Indians had used this trail for ages before the first European explorer, a Frenchman, recorded it in 1722.

The French explorers, who continued to search for an easy passage to the western sea, and the French missionaries, who sought converts in the wilderness, gave the trail its name—"Le Grande Portage," The Great Carrying Place. It remained, however, for the Highland Scots and their partners in the North West Company to give Grand Portage its place in history as the vital link in a network of waterways that nurtured the fur trade empire.

The fur trade of North America developed in the 16th century between French fishermen and Indians along the banks of Newfoundland and the mainland coast. Furs gathered by the French for sale in Europe soon became the cash crop of New France. When fur-bearing animals, particularly beaver, became scarce, the French traders searched westward. Blocked to the north by the British fur domain of the Hudson's Bay Company, the French traders were forced over a long water and land route from Montreal through the Ottawa River and the Great Lakes to Grand Portage—gateway to the untapped fur riches of the Northwest.

Under British auspices after 1763, the route over the Grand Portage was inherited by independent traders who founded the North West Company. There was a fur trade empire based primarily on the exportation of beaver fur to supply the particular tastes of European fashion. Beaver pelts, from which the finest quality felt hats were made, were in tremendous demand.

In July the post at Grand Portage was the scene of the North West Company's annual rendezvous. From the east came canoe loads of trade goods from the warehouses in Montreal destined for the interior. From the northwestern outposts came wintering traders with loads of furs en route to Montreal.

Though it was the North West Company's most important inland trading center, the Grand Portage post was short-lived; it was founded about 1778 and abandoned in 1803 when the North West Company moved north to avoid American taxation and established the post of Fort William. The buildings at Grand Portage were left to the elements and quickly disappeared. Traffic along the portage trail dwindled; then it, too, disappeared.

From Montreal the route of the fur trade swept westward for nearly 5,000 kilometers (about 3,000 miles) over a network of rivers and lakes, linked by portages in those places where travel by canoe was impossible. The far northern terminus was Fort Chipewyan on Lake Athabasca. At the peak of the trade hundreds of tons of pelts and trade goods were paddled and portaged each season along this waterway.

The short season between break-up and freeze-up of the ice spurred the voyageurs in their dash to Grand Portage. In 5 months they had to cross half a continent and return. In early May as soon as the ice broke up, brigades of lake canoes, laden with several tons of cargo, moved out from Lachine, just above Montreal at the mouth of the Ottawa River. Eight weeks and 36 portages later they glided into Grand Portage Bay. In the northwest, crews of seasoned voyageurs, the "homme du nord," waited for the ice to break up, usually around May 15. Then Athabaska brigades, burdened with furs, began traveling down from the fur country to rendezvous in mid-July with traders at Rainy Lake and Grand Portage. Return journeys had to get underway by August 1 to allow northmen to be in Chipewyan and voyageurs in Montreal by October.

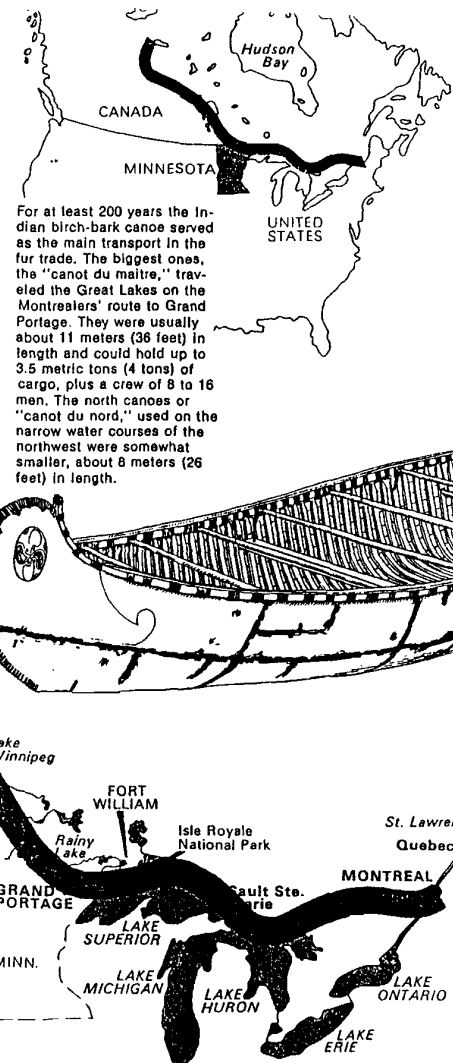
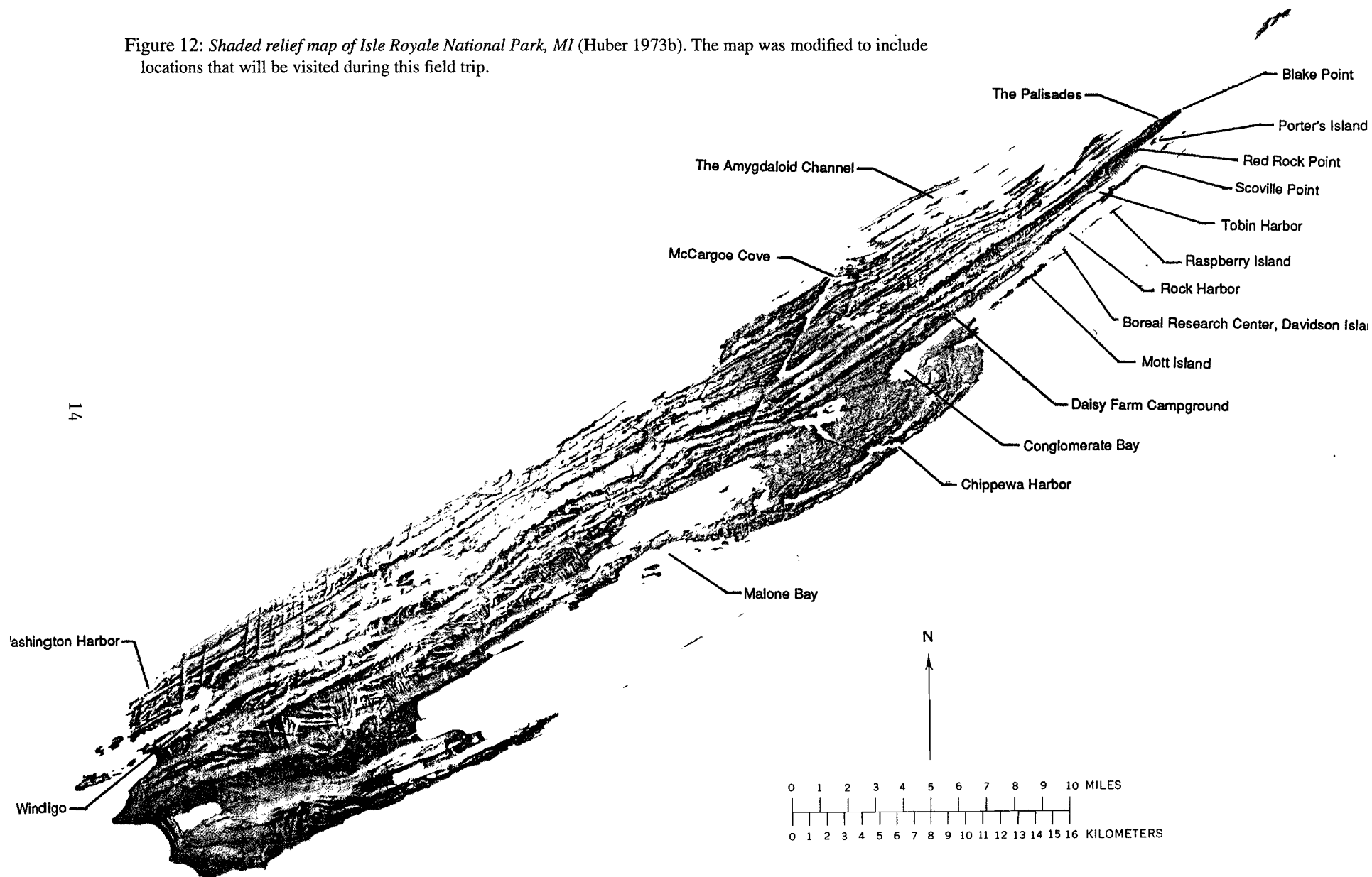


Figure 11: Description of the geography of the fur trade in relation to Grand Portage, MN (Grand Portage National Monument 1986).

Figure 12: *Shaded relief map of Isle Royale National Park, MI* (Huber 1973b). The map was modified to include locations that will be visited during this field trip.



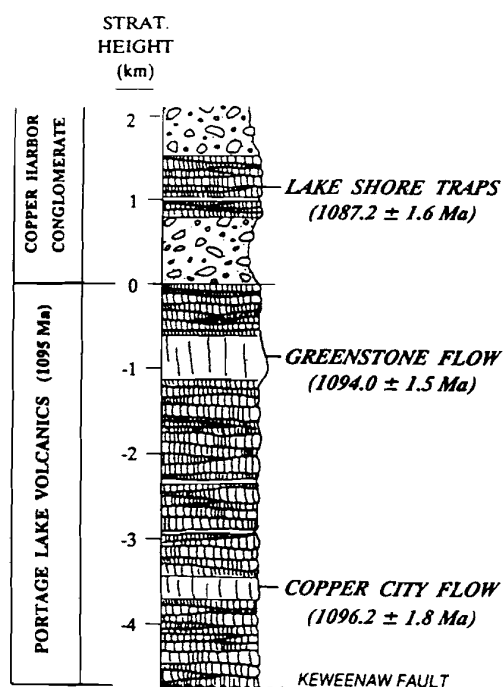


Figure 13: Conceptual diagram of Portage Lake Volcanics showing ages (from unpublished data of Paces).

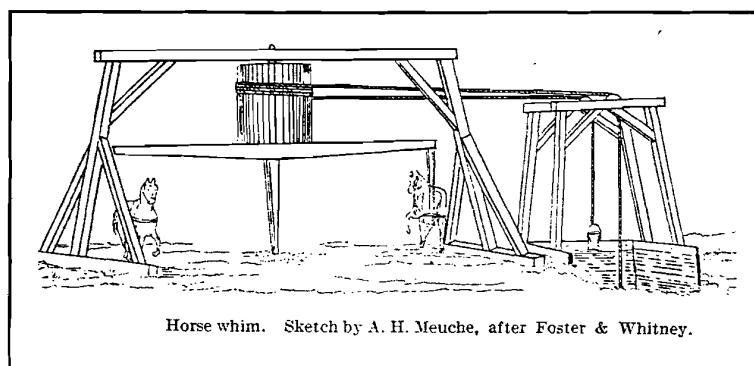
ageur E to Washington Harbor and Windigo (Figure 14), about 35 km (22 mi) offshore. (The keys, to the maps that are shown in Figures 14, 17-21, 23, 28, 34, and 35, are shown in Figure 15a and b). The bedrock geology of the Washington and Grace Harbor areas includes four large flows that continue all the way to the other end of the island. The Greenstone flow (pg) crosses the center of Washington Island and outcrops in several places SSE of Windigo. The Tobin Harbor flow (pth) outcrops at South Rock, SW of Washington Island. The Mi-

nong flow (pm) outcrops S of McGinty Cove, and the Scoville Point flow (psp) outcrops near Middle Point on the S side of Grace Harbor. Figure 16 shows the variations in thickness of the PLV.

The thickest flows in this area are the Washington Island flow (pwi) and the Grace Island flow (pgi). Both of these flows occur only locally, from the end of Washington Island to a point between Windigo and Sugar Mountain, a distance of about 14.5 km (9 mi) along strike. The lava flows here dip at 15-20° SE, an attitude that is similar almost everywhere on Isle Royale. Vertical N-S trending fractures, with little offset, cut across the bedrock strata near Washington Harbor. Huber (1983) interprets these as structures related to the warping of the Lake Superior Syncline. S of Grace Harbor, the bedrock of the island is buried by till.

Windigo

The Windigo area was the site of the last serious mining on Isle Royale, from 1890 to 1892. After failure and closure of mines further E, the Wendigo Copper Company (renamed from the Isle Royale Land Corporation) founded a mining venture on 8000 acres of land at Washington Harbor, under the leadership of Jacob Houghton, who was the brother of Douglass Houghton. The town site was named Ghyllbank and was located near the present site known as Windigo. The mine site, about 2 km (1.25 mi) inland to the NE, was named Wendigo. People built roads all around the W end of Isle Royale, and 135 people lived at the mine site. The company did diamond drill exploration, as well as extensive trenching. In 1892, the miners gave up



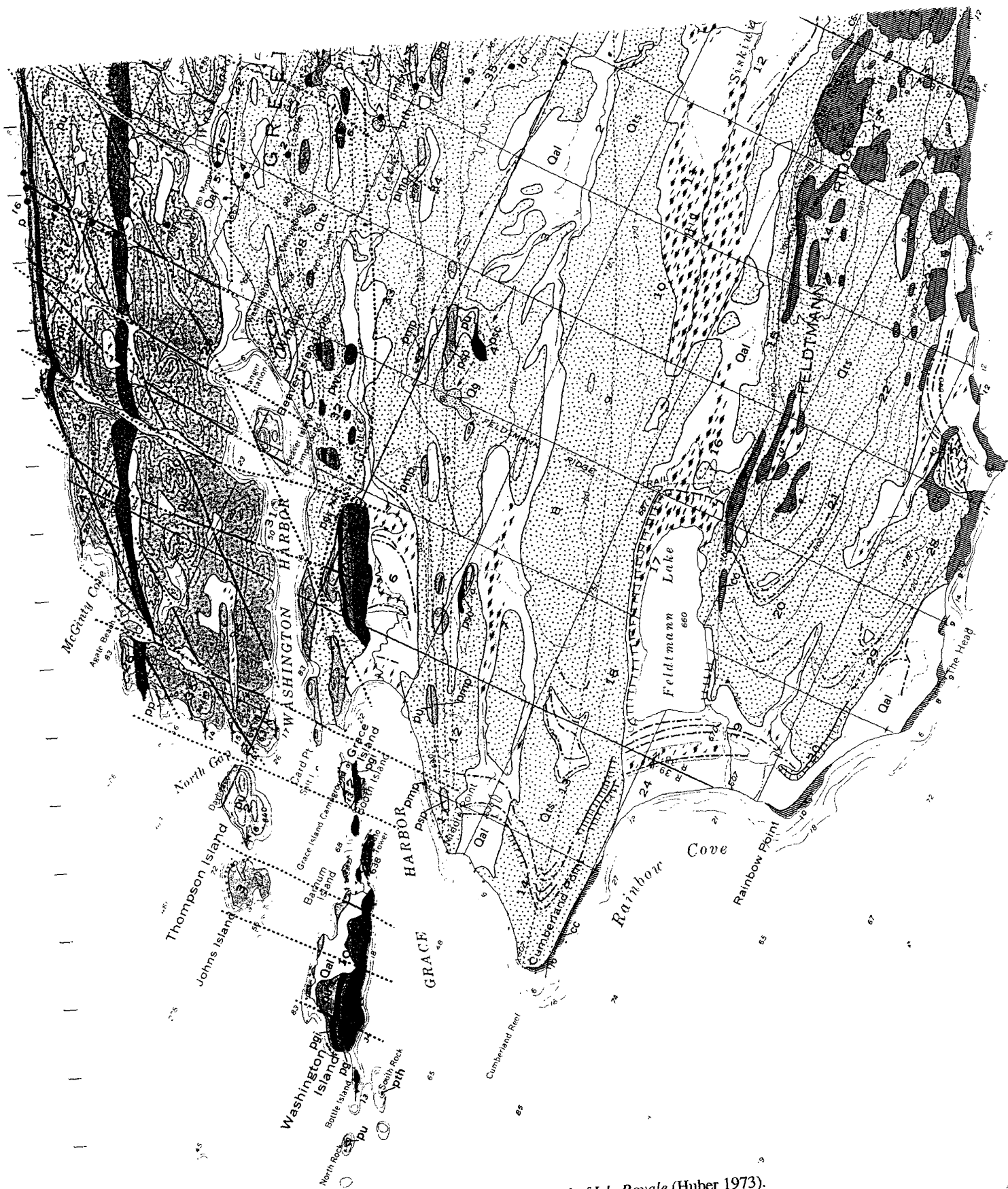


Figure 14: Geologic map of the S end of Isle Royale (Huber 1973).

