Isle Royale: Keweenaw Rift Geology

Figure 1: *Native copper in a vein on Washington Island, Isle Royale (photo by Justin Olson). This occurrence of copper was found all over the Keweenaw and Isle Royale, but humans dug them out and made pits and small mines to extract the precious metal. It was traded across the North American continent by Native Americans. Later Europeans re-excavated the indigenous pits and eventually developed major mining activity. This mining of copper was an economic pay-off of a geologic event that brought deep-seated heavy elements to Earth's surface more than one billion years ago.*

The wilderness preservation of Isle Royale may explain why such occurrences happen there but not on the Keweenaw, except in underwater places like Great Sand Bay.

Physical Volcanology of Large Lava Flows

Middle Proterozoic Continental Tholeiitic Flood Basalts of the 1.1 Ga Keweenaw Rift (Rodinia).

Field trip
Institute of Lake Superior Geology,
May 25-30, 2013

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Table of Contents

Purpose and Philosophy

This field guide aims to give anyone interested in geology and Isle Royale an interpretation of things that can be seen outside in this unique National Park. We try to avoid jargon, in spite of some of the words above on this page. Each part of the Earth's surface offers part of the evidence of past events for us to interpret. On Isle Royale we see rocks which reflect Earth about 1.1 Billion years ago, and we can interpret what this rock record means. These interpretations are speculative and they evolve constantly, reflecting new observations. This field guide is an update of a guide from 1994. One very important source is a geologic map done by N. King Huber of the US Geological Survey. On this geologic map of Isle Royale, this geologic map (**Figure 2**) the western part is mostly tan, and the eastern part is mostly green. The colors reflect glacial outwash gravels and moraines that mostly bury the bedrock in the west, while those materials are absent in the east. Because of our interest in the rift lavas, this trip focuses on the **eastern part of Isle Royale**, which has only minimal glacial cover, although we do pass through Washington Harbor and part of the western portion.

Isle Royale has remarkably 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. **But 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 40 years, I have had direct contact with hundreds of ecologically-minded 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 for years 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 guide and its website (http://www.geo.mtu.edu/~raman/SilverI/IRKeweenawRift) 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 and using kayak, canoe or motor boat (bring along or rent from the park concession) to allow access to the many wave-washed outcrops.

...Bill Rose April 2013

Introduction

Before you go to Isle Royale on the field trip, you may wish to read some geological sources. Which ones you read could depend on your interests.

One source for all who are interested in the geology is Huber (1975): USGS Bulletin 1309 (http://pubs.usgs.gov/bul/1309/report.pdf). This booklet covers much of Isle Royale geology and is well illustrated. A more academic version of Huber's geology is USGS Prof Paper 754-C--also downloadable for free (http://pubs.usgs.gov/pp/0754c/report.pdf). There is also a report on the glacial geology, more useful in Western Isle Royale (http://pubs.usgs.gov/pp/0754a/report.pdf).

The geologic map (Figure 2) is downloadable also and can be used in GIS format with Google Earth or other base maps. For the Keweenaw Peninsula, GIS data on the geology and mineral deposits is available from Cannon *et al*., USGS OFR 99-149, 1999 (http://pubs.usgs.gov/of/1999/of99-149/).

The age information on the Keweenawan rocks is one of the most vital pieces of data. Those interested in age should consult Davis & Paces, 1990, and Nicholson et al., 1997. The petrology and geochemistry of the Volcanic Rocks of the Portage Lake Volcanics is thoroughly explored by Paces, 1988.

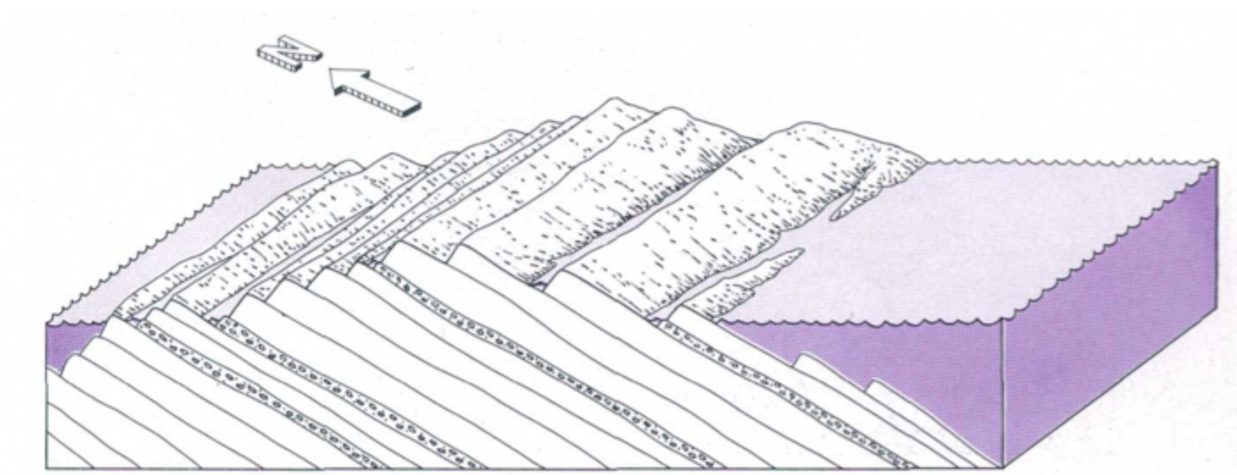
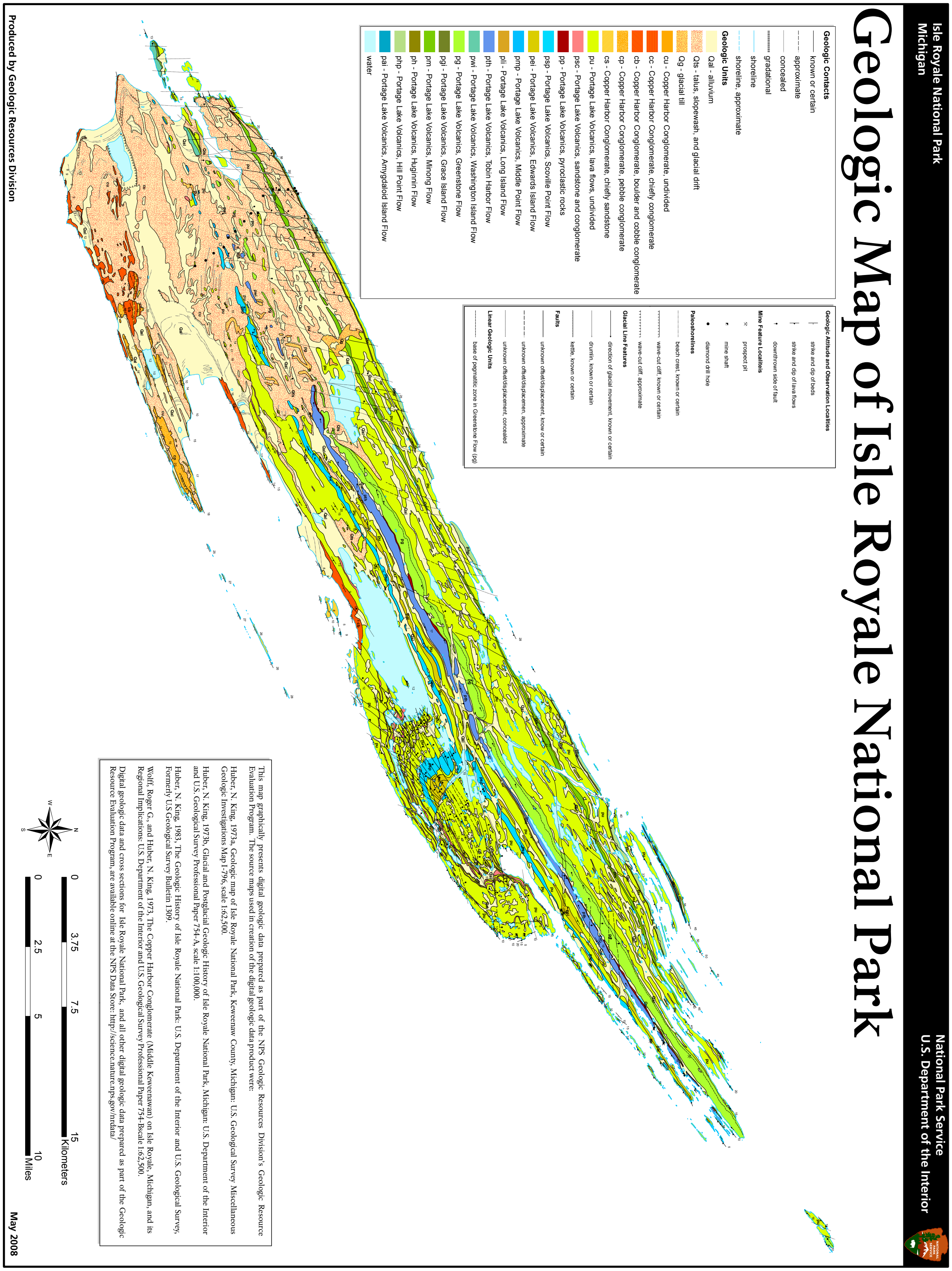


Figure 3: *Schematic cross section of Isle Royale, showing tilted lava and conglomerate layers.*

The sections which follow are specifically designed to provide background information on various geologic topics.

Figure 2 *(next page): Geologic map of Isle Royale National Park (Huber, 1973).*
(http://www.nature.nps.gov/geology/inventory/publications/map_graphics/isro_map_graphic.pdf)


Isle Royale National Park
Michigan
Geologic Map of Isle Royale National Park
National Park Service
U.S. Department of the Interior
Geologic Contacts
known or certain
approximate
concealed
gradational
shoreline
shoreline, approximate
Geologic Units
Qal - alluvium
Qts - talus, slopewash, and glacial drift
Qg - glacial till
cu - Copper Harbor Conglomerate, undivided
cc - Copper Harbor Conglomerate, chiefly conglomerate
cb - Copper Harbor Conglomerate, boulder and cobble conglomerate
cp - Copper Harbor Conglomerate, pebble conglomerate
cs - Copper Harbor Conglomerate, chiefly sandstone
pu - Portage Lake Volcanics, lava flows, undivided
psc - Portage Lake Volcanics, sandstone and conglomerate
pp - Portage Lake Volcanics, pyroclastic rocks
psp - Portage Lake Volcanics, Scoville Point Flow
pei - Portage Lake Volcanics, Edwards Island Flow
pmp - Portage Lake Volcanics, Middle Point Flow
pli - Portage Lake Volcanics, Long Island Flow
pth - Portage Lake Volcanics, Tobin Harbor Flow
pwi - Portage Lake Volcanics, Washington Island Flow
pg - Portage Lake Volcanics, Greenstone Flow
pgi - Portage Lake Volcanics, Grace Island Flow
pm - Portage Lake Volcanics, Minong Flow
ph - Portage Lake Volcanics, Huginnin Flow
php - Portage Lake Volcanics, Hill Point Flow
pai - Portage Lake Volcanics, Amygdaloid Island Flow
water
Geologic Attitude and Observation Localities
strike and dip of beds
strike and dip of lava flows
downthrown side of fault
Mine Feature Localiteis
prospect pit
mine shaft
diamond drill hole
Paleoshorelines
beach crest, known or certain
wave-cut cliff, known or certain
wave-cut cliff, approximate
Glacial Line Features
direction of glacial movement, known or certain
drumlin, known or certain
kettle, known or certain
Faults
unknown offset/displacement, know or certain
unknown offset/displacemen, approximate
unknown offset/displacement, concealed
Linear Geologic Units
base of pegmatitic zone in Greenstone Flow (pg)
This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resource Evaluation Program. The source maps used in creation of the digital geologic data product were:
Huber, N. King, 1973a, Geologic map of Isle Royale National Park, Keweenaw County, Michigan: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-796, scale 1:62,500.
Huber, N. King, 1973b, Glacial and Postglacial Geologic History of Isle Royale National Park, Michigan: U.S. Department of the Interior and U.S. Geological Survey Professional Paper 754-A, scale 1:100,000.
Huber, N. King, 1983, The Geologic History of Isle Royale National Park: U.S. Department of the Interior and U.S. Geological Survey, Formerly U.S Geological Survey Bulletin 1309.
Wolff, Roger G., and Huber, N. King, 1973, The Copper Harbor Conglomerate (Middle Keweenawan) on Isle Royale, Michigan, and its Regional Implications: U.S. Department of the Interior and U.S. Geological Survey Professional Paper 754-Bscale 1:62,500.
Digital geologic data and cross sections for Isle Royale National Park, and all other digital geologic data prepared as part of the Geologic Resource Evaluation Program, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/
N
E
S
W
0
3.75
7.5
15
Kilometers
0
2.5
5
10
Miles
Produced by Geologic Resources Division
May 2008

Broad Background

Any individual place on Earth exhibits only tiny windows of Earth history. In the Keweenaw and Isle Royale, we can see into events that range from about **1.2 billion years ago until perhaps about 0.9 billion (Davis and Paces, 1990)**, and we can also see the deposits of the glacial periods of the last few million years. To see the record of other times we must travel to where we can see rocks of those ages are at the surface.

This is the very best place to see the exposed rocks of the midcontinent rift (Figure 4). This rift extended from at least Kansas to Detroit, but it is exposed only near Lake Superior. At the time of rifting there were huge differences in the configuration of the continents and a huge supercontinent, Rodinia, was assembled, a hodgepodge of pieces of what is now North America, Antarctica, Europe and South America. And it was beginning to break up.

In the Keweenaw we get a remarkable opportunity to look at rocks produced during the **rifting period of Rodinia**, which preceded the orogens shown in green in Figure 5. The orogens mark the areas where continental blocks approached each other at about 1.1 by ago. The orogeny in eastern North America, which eventually ended the Keweenaw Rifting episode, produced an orogen known as the **Grenville Front**. (Cannon, 1994).