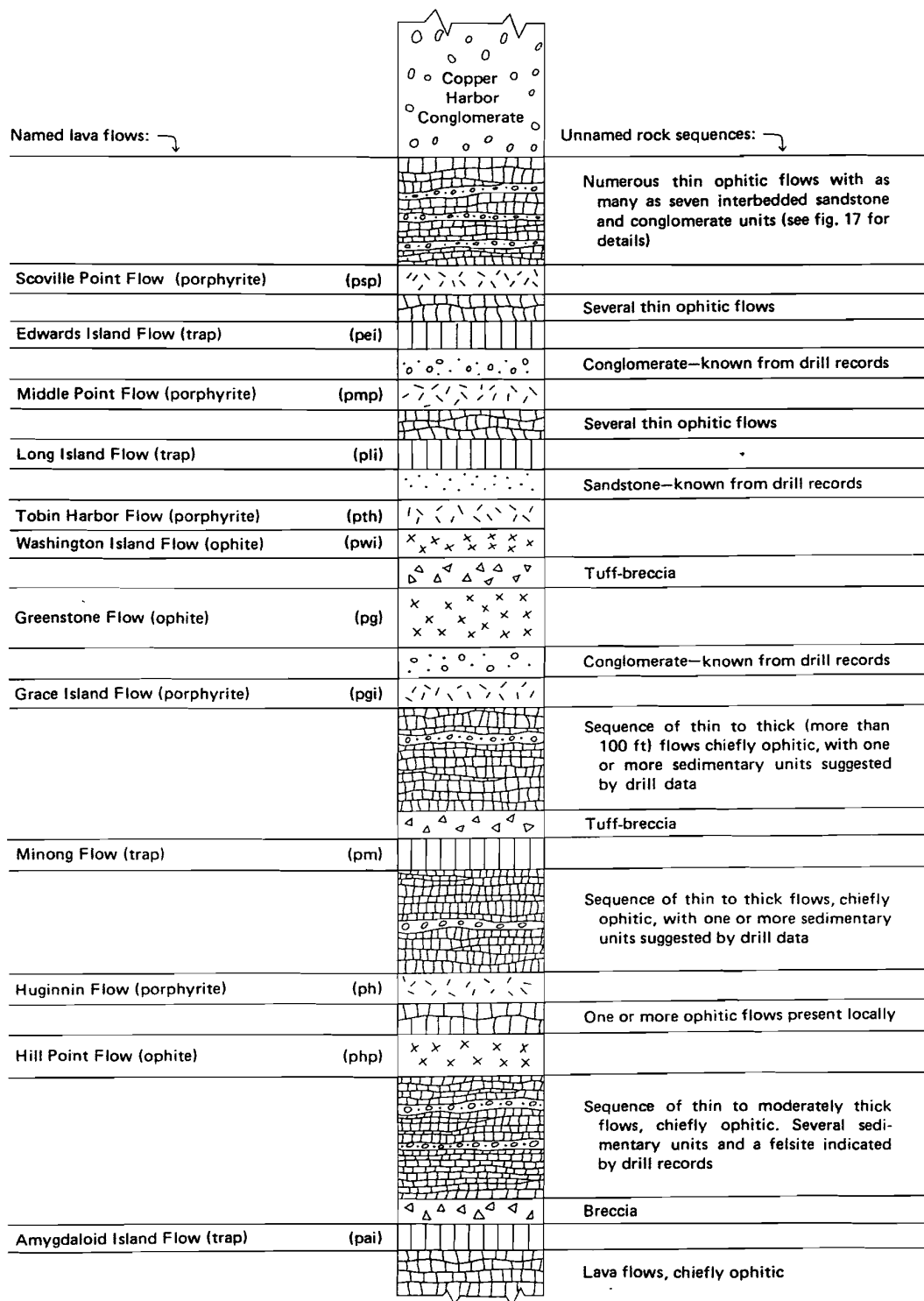
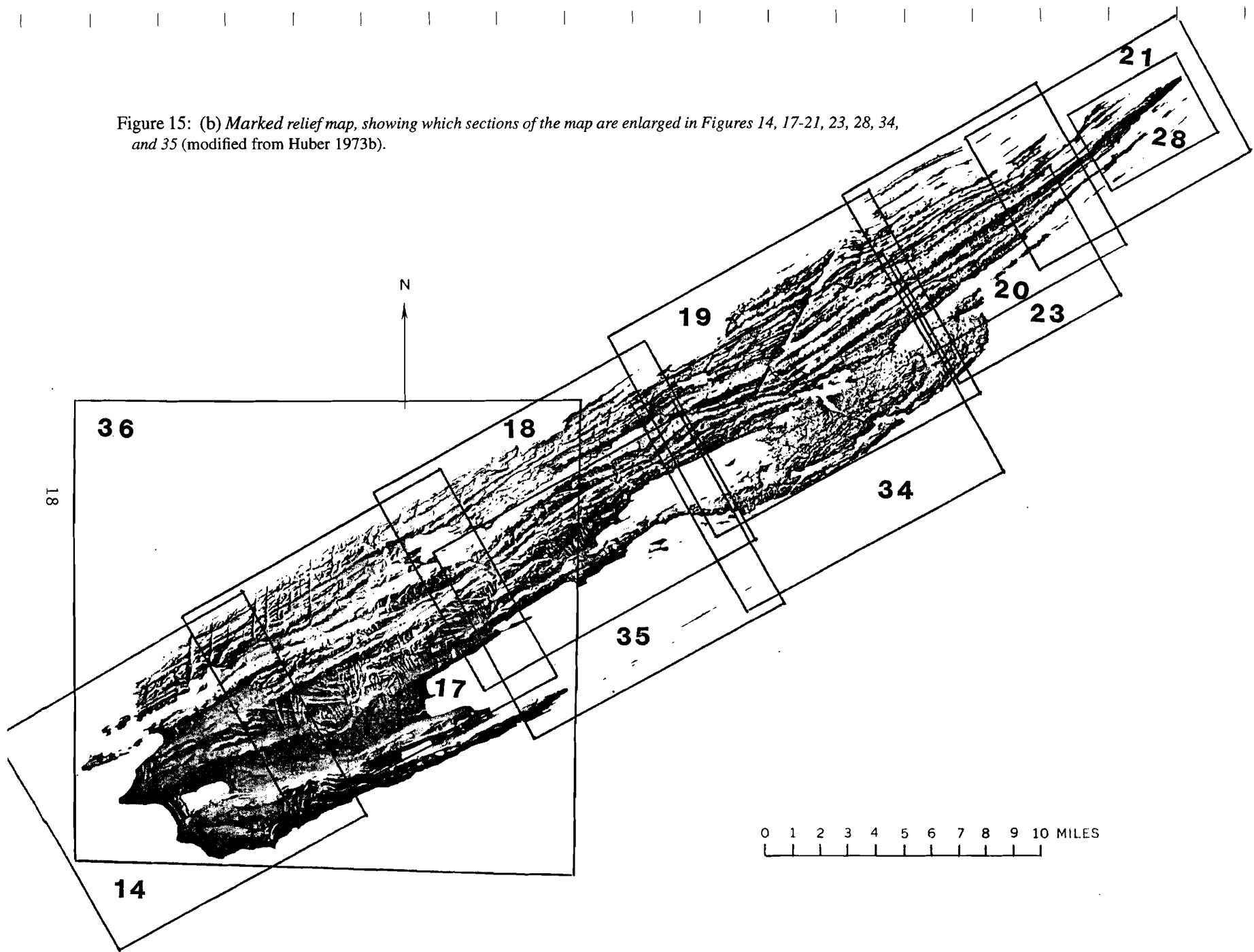


Figure 15: (a) Key to maps shown in Figures 14, 17-21, 23, 28, 34, and 35 (Huber 1973). This is a schematic columnar section of the PLV on Isle Royale; not drawn to scale.

Figure 15: (b) *Marked relief map, showing which sections of the map are enlarged in Figures 14, 17-21, 23, 28, 34, and 35 (modified from Huber 1973b).*



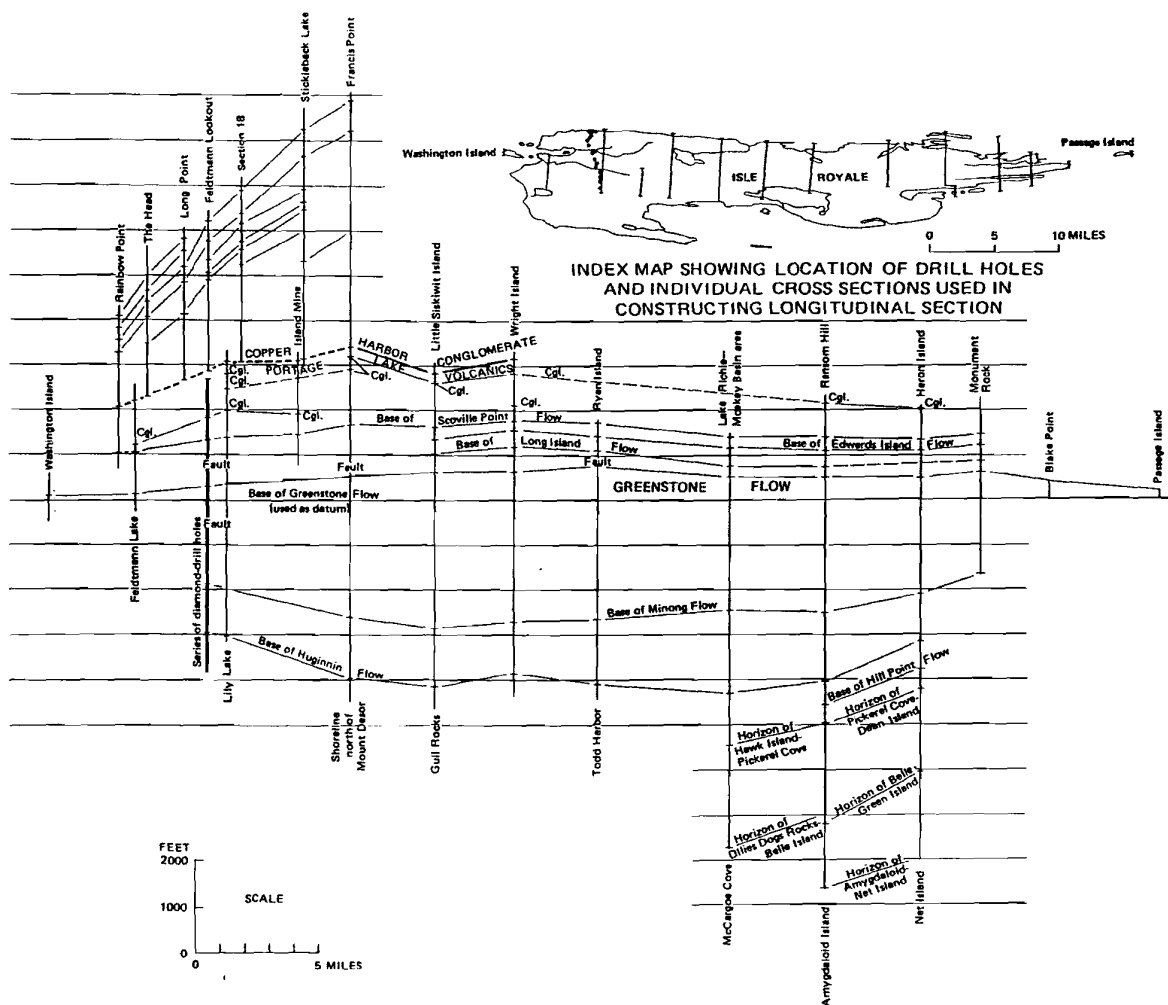


Figure 16: Longitudinal stratigraphic section showing variations in thickness of the PLV on Isle Royale (Huber 1973a).

and left. When mining stopped, the company tried to sell land to tourists and resort owners (Rakestraw 1965).

The N Side of Isle Royale: The Hill Point Flow

From Windigo and Washington Harbor, we will take the Voyageur first N and then E along the N side of Isle Royale. With the flows dipping toward the SE, moving toward the N side of the island takes us further into the PLV section, until we reach the horizon of the Hill Point flow (php). This is an

ophitic flow, which forms imposing cliffs along the shore from Hugginin Cove all the way to Todd Harbor, a distance of about 24 km (15 mi) (Figures 17-19). This flow also makes up the majority of shoreline from Pickerel Cove all the way to Hill Point itself, at the W end of Five Finger Bay, about 64 km (40 mi) from Windigo. The tilted strata along the shore make the shoreline steep, and the prevailing winds from the NNW can make conditions treacherous for small boats.

The Hill Point flow is a coarse-grained, ophitic unit with augite oikocrysts of 2 cm (0.8 in) or more.

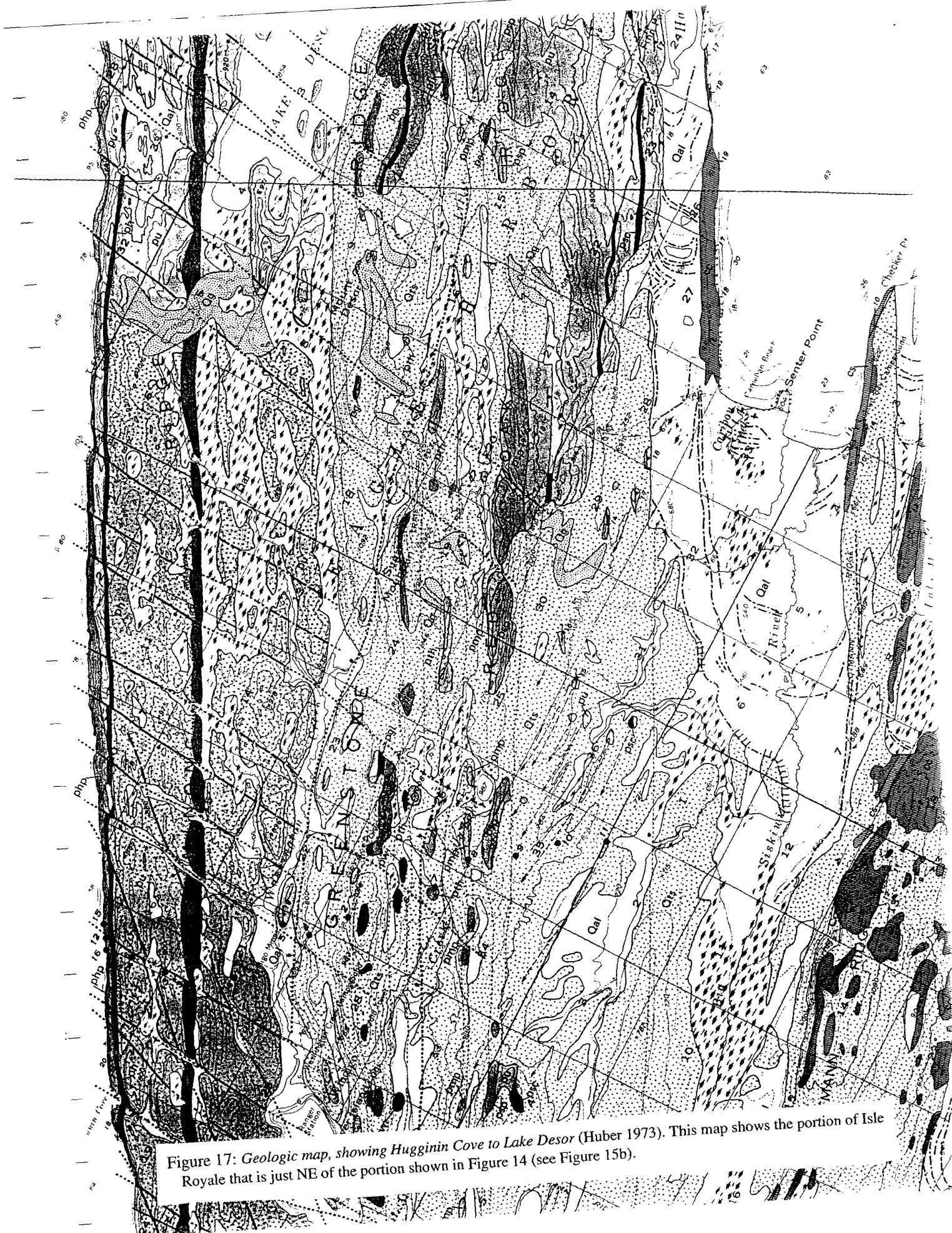




Figure 19: Geologic map, showing Todd Harbor to McCargoe Cove (Huber 1973). This map shows the portion of Isle Royale that is just NE of the portion shown in Figure 18 (see Figure 15b).

The vertical fractures are superimposed across the dipping strata and are noticeable throughout the entire flow. From the W area of the flow to the E area, the fractures gradually begin to change from N-S to more N-E trending. According to Longo (1984), the Hill Point flow may correlate with a large flow on the Keweenaw Peninsula, the Scales Creek ophite, which extends all along the Keweenaw Peninsula for more than 160 km (100 mi) of strike length, and right through Houghton, which is about 110 km (68 mi) SSE of Huginin Cove.

McCargoe Cove

At the midpoint of the island is McCargoe Cove (Figure 19), which is a fiord-like, 3.2 km (2 mi) long inlet that follows a large fracture zone, trending N 30° E to a campground site located along an ancient Native American portage route and near another mine, the Minong Mine. Native Americans left hundreds of ancient pits as relics of mining over centuries at this site, and in 1874 three companies were formed in Detroit to exploit the potential here. They built a dock and a warehouse and started to build a railroad. Some large masses of copper were successfully mined, and the community here grew for several years in spite of difficult winter conditions. But mining did not last beyond 1885 (Rakestraw 1965).

The Amygdaloid Channel

From McCargoe Cove, we will continue to the NE (Figures 20 and 21), passing through the Amygdaloid Channel. Amygdaloid Island is composed of the oldest lavas of the PLV on Isle Royale and is supported by a large flow, the Amygdaloid Island flow (pai), which is a fine-grained basalt (termed "trap"). At the W end of Amygdaloid Island is the National Park Service (NPS) ranger station near Kjaringa Kjeft. Crystal Cove is 3.2 km (2 mi) E of the station, which was, beginning in 1906, a private residence and fishery.

As we travel through the Amygdaloid Channel, the drowned ridge and valley topography of Isle Royale will become very visible, with more resistant lava flows holding up linear islands. Shipwrecks are numerous on the many "reefs" found all around

the NE end of Isle Royale. Opposite of Crystal Cove on the S side of Amygdaloid Island is Belle Isle, which is a beautiful campground, accessible only by boat and canoe, located on the site of a resort that operated in the 1920s, serving the grand lake steamers of that period.

The Palisades: The Greenstone Flow

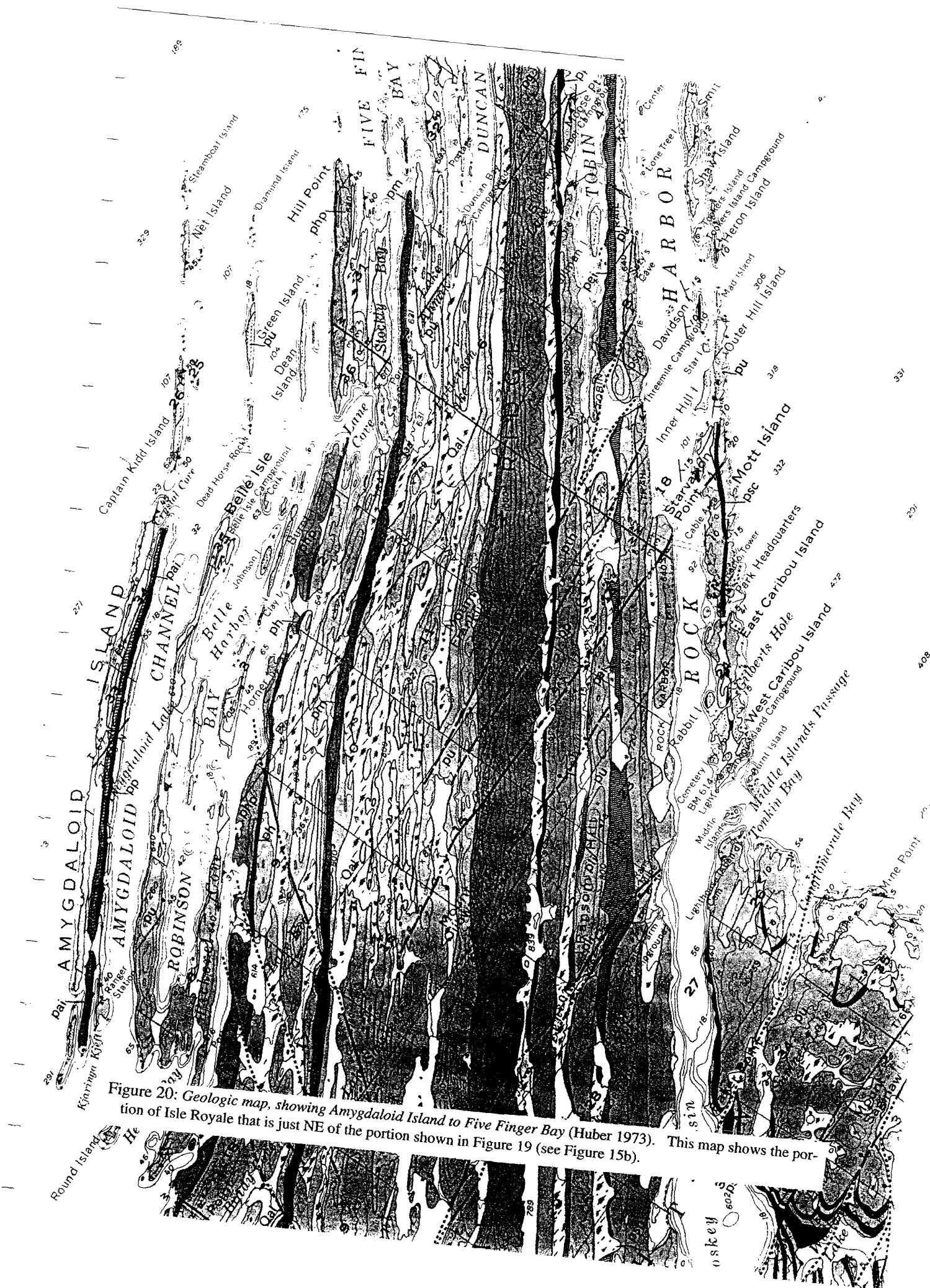
From this point, we will head toward the tip of Isle Royale to Blake Point (Figures 21 and 22), moving up in the stratigraphic succession. We will first cross the Hill Point flow (php) at Hill Point, then the Minong flow (pm) near Locke Point, and finally the Greenstone flow (pg) at the Palisades. The Greenstone flow is perhaps the earth's largest lava flow. The following are comments by Longo (1984):

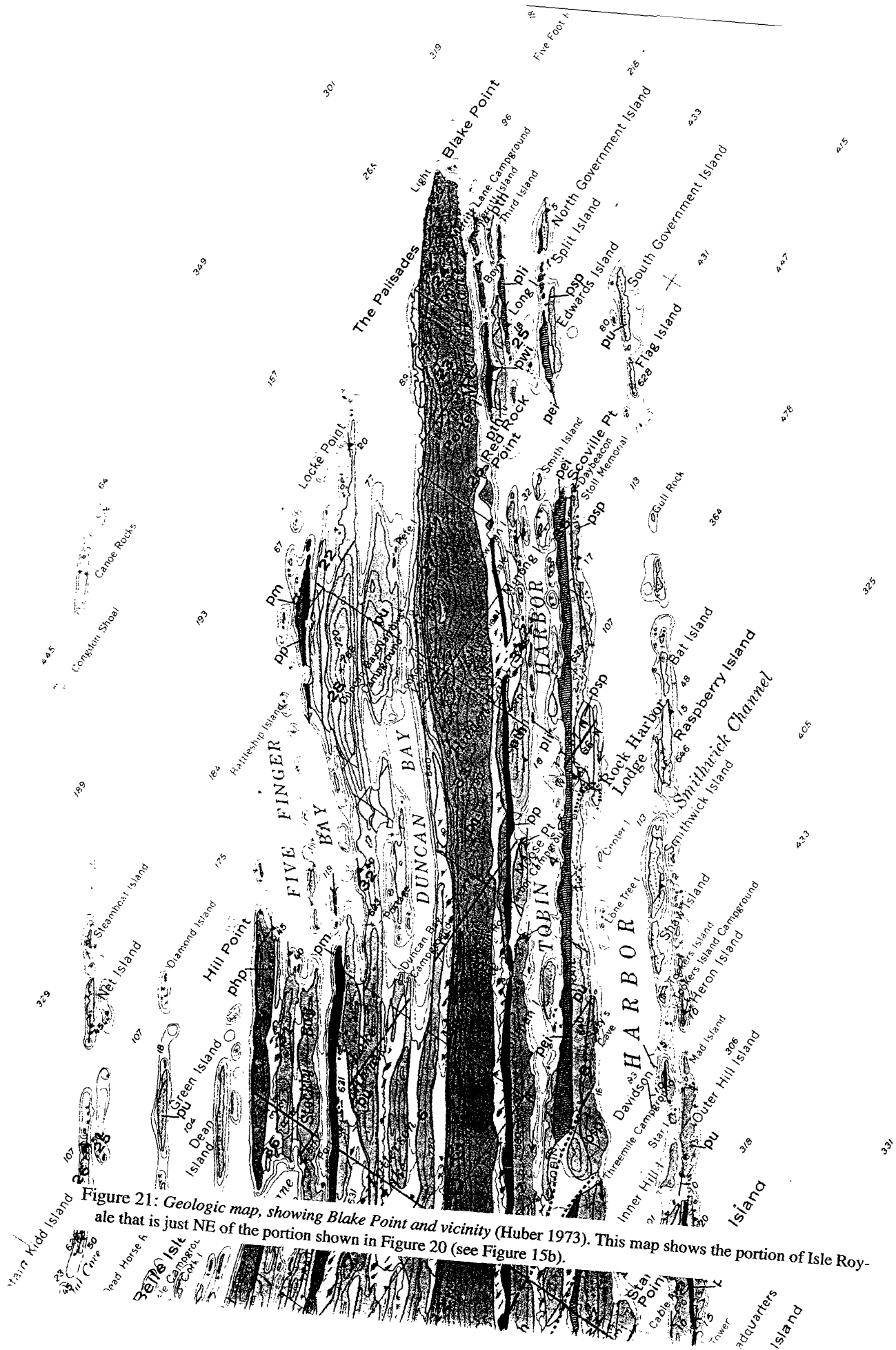
Similarities in the stratigraphic sequence of Isle Royale and the Keweenaw Peninsula of Michigan were recognized by numerous workers prior to 1851. The first thorough study of both areas, conducted by Lane (1893, 1911), resulted in the correlations of specific rock units. One unit in particular, due to its persistence as a prominent ridge on both Isle Royale and the Keweenaw Peninsula, became Lane's most convincing evidence for a correlation across this section of the Lake Superior syncline. Lane (1893) states, "The backbone ridge thus agrees in every way with the great corresponding ridge on the Keweenaw Point." Outcrop and drill core data by Lane (1893) reveal this unit as a single immense, differentiated lava flow. Lane (1893) refers to the flow as "the Greenstone, the 'backbone' and biggest ophite of all, with the bed at its base we correlate as the Allouez Conglomerate."

The Greenstone's great thickness and differentiated nature led some workers to consider it as an intrusive sill (Seaman and Seaman 1944; Van Hise and Leith 1911). However, convincing data have proven this unit to be a lava flow (Lane 1893, 1911; Butler and Burbank 1929; Broderick 1935, 1946; Cornwall 1951), and henceforth known as the Greenstone flow. Huber (1973a) confirms the similarities of the Greenstone flow on Isle Royale and the Keweenaw Peninsula, and he supported the correlation.