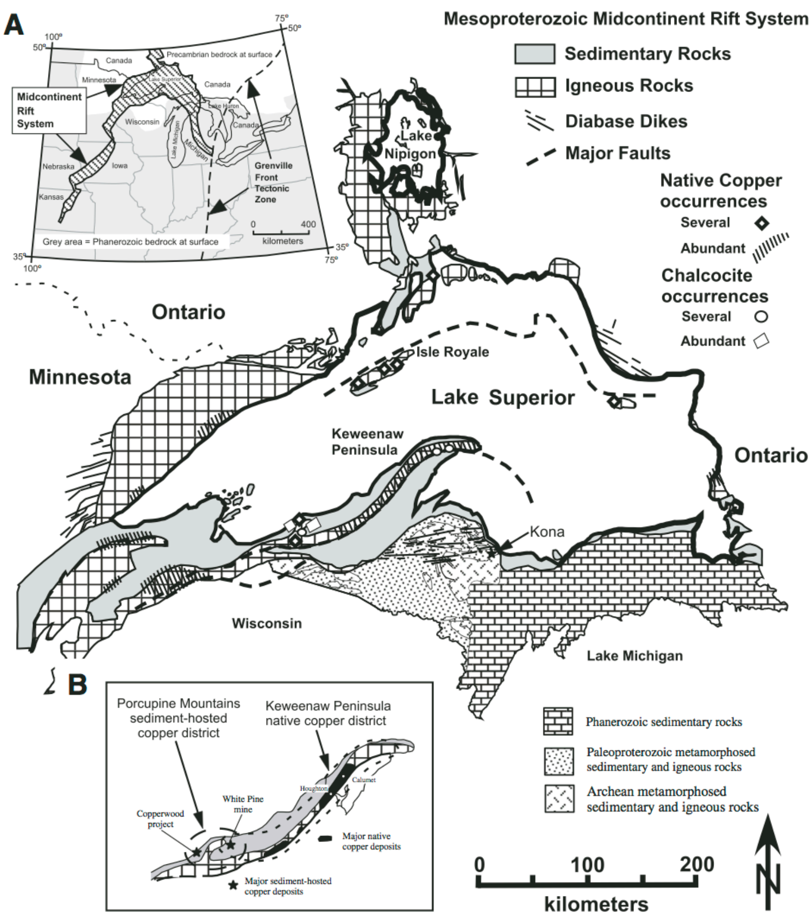


Figure 4
Map of the Mesoproterozoic Midcontinent Rift System, showing insets A: the extent of the rift as currently known and B: The main copper districts. from ***Bornhorst and Barron, 2011.***

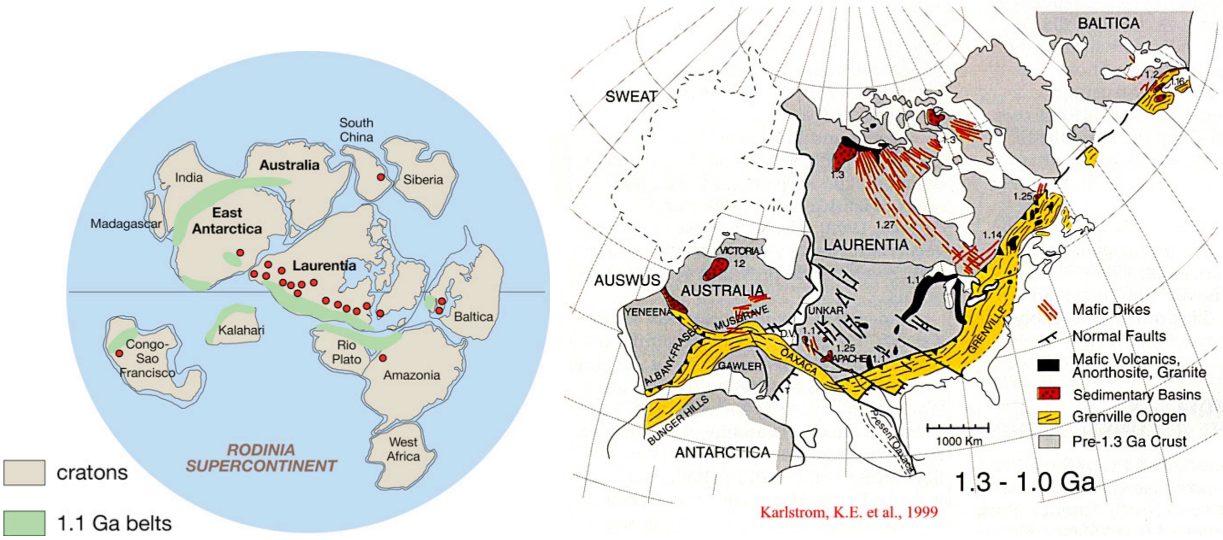


Figure 5 *Two schematic maps of the Rodinia supercontinent showing how pieces of various modern continents are thought to have been assembled more than 1 billion years ago. Sources: John Goodge (left) and KE Karlstrom et al., 1999 (right).*

Rodinia's assembly acted like a great blanket for a large area of Earth's surface, preventing heat loss and creating an opportunity for heat to build up underneath. A great hot spot formed under the blanket. The continent began to split with very hot dike swarms. When the splitting opened the rift, magma was erupted in huge amounts—a supereruption. The ancient Earth contained more radioactive heat producers so the potential for big eruptions was greater. We still think that most of Earth's heat comes from radioactivity, and we still expect Large Igneous Provinces (LIPs) to develop when and where mantle hot spots occur. But perhaps LIPs are getting smaller as time passes and natural radioactivity declines.

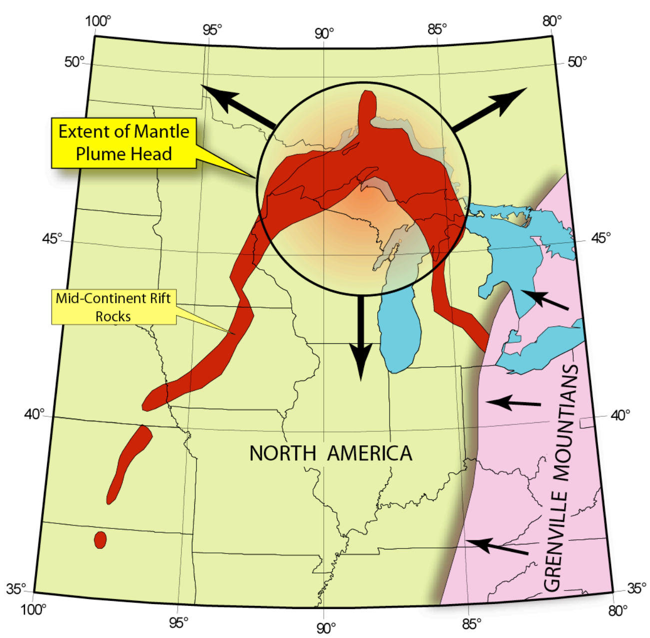


Figure 6:
Schematic view of the mantle plume head which developed over a hotspot, and which is thought to have led to the midcontinent rift, the great ponded flood basalt lavas of the Keweenaw and Isle Royale. High heat flow focussed on the Lake Superior region led to continental splitting and spreading, forming a rift basin (shown in red) which curved around the current Keweenaw Peninsula. From K Schulz, pers comm., USGS.

Heat flow on Earth is declining with time as natural radioactivity continues to be spent. Convection of Earth's core and mantle do not produce steady heat transfer from Earth's core to the surface. Since volcanism is driven by higher than average heat flow, volcanism comes and goes as heat flow changes in time and place. Overall, heat declines, but in any time or place, it can vary markedly in both directions. Super-eruptions result from very high heat flow conditions.

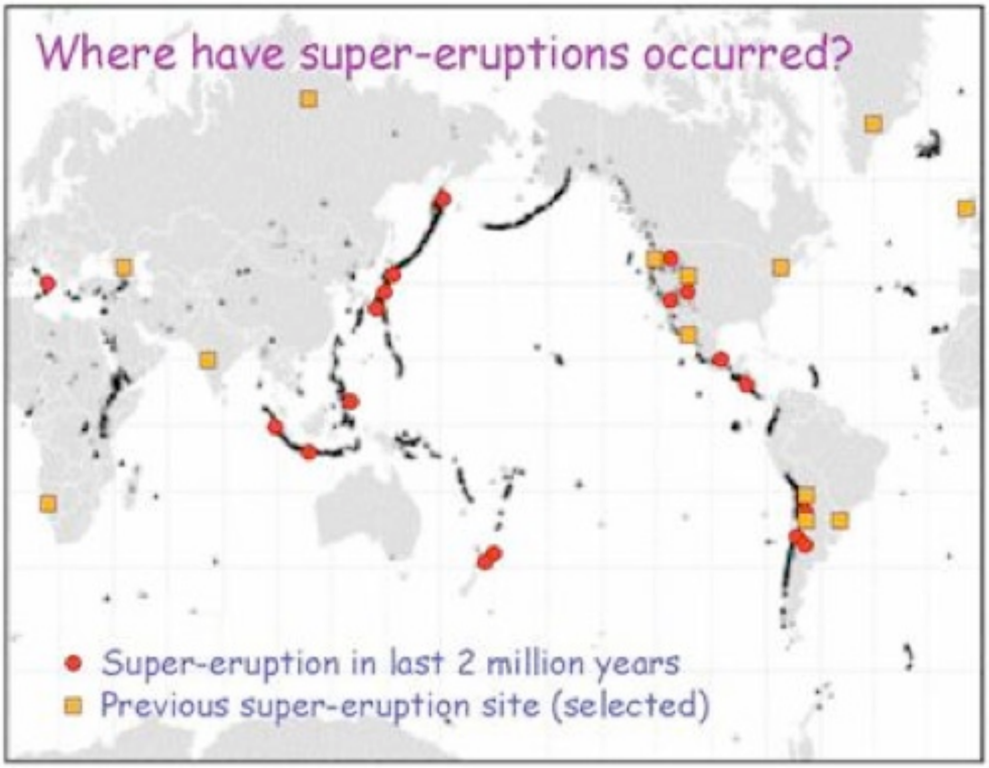


Figure 7: *Map of Supereruptions of the past 2 million years on Earth. Note correlation with the ring of fire. From Geological Society of London.*

The Midcontinent rift was driven by high heat flow, and it certainly represents a type of supereruption or Large Igneous Province (LIP). To explain the distributions of LIPs in time and place, volcanologists refer to plates, hotspots and/or mantle plumes, much of which which are far from our direct access. These plates, hotspots and plumes come and go, plates move over hotspots and/or plumes, and time/space series patterns are not clearly defined or predictable. This requires volcanologists to consider the deep thermal origin of volcanism, which is fundamental geophysics of the deep Earth and especially the mantle and core. We lack explanations to explain why deep Earth heat transfer leads to massive volcanism at rare intervals and in widely scattered surficial locations. The surface manifestations may be huge volumes of volcanic rocks. The environmental consequences must be large, but are mostly uncertain. From the recent record of LIPs, a relationship of the timing of LIPs with extinctions of living species is advanced. Volcanologists agree that super-eruptions lie in Earth's future, but the time and place is uncertain.

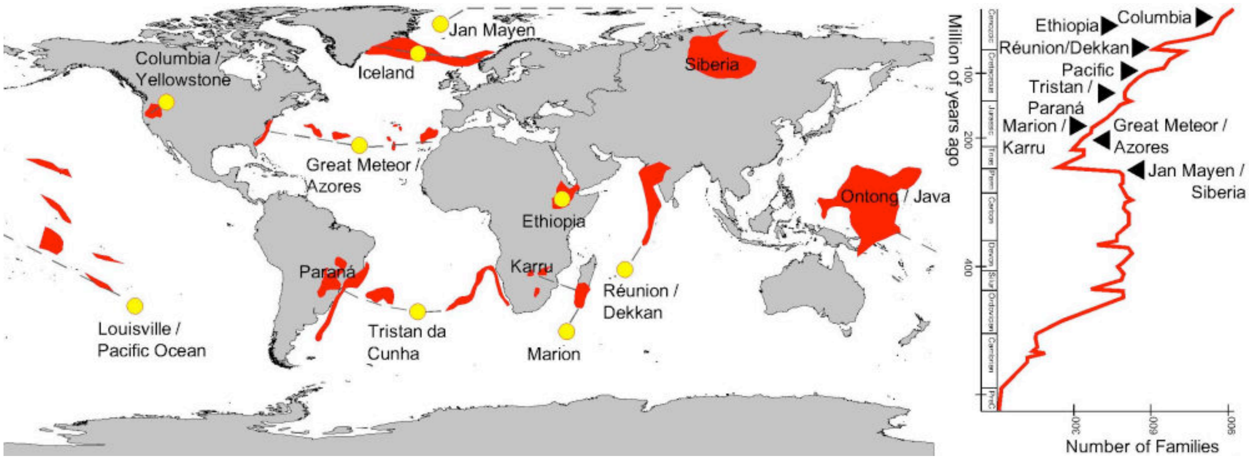


Figure 8: *Map of some LIPs on Earth, plotted in red with yellow hotspot locations and at right, their ages and with extinction evidence, based on the number of animal families represented. Interruptions in the trend toward diversity occur at extinctions. From Bresson, 2011.*

Heat flow bottom line:

The Keweenaw Rift record shows how the Earth has highly irregular deep-seated convective events that help shape the planet. They come and go in time and space. Once the hot spot of the whole world, the Keweenaw now has heat flow that is far below average.

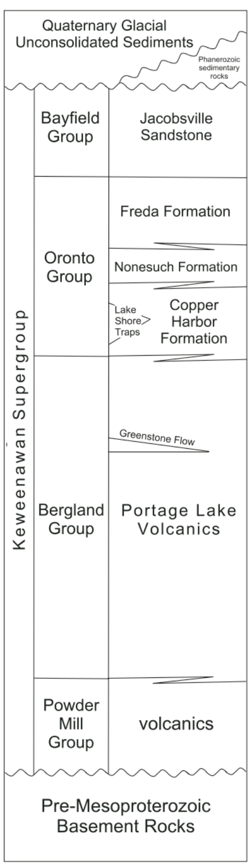


Figure 9*: Stratigraphic units of the Keweenawan from Bornhorst and Barron, 2012. On Isle Royale the upper part of the Portage Lake Volcanics and the Copper Harbor Conglomerate are found.*

Figure 9 shows this mid-Proterozoic **Keweenawan Supergroup,** which contains all the formations of the rift. These consist of lavas from the deep Earth and redbed sediments, shed off of the top of Rodinia into the gaping rift.

On Isle Royale we find only the Portage Lake Volcanics and the Copper Harbor Conglomerate, while on the Keweenaw we have all the formations. The Lavas of the Portage Lake Lava Series are the result of a continental rift, very much like the currently active Red Sea. Existence of a rift is a way to explain how such huge volumes of lava could have been erupted. It also helps explain the syncline shown in Figure 11. A great crack across North America formed, stretching from Kansas to the UP and then on to Detroit. Figures 4 and 6 show the western limb of a feature called the "mid-continent gravity high," a linear feature that extends from Kansas to Lake Superior where it coincides with the Lake Superior Syncline. This feature is mostly completely invisible, but was detected by geophysicists working with gravity meters, who showed that the gravity attraction of

Earth to the instrument is measurably higher, indicating dense rock underneath. Figure 6 shows a buried dense rock region colored red. The dense rock could be the dense black lava flows we have in the Keweenaw, and their gravity shows that the rift was hundreds of miles long. Drill holes have penetrated the lavas in Kansas and Iowa, so we know that lavas are there—it is not just gravity detection.

A second geophysical anomaly, this one even more deeply buried, has been discovered extending from Lake Superior southward to near Toledo Ohio (Figure 4 or 6). This adds to the definition of the hypothesized Keweenaw rift, which is sometimes described as a continental scale fissure, which resembles what happened in the Atlantic to separate Europe from North America. The rift breaks through all the older rock units (Figure 10).

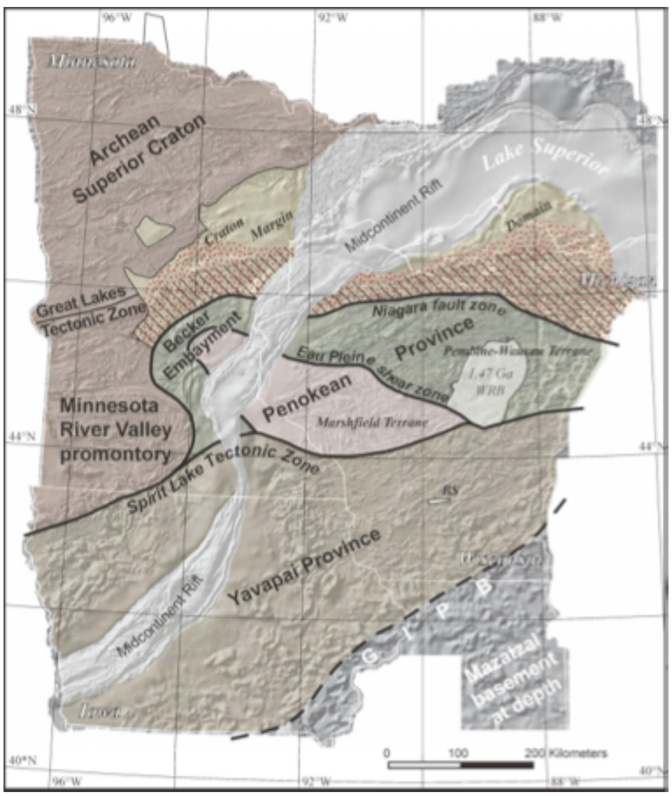


***Figure 10**: Map of Minnesota, Wisconsin, Iowa and Upper Michigan, showing the rift rocks in grey, over the proposed geologic terrane map of Precambrian basement rocks in the northern U.S. continental interior. WRB: Wolf River batholith. Underlying gray-toned base map is the newly compiled regional aeromagnetic anomaly map "Craton margin domain" represents sedimentary and volcanic rocks deposited during the interval 2.3–1.77 Ga; stippled pattern represents area affected by Penokean deformation; cross-hatched pattern represents area termed 'gneiss dome corridor' which was affected by Yavapai-interval deformation (Schneider et al., 2004). GIPB: Green Island plutonic belt; BS: Baraboo syncline. Figure and caption from Holm et al., Pre-C Res., 2007.*

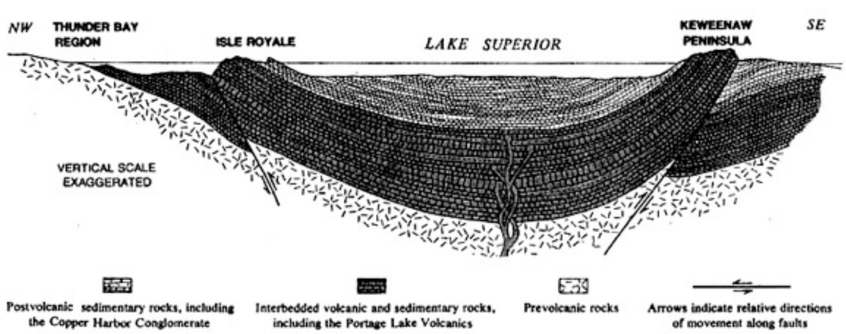


***Figure 11:** The Synclinal nature of the layers on the Keweenaw and Isle Royale, visualized by NK Huber, USGS.*

www.geo.mtu.edu/~raman/SilverI/IRKeweenawRift

The idea of a syncline comes from observed features in geology. In the Keweenaw we cannot see the whole syncline--far from it! We just see the rocks dipping toward the north at Copper Harbor and those dipping to the south on Isle Royale. In between is how geologists earn their money! Figure 12 shows a confirmation of the synclinal nature of the rift rocks, based on seismic geophysics.

Implications of this hypothesis: 1. Layers of rock extended from the Keweenaw to Isle Royale, apparently filling a basin. 2. Something caused the basin to subside. 3. The basin has influenced the formation of Lake Superior. 4. The basin may continue beyond the Lake. 5. Its importance could extend much farther than explaining the tilting.

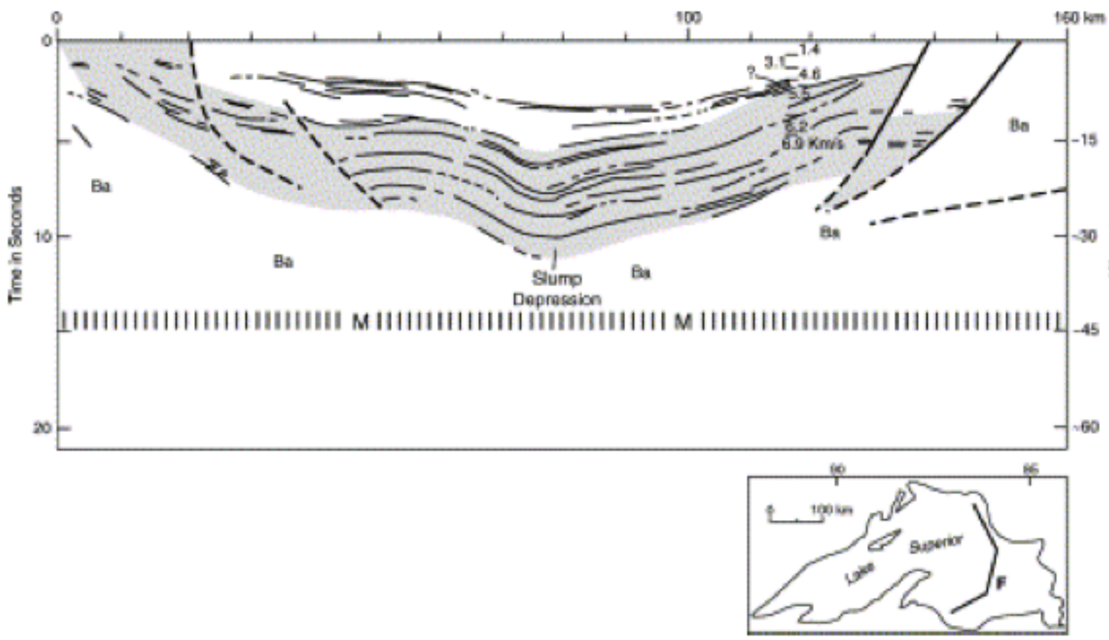


Figure 12: *Profile across eastern Lake Superior, confirming the geometry of the rift with seismic geophysics (Modified from Behrendt et al. (1988).*

Basalt

Isle Royale is mainly underlain by basaltic lava, the result of hundreds of successive eruptions from the Rift. Mostly this basalt made its way to the surface rapidly, but some was held in magma chambers and evolved before erupting. Basalt is the most common composition of lava rocks that cool from magma, liquid rock that rises from the deep Earth at volcanoes. Today basalt is forming at many active rifts, including Iceland, the East African Rift Valley, the Red Sea and the Rio Grande Valley of New Mexico and Colorado.

Basalt is the result of partial melting of meteoritic material, so it forms on other terrestrial planets as well as Earth, making it the "mother liquor" of volcanoes on terrestrial planets. It is found all over Earth, but especially under the oceans and in other areas where Earth's crust is thin. It formed in the Isle Royale-Keweenaw region because of the Midcontinent Rift. Most of Earth's surface is basalt lava, but basalt makes up only a small fraction of continents.

Keweenaw lavas are mainly basaltic: continental flood basalts with isotopic signatures close to bulk composition of Earth (Paces, 1988). Within the sequence of flows there are several cycles of evolution in subcrustal magma chambers. Overall the lavas become slightly more primitive with time. The ages are well established from U-Pb dating of zircons. Most of the great outpouring of rift lavas occurred in about 2 million years.

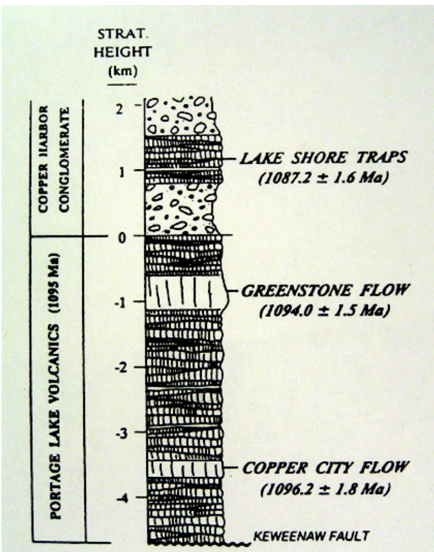


Figure 13: *U-Pb dates on zircons from pegmatite zones of the Portage Lake Volcanics, Keweenaw Peninsula (Paces and Miller, 1993).*

Lane (1911) first recognized and described the mirror-image geological and lithological similarity of the PLV and the CHC on both sides of the Syncline (Figure 14), and further suggested that the great lava flow of the Keweenaw Peninsula (Greenstone Flow, Figure 13) 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 also strongly confirms the correlation of the Greenstone flow.

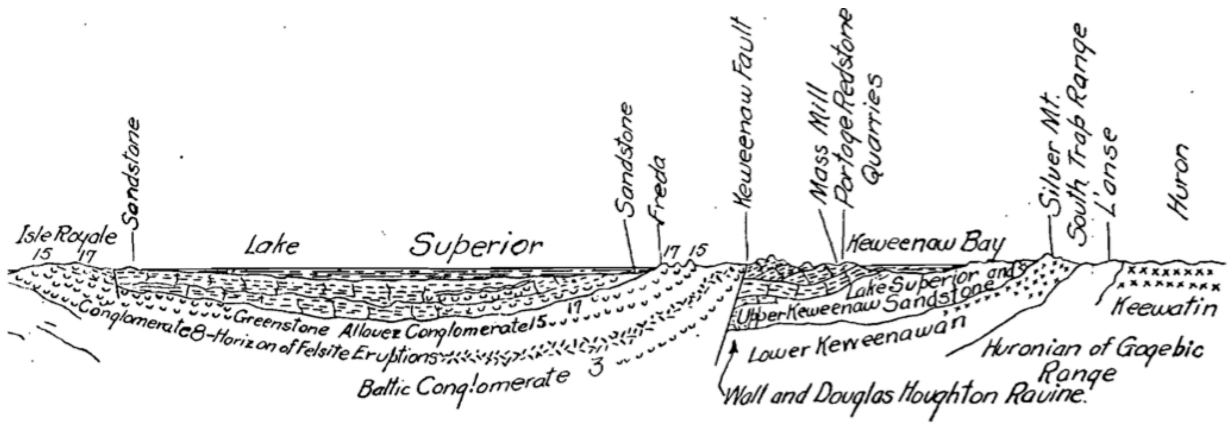


Figure 14: *Sketch map of Lane, 1911, which suggest the correlations of layers between the Keweenaw and Isle Royale.*

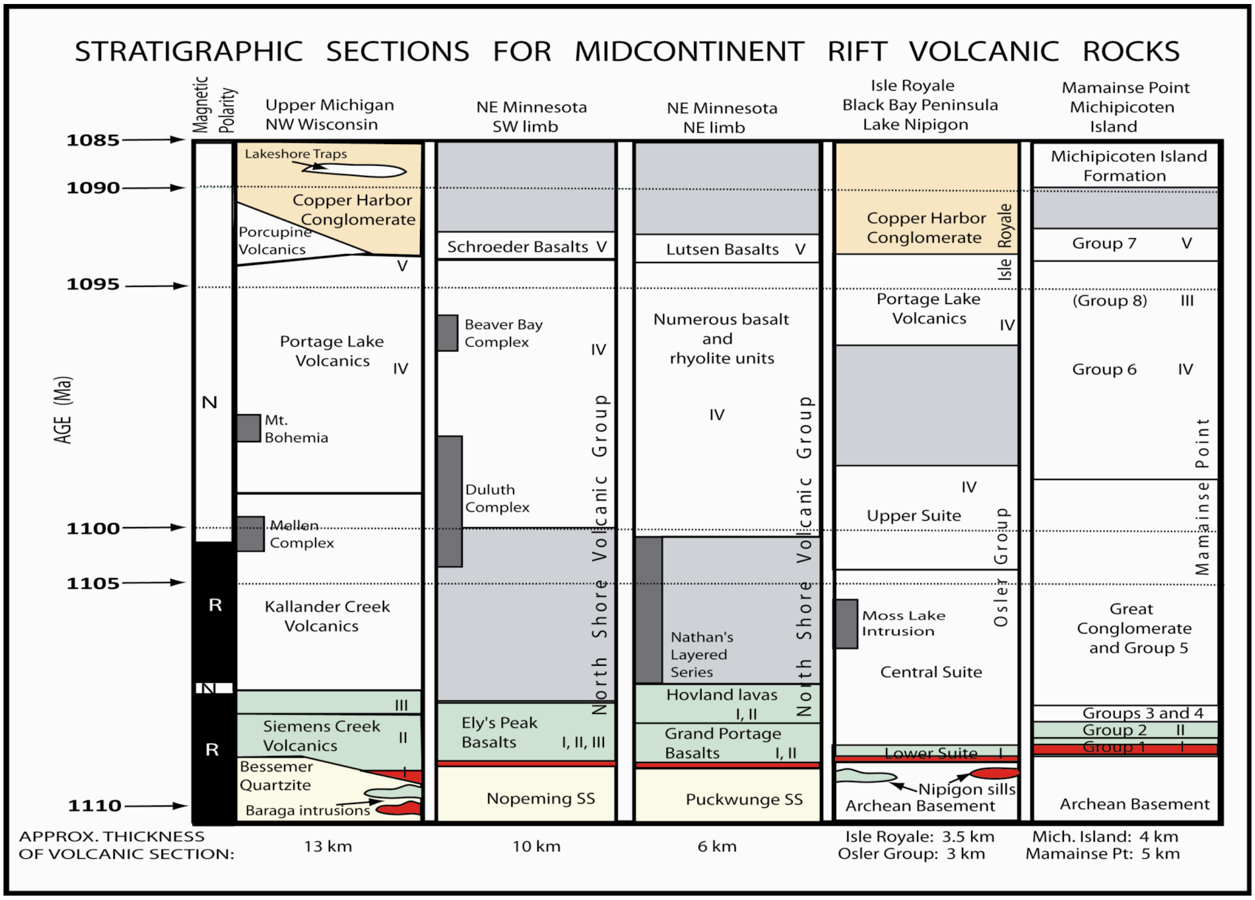


***Figure 15**: Summary of ages and correlations of Keweenawan age rocks around Lake Superior (from K Schulz, pers comm, USGS, modified from Nicholson et al., 1997).*

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 km^3 (396 mi^3), comparable to the Roza flow of the Columbia River Flood basalts, which is estimated to be 1300 km^3 (312 mi^3) by Swanson *et al.* (1975). The areal extent of the Roza, 40,000 km^2 (15,450 mi^2), is much larger than the Greenstone flow, 5000 km^2 (1930 mi^2), 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. Table 1 at left is from Self *et al.*, 1998.

TABLE 1 Examples of large basaltic lava flow fields

Name[a]	Age	Length (km)[b]	Volume (km^3)[b]	Dominant surface
Mauna Loa, Hawaii	1859	>47	>0.11	Pahoehoe
Mauna Loa, Hawaii	1859	>51	>0.27	Aa
Carrizozo, New Mexico	~1 Ka	75	4.5	Pahoehoe
Toomba, Australia	13 Ka	120	12	Pahoehoe
Laki, Iceland	1783	65	14.7	Pahoehoe
8°S, East Pacific Rise	~1960	18	15	Unknown
Eldgja, Iceland	934	>70	>15	Pahoehoe
Thjorsa, Iceland	8.5 Ka	>140	>21	Pahoehoe
Undara, Australia	190 Ka	160	~25	Pahoehoe
North Arch, Hawaii	<2 Ma	100	>25	"Sheet"
Pomona, CRBG[c]	12 Ma	>600	>760	Unknown
Roza, CRBG	~15 Ma	350	1300	Pahoehoe

[a]Listed by increasing volume.
[b]> indicates that only subaerial portion of flows reaching the sea are given.
[c]CRBG = Columbia River Basalts Group.

Paleomagnetism

The conceptual model for Earth's magnetic field is that of a dipole (i.e., bar magnet) positioned at Earth's center and aligned with the rotational axis of the Earth. This allows us to predict the direction of the magnetic field at any location on Earth's surface using the fundamental equations of a dipole field. This equation gives a direct relation between magnetic inclination and geographic latitude at the point of observation. The geomagnetic field irregularly reverses (i.e. a magnetic compass which points north will now point south and vice versa) and these reversals are symmetrical (i.e. the normal and reversed field directions are exactly anti-parallel). The above is the fundamental assumption used to reconstruct continents to their past positions using the ancient magnetic field recorded in rocks (fossil magnetism).