--Longo 1984

The columnar character of the exposure seen at





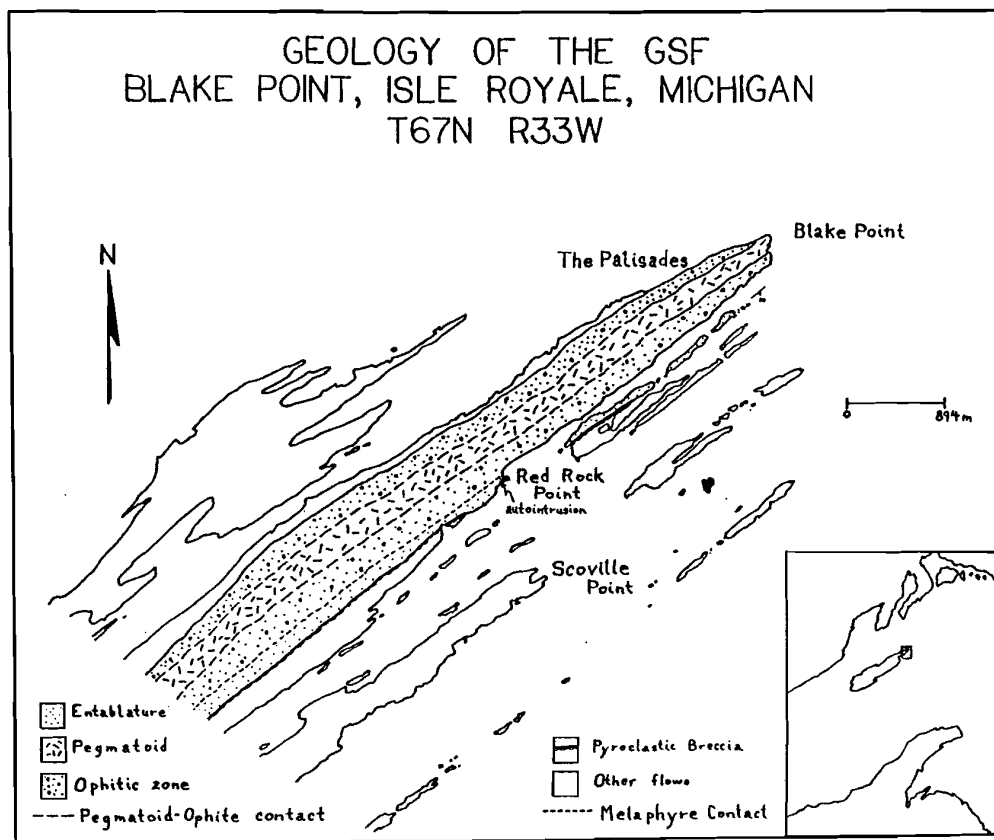


Figure 22: The geology of the Greenstone flow at Blake Point on Isle Royale (Longo 1984).

the Palisades is interpreted by Longo (1984) as a colonnade, following the terminology of Tomkeieff (1940). The cliffs are formed in the lower part of the great lava flow, which is 122 m (400 ft.) thick at the Palisades. The unit that comprises the cliffs is called the lower ophite and is about 30 m (98 ft.) thick. The rude columns are typically a few meters in diameter, and the rock is a coarse ophite with large pyroxenes enclosing many tiny plagioclases. The pyroxene oikocrysts increase in size from the bottom until they reach about 1.5 cm (0.6 in) in diameter near the top of the lower ophite. The lower ophite commonly forms steep anti-dip slopes on the N side of the Greenstone ridge (Huber 1973a). We will return to the Palisades and will also walk around to Blake Point later in the trip to look at this exposure more carefully.

Blake Point

As we take the Voyageur around Blake Point, we will see that the layers of the Greenstone flow are clearly delineated (Figures 21 and 22). Under the navigation light at the water line is the contact between the lower ophite and the pegmatoid (or pegmatitic) zone, about 23 m (75 ft.) thick. The pegmatoid represents the flow interior and has a texture that is strikingly different from the ophite, consisting of a mat of interlocking plagioclase laths as long as 2 cm (0.8 in) each. The pegmatoid is a bit less resistant to weathering, causing an indentation of the shoreline S of the light that marks the pegmatoid zone.

Farther S, a cliff face with columns marks the beginning of a third layer of the Greenstone flow, the upper ophite. Like the Palisades, this part is also marked by colonnade columnar jointing. We will

have an opportunity to examine this location on the ground later in the trip.

The uppermost parts of the Greenstone flow consist of an entablature jointed part, which is locally prominent, and a fragmental flow top with abundant agates. The flow top is not well exposed because it erodes much more readily than the interior.

Around the point, we will pass between Third Island and North Government Island. On the N side of Edwards Island, exposures of entablature style columnar jointing are spectacular in the Edwards Island flow (pei). N of Edwards Island are exposures of the Long Island flow (pli), recognized by characteristic blue agate amygdules. Both of these flows can be traced along Tobin Harbor and through scattered outcrops as far as 50 km (31 mi) to a point near Hay Bay (Huber 1973).

Rock Harbor

Heading SW to Rock Harbor (Figure 23), we will pass Scoville Point, which is the site of the Scoville Point flow (psp), a porphyritic basalt with fine, equant, millimeter-sized plagioclases. This flow extends all the way across Isle Royale and is very resistant to erosion, forming shoreline exposures and topographic highs. We will see this flow on numerous occasions throughout the next several days.

Rock Harbor is the National Park's main visitor center and the location of the only hotel on Isle Royale, Rock Harbor Lodge. Upon arrival, we will be taken by a smaller boat to Three Mile Campground about 5 km (3.1 mi) farther SW.

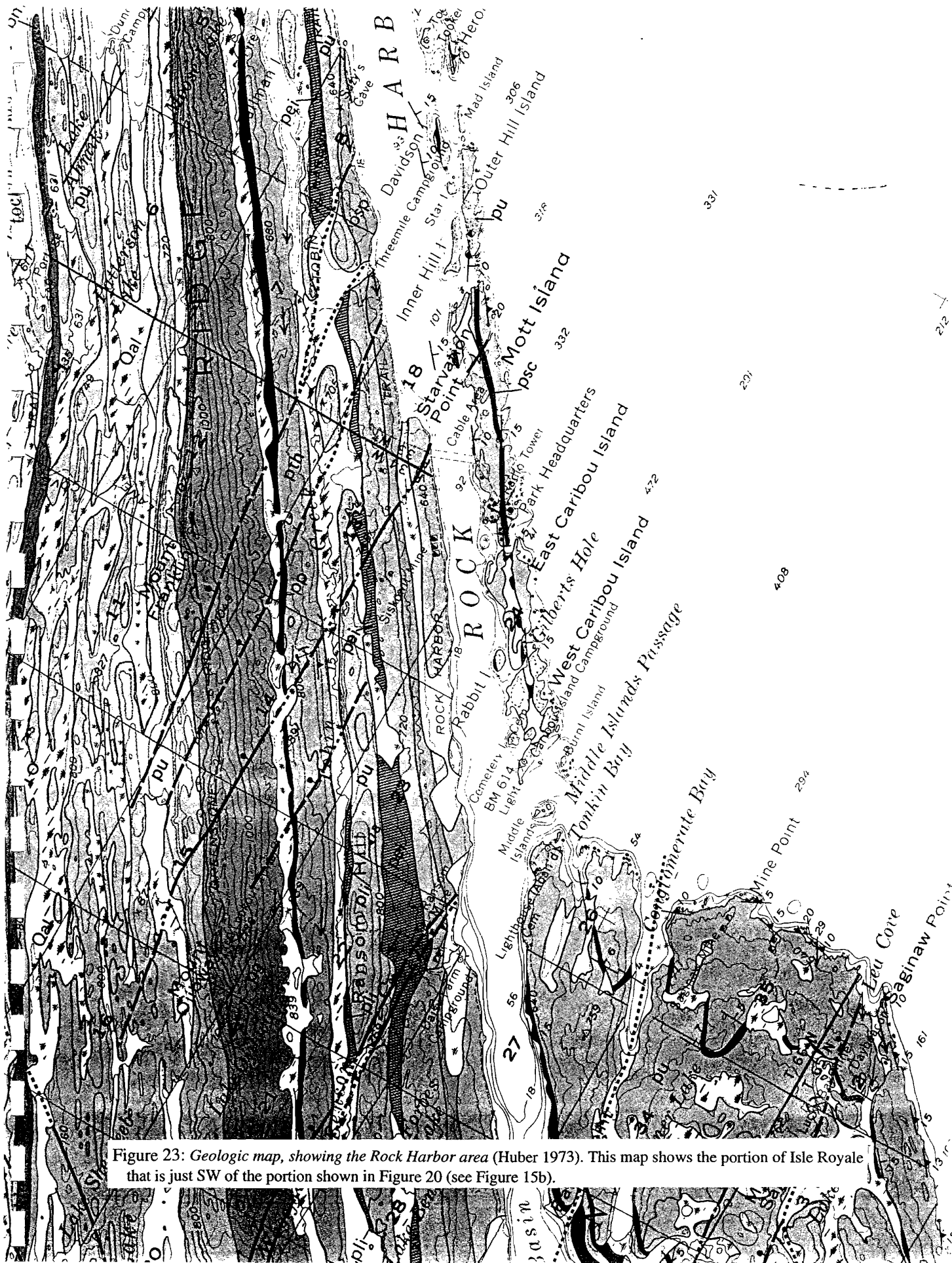


Figure 23: Geologic map, showing the Rock Harbor area (Huber 1973). This map shows the portion of Isle Royale that is just SW of the portion shown in Figure 20 (see Figure 15b).

The Second Day: An Overview Day

Mount Franklin

The day begins with a morning hike. We will take the Mount Franklin Trail, which begins 0.3 km (0.2 mi) W of Three Mile Campground (Figure 23). The trail immediately climbs a ridge supported by the Scoville Point flow (psp), then levels off and descends. We will cross a boardwalk over a swamp and arrive at a valley where there is a junction with the Tobin Harbor Trail, 0.8 km (0.5 mi) from Three Mile Campground. We will continue on the Mount Franklin Trail, straight ahead, crossing the Tobin Creek swamp and then climbing a ridge underlain by the Tobin Harbor flow (pth). From here we will descend to cross another swamp and then begin the 300 ft. ascent of the Greenstone ridge. The entire swamp and ascent is underlain by the great Greenstone flow (pg). At the top of the ridge there is a junction with the Greenstone Ridge Trail, which we will take left to go about 0.5 km (0.3 mi) to Mount Franklin, elevation 330 m (1080 ft.).

Here there is a good view of the N side of the island, including Five Finger Bay, Lane Cove, and Amygdaloid Island, as well as of the Canadian Shoreline, including the Logan Sills and the Sleeping Giant. The Greenstone flow is indeed the backbone of the island, forming the most prominent ridge all along; only at Blake Point, however, is a reasonably complete section through the flow exposed. The contact between the pegmatoid and the lower ophite units of the Greenstone is mainly located near the crest of the Greenstone ridge. The lower ophite underlies the N slope, which is a steep, anti-dip slope, and the pegmatoid armors the gentler dip slope to the S.

The Mount Ojibway Tower

From this point, still following the same trail, we will descend sharply to a wooded area and level off for about 0.4 km (0.25 mi) before climbing again. We will then reach the ridge crest and follow it for another 3.2 km (2 mi), with occasional outstanding views, to the Mount Ojibway tower. This structure was built in 1962 and was used initially as

a fire tower. Now it is used for monitoring acid rain, along with other environmental monitoring. We can climb the tower stairs for full views of the surroundings, both to the N and S.

Daisy Farm Campground

From the tower we will descend to the Daisy Farm Campground via the Mount Ojibway Trail. We will go down from the ridge to the first level spot and then begin to rise over a smaller ridge. The beginning of this small ridge is the approximate location of the top of the Greenstone flow; the ridge top and the dip slope to the S is underlain by the Tobin Harbor flow (pth). At the base of this ridge we will cross a swamp fed by Tobin Creek. Then we will ascend Ransom Hill, which has the Long Island flow (pli) on its anti-dip (N) side and the Edwards Island flow (pei) on its dip slope (S) side, where there is some entablature jointing. From Ransom Hill, the trail descends to Daisy Farm Campground.

Daisy Farm is located on the site of an old mining community, called Ransom, which was founded in 1847 with the clearing of land and the construction of a smelter. The mining prospects dimmed quickly, however, and the mining activity ended only two years later in 1849. Then, in 1866 all the buildings burned down. In later years, the place was the site of a sawmill, a garden that supplied vegetables to Rock Harbor Lodge, and a Civilian Conservation Corps (CCC) camp, which was a foundation for youth employment, developed by Roosevelt during the depression (Rakestraw 1965).

Edison's Fishery and The Lighthouse

From Daisy Farm we will travel by boat across Rock Harbor to Edison's Fishery. The fishery itself is a restored camp that is occupied each summer by a retired Lake Superior fisherman and his family; this man is employed by the park to interpret what life was like here during the heyday of Isle Royale Fishing camps, from before the establishment of the park in 1936 until the sea lamprey invasion of the 1950s.

The lavas that underlie the site of the fishery and the lighthouse are a sequence of 45-50 ophitic flows (Figure 24), which occur between the Scov-

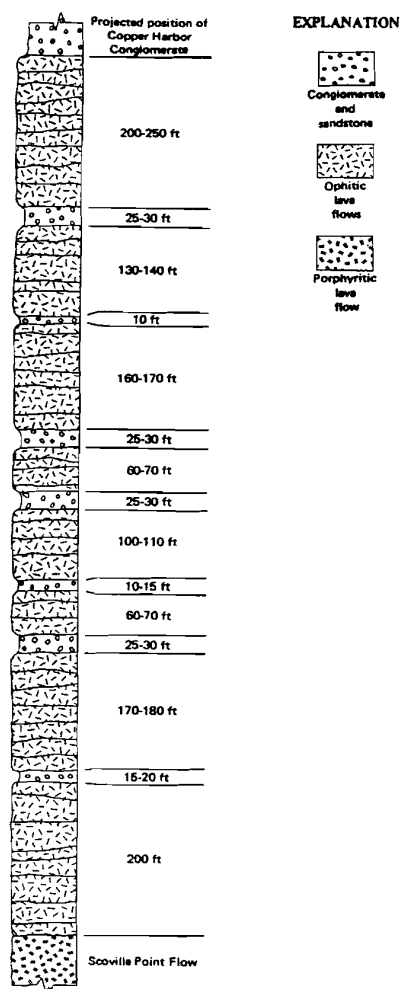


Figure 24: Columnar section of upper part of Portage Lake Volcanics showing distribution of sedimentary units in the Chippewa Harbor area (Huber 1973). All the ophitic flow zones consist of multiple flows.

ille Point flow (psp) and the overlying CHC. As we walk around the point we will see several flow tops exposed, good examples of cellular amygdaloids. This is an excellent place to find greenstone, a nodular, compact form of pumpellyite that is prized as a semi-precious gemstone (Huber 1983, see pp 58-9).

The geological purpose of stopping here is to look at the flow sections along the wave-washed shoreline, following it from this point to Tonkin Bay (no relation to the Gulf of Tonkin!). We can also look at the amygdule mineral suite, which can be found on the pebble beaches. The amygdules of Isle Royale's flows contain a variety of secondary minerals, listed alphabetically (by Huber) as barite, calcite, chlorite, copper, datolite, epidote, laumontite, natrolite, prehnite, pumpellyite (chloastrolite or greenstone), quartz (agate), and thomsonite (see Table 3 for information about each). The prehnite is unusual in that it contains disseminated native copper inclusions and has a pink color, which has caused some to confuse it with thomsonite (Huber 1969). Overall, the assemblage is zeolite facies and prehnite-pumpellyite facies, representing a slightly lower grade than much of the Keweenaw Peninsula area. This may partially explain the lower abundances of native copper on Isle Royale than the amount found on the Keweenaw Peninsula.