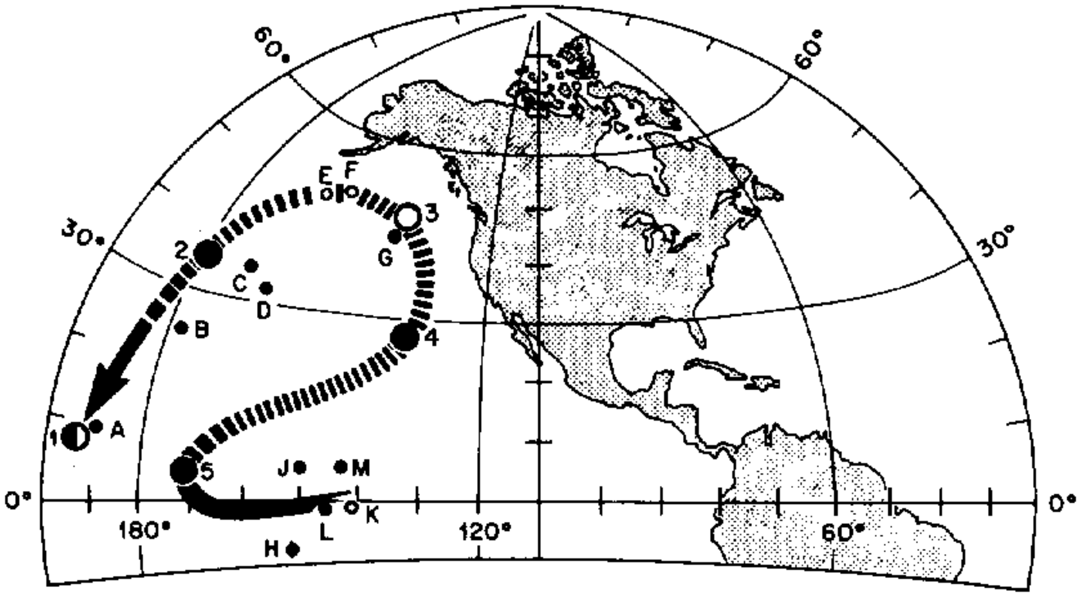
The record of the strength and direction of Earth's magnetic field (paleomagnetism, or fossil magnetism) is an important source of our knowledge about Earth's evolution throughout the entire geological history. This record is preserved by many rocks from the time of their formation. The paleomagnetic data have played an instrumental role in deciphering the history of our planet including a decisive evidence for continental drift and global plate tectonics. The data have also been crucial for better understanding the problems of regional and local tectonics, geodynamics, and thermal history of our planet.

The ~1.1 billion-year-old North American Midcontinent Rift paleomagnetism has been intensively studied since early 1960s (for example, see a review in Halls and Pesonen, 1982). The rifting began during an interval of reversed polarity of geomagnetic field. The reversely magnetized ("reversed") lavas (the Siemens Creek Formation of Powder Mill Group, the lowermost part of North Shore Volcanics, Osler Volcanics, and the lower part of Mamainse Point Formation) are found in many locations around Lake Superior (see figure 15).

This early stage magmatism occurred from 1108 to approximately 1105 million years ago. The period of active magmatism was followed by a quiescence period when a geomagnetic field reversal took place.

Magmatism renewed by 1102 Ma (Ojakangas *et al*., 2001) during the normal polarity interval. During this interval, a sequence of Portage Lake lava flows erupted within a two to three million year interval around 1095 million years ago. These rocks represent the main stage of the rift-related magmatism. All younger sedimentary and igneous suites exposed on the Keweenaw peninsula (the Copper Harbor conglomerate, LST, etc) have normal polarity magnetization.

However, the geomagnetic field reversal mentioned above is characterized by an asymmetry, manifested in natural magnetization recorded by Keweenawan rocks that crop out around the Lake Superior (e.g., Palmer, 1970; Halls and Pesonen, 1982; Pesonen and Halls, 1983; Schmidt and Williams, 2003). Most but not all of the reversely magnetized lava flows and dikes of this age consistently have characteristic



Symbol	Formation	Polarity	Age* (m.y.)	S	Pole position	A_{95}	References
A	Frieda and Nonesuch shales	N	—	13	170°E, 9°N (2, 4)	4	DuBois 1962
B	Portage Lake lavas	N	< 1115	14	177°W, 24°N (6, 10)	9	Vincenz 1968
C	Minnesota normal	N	—	131	168°W, 35°N	2	Beck 1970
D	North Shore volcanics normal	N	1115	14	173°W, 32°N	—	Palmer 1970
E	North Shore volcanics reversed	R	1115	54	160°W, 47°N	—	Palmer 1970 Age: Faure *et al.* 1969
F	Osler lavas	R	—	12	157°W, 49°N	9	Palmer 1970
G	Mugford	N	950		141°W, 45°N (8, 10)		Murthy and Deutch in press. Age: Wanless *et al.* 1966
H	Front Range	M	1410	5†	151°W, 8°S (4, 6)	4	Eggler and Larson 1968 Age: Ferris and Krueger 1964
J	St. Francois Mountains, Miss.	N		5‡	150°W, 5°N	—	Hays and Scharon 1966
K	St. Francois Mountains, Miss.	R	1300–1400	11	141°W, 1°S	5	Hsu *et al.* 1968
L	Michikamau Anorthosite	N	1400	6	145°W, 1°S	6	Murthy *et al.* 1968
M	Croker Island Complex	N	1475	19	143°W, 5°N (7, 11)	9	Palmer 1969

*Unlike Table 6, these formations are not necessarily in correct chronological sequence, as there is not adequate age control in many instances, and the reliability of the stated ages range widely.

†Each site is a separate petrological unit.

‡This is the mean of 5 units, of which the Stouts creek rhyolite was extensively sampled and 10 or more samples were taken from the remaining units.

S = the number of sites, such as a quarry, single rock outcrop, or lava flow, that were sampled. However, the method of sampling varied widely – some sites are represented by a single sample of unknown reliability, while from others the direction was obtained from the mean of a group of independently oriented samples, so that the reliability of the direction could be assessed.

A_{95} = the half-angle of the cone of confidence at a probability $P = 0.95$, using the sites as units.

Figure 16: *Equal area projection of the western hemisphere showing the Logan Loop on the polar wandering curve. Letters are keyed to the table below. From Robertson and Fahrig, 1971.*

directions of magnetization that are about 20 to 40 degrees steeper in inclination than their normally magnetized ("normal") equivalents, while declinations show the expected 180 degree relationship. The paleomagnetic pole positions derived from these normally and reversely magnetized rocks define a noticeable amount of apparent polar wander that forms the western arm of the so-called "Logan Loop" (Robertson & Fahrig, 1971).

The two most favored hypotheses for this reversal asymmetry are either apparent polar wander during Keweenawan times (Davis and Green, 1997; Schmidt and Williams, 2003) or the presence of a persistent non-dipole field causing the geomagnetic field to depart from a geocentric axial dipole geometry (Pesonen and Nevanlinna, 1981; Halls and Pesonen, 1982; Nevanlinna and Pesonen, 1983; Pesonen and Halls, 1983). The recent study of this problem (Swanson-Hysell *et al*., 2009) on lavas from Mamainse Point shows that the geomagnetic reversal asymmetry observed in rocks of Keweenawan age is an artifact of the rapid motion of North America during this time. The other study by Kern et al, (2012) on rocks of the alkaline Coldwell Complex (Ontario, Canada) also suggests no asymmetry in geomagnetic reversal during Keweenawan time.

Basalt Geochemistry and field types of basalt on Isle Royale

Paces (1988) conducted detailed study of the composition of the lavas of the PLV, studying a complete section on the Keweenaw Peninsula. He provided a description of the texture and thickness (see Basalt Types); chemical composition (Table 2); mineral chemistry (Figure 2); and petrography (Table 3). The lavas resemble other younger examples of continental flood basalts (see also LIPS sources) with their main composition being olivine tholeiite that contains high MgO and Ni, but also have enrichment of highly incompatible elements. There are only minor amounts of more evolved (have more complicated history) magmas and overall the magmas become more primitive (less complicated history) with time. Isotopically (Nd and Sr) the lavas are very close to bulk Earth values. Paces (1988) describes the rocks:

*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 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, 1971*) including skeletal, dendritic or spherulitic olivine and pyroxene, have not been observed in PLV basalts.*

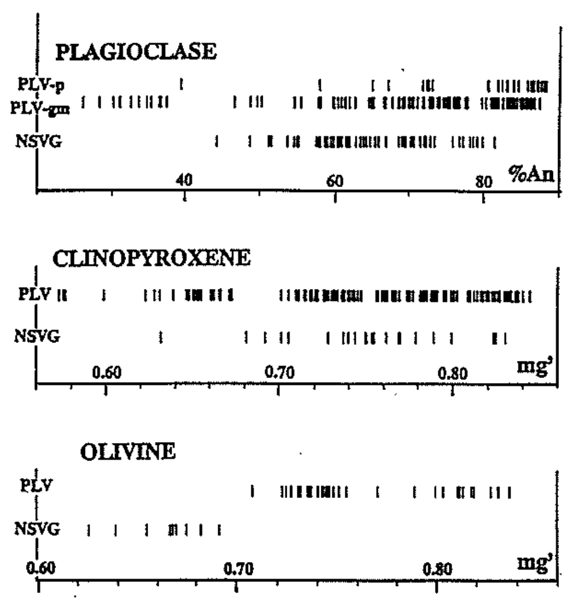
PLV lava flows do not preserve evidence of an extensive pre-eruptive crystallization history. Chilled margins are generally aphanite. Occasionally, lavas contain minor amounts (usually less than 1%) of small euhedral phenocrysts of plagioclase (often with melt inclusion-rich cores) and sometimes olivine.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

	POT	OT1	OT2	IOT	FOT	AND	DAC	RHY
Ni(ppm)	400-300	300-250	250-200	200-100	100-15	D58-	83JP-7	85MH-1
	n=5	n=9	n=14	n=8	n=6	1297		
SiO_2	47.82	47.34	48.03	48.55	49.94	56.39	68.44	77.89
Al_2O_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_2O	2.04	2.10	2.25	2.31	2.91	3.94	4.74	3.67
K_2O	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_2O_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 2 *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.

	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 ± Olv	<1	(<1-9)	<1	<1

Table 3 : *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.



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.

disequilibrium with the 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.

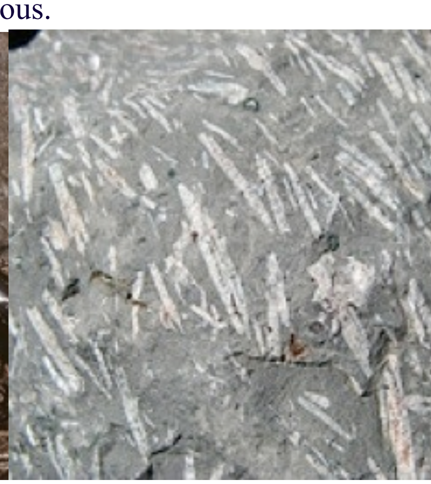
The second most prominent textural element is defined by clinopyroxene crystals and their relationships to the plagioclase lath framework. In all cases, clinopyroxene has clearly crystallized later than olivine and plagioclase. Clinopyroxene crystals exhibit *intergranular to ophitic textures depending 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 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 lavaflows 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 intersertal 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

We conclude that the lavas of the Portage Lake Volcanics are typical of basaltic LIPs on Earth and also chemically resemble the basalts of the moon and Mars.

In the field, we can see some textural variety of basalts. Basalt is mainly made of two minerals: Plagioclase feldspar and pyroxene. Basalt has several textural varieties such as glassy, massive, porphyritic, vesicular, scoriaceous.


Porphyrite or **porphyritic basalt** (see photos above) is characterized by obvious crystals, usually of plagioclase, which is often white or tan in color. These crystals are typically interpreted as phases that formed before eruption, where magma was being stored (in a "magma chamber").On Isle Royale, there are five main examples of porphyritic basalt flows: The Scoville Point (**psp**), Hill Point (**php**) Tobin Harbor (**pth**) Grace Island (**pgi**) and Huginnin (**ph**).

"Trap," melaphyre, or **massive basalt** typically has no conspicuous crystals, and in its interior regions has a uniform grey or grey brown color (see photos above). On Isle Royale there are four large "Trap" flows: Edwards Island (**pei**) Long Island (**pli**), Minong (**pm**) and Amygdaloid Island (**pai**).

Ophite or **Ophitic basalt** (see photos above) exhibits a sometimes subtle, knobby texture with equidimensional pyroxenes usually between 0.5 and about 3 cm. On Isle Royale there are 3 main ophitic flows: Washington Island (**pwi**), Greenstone (**pg**) and Hill Point (**php**) .

These textural types of basalt reflect environment of deposition in part. Thicker flows which cooled more slowly are more likely to be ophitic, as figure 17 shows.

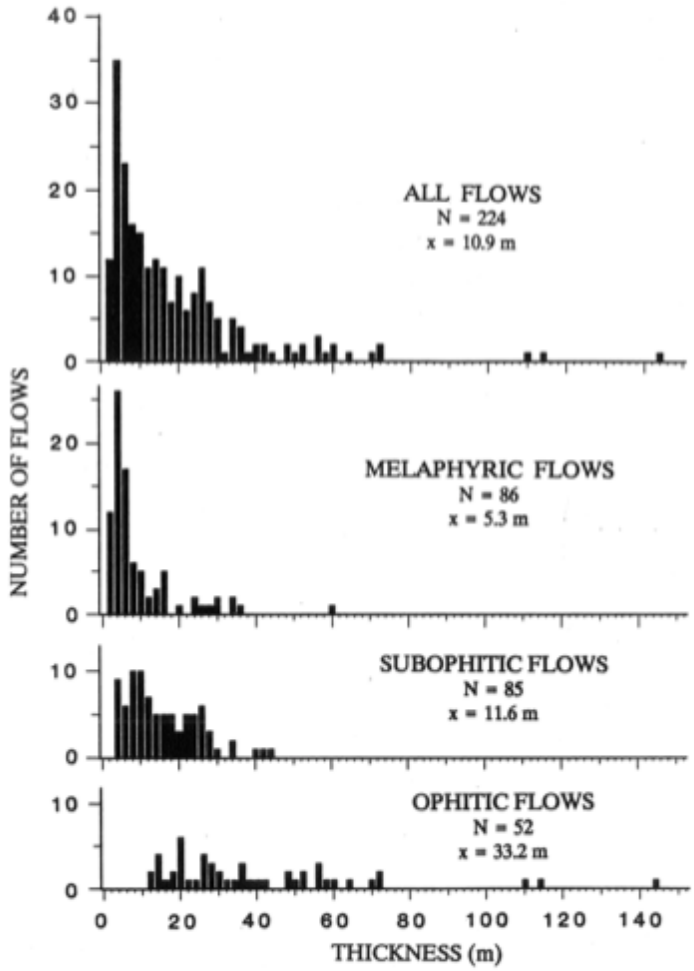


Figure 17*: Histogram plots of numbers of flows within the Portage Lake Volcanics which had melaphryic (Trap), and Ophitic textures. Subophitic textures are intermediary between ophitic and melaphyric. From Paces, 1988.*

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.

Physical features of lava flows

A summary statement from a review paper about basalt flows (Self *et al*., 1998):
The most common rock type at the surface of the Earth, and on the other terrestrial planets, is basalt. Basaltic lavas come in two forms: aa and pahoehoe (from the Hawaiian 'a'ā and pāhoehoe). Pahoehoe flows have often been thought of as small, slow-moving, inconsequential lavas. It is thus not surprising that the processes involved in the emplacement of large, fast-moving, channelized aa flows have received greater attention (see Kilburn & Luongo 1993, Crisp & Baloga 1994, Pinkerton & Wilson 1994, and references therein). However, as in the fable of the tortoise and the hare, it is the slow but unrelenting pahoehoe lava flows that

ultimately grow larger and longer than the spectacular but short-lived channelized rivers of lava that produce aa flows.