Mott Island

From the lighthouse, we will return to the fishery and take the boat across the Middle Island Pas-

Mineral	Formula	Hardness	Color	Notes
Barite	BaSO ₄	2.5-3.5	white	vein occurrences
Calcite	CaCO ₃	3	white	vy common, veins, amygdules
Chlorite	(Mg,Fe) ₅ Al ₂ Si ₃ O ₁₀ (OH) ₈	2-2.5	olive - dk green	very common
Copper	Cu	2.5-3	copper	rare, veins, amygdules
Datolite	HCaBSiO ₅	5-5.5	white, various	porcelaineous, opaque
Epidote	Ca ₂ (Al,Fe) ₃ Si ₃ O ₁₂ (OH)	6-7	pistachio	crystalline, amygdules
Laumontite	CaAl ₂ Si ₄ O ₁₂ ·4H ₂ O	3.5-4	white, red-yel	amygdules
Natrolite	Na ₂ Al ₂ Si ₃ O ₁₀ ·2H ₂ O	5-5.5	colorless	radiating fibers, amygdules
Prehnite	Ca ₂ Al ₂ Si ₃ O ₁₀ (OH) ₂	6-6.5	lt green-pink	radiating fibers, amygdules
Pumpellyite	Ca ₂ MgAl ₂ Si ₃ O ₁₁ (OH) ₂ ·H ₂ O	5.5	green	mosaic, segmented pattern
Quartz	SiO ₂	7	colorless, varied	agate amygdules
Thomsonite	NaCa ₂ Al ₅ Si ₅ O ₂₀ ·6H ₂ O	5-5.5	pink	radiating amygdules

Table 3: Characteristics of secondary minerals at Isle Royale.

sage to Mott Island (about 3.2 km (2 mi) NE). We will stop here to visit one of the best exposures of sedimentary units within the PLV, found at the SW end of the island, facing East Caribou Island near the park headquarters complex. There are seven such units mapped by Huber (1973) in the Chippewa Harbor area. Most of them are remarkably constant in thickness and lithology throughout their lateral extents, which are 65 km (40 mi) or more. Paces (1988) reports the following about interflow sediments in the PLV:

Occasionally, lava flows are separated by intervening sheets and lenses of terrigenous clastic sediment. Twenty two major interflow sedimentary horizons occur scattered throughout the PLV section and are described by Butler and Burbank (1929), White (1952), and Merk and Jirsa (1982). Interflow sedimentary beds vary in thickness from less than 1 cm (0.4 in) thick fine-grained siltstones filling fractures between flow top fragments to coarse boulder conglomerates over 100 m (330 ft.) thick locally. Typically, interflow sediments are poorly sorted, lithologically immature conglomerates and sandstones derived from a nearby volcanic source of some relief and deposited in an alluvial fan-type environment (Merk and Jirsa 1982). Transportation was generally from the SE to NW, or from basin margins towards the center of the subsiding graben (White 1952). Although the interflow sediments are volumetrically insignificant within the PLV (3% of the total lithologic volume) (Merk and Jirsa 1982; White 1971), they form distinct and relatively continuous stratigraphic marker horizons within an otherwise monotonous volcanic pile.

The occurrence of occasional interflow sediments implies that rates of lava flow extrusion, sedimentation, and/or tectonic subsidence were not constant during the formation of the PLV. White (1960) shows that a subsidence-depositional equilibrium was established so that both lava flows and sediments were deposited on near-horizontal surfaces. Most lava flows were deposited directly on

top of the underlying lava flow top indicating a more-or-less constant and relatively short repose period between eruptions. The infrequent presence of sedimentary beds between lava flows may indicate occasional hiatuses in magma extrusion, which allowed for alluvial fans to transgress out towards the center of the basin. Conversely, interflow sedimentary horizons may mark brief periods of increased depositional rates possibly related to episodic normal faulting and basin subsidence.

--Paces 1988

The pebble conglomerate unit at Mott Island is thicker than most, about 12 m (40 ft.). The pebbles are essentially all of volcanic rock, with mafic varieties about twice as abundant as felsic ones. The sandstones are very feldspathic, plagioclase being most abundant. Fine-grained hematite is ubiquitous. The rocks have scour and fill structure, suggesting an origin in braided stream environments. Desiccation cracks and raindrop impressions have also been noted. Paleocurrent data suggest transport to the SE, similar to the CHC (Huber 1973a).

Boreal Research Center, Davidson Island

Next, we will go by boat for a brief stop at Davidson Island, opposite Three Mile Campground. On this island is the Boreal Research Center, a residence for researchers at Isle Royale. After stopping at the dock in front of the center, we will walk around this small island, visiting another exposure of the epiclastic sedimentary rocks and an exposure of a columnar jointed, ophitic flow on the SE corner of the island. The wave-washed shoreline has exposed a surface perpendicular to the columns, which are 2-3 m (6-10 ft.) across. We will see many exposures of large columns like these in the next few days, as they seem to be a regular feature of ophitic flows at Isle Royale.

We will then return to Three Mile Campground for dinner.

The Third Day: A Good Look at the Greenstone Flow

Blake Point

Weather permitting, this is a day to visit one of the most dramatic places on Isle Royale, Blake Point (Figure 21). The shoreline around Blake Point offers the best view of the Greenstone flow, better than any other sites at Isle Royale or the Keweenaw Peninsula. On the way to Merrit Lane, the starting point of our Blake Point walk, we will pass several islands that have interesting wave-washed exposures of lava flows. Among the sites we may see from the boat are: the SE sides of Heron, Shaw, and Smithwick Islands, where there are exposures of calcite veins and columnar jointed surfaces like the one we visited at Davidson Island; the SE side of Raspberry Island, which we will visit on the fifth day and which has many interesting features of the ophitic flows; and the NW side of Edwards Island, which has good exposures of entablature columnar joints in the Edwards Island flow (pei).

The boat will let us off at the Merrit Lane Campground for our walk to Blake Point. We will follow the shoreline from Merrit Lane around the point, remaining close to the wave-washed rocks, yet trying to keep our feet dry.

Most of the walk is on the upper ophite unit of the Greenstone flow. (The entablature part of the Greenstone and its flow top is underneath Merrit Lane, and we will see parts of this from the boat later). The upper ophite exhibits a rude columnar structure all along the walk, with the columns perpendicular to the bedding. The size of the oikocrysts increases from top to bottom.

After rounding the corner, we will cut through the bushes to descend a cliff that marks the lower anti-dip face of the upper ophite. At the base of this cliff, we will see wave-washed exposures of the pegmatoid, here about 23 m (75 ft.) thick. The contact here appears to be quite sharp, although Huber (1973a) says it is frequently gradational. The following description of the pegmatoid is from Longo (1984):

Lacroix (1928, 1929) coins the term "pegmatitoide" to describe the coarse-grained zones consid-

ered to represent the final stages of differentiation in basaltic lavas of France. The lavas of Michigan's Copper Country show similar differentiates for which Lane (1893) applies the term "doleritic." Cornwall (1951) adopts the textural term "pegmatite" from the usage of Butler and Burbank (1929). He changed the confusing "doleritic" term to "pegmatitic facies," and subsequently described such units in the Greenstone flow, Big Trap, and several other large flows within the PLV on the Keweenaw Peninsula. For the present study, the term "pegmatoid zone" from Lindsley et al. (1971) is adopted to encompass the portion of the Greenstone flow with numerous en echelon, lens-shaped pegmatoids, associated granophyric phases, and subophitic layers.

Texturally, pegmatoids are coarse grained when compared to ophitic zones. Coarse plagioclase laths dominate with interstitial, subhedral clinopyroxene and abundant interstitial to somewhat poikilitic magnetite and ilmenite. Consequently, the pegmatoids are strongly magnetic compared to ophitic units. This suggests that a higher titaniferous magnetite/ilmenite ratio for magmatoids than for ophites. Visual inspection generally reveals a greater overall opaque (oxide) concentration in the pegmatoids.

Subophitic layers are often found hosting the en echelon pegmatoids. These layers, like pegmatoids, are strongly magnetic and very coarse grained stratiform features, but contain less abundant, smaller sized pyroxene. The contacts between pegmatoids and subophitic units are usually sharp, although instances of gradational contacts have been observed. Subophitic layers grade into the ophites and seem to occupy the greatest volume of the pegmatoid zone. They have been observed to pinch out within pegmatoid units and may not be continuous planar features throughout the flow. Perhaps pegmatoid units are not only lens-shaped but also flattened amoeboid-like features interfingering with subophitic layers.

The frequency of pegmatoids and subophitic layers increases proportionally with increasing flow thicknesses. Both vary in thickness and shape and typically occur in the upper half of a lava flow. Pegmatoids have also been observed as autointrusions, such as in the entablature on Isle Royale and the upper ophite on the Keweenaw Peninsula. The stratiform pegmatoids are usually found armoring the tops of cliffs formed of the lower ophite. The ex-

tension of weak vertical joint patterns into the pegmatoid (forming crude large columns) suggests that pegmatoids may be part of the colonnade. In most cases pegmatoid zones separate a basal colonnade from an upper colonnade.

Pegmatoids are not unique to thick flows of the PLV. Lindsley et al. (1971) assert that three of the thicker flows from the Picture Gorge Basalt contained pegmatoid lenses. Santin (1969) discusses the presence of pegmatoids in horizontal basalts of the Lanzarote and Fuerteventura Islands in the Canadian Archipelago.

--Longo 1984

The pegmatoid underlies the low shoreline and also the area under the light tower. A section of the Greenstone flow is exposed on Passage Island, a 2 km (1.2 mi) long island that can be seen about 4 km (2.5 mi) offshore from Blake Point. Around the corner from the tower and vertically down about 4 m (13 ft.) is the contact with the lower ophite (which is too difficult for us to reach safely). Longo (1984) describes the contact as a gradation over about 1 m of thickness.

From here, we will return by the same route to Merrit Lane. Weather permitting, we will travel around the point in the boat to examine the lower ophite cliffs along the Palisades. The columns exposed on the anti-dip slope are up to several meters across. The base of the Greenstone flow is not exposed here.

Porter's Island

Upon returning to Merrit Lane, we will head S to Porter's Island, which includes exposures of a fragmental rock that Huber (1973a) interprets as pyroclastic. However, according to Longo (1984), these exposures may represent a fragmental top of the flow. The breccia unit, which is about 1-5 m (3.3-16.4 ft.) thick, contains rounded and semi-rounded fragments of the Greenstone flow set in a finer matrix that has amoeboid-shaped, agate amygdules. Longo did an extensive perographic study but could not find any evidence of shards or pumice. He did, however, find bow-tie spherulitic plagioclases in the matrix, which suggests an under-cooled texture for the basaltic material there. This unit occurs at the top of the Greenstone flow along about 15 km (9.3 mi) of strike length (approximately to Mt Ojibway), according to Huber's map. Similar units are found at the top of the Greenstone flow on the Keweenaw Peninsula (Longo 1984). Figure 25 shows an old drawing of a cross section through Lake Superior, including Isle Royale and the Keweenaw peninsula.

Red Rock Point

At Red Rock Point, we will pass excellent examples of entablature jointing of the upper part of the Greenstone flow. The basalt of the entablature is

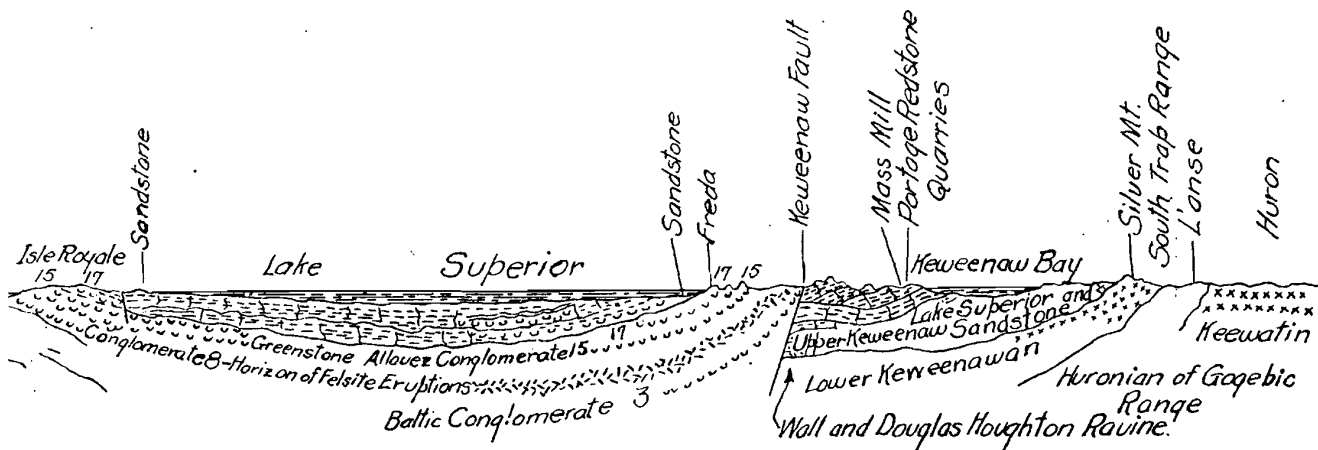


Figure 25: An older drawing of a cross section through Lake Superior, from the Huron Mountains to Port Arthur (Lane 1911).

melaphyre, very fine grained. The curvicolunar nature of a few of the columns resembles some of the Columbia River basalt descriptions (Figure 5). Long and Wood (1986) suggest that entablature jointing results when extensive floods that are created from deranged drainages cause dramatic quenches of solidifying flood basalts.

Around the corner of Red Rock Point is an autointrusion of the Greenstone's entablature zone by material that is apparently from the pegmatoid zone. Longo (1984) describes the feature:

A large autointrusive dike was found intruding (N 20° W, 65° E) the columnar-jointed melaphyre at Red Rock Point. Despite an apparent lack of aplites, the dike is texturally similar to the strati-form pegmatoid. It is composed of randomly oriented, euhedral plagioclase laths with interstitial, subhedral augite and pigeonite (no poikilitic textures occur). The plagioclase laths are immense by comparison to the microlites of a typical ophitic unit.

Three characteristic features of the dike are: (1) the abundant plagioclase phenocrysts (up to 1 cm (0.4 in)), (2) a blue-green hue from plagioclase altered to chlorite in the dike, and (3) alignment of plagioclase laths parallel to the dike contact, forming an igneous lamination. Amygdules are more abundant along the dike contact also.

The process of autointrusion is similar to the mechanisms of pegmatoid formation, except that after the residual liquid is pressed out of the hosting crystal mesh, the differentiated magma is squeezed up into the vertical tensional fractures.

--Longo 1984

Longo (1984) interprets the auto intrusion to be related to a sag flowout structure, described by McKee and Stradling (1970) as: a large structure that

develops as the crust of a partly solidified flow founders and causes the upward escape of the flow's fluid interior (Figure 26).

Below the water level at Red Rock Point is an occurrence of coarse grained granophyric rock, which can be found in beach cobbles and boulders and may occur within the Greenstone flow itself.

Tobin Harbor

Continuing to the SW along Tobin Harbor, we will pass Newman Island. Opposite this island on the N shoreline of Tobin Harbor are outcroppings of the volcanic breccia that may represent the fragmental top of the Greenstone flow. We will continue SW to Hidden Lake dock.

Lookout Louise

From Hidden Lake to Lookout Louise, we will hike about 1.6 km (1 mi) long and 85 m (280 ft.) up. We will begin on the Tobin Harbor flow, but after passing the lake we will be on the Greenstone flow, following a dip slope up to Lookout Louise. At about the halfway point, the trail passes Monument Rock (Figure 27), an individual column from the colonnade of the upper ophite that is exposed as an erosional remnant. Huber (1983, see especially pp 47-55) suggests that Monument Rock was formed by wave cut shoreline processes along a former "raised" shoreline, which he associates with glacial Lake Minong, about 10 Ka. From Lookout Louise we will look over the steep anti-dip slope of the lower ophite and see Five Finger Bay, Duncan Narrows, and Amygdaloid Island.

The plan is to return from Lookout Louise to Hidden Lake and take the boat back to Three Mile Campground for the night.

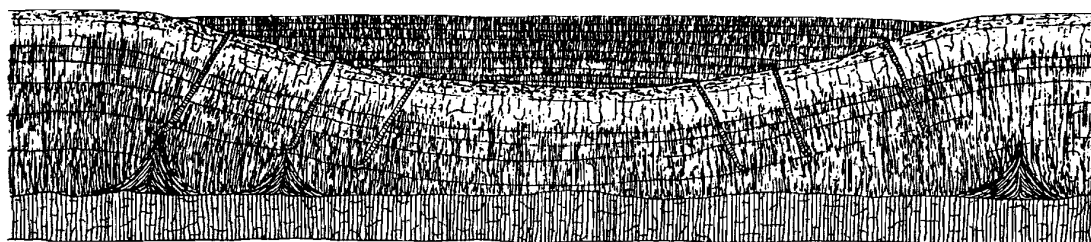


Figure 26: Idealized cross section of a sag flowout structure (McKee and Stradling 1970). Following erosion, the dikes commonly remain as topographic highs in a circular pattern around the central sag area.



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MONUMENT ROCK (NORTH EAST VIEW) ISLE ROYALE.

Figure 27: An old drawing of the NE view of Monument Rock on Isle Royale (Foster and Whitney 1851).

The Fourth Day 4: Scoville Point

Rock Harbor

For part of this day's trip we will walk on the rocky dip slope of the Scoville Point flow (psp), facing Rock Harbor along the shore. Huber (1973) describes the basalt of this flow as containing "fine, equant, millimeter sized, plagioclase crystals distributed uniformly through a fine grained matrix." He says the thickness is 30-60 m (100-200 ft.). There are not many features that can be seen in outcrop, but the flow is very resistant to erosion and buttresses the shoreline. At Suzy's Cave, about 1.8 km (1.1 mi) E of Three Mile Campground along the Nipissing shoreline, waves cut a sea arch at a contact between two lava flows about four thousand years ago, selectively eroding the region of the flow top.

After passing Suzy's Cave, the trail to Snug Harbor, where the Rock Harbor Lodge is located, parallels the shore of Rock Harbor and lies on thin ophitic flows, which are stratigraphically below the Scoville Point flow. At Snug Harbor (Figure 28), the Scoville Point flow crops out only within the recessed part of the harbor, and the point where the Americas Dock is located is underlain by ophitic flows above the Scoville Point flow.

We will take the Stoll Trail, which goes along the shore of Rock Harbor. Along here, we will see Nipissing shorelines and outcrops of the Scoville Point flow. Also, we will be able to see the ophitic flows above and below the Scoville Point flow along the way. About 0.8 km (0.5 mi) from the

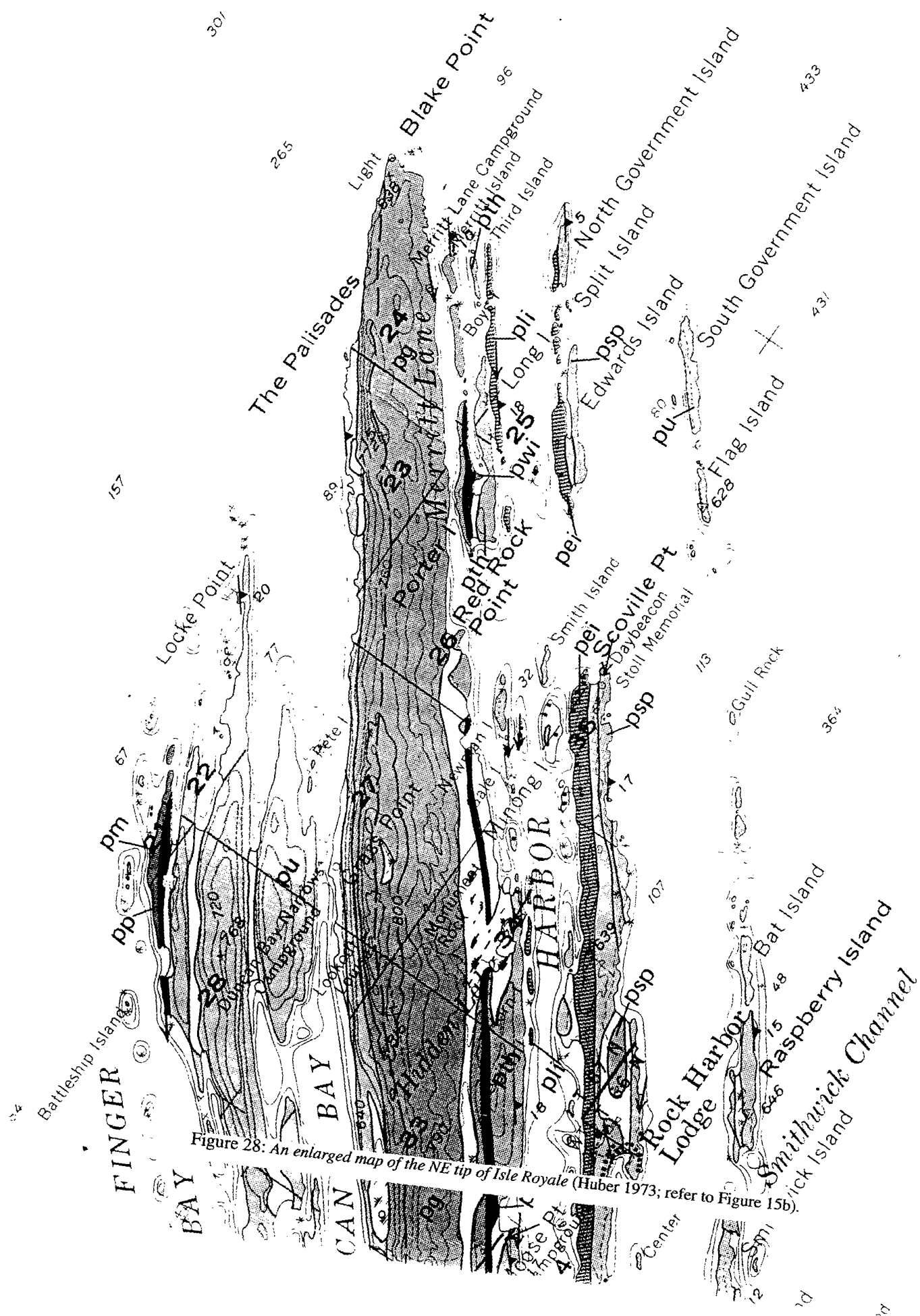
lodge lie ancient mine pits, attributed to Native Americans who occupied this area from about 2500 BC during the period of the Nipissing stage. The mining was apparently informal and quite limited in any one place, but there are more than 1000 such pits all over Isle Royale according to Rakestraw (1965).

Scoville Point

As we near the Scoville Point, the Scoville Point flow dominates the shoreline and has steep smooth exposures. At the point itself, we will look at the excellent exposures of the Scoville Point flow, the ophitic flows below it, and the Edwards Island flow (pei), which underlies the companion point located just to the NW of Scoville Point. There is a good exposure of cellular amygdaloid in one of the ophitic flows and the Edwards Island flow shows well developed entablature jointing.

We will return to the lodge and to Three Mile Campground via the Tobin Harbor Trail, which is easier to hike. It stays near the shore of Tobin Harbor, mostly atop the Edwards Island flow. Just NE of the Rock Harbor Lodge on the return trail is the site of the Smithwick Mine remains; this mine was discovered in 1843 and actually operated in 1847 and 1848. The work done here mostly consisted of exploratory shafts and excavations, and it is unclear whether or not much ore was found (Rakestraw 1965).

From Rock Harbor Lodge we return to Three Mile Campground via the Tobin Harbor Trail.



The Fifth Day

Raspberry Island

We will go by boat to Raspberry Island (Figure 28), about 0.5 km (0.3 mi) SE of Rock Harbor Lodge, and spend the entire day looking at a remarkable set of exposures nearby that provide an impression of some of the solidification features of an ophitic flow (approximately 20-30 m thick).

Raspberry Island, which is one of many small islands along the S side of Rock Harbor, is a sequence of three ophitic flows dipping 15° SE. The uppermost of these flows is extensively exposed on a wave-washed dip slope along the SE shore. This shoreline receives strong storm waves and, therefore, has extensive wave-washed exposures about 1 km (0.6 mi) long. These expose the flow interior, although neither the top nor the base of the flow is clearly exposed.

A loop trail goes around the W half of the island, marked by informative signs about the unique ecosystem of this island, which features frequent fog and damp, moss-rich swamps. Among the unusual plants is the pitcher plant (*Sarracenia puerperia*), which is an insectivorous plant that flourishes in the swamp along the loop trail.

First, we will visit the most W point of the island, where the regional attitude of the lava flows is seen in the view along strike toward Smithwick Island across the Smithwick Channel. The point facing the channel on Raspberry Island is underlain by the oldest of the three flows on Raspberry Island. We will walk on a dip slope that shows some of the jointing pattern we observed on the SE sides of Davidson and Smithwick Islands. Next, we will head to the SE corner of the island to observe some rude columns in the uppermost Raspberry Island flow.

The W Part of the SE Shore: Vesicle Cylinders

We will next move out to the wave-washed SE shore, where there are two zones of exposures of vesicle cylinders. Paces (1988) describes *vesicle cylinders* (Goff 1977) in the PLV:

Vesicle pipes are elongated, tube-like struc-

tures, 10-30 cm (4-12 in) in diameter and 0.5-2 m (1.6-6.6 ft.) in length, containing somewhat coarser and more prismatic crystals compared to the adjacent groundmass. They are oriented vertically and occur predominantly in the bottom half of the flow. The origins and dynamic behavior of vesicle cylinders are poorly understood; however they appear to represent an accumulation of exsolved magmatic gas bubbles which migrate upwards through the magma during the period when the cooling magma behaves as a Bingham plastic (i.e., possesses a finite yield strength, Walker 1987).

--Paces 1988

Here at Raspberry Island, exposures of vesicle cylinders show a regular spacing between them, 1-3 m (3-10 ft.) apart, and a marked variety of textures; some were evidently preserved almost as voids, while others are filled with material that closely resembles vesicular pegmatoid. An interesting aspect of the exposures here is the relationship between the ophitic textures of the flow and the vesicle cylinders: The grain size of oikocrysts seems to be influenced by the proximity to the vesicle cylinder.

Vesicle cylinders are found mainly in only two areas along this shoreline. This may reflect their restricted occurrence in a thin part (less than a few meters thick) of this flow. Based on limited field examination, this thin part seems to be in the lower part of the flow. The comparisons between this occurrence and written descriptions, one by Paces (1988) of the PLV on the Keweenaw (Figure 29) and one by Marsh et al. (1991) of solidification in sheet-like basaltic bodies (Figure 30), are illuminating.

Both descriptions show the vesicle cylinders as developing in the upper part of the lower capture front of a solidifying body and continuing upward to the liquid zone. This suggests that the segregations formed during solidification--when the region around the cylinders was mushy. The vertical movement of the cylinders was accommodated by the positive thermal gradient and by more fluid material that overlay the mush region.

The process forming the cylinders could possibly be common to the solidifying process of a wide variety of materials, such as metals, aqueous solu-

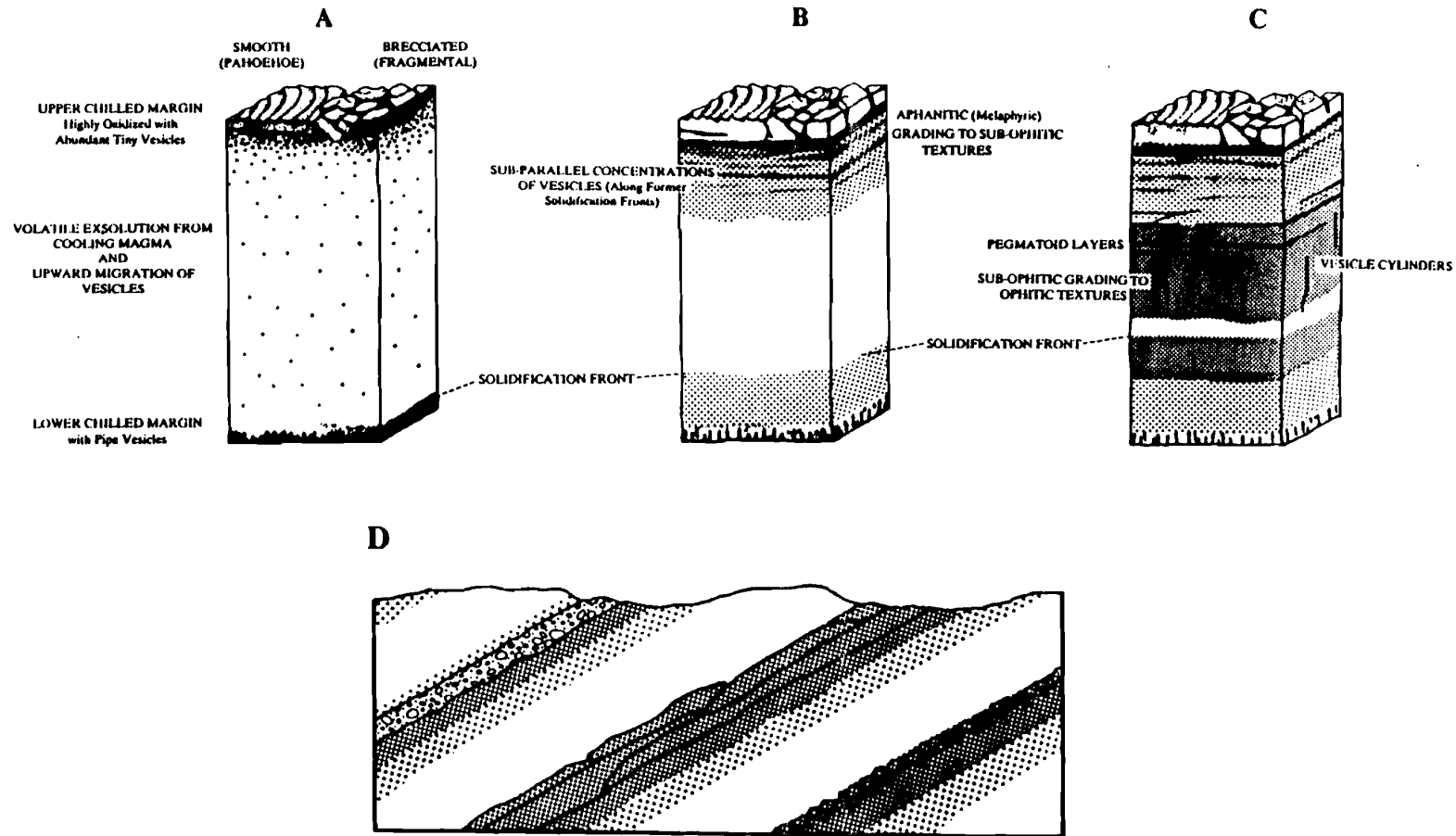


Figure 29: (a-c) *Illustration of the development of volcanic rock textures and flow structures typical in sub-aerially erupted PLV flood lavas* (Paces 1988). Unstippled areas within the cooling lava flow interior represent molten material. (a) Pondered lava flow after emplacement. (b) Partially solidified. (c) Solidification near complete. (d) Illustration of a portion of four successive lava flows summarizing the hydrodynamic characteristics of the volcanic pile. Very high permeability is present in interflow sediments and in highly vesicular and/or brecciated flow tops (heavy stippling). Permeability decreases gradually as the degree of vesicularity diminishes (light stippling) towards the center of the flow. Massive interiors of thicker flows (unpatterned) are largely impermeable to migrating ground water and secondary hydrothermal fluids. Lava flows were originally deposited in a near-horizontal orientation and have been subsequently tilted by both depositional and compressive tectonic mechanisms.