In terms of both areal coverage and total volume, pahoehoe flows dominate basaltic lavas in the subaerial and submarine environments on Earth. The most abundant type of lava, submarine pillows, is closely related to pahoehoe in their style of emplacement (e.g. Macdonald 1953, Williams & McBirney 1979). A compilation of the rather sparse information on intermediate length (50–100 km) and long (>100 km) lava flows on the Earth (Table 1) shows that pahoehoe is far more common in these larger flows. Several large extraterrestrial flows also seem to be pahoehoe (e.g. Theilig & Greeley 1986, Bruno et al 1992, Campbell & Campbell 1992). The emplacement of pahoehoe flows is therefore a fundamental process in crustal formation on the Earth and the other terrestrial planetary bodies.

Isle Royale and Keweenaw lava flows exhibit pahoehoe features, and do not show pillows or other subaqueous physical aspects. Therefore, here we use descriptive material from volcanological literature that describe pahoehoe flood basalts (Hon et al. 1994; Goff, 1996, Self et al., 1998 and Thordarson & Self, 2012). A generalized cross section of an "inflated" pahoehoe flood basalt is shown in Figure 18.

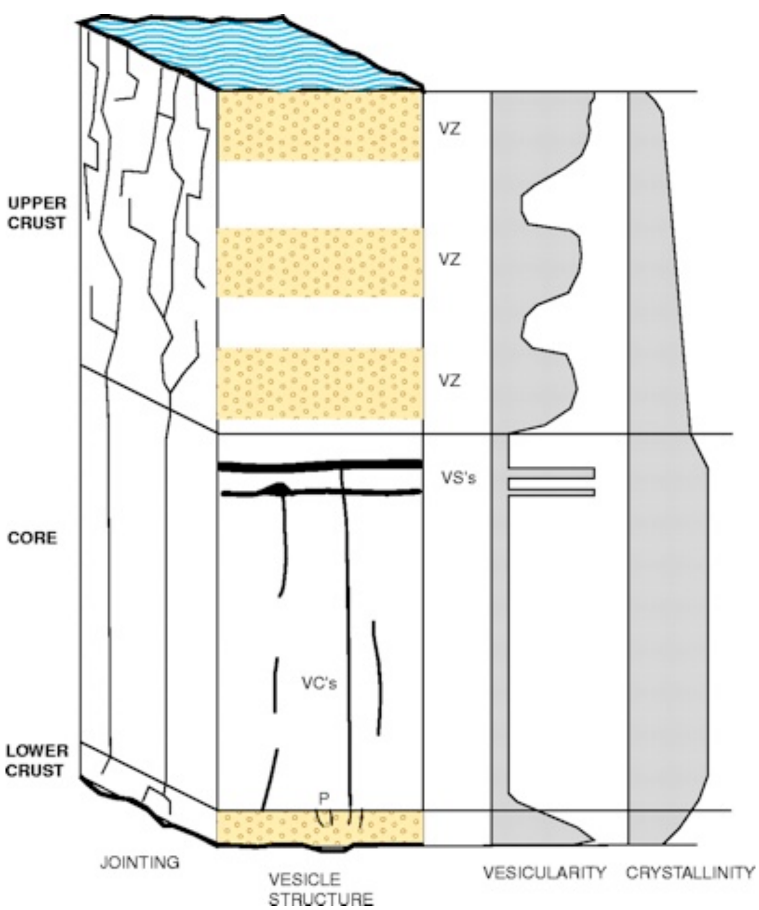


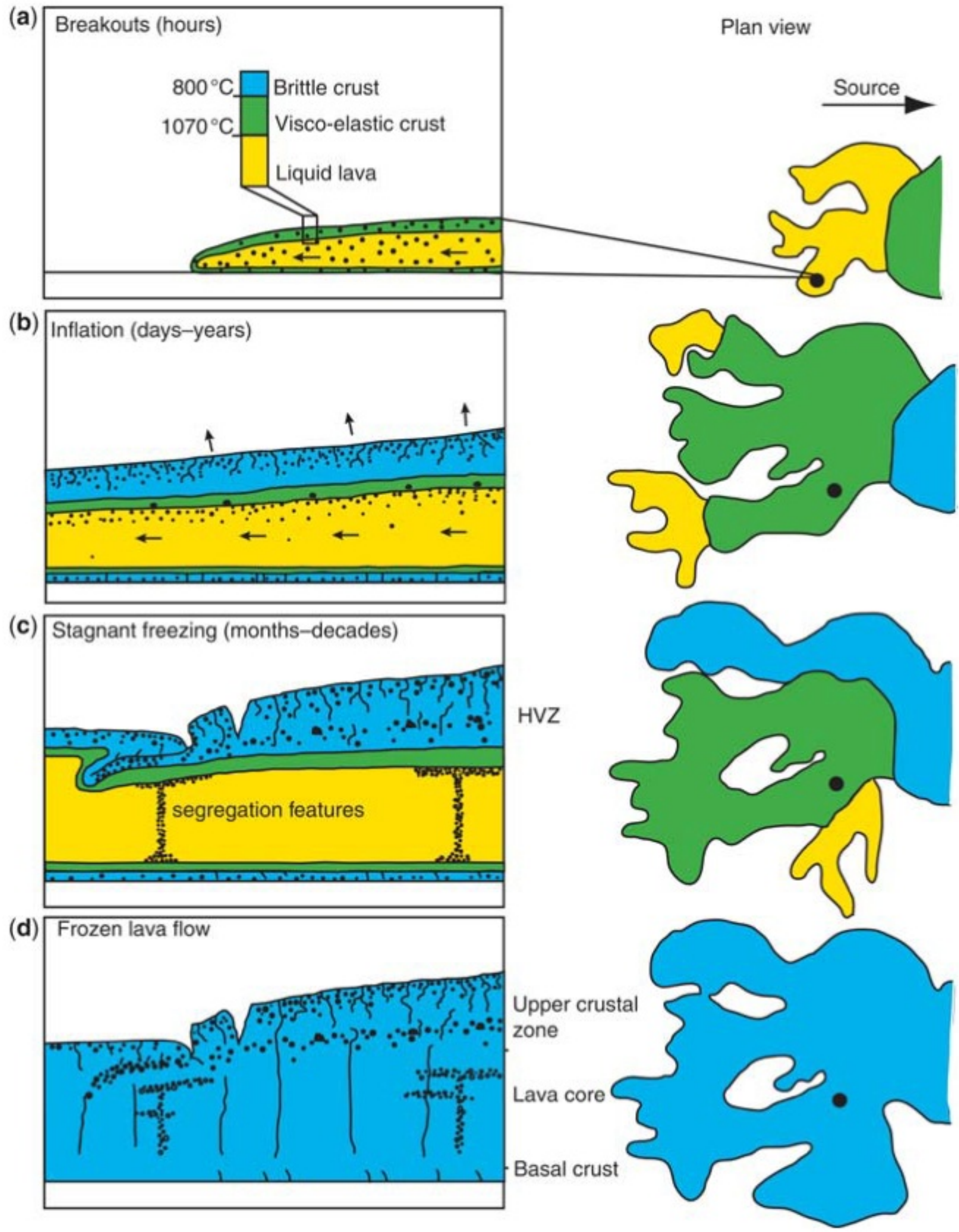
***Figure 18:** Idealized cartoon of the cross section through an inflated pahoehoe lobe. The lobe is divided into three sections on the basis of vesicle structures, jointing, and crystal texture. The upper crust makes up 40–60% of the lobe and the lower crust is 20–100 cm thick, irrespective of the total lobe thickness. Upper crust: Vesicular, often with discrete horizontal vesicular zones (VZs) that form during active inflation. Bubble size increases with depth. Prismatic or irregular jointing, sometimes equivalent to the entablature in thick lava flows. Petrographic texture ranges from hypohyaline to hypocrystalline (90–10% glass). Core: Very few vesicles. Porosity is dominated by diktytaxitic voids. Vesicles are mostly in the silicic residuum, which forms vesicle cylinders (VCs) and vesicle sheets (VSs). Holocrystalline (<10% glass). Lower crust: Nearly as vesicular as the upper crust, few joints, and 50–90% glass. from Self et al., 1998.*

Development of the layers shown in Figure 18 is likely the result of a sequence of inflation and deflation events as observed at Kilauea and Mauna Loa and depicted and explained by Hon *et al.*, in Figure 19 and below:

Inflated pahoehoe sheet flows have a distinctive horizontal upper surface, which can be several hundred meters across, and are bounded by steep monoclinal uplifts. The inflated sheet flows we studied ranged from 1 to 5 m in thickness, but initially propagated as thin sheets of fluid pahoehoe lava, generally 20-30 cm thick. Individual lobes originated at outbreaks from the inflated front of a prior sheet-flow lobe and initially moved rapidly away from their source. Velocities slowed greatly within hours due to radial spreading and to depletion of lava stored within the source flow. As the outward flow velocity decreases, cooling promotes rapid crustal growth. At first, the crust behaves plastically as pahoehoe toes form. After the crust attains a thickness of 2-5 cm, it behaves more rigidly and develops enough strength to retain incoming lava, thus increasing the hydrostatic head at the flow front. The increased hydrostatic pressure is distributed evenly through the liquid lava core of the flow, resulting in uniform uplift of the entire sheet-flow lobe. Initial uplift rates are rapid (flows thicken to 1 m in 1-2 hours), but rates decline sharply as crustal thickness increases, and as outbreaks occur from the margins of the inflating lobe. One flow reached a final thickness of nearly 4 m after 350 hr. Inflation data define power-law curves, whereas crustal cooling follows square root of time relationships; the combination of data can be used to construct simple models of inflated sheet flows.

As the flow advances, preferred pathways develop in the older portions of the liquid-cored flow; these pathways can evolve into lava tube systems within a few weeks. Formation of lava tubes results in highly efficient delivery of lava at velocities of several kilometers per hour to a flow front that may be moving 1-2 orders of magnitude slower. If advance of the sheet flow is terminated, the tube remains filled with lava that crystallizes in situ rather than draining to form the cave-like lava tubes commonly associated with pahoehoe flows.

Inflated sheet flows from Kilauea and Mauna Loa are morphologically similar to some thick Icelandic and submarine sheet flows, suggesting a similar mechanism of emplacement. The planar, sheet-like geometry of flood-basalt flows may also result from inflation of sequentially emplaced flow lobes rather than nearly instantaneous emplacement as literal floods of lava.



A four-stage diagram illustrating emplacement of lava by lobes and lobe-breakouts.

Figure 19*: A figure schematically describing the development of Hawaiian pahoehoe lavas with inflation and deflation (from Hon et al., 1994).*

An inflated view of lava flow sections is probably appropriate for Isle Royale, given the ponded constraints of the rift valley and the thickness of flows observed in the Portage Lake Volcanics. Figure 20 shows a sequential interpretative development of layers in Portage Lake lava flows, based on numerous examples of flows exposed in cross section. This view has similarities with Figure 18, and also is analogous with solidification in sills, based on work by Bruce Marsh (Figure 21; Marsh *et al*., 1991; Mangan & Marsh, 1992), and also shows how liquid can be squeezed out of mush below forming a cylindrical feature moving up and then trapped in a horizontal layer.

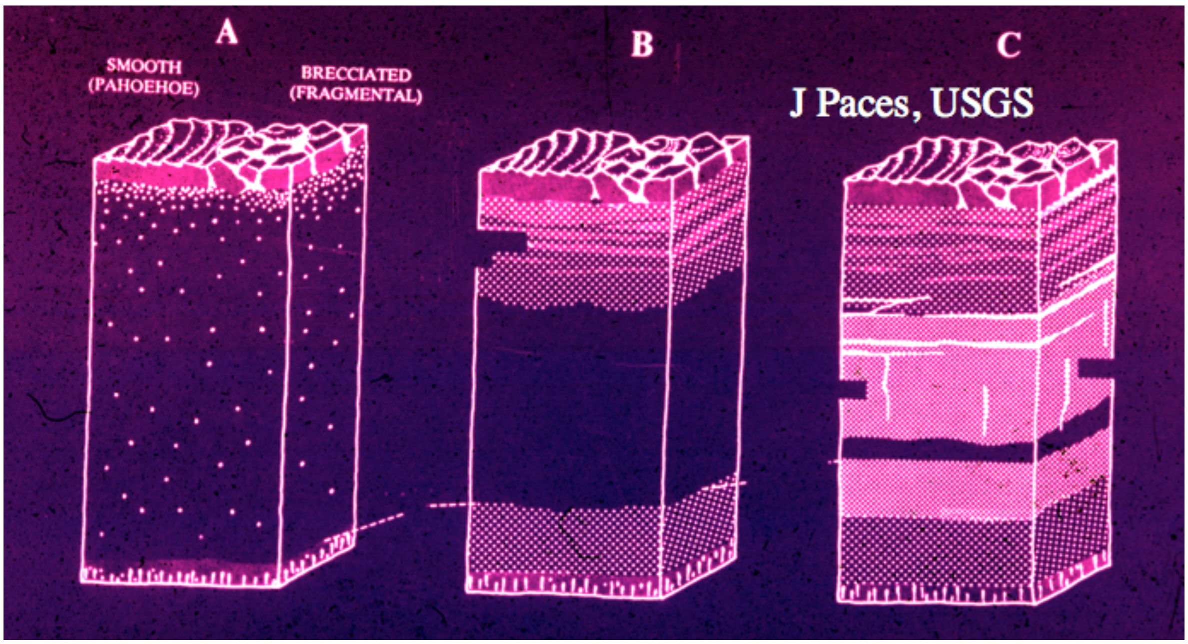


Figure 20: *Cross section cartoons of Keweenawan lava flows at various stages of solidification, from Paces (1988). A is an early stage when crust has formed on the top and bottom of the flow, While B and C show later stages in solidification as liquid (darkest color) is progressively restricted to the interior, away from the cooling margins where magma is becoming a crystal mush and eventually a solid, and segregations develop from mushy regions.*