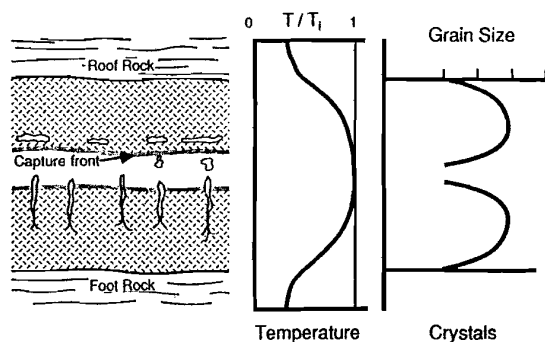


Figure 30: Conceptual diagram, showing residual fluids forming lenses in the Shonkin Sag and the schematic temperature and grain size relationships at the time of their formation (Marsh 1991, personal communication). This is comparable to the observed relationship of vesicle cylinders and pegmatoids on Raspberry Island.

tions, and organic mixtures; this process is described as channel convection in partly solidified systems (Hellawell et al. 1993). In experiments with aqueous solutions, Hellawell et al. (1993) present observations of plumes that formed above the channels and extended into the liquid zone above (Figure 31).

The Central Part of the SE Shore: Slickenside Surfaces

Featured conspicuously along the E shore of Raspberry Island are slickenside surfaces. A study of the fault slickenfibers allowed Witthuhn (1993) to use geometrical and statistical methods to define the kinematics of the closing of the rift.

In Witthuhn's study, Raspberry and Edwards Islands offered one of the largest populations of measurements (Figure 32). The measurements revealed two consistent stress fields, for each limb of the syncline, that would satisfy the conditions envisioned for the opening and closing of the Midcontinent rift. Most of the faults on Isle Royale, including both normal and reverse faults, trend NE. This suggests that the reverse faults represent reactivated normal faults. The orientation of reverse faults at Isle Royale differs significantly from the predomi-

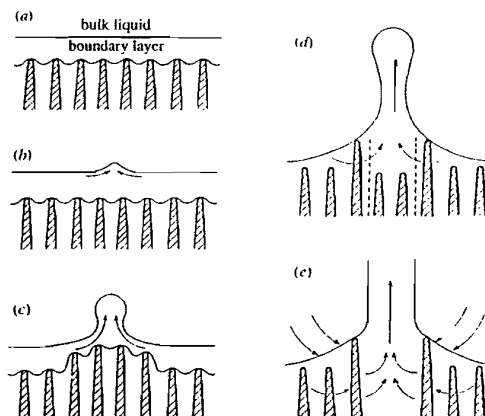


Figure 31: Schematic representation of boundary layer perturbation leading to plume and channel formation (Hellawell et al. 1993). Note that the entrainment of bulk liquid must first accelerate the dendritic growth front locally, while the release of solute-rich liquid from below causes subsequent melting, in the order of (a to e).

nately N-S trending structures measured in the PLV on the Keweenaw Peninsula (Figure 33).

The E Part of the SE Shore: Pegmatoid Zones

About two-thirds of the way along the shore of Raspberry Island, the exposures that occur are stratigraphically higher in the flow. Here the flow has a laminar structure that consists of fractures that are parallel to the bedding and spaced about 0.5-3 cm (0.2-1.2 in) apart. Within this part of the flow, vesicle cylinders are not seen, but small pegmatoid lenses occur. Paces (1988) describes what these lenses look like:

Pegmatoid horizons are similar to vesicle cylinders in that they consist of gas-rich, coarsely crystalline, granophyric material. However, they occur as discontinuous lenses and layers, typically 10 cm (4 in) to several meters thick, and are usually located between the flow top and most massive portion of the flow interior. Pegmatoids are best developed in thicker flows that have cooled slowly enough to allow in situ differentiation (Cornwall 1951; Lindsley et al. 1971). This material represents the last remaining volatile-rich liquid, which is injected into fractures oriented sub-parallel to the upper flow surface. Both vesicle cylinders and pegmatoid layers contain significant void space in

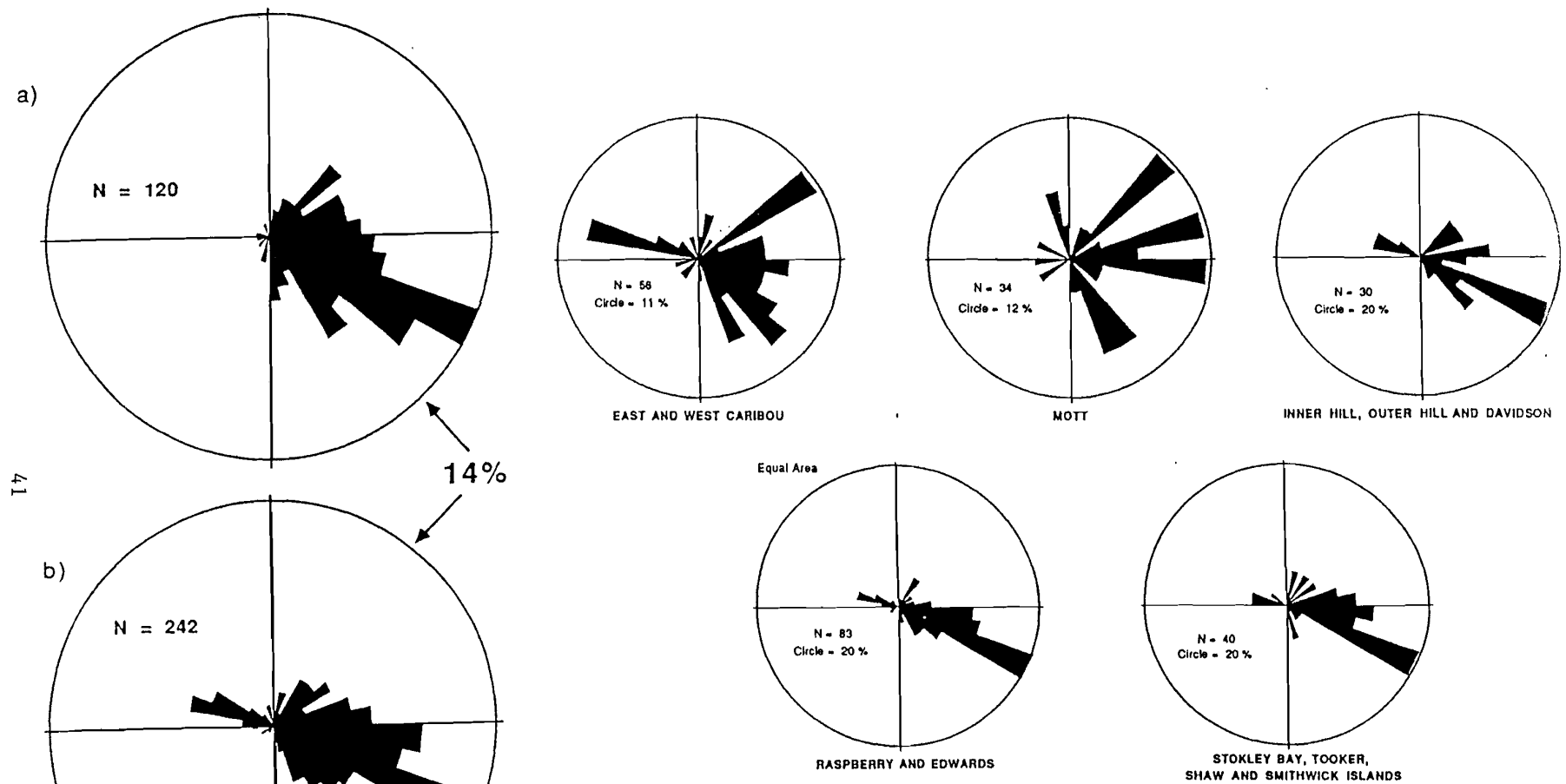


Figure 32: *Left: Equal area rose diagrams of the trend of slickensides on (a) normal and (b) reverse faults on Isle Royale (Witthuhn 1993). Notice the similar trends that define the resolved shear stress on the faults. Right: Rose diagrams of the trends of slickensides on reverse faults measured on islands along the SE shoreline of Isle Royale (Witthuhn 1993).*

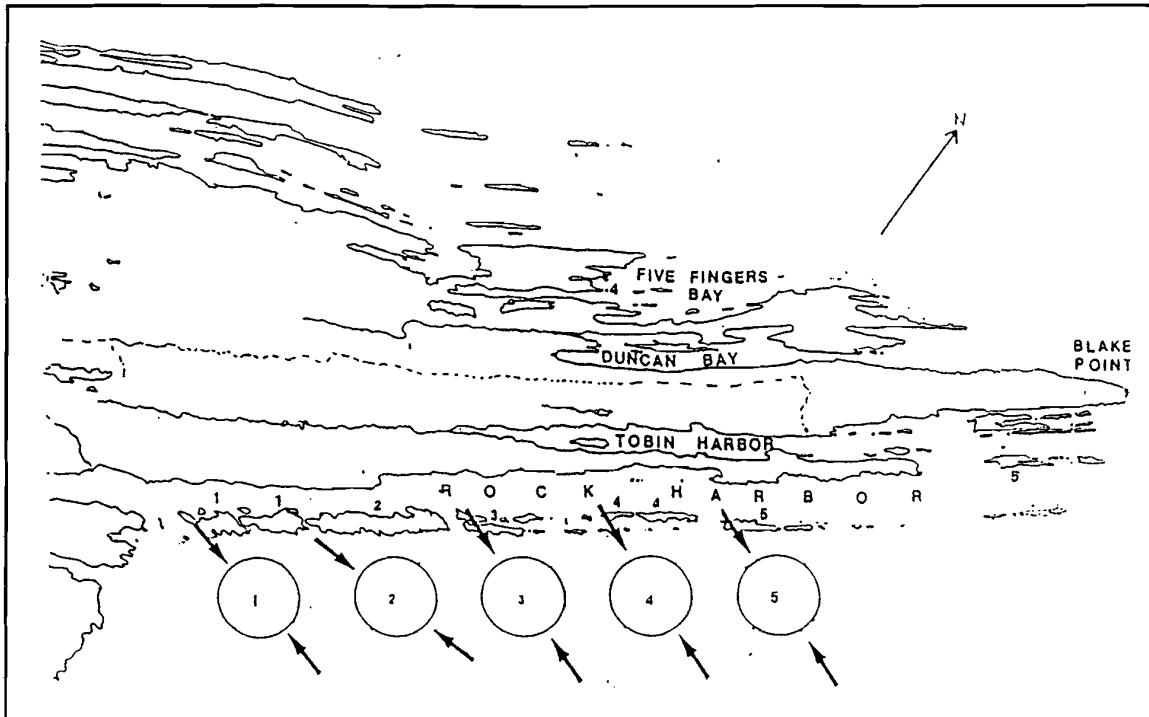


Figure 33: Compression directions deduced from slickenlines on reverse faults from the island groupings along the SE shoreline of Isle Royale (Witthuhn 1993). Identification of circles from left to right: (1) West and East Caribou islands; (2) Mott island; (3) Inner Hill, Outer Hill, and Davidson islands; (4) Tooker, Shaw, and Smithwick islands and Stokley Bay peninsula; and (5) Raspberry and Edwards islands.

the form of vesicles and gas pockets and contribute to the permeability of the lava flows.

--Paces 1988

The origin of the pegmatoids is possibly related to the process by which the vesicle cylinders were formed. However, for the pegmatoid origin, the rise of material in channels is *limited* by the thermal gradient and by the associated solidification that happens above the zone of pegmatoids, so the material is blocked and accumulates in lensoid layers (Figure 30).

It is possible that this flow has frozen a snapshot of what was happening late in the solidification

history; also, the vesicle cylinder zones and the pegmatoid zones may represent comparable and complementary features that formed at about the same time. (A Master's student at Northern Illinois University, Matt Wollert, has begun a study on the origin of pegmatoid layers in thick Keweenawan lavas. Suggestions for Matt that result from our trip here are very welcome.)

After examination and discussion of these outstanding exposures, we will return to Three Mile Campground for the night. We need to be well-prepared for departure because we must leave very early for Snug Harbor in the morning.

The Sixth Day: *Back to the Mainland*

We will leave early to get to Snug Harbor in time for the departure of the *Voyageur* for our return to Grand Portage. The route will be via Chippewa Harbor, Malone Bay, and Windigo, so we will complete a circumnavigation of Isle Royale.

Conglomerate Bay

The first leg of the trip is SW along Rock Harbor to Daisy Farm Campground, and then past the Isle Royale Lighthouse and Tonkin Bay to Conglomerate Bay (Figure 20). Conglomerate Bay is named for one of the interflow sediments that crops out halfway along the inlet. On the edge of this bay was the site of the Saginaw Mine, which was a very brief mining effort with two shafts and a winze from 1877 to 1879.

The regular 15° dip of the PLV strata is disrupted in this part of Isle Royale with a system of steep and curved faults. This causes the more SE parts to be offset progressively upward, as though the regular subsidence of the rift basin was disrupted in this place.

Chippewa Harbor

The entire region of Middle Island Passage to Siskiwit Lake consists mainly of the ophitic flows and their intervening sedimentary units (Figure 24). At Chippewa Harbor, we will see exposures of these flows and the sedimentary units, and near the dock is an outcrop of the interflow conglomerate.

The harbor is the site of a fishing camp and is now a favored campsite. The beaches S of Chippewa Harbor are some of the best for finding Isle Royale greenstones (see "Greenstone Beach" on Figure 34 and Huber 1983, pp 58-9).