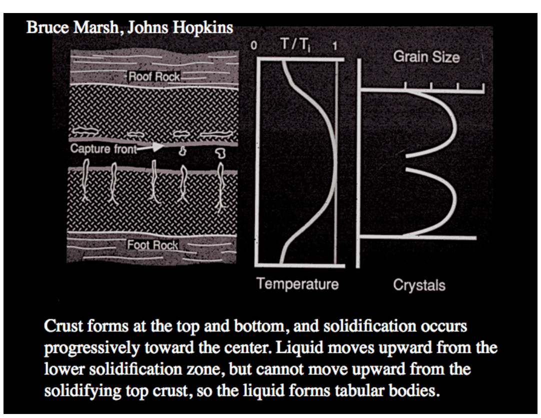
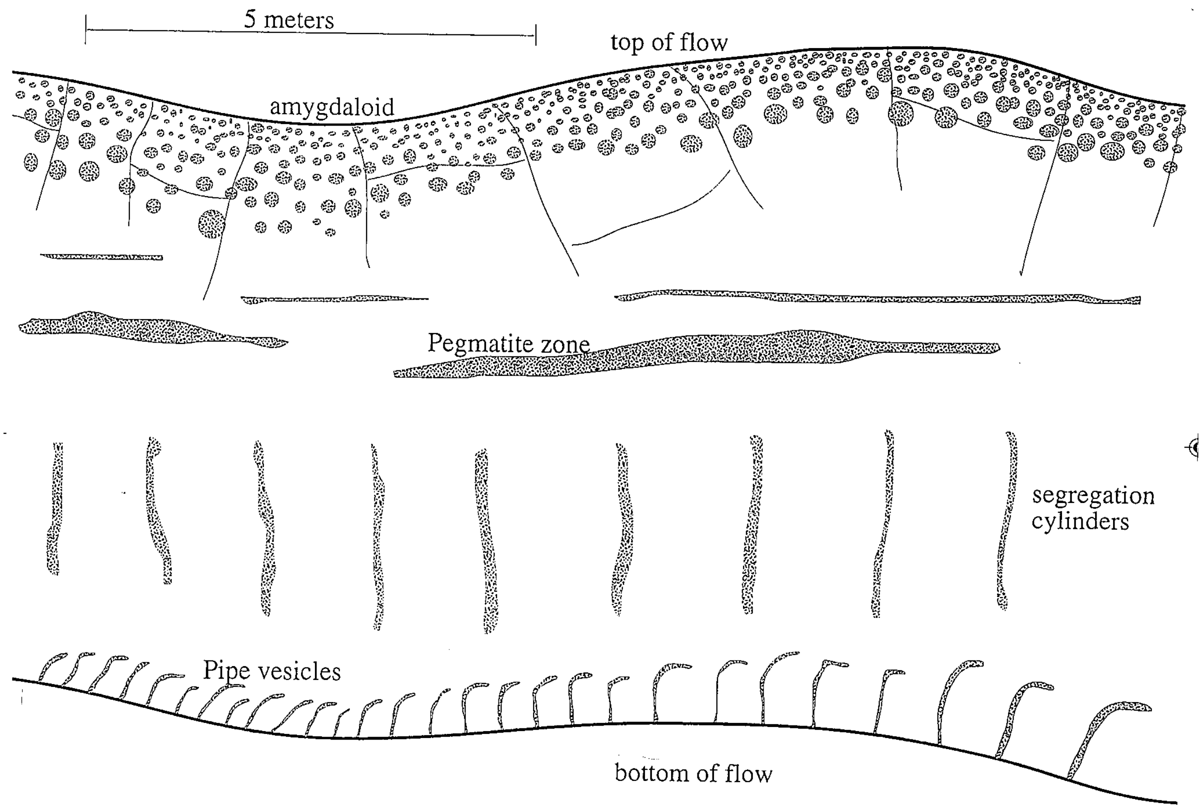


Figure 21: *Cross section of a sill, solidifying from its top and bottom and building crystal mush layers from its cooling surfaces both above and below a liquid layer near the sill's center. Temperature and crystal size vary with height as shown and segregations form and can rise from the lower part of the flow, but get trapped in tabular zones above the center.*

Vesicular zones in the PLV tend to be mineralized by zeolite and prehnite-pumpellyite facies minerals, which is an overprint over strictly physical volcanological features. Figure 22 shows a typical pattern of vesicular zones within these lavas and Figure 24 shows some typical segregation cylinders. Goff (1996) has made an extensive study of vesicle cylinders which we suggest are equivalent to segregation cylinders, and develop above the lower solidification front of the lava flow.



Idealized Cross section of a Keweenawan Basalt flow, showing sites for secondary minerals.

Figure 22*: Cross section of an idealized lava flow within the Portage Lake Volcanics, showing four kinds of regions where gas filled vesicles typically later become mineralized by hydrothermal fluids.* ***Pipe Vesicles*** *(see Figure 23) develop at the base of the flow, perhaps the result of boiling of trapped meteoric water from the soil below the flow.* ***Segregation cylinders or vesicle cylinders*** *(Figure 24) develop above the solidifying lower contact zone, and rise to the flow center or beyond, creating vertical vesicle rich features. At the flow top, vesicles develop as the lava crust thickens and solidifies, with* ***vesicles*** *being more numerous and smaller at the top and less numerous and larger across the first meter or so of flow thickness. A* ***pegmatite*** *zone is found occasionally above the flow midpoint, marked by tabular zones, with thin flows marked by vesicular layers (called vesicle sheets) and thicker flows being termed* ***doleritic****, with larger and more conspicuous plagioclase laths.*

Figure 23: *Pipe vesicles, filled with Calcite and laumontite, seen at the base of a 5m thick PLV lava flow from near Eagle Harbor on the Keweenaw Peninsula.*

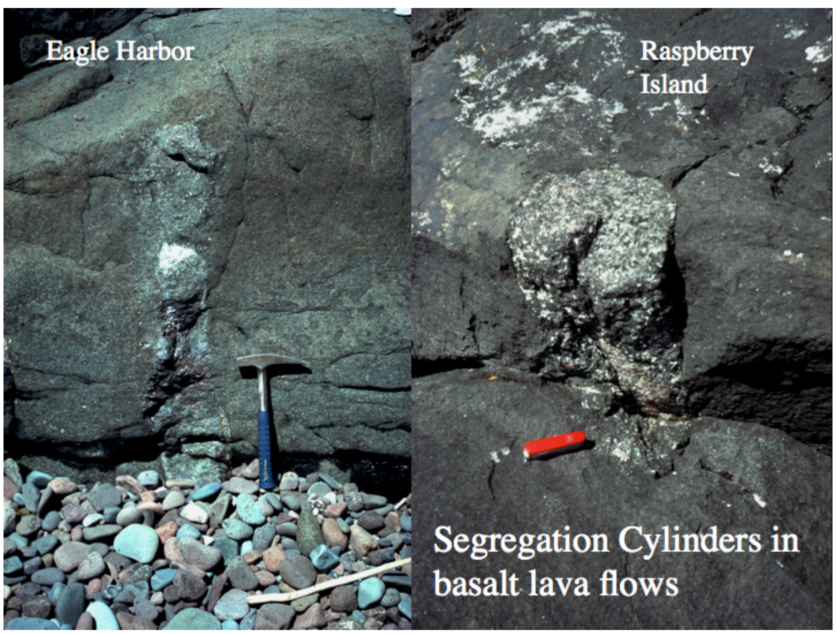


Figure 24: *Two examples of mineralized vesicle cylinders or segregation cylinders, from the Keweenaw (left) and Isle Royale (right). These features are generally found below the flow midpoint, and have variable vertical extension.*

Some conclusions about the lavas of the Keweenaw Rift:

1. The overall physical characteristics resemble other examples from much younger flood basalts and other basaltic volcanoes.
2. The PLV are subaerial, inflated pahoehoe flows which are ponded and do not deflate after eruption.
3. The volumes of PLV flows are as large as any known in other flood basalts.
4. Because their thicknesses are in excess of hundreds of feet, PLV flows show more pronounced *in situ* differentiation than other examples.

Columnar Joints

Like mudcracks, columnar joints form from volume contraction. In the mudcracks, volume decreases with drying, while in lava flows or volcanic tuffs it is cooling that drives the contraction.

Lava flows display a variety of columns (Figure 25), often with a stratigraphic pattern. **Colonnade** is a coarser, more regular pattern often found at the base of the flow. **Entablature** is more irregular, and often found near the top. Sometimes there is a sandwich colonnade-entablature-colonnade structure like Figure 25 (Long & Wood, 1986). The Portage Lake Volcanics show columnar joints in many places. They also exhibit difference scales and styles of jointing.

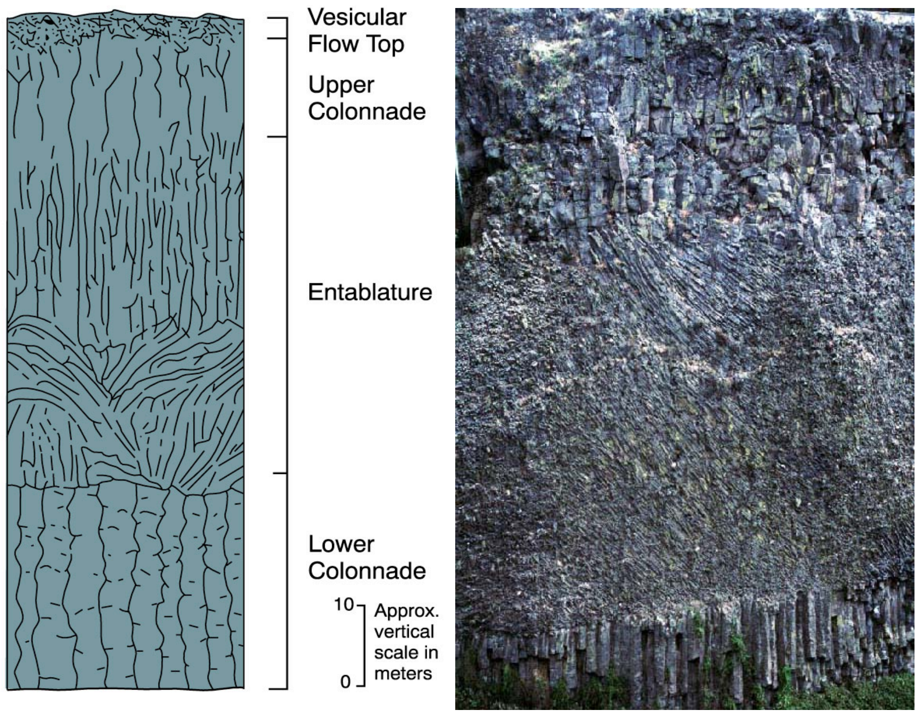


Figure 25: *Schematic diagram of columnar jointing pattern in the Columbia River flood basalt near Bend, Oregon (left), compared with an actual photograph of one good example of a lava cross section. Individual sections never match perfectly because of environmental variables.*

The recognition of the role of water infiltration in the formation of certain kinds of entablature jointing (see above) in the Columbia River Flood basalts by Long & Wood, 1986 was an especially important insight (see Iceland examples especially), as was the detailed work on column formation by DeGraff and Aydin (1993) and DeGraff et al. (1989).

On Isle Royale, colonnade style jointing can be seen in many places, although it is less perfectly developed than many worldwide examples. Entablature jointing is also prominent at Isle Royale, especially in the Edwards Island flow (pei) and the top of the Greenstone Flow (pg). To demonstrate the variability of columnar joints in lavas and tuffs, the field trip website explores a large collection of columnar joint photographs (http://www.geo.mtu.edu/~raman/SilverI/IRKeweenawRift/Columnar_Joints/Columnar_Joints.html).

Figure 26: *Colonnade style jointing on Isle Royale. Left photo shows Monument Rock, an exhumed (sea stack) column several meters in diameter. Right photo shows rude 5m diameter columns in the Greenstone Flow (pg). For more, see also (http://www.geo.mtu.edu/~raman/SilverI/IRKeweenawRift/IR_Column_examples/IR_Column_examples.html)*

Figure 27: *Entablature style jointing in the Edwards Island Flow, Scoville Point, Isle Royale. Scale of these joints is 7-12 cm.*

Mafic Volcaniclastic Deposits

Kilauea and Iceland mainly produce lava flows like those on Isle Royale, but near their vents we find compositionally similar pyroclastic rocks of a variety of types. These pyroclastic rocks, called *mafic volcaniclastic deposits* (MVD) are also a minor part of the rock record at Isle Royale. We note that such rocks are well known at most continental flood basalt provinces (see Ross *et al*. 2005). Mechanisms for generation of these deposits include magmatic and phreatomagmatic processes. On both Isle Royale and the Keweenaw such deposits are noted in a few stratigraphic horizons.

In a review paper, Ross *et al*., 2005, have summarized worldwide occurrences of MVD:

Flood volcanic provinces are assumed generally to consist exclusively of thick lavas and shallow intrusive rocks (mostly sills), with any pyroclastic rocks limited to silicic compositions. However, mafic volcaniclastic deposits (MVDs) exist in many provinces, and the eruptions that formed such deposits are potentially meaningful in terms of potential atmospheric impacts and links with mass extinctions. The province where MVDs are the most voluminous—the Siberian Traps—is also the one temporally associated with the greatest Phanerozoic mass extinction. A lot remains to be learned about these deposits and eruptions before a convincing genetic link can be established, but as a first step, this contribution reviews in some detail the current knowledge on MVDs for the provinces in which they are better known, i.e., the North Atlantic Igneous Province (including Greenland, the Faeroe Islands, the British Isles, and tephra layers in the North Sea basin and vicinity), the Ontong Java plateau, the Ferrar, and the Karoo. We also provide a brief overview of what is known about MVDs in other provinces such as the Columbia River Basalts, the Afro-Arabian province, the Deccan Traps, the Siberian Traps, the Emeishan, and an Archean example from Australia.

The thickest accumulations of MVDs occur in flood basalt provinces where they underlie the lava pile (Faeroes: >1 km, Ferrar province: ≥400 m, Siberian Traps: 700 m). In the Faeroes case, the great thickness of MVDs can be attributed to accumulation in a local sedimentary basin, but in the Ferrar and Siberian provinces the deposits are widespread (>3×10^5 km^2 for the latter). On the Ontong Java plateau over 300 m of MVDs occur in one drill hole without any overlying lavas. Where the volcaniclastic deposits are sandwiched between lavas, their thickness is much less.

In most of the cases reviewed, primary MVDs are predominantly of phreatomagmatic origin, as indicated by the clast assemblage generally consisting of basaltic clasts of variable vesicularity (dominantly non- to poorly-vesicular) mixed with abundant country rock debris. The accidental lithic components often include loose quartz particles derived from poorly consolidated sandstones in underlying sedimentary basins (East Greenland, Ferrar, Karoo). These underlying sediments or sedimentary rocks were not only a source for debris but also aquifers that supplied water to fuel phreatomagmatic activity. In the Parana´–Etendeka, by contrast, the climate was apparently very dry when the lavas were emplaced (aeolian sand dunes) and no MVDs are reported.

Volcanic vents filled with mafic volcaniclastic material, a few tens of metres to about 5 km across, are documented in several provinces (Deccan, North Atlantic, Ferrar, Karoo); they are thought to have been excavated in relatively soft country rocks (rarely in flood lavas) by phreatomagmatic activity in a manner analogous to diatreme formation.

On Isle Royale at least three occurrences of MVDs were noted by NK Huber: 1. A breccia found above the Amygdaloid Island Flow (pai) (Figure 28), 2. a Tuff-breccia unit at the top of the Minong Flow (pm) and 3. A Tuff-breccia above the Greenstone Flow (pg). On the field trip we plan to visit the Amygdaloid Island occurrence. We will also see sedimentary units on Mott Island which resemble MVD.