Malone Bay: *The Copper Harbor Conglomerate*

We will take the boat to Malone Bay (Figure 35), the site of exposures of the conglomerate beds of the CHC. On our way, we will pass Schooner, Hat, and Ross Islands, which are all underlain by

sandstone of the CHC. This formation is described by Wolff and Huber (1973):

The CHC at Isle Royale is the N limb counterpart of the type CHC exposed on the S limb of the Lake Superior syncline on the Keweenaw Peninsula. In both areas, the formation, which is of middle Keweenawan age, overlies the middle Keweenawan PLV and is largely derived from older Keweenawan volcanic source terranes that shed debris into the subsiding Lake Superior basin from opposite sides; for Isle Royale, the source terrane would have been the North Shore Volcanic Group in Minnesota. The deposits appear to be piedmont fan deposits and flood-plain deposits formed under a combination of fluvial and lacustrine conditions.

Various sedimentary features at Isle Royale indicate that the sediments were transported generally E, with a range in direction from NE to SE. The formation also increases in thickness and in textural and compositional maturity in this direction; it varies from a boulder conglomerate, through a mixture of cobble and pebble conglomerates and sandstone, to sandstone alone. This clastic wedge thickens within a distance of 32 km (20 mi) from a minimum of 460 m (1,500 ft.) to more than 1830 m (6,000 ft.) between stratigraphic marker horizons; the top of the formation is nowhere exposed, however, and the total thickness probably is considerably greater.

The clastic materials in the formation are predominantly derived from older Keweenawan volcanic rocks. Felsic varieties are slightly dominant over mafic varieties. Metamorphic rocks are minor components, and clasts of intrusive igneous rocks appear to be absent. The overall local composition of the formation, chiefly reflecting degree of sediment maturity, is closely related to grain size; rocks of similar grain size have the same composition throughout the formation. Calcite cement is ubiquitous; in the conglomerate and coarse-grained sandstone, it commonly amounts to about 15 percent. As the textures become finer, rock fragments and calcite cement decrease in abundance, whereas quartz, feldspar, and opaque mineral percentages increase.

The felsic and many of the mafic Keweenawan rock types that occur as clasts in the CHC are not known to occur as flows within the PLV on the island. Most of the rock types, however, are known to occur as flows in the North Shore Volcanic Group, which is stratigraphically lower than the PLV and





is present in the direction from which the clastic debris was transported. Several lines of evidence suggest the presence of an unconformity between the North Shore Volcanic Group and the PLV. Such an unconformity would facilitate the erosion of the North Shore Volcanic Group and the deposition of the erosional debris basinward on top of the PLV.

The situation would be analogous to that on the S side of the Lake Superior syncline. There, many clasts in the CHC appear to have been derived from the lowermost Keweenawan volcanic terrane, the volcanic rocks of the South Trap Range which underlie the PLV.

--Wolff and Huber 1973

We will move along shorelines underlain by the CHC all the way to Grace Harbor, passing Menagerie Island, Long Island, Point Houghton (Figure 35), McCormick Reef, Long Point, the Head, Rainbow Point, and Cumberland Reef (Figure 36). Figure 37 shows the variation of sediment lithology across the section, and Figure 38 shows sediment disposal patterns measured by Wolff and Huber (1973).

SW Isle Royale: The Glacial Deposits

It is in this SW section of Isle Royale (Figure 36) that the thickness of glacial deposits is the greatest. The glacial setting is summarized by Huber (1973b):

Isle Royale was overridden by glacial ice during each of the four major glaciations of the Pleistocene Epoch, and each successive glaciation essentially obliterated all direct evidence of preceding glaciations on the island. In the waning phase of the last major glaciation, the Wisconsin Glaciation, the frontal ice margin retreated N from at least the greater part of the Lake Superior basin, then readvanced into the basin during Valders time, about 11,000 years ago. We can attribute to the Valders ice the final aspect of glaciation at Isle Royale, including both erosional and depositional features.

It is impossible to estimate the quantity of glacial debris or other surficial materials that might have been present at Isle Royale prior to the Valders readvance, but the readvancing ice appears to have removed most of what might have been present, as judged by the thin surficial cover on the E two-thirds of the island today. During the

Valders retreat, a series of lakes formed in the Lake Superior basin in front of the retreating ice margin.

The retreating ice opened successively lower outlets, and thus the general trend of lake elevations is downward. Distinct lake stages reflect periods of relative stability during which well-defined shoreline features developed. The ice front forming the N margin of the earlier lakes probably remained S of Isle Royale until about the time of glacial Lake Beaver Bay, when it retreated to a position straddling Isle Royale W of Lake Desor. Abundant deposits of glacial debris were left upon the newly deglaciated W end of the island, and the ice front remained stable long enough to build a complex of ice-margin deposits across the island. Shorelines formed by the glacial lake associated with this ice front are found on the W part of the island about 61 m (200 ft.) above present Lake Superior.

Subsequent renewed and complete retreat of the ice margin from Isle Royale was rapid enough that only a minor amount of glacial debris was deposited on the central and E parts of the island. When the ice margin reached the N edge of the Lake Superior basin, Lake Minong was formed, and the entire basin was filled for the first time since the Valders advance. Lake Minong marked a relatively stable episode in the history of the basin, and its beaches are among the best developed of the abandoned shoreline features on Isle Royale. Lake Minong beaches and later lower beaches are best developed on the SW end of Isle Royale, where abundant glacial debris provided easily worked materials for beach construction.

--Huber 1973b

The discussion about changing shoreline levels in Huber (1983, see pp 41-55) is important to understand the geomorphology we will be seeing, and if you are a field trip participant, you should particularly read the discussion of shorelines at Rainbow Cove, which includes clear exposures of both Nipissing and Minong shorelines (Huber 1983, see pp 52-3).

Washington Harbor: The End of Our Trip

Rounding the Cumberland Reef we will arrive once again at Washington Harbor, where we began on the first day. You have now seen Isle Royale from all sides.

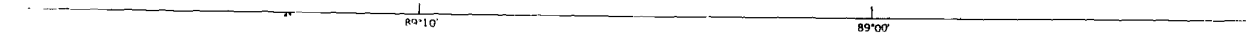


Figure 36: Map showing the glacial features and abandoned shorelines of SW Isle Royale (Huber 1973b).

Composition of very fine grained sandstones, very coarse grained sandstones,
and pebble conglomerates taken from the measured section on Houghton Ridge
[Specimen numbers indicate relative position with lowest number lowest in section. See plate 1 for locations]

Specimen No.	Very fine grained sandstones						Very coarse grained sandstones						Pebble conglomerates				
	4	6	7	11	13	28	12	15	18	22	24	27	5	16	30	31	32
MV	0.3	0.6	0.9	Trace	0.9	0.0	30.7	36.9	35.5	35.6	23.9	21.7	22.7	34.3	28.2	22.9	29.4
FV	.9	.6	.9	0.9	.6	.0	31.8	38.8	31.7	33.6	24.2	39.6	43.7	39.9	37.2	21.9	34.6
SF	4.2	.3	.0	Trace	.0	.0	.0	.9	.6	.9	1.6	Trace	.9	.3	1.9	3.5	.3
MF	.0	.0	.3	.0	Trace	.0	.6	Trace	2.3	Trace	.6	.3	.9	.3	1.3	1.3	Trace
UQ	45.2	39.7	42.3	36.6	32.4	28.1	4.8	3.5	3.9	4.6	4.6	1.6	1.9	2.9	4.2	6.1	4.2
UnQ	21.6	16.2	18.8	24.2	23.2	11.9	4.8	1.6	1.9	1.3	2.9	1.9	.9	.6	1.3	3.5	1.3
PQ	.6	.6	.6	.0	.9	.0	.3	.6	.9	.6	1.6	1.3	1.3	1.9	.6	1.3	.9
PF	4.8	15.5	12.9	23.3	18.6	22.9	1.6	1.6	.9	.9	3.9	4.5	7.1	.6	1.6	2.9	1.9
PIF	6.6	8.4	5.2	5.5	6.1	20.6	9.0	11.6	5.4	6.8	10.0	2.3	2.9	5.9	1.9	2.9	4.5
O	6.6	6.8	8.1	5.2	5.8	6.6	6.1	2.3	1.3	6.2	7.1	1.6	1.3	1.6	.9	8.1	7.1
Ca	5.1	6.8	5.5	1.9	8.4	4.5	9.4	1.3	16.3	9.7	17.1	22.3	14.8	9.8	19.0	23.3	14.2
Other	3.2	4.5	4.5	3.5	3.2	5.4	.9	.9	.3	.9	2.6	2.9	1.6	1.9	1.9	2.3	1.6

NOTE.—Abbreviations:
MV. mafic volcanic rock fragments
FV. felsic volcanic rock fragments
SF. sedimentary rock fragments (shale and sandstones)
MF. metamorphic rock fragments
UQ. unstrained quartz grains
UnQ. undulatory quartz grains
PQ. polycrystalline quartz grains
PF. potassium feldspar grains
PIF. plagioclase grains
O. opaque grains
Ca. Calcite cement
Others. epidote, pyroxene, zeolites

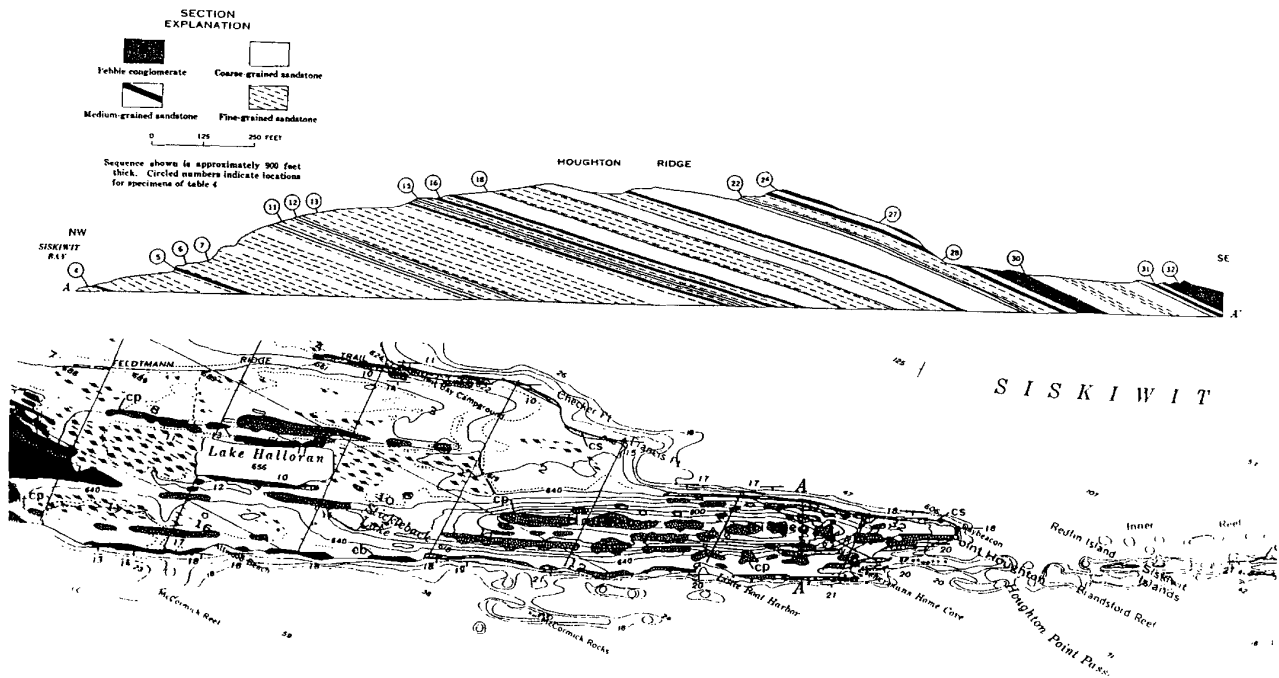


Figure 37: The variation of sediment lithology across Houghton ridge (Wolff and Huber 1973).

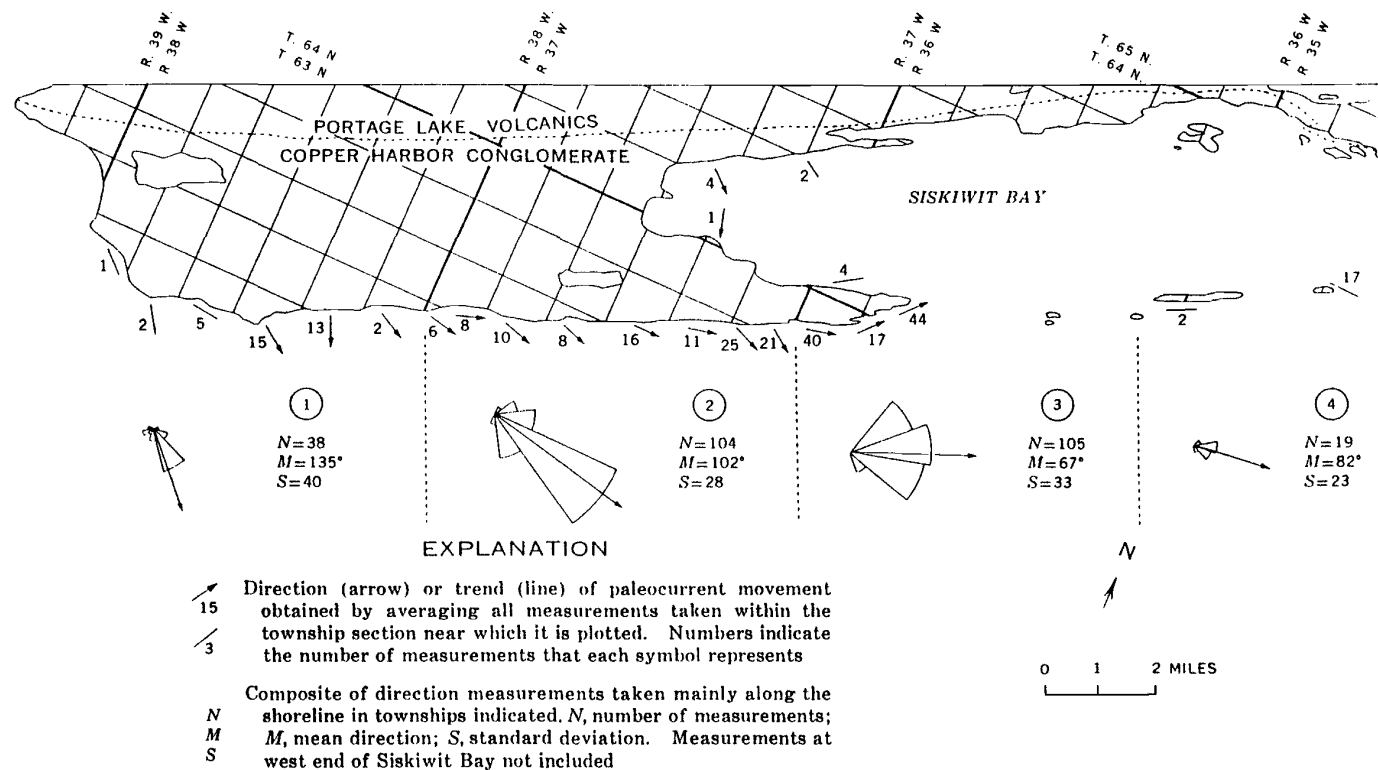


Figure 38: Sediment dispersal patterns in the Copper Harbor Conglomerate on Isle Royale (Wolff and Huber 1973).

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