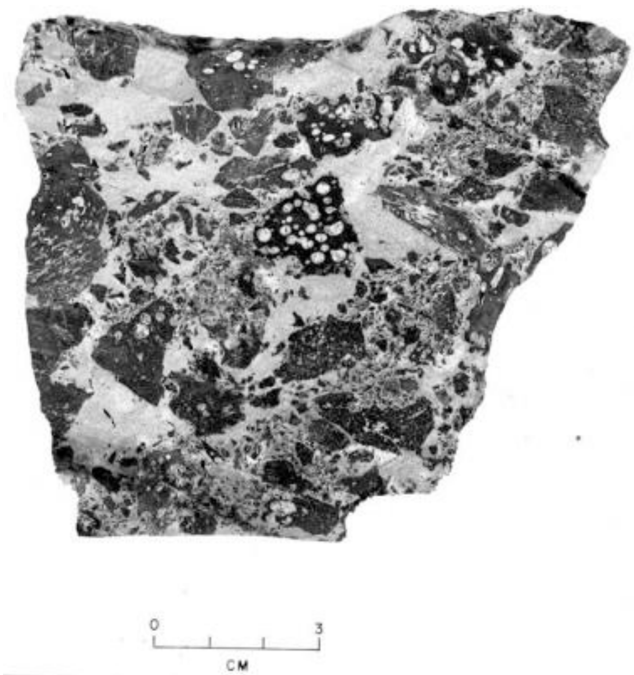


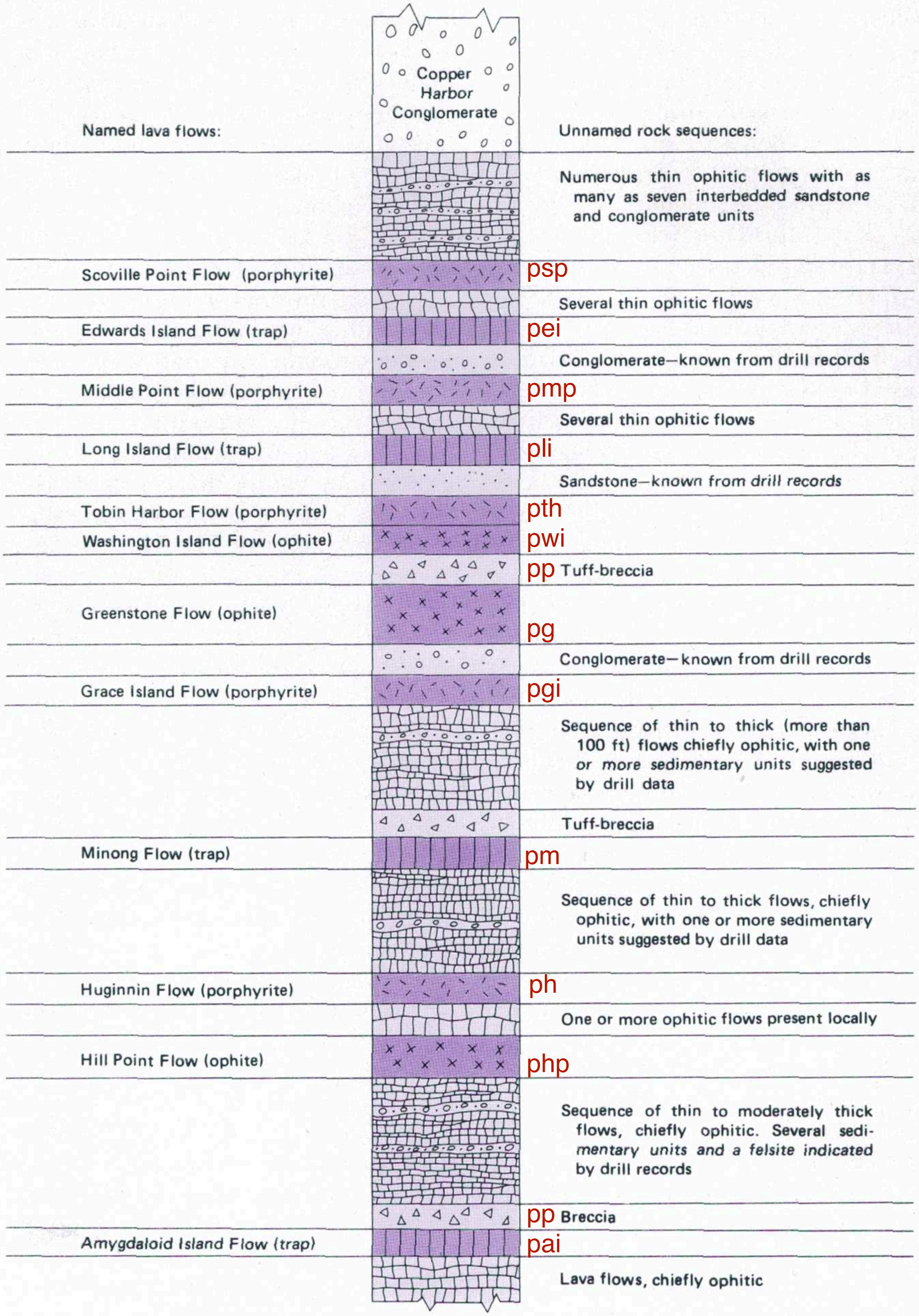
Figure 28: *Breccia occurring above the Amygdaloid Island Flow, collected from the south shore near the E end of the island (from Huber, 1973).*

Lava Stratigraphy on Isle Royale.

Huber (1973) named eleven distinctive lava flows (Figure 30) from the sequence of lava units on Isle Royale, using their field characteristics (see above). These units can be traced across the island generally paralleling the elongation of the whole island. These named flows are generally the thickest and most resistant to erosion so they make topographic highs and project as islands at the margins of the main island, accounting for the smaller units of the archipelago. This layered stratigraphy is quite regular (Figures 29, 30, 31).

Figure 29: *Cliff section of Icelandic lavas, showing a sequence of parallel layers with variable thicknesses. We do not generally have vertical sequences like this at Isle Royale, but the layers must have very similar geometry. Photo from along the south coast of Iceland near Hof, 2008.*

Figure 30: *Named lava flows of Isle Royale (from Huber, 1973). Map symbols in red.*



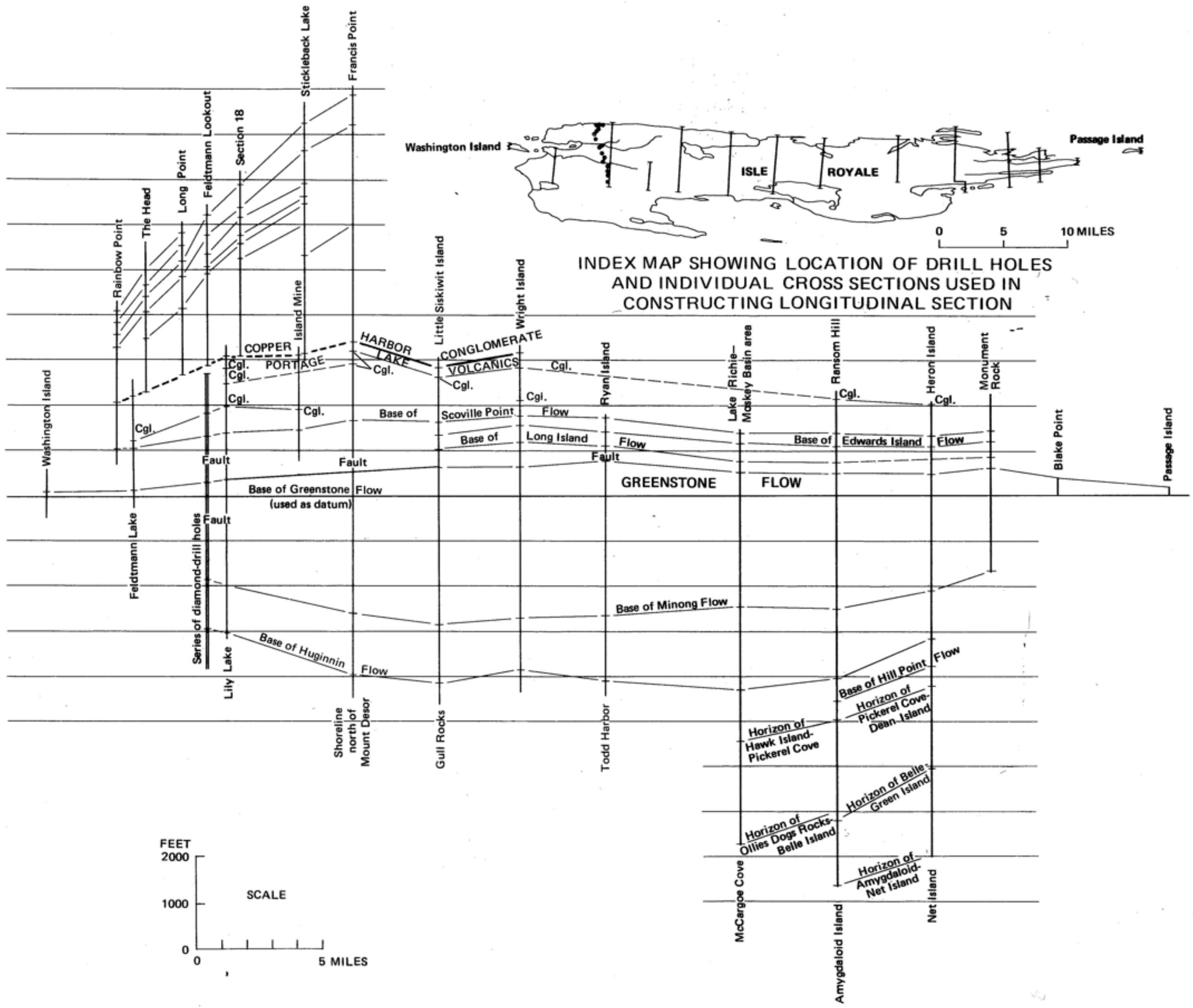


Figure 31: *Longitudinal Stratigraphic section showing variations in thickness of the Portage Lake Volcanics and Copper Harbor Conglomerate on Isle Royale. From Huber, 1973.*

Ophitic Texture and Ophite significance

Keweenaw rift rocks include a somewhat rare textural variety of basalt called ophite or ophitic basalt. Ophitic texture is defined inconsistently, but it is an important variety of basalt texture where pyroxene (or occasionally olivine) forms larger crystals and typically contains numerous crystals of plagioclase (Figure 32). Pyroxenes may vary from < 1 to 10 cm and may include as many as hundreds of plagioclases. In the field the pyroxenes are often 1-2 cm in diameter and give the rock a distinctive aspect. There may be a brownish or orange region surrounding the pyroxenes which may represent a glassy remnant of magma melt. Overall the ophite is thought to represent a solidified remnant of a dendritic crystal mush.

Crystal size and form in volcanic rocks is known to be influenced by the rates of cooling in the immediate vicinity of the growing crystal. Slow cooling in a pluton leads to large,

Figure 32: *Ophitic cobbles (left) and a wet surface of an ophitic lava flow (right) are common on Isle Royale and the Keweenaw, and quite rare elsewhere in the world. The ovoid features in both photos are clinopyroxenes, while the orange or reddish material surrounding the pyroxene is typically a glassy mesostasis which is now altered to chlorite or corrensite.*

equidimensional crystals, while very rapid cooling can lead to no crystals at all (glass or obsidian). Intermediate cooling rates can lead to unusual shapes of crystals (spherulites, "bow ties", spinifex, and ophitic) as crystals nucleate or grow at accelerated rates as crystallization, which requires more time than allowed by the environmental cooling of the lava, cannot keep pace and exhibits disequilibrium (Lofgren, 1980). The rate of heat loss (undercooling or supercooling) during the solidification is thus thought to cause ophitic texture, where pyroxene is growing rapidly and plagioclase is forming many more nuclei. Because ophites may completely crystallize and can be coarse-grained, especially with respect to pyroxene, some are termed gabbro rather than basalt. At first geologists looking at ophitic lava flows in the Keweenaw wondered whether they were sills.

There is a tendency for ophitic textures to be found in large basaltic intrusive rock bodies such as sills, suggesting that overall they reflect relatively slow solidification. Overall ophitic texture is ubiquitous and could be a hallmark of the Keweenaw Rift lavas. Paces (1988; see Figure 17) found that the average thickness of ophitic Keweenaw flows was 33 m (range 11-140m), while subophitic ones were 12 m (range 4-45 m), and traps (melaphyres) about 5 m thick (range 2-60m). We note that the overall average thickness of Keweenawan flows is about 10-11m, much greater than what we see at modern volcanoes like Kilauea (average flow about 0.5 m thick). The differences are likely the result of ponding within the rift valley, where volcanism filled the rift basin rather than running off a slope away from the vent, as happens at Kilauea. So ophitic texture is a hallmark of slow cooling that is apparently related to ponding of the lavas.

Pegmatites or pegmatoids in lava flows

In Keweenawan flows pegmatite (or pegmatoid) layers are conspicuous (Fig 33), especially in the thicker flows. They appear to be analogous to *vesicle sheets* that are found in most flood basalts, but they may result from more evolution during the longer solidification times.

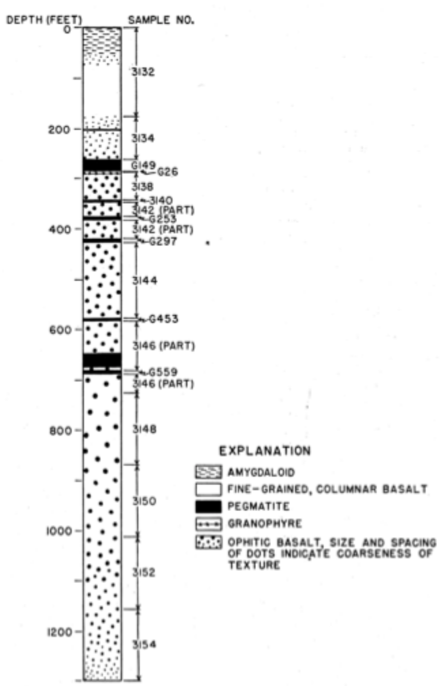
***Figure 33**: This collection of beach cobbles shows obvious texture of Keweenawan lava pegmatite—note conspicuous plagioclase laths. These layers have vesicular texture and are typically mineralized with zeolite facies minerals.*

The thickest lava flows in the Keweenawan Portage Lake Volcanics contain horizons called "pegmatites," "pegmatoids," or "dolerites." The following description of these features is from Longo (1984):

Lacroix (1928, 1929) coins the term "pegmatitoide" to describe the coarse-grained zones considered 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 auto intrusions, 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 extension 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 at. (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 Canarian Archipelago.
--Longo 1984

Pegmatites are found to be especially well developed in thicker flows such as the Greenstone (pg), which can be more than 1200 ft thick. Pegmatite layers up to 30 ft thick are found above the flow's midpoint at a stratigraphic layer analogous to the vesicle sheets near the top of the core of idealized pahoehoe flows as described by Self *et al.*, 1998 (see Flow Structure section, above). Cornwall (1951) shows a Greenstone flow section from the Keweenaw in Figure 34.



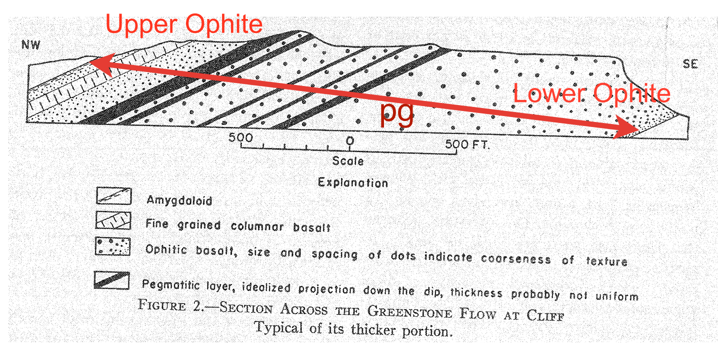


Figure 34: *Columnar section (left) and cross section (above) of the Greenstone flow (pg) as exposed in overlapping diamond drillholes from Delaware, Michigan (Keweenaw Peninsula). Pegmatite is shown as black layers and occurs in the upper part of an unusually thick (1300 ft) lava flow. Granophyre was not found in the cores but is projected based on field data (from Cornwall, 1951).*

The texture of pegmatite in thick flows is coarser and the plagioclase laths may be as large as several cm (fig 35).

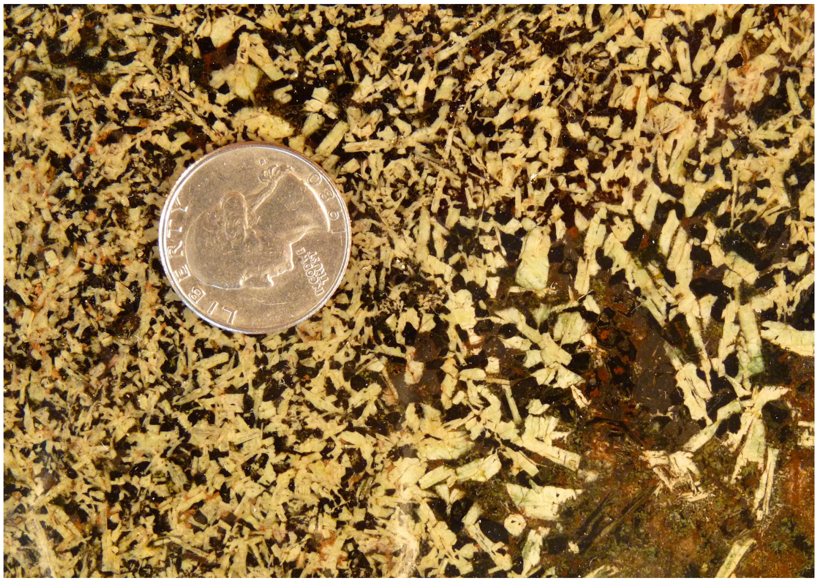


Figure 35: *Polished surface of pegmatite boulder from Passage Island, Isle Royale, showing plagioclase laths of several cm.*

In thinner flows pegmatite layers are thin (often a few cm) and resemble vesicle sheets (see figure 36).

Figure 36: *Thin pegmatite or vesicle sheet from 6 m thick lava flow of Lake Shore Traps, Silver Island, Keweenaw Peninsula.*

Pegmatite layers or vesicle sheets in thinner flows are texturally similar to segregation cylinders and lie stratigraphically above them (Figure 37).

***Figure 37:** Tabular pegmatite layer within horizontally fractured section of 20-30 m thick flow on Raspberry Island. This 6 cm thick layer is about 5 m stratigraphically above segregation cylinders.*

Amygdaloidal Minerals in Portage Lake Volcanics on Isle Royale

To find minerals at Isle Royale or in the Keweenaw, you should walk the coastlines, especially those that are well wave-washed. The waves expose the minerals and pebbles of various minerals, can be found on adjacent beaches. Using a canoe or small boat, and watershoes and taking plenty of time, walk the shore and watch for veins and amygdaloids. Observe the interiors of basalt flows where vesicle cylinders, pegmatites, joints and veins may expose these distinctive minerals (Figure 22).

Individual minerals are sometimes difficult to identity, even for experts, but certain groups of minerals can be distinguished very easily (see Table below).

Name *abundance*	**Moh's hardness**	**Color**
Analcime ***r***	5-5.5	Colorless, white
Barite *c*	3-3.5	white
Calcite *a*	3	Colorless, white, pink
Chlorite *a*	2-2.5	Olive-dark gr, black
Chrysocolla ***C***	2.5-3.5	Blue-Green
Copper *r*	2.5-3	Copper, gr-black coatings
Corrensite *a*	1-2	Dk-green to black
Datolite *r*	5.5	White, pink, yellow
Epidote *c*	7	Pistachio green
Laumontite c	3.5-4	White-brown, yellow, pink
Microcline *r*	6	Flesh pink
Mohawkite r	3-3.5	Metallic brassy to gray
Natrolite *r*	5.5-6	Colorless-white
Prehnite *r*	6-6.5	Light green-pink
Pumpellyite *c*	5.5	Green
Quartz *c*	7	Colorless, varied
Saponite *r*	1.5-2	Light green, yellow green
Thompsonite *r*	5-5.5	Pink, white

The colors of amygdaloidal minerals are highly variable and distinctive (Figure 38).

Figure 38: *A selection of beach pebbles showing various colors of amygdaloidal minerals. See also photos of specific minerals (http://www.geo.mtu.edu/~raman/SilverI/IRKeweenawRift/Amygdaloid/Pages/Amygdaloid_2.html)*

The phyllosilicates, chlorite, corrensite, and saponite are all of green color and very soft minerals. You can easily scratch them with your finger nail. The other green minerals as pumpellyite or prehnite are much harder and you will not be able to scratch them with your fingernail. In fact, in pebbles along the shore pumpellite and prehnite projec out, since they are not as easily eroded as the surrounding rock. The pink, unusual color of prehnite of Isle Royale often is the result of very tiny inclusions of native copper which makes it similar to the zeolite thomsonite. The zeolite family is a group of minerals that are challenging to distinguish from each other, but the zeolite, laumontite, can easily be recognized. It is of white or pink color and if you touch it with your finger nail it will split up into small fibers.

What's next? After mastering the mineral identifications in the boulders, students can also look at amygdular minerals to study the order that minerals were deposited in those vesicles, what mineralogists call paragenesis. Many vesicles were filled by a succession of minerals.

Native Copper and the mining

The Midcontinent Rift is the **most important and notable location on Earth for native copper**. This is truly a cosmic oddity, because copper in nature is typically found as a sulfide. Indeed, Goldschmidt classified copper with a group of elements called "chalcophile". So why does copper occur in the Midcontinent Rift as native copper (Fig 39)? This is a major puzzle.

Figure 39: Native copper vein on Washington Island, Isle Royale National Park. This view may be like what Native Americans found when they first visited the copper country. Such occurrences are not common anymore— they were all dug out of wave-washed shorelines. *(Justin Olson photo)*

Could sulfur have been purged from the magma source region or from its magma chambers? This idea is suggested by the early ultramafic dikes which apparently represent the beginning of Midcontinent Rift and which contain apparently immiscible sulfide bodies containing Ni, Cu and rare earth elements (Ding *et al.*, 2012). These dikes could represent magmas derived from mantle material that was melted more completely than when the mantle produces basalt. And this magma may have exsolved sulfide liquid before it was intruded into dikes. Loss of sulfur from the source region or a magma chamber may result in a sulfur-depleted environment favoring native copper? This is a speculation!

Another explanation of sulfur loss is that loss of sulfur through degassing of magma from magma oceans would be facilitated by the ponding and long solidification times. Awareness of sulfur emissions from eruptions is heightened by recent studies of eruptions and climate. Could extensive degassing during Keweenawan rifting play a role in eventually forming native copper ore deposits? Speculation!

Keweenawan native copper deposits seem to be associated with widespread hydrothermally-induced zeolite and prehnite-pumpellyite facies metamorphism (Stoiber & Davidson, 1959; Jolly, 1974) which mineralized the permeable lava flow tops and sediment layers of the Portage Lake Volcanics, apparently about 30 ma after the rift volcanism, during the period of Grenville-induced deformation of the rift syncline (Bornhorst & Barron, 2011; Nicholson *et al.*, 1997 ,Cannon, 1994; Bornhorst et al., 1988) when there was faulting of the rift which enhanced fluid flow within the syncline.

There is a rich lore about indigenous ancient copper mining in the Lake Superior region. Most of it is highly speculative and is unsupported, but it is fervently believed. The abundant archeaological copper relicts (Figure 40) leave no doubt that copper was mined at Isle Royale thousands of years ago and traded across North America and beyond. These early mines found native copper in veins at the surface. They left behind pits and dumps.

Figure 40: *Archeological Copper relicts of midcontinent rift native copper from the Michigan Tech Archives. These materials and open pits left behind show that ancient people mined copper in the Keweenaw and on Isle Royale.*

Mining by Europeans started in the 1800s on both the Keweenaw and Isle Royale. The Isle Royale mines were all marginal efforts and did not last more than a few years.

Copper Harbor Conglomerate

The Copper Harbor Conglomerate occurs on the SW sector of Isle Royale and has been studied by N K Huber, USGS OFR 754-B. Huber gives the following introductory comments:

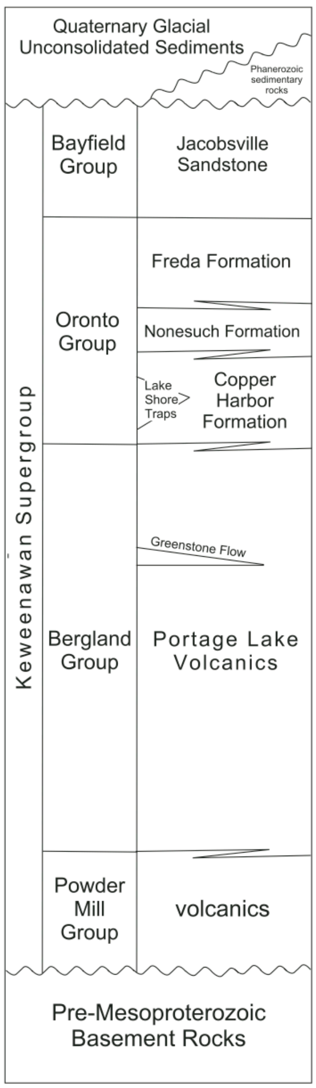


Figure 41: *Local Stratigraphic units.*

The Copper Harbor Conglomerate, in its type area on the Keweenaw Peninsula of Michigan, was named and defined so as to include a thick sequence of sedimentary rocks, previously separated (in ascending order) into the Great, Middle, and Outer Conglomerates, with intervening lava flows, the Lake Shore Traps (Lane and Seaman, 1907, p. 690-691; Lane, 1911, p. 37-40). On the Keweenaw Peninsula, the Copper Harbor Conglomerate conformably overlies the Portage Lake Volcanics (middle Keweenawan), and locally the two formations interfinger. The Portage Lake Volcanics consists primarily of lava flows; minor sedimentary rocks, similar to those within the Copper Harbor Conglomerate, are intercalated between flows (hereafter referred to as interflow sedimentary rocks). The transition between the two formations reflects a gradual cessation of volcanic activity and the growing dominance of a sedimentary regime. The Copper Harbor Conglomerate is overlain by the Nonesuch Shale and Freda Sandstone (upper Keweenawan, Fig 41).

Approximately four-fifths of Isle Royale is underlain by volcanic flows and minor clastic rocks of the Portage Lake Volcanics, which dip 10°-20° to the southeast in the vicinity of their contact with the overlying Copper Harbor Conglomerate (Huber, 1973b, Wolff & Huber, 1973). The Copper Harbor Conglomerate underlies the remaining one-fifth of Isle Royale and is confined to the southwestern part of the archipelago; it dips 5°-28° to the southeast. The contact between the Copper Harbor Conglomerate and the Portage Lake Volcanics appears to be conformable; the top of the Copper Harbor Conglomerate, however, is not exposed. If the Nonesuch Shale and other formations that overlie the Copper Harbor Conglomerate on the Keweenaw Peninsula are present in the Isle Royale area, they lie beneath Lake Superior to the southeast.

Consisting of fluvial subaerial sandstones, siltstones and conglomerates, The CHC shows transport directions that generally spill into the rift valley (see Fig 42). Huber gives many details of the CHC on Isle Royale in his OFR.

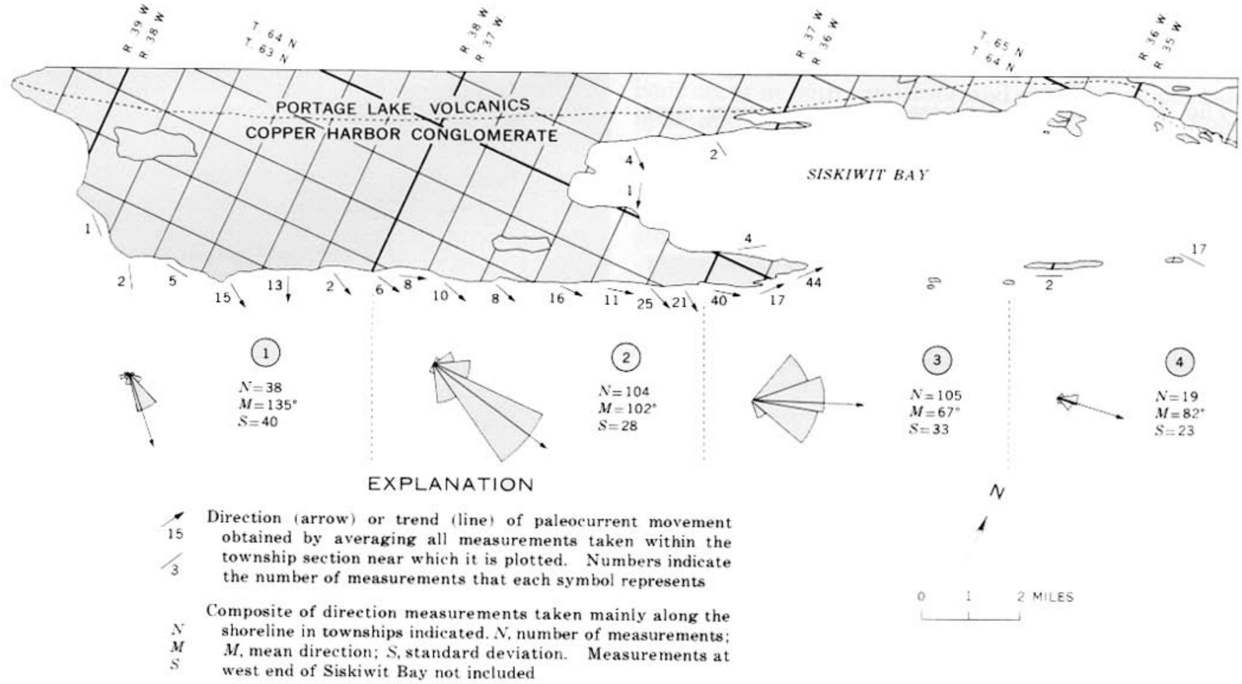


Figure 42: Plot of observed and interpreted paleocurrents seen in the Copper Harbor Conglomerate, Isle Royale (Wolff & Huber, 1973).

On the Keweenaw Peninsula the Copper Harbor Conglomerate is partly made up of alluvial fans (Elmore, 1984). On Isle Royale the sandy and silty units are more abundant and cobble sizes are generally smaller.

LIDAR Topographic Surveys of Isle Royale

LIDAR (LIght Detection and Ranging or Laser Imaging Detection and Ranging) survey of all of Isle Royale, with a nominal resolution of about 2 m is a new resource for understanding landscapes. The data we show here came from Seth De Pasqual, at Isle Royale National Park. It reveals a striking topography which shows the dipping lava beds, and the prominent large lava flows, like the the region NE of Windigo. Differential erosion of lava flows occurs when soft material, like what is found in the amygdaloidal flow tops and along faults is preferentially removed and makes a topographic low, while the massive flow interiors resist erosion and become topographic highs.   Glacial deposits mask the lava layers in part, especially southward in the image, where the flows are mostly covered, but protrude through glacial cover. The glacial materials are softer, but they also reveal wonderful geological information.

Drumlins are asymmetrical glacial features (Figure 43) which reveal the direction of glacial movement. Figure 44 shows an area near Lily Lake, which depicts conspicuous drumlins south of the lake. The pattern shows the direction of movement (from east to west) clearly, and the degree of elongation is also indicative of the rate of movement.

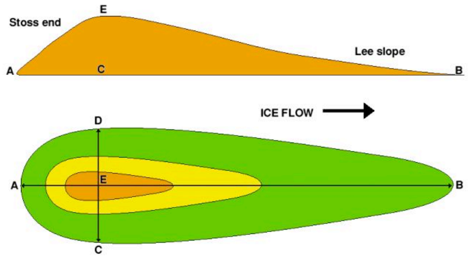


Figure 43: *Schematic diagram of a drumlin, showing how its shape may be related to the direction of ice movement (figure from www.geography-site.co.uk).*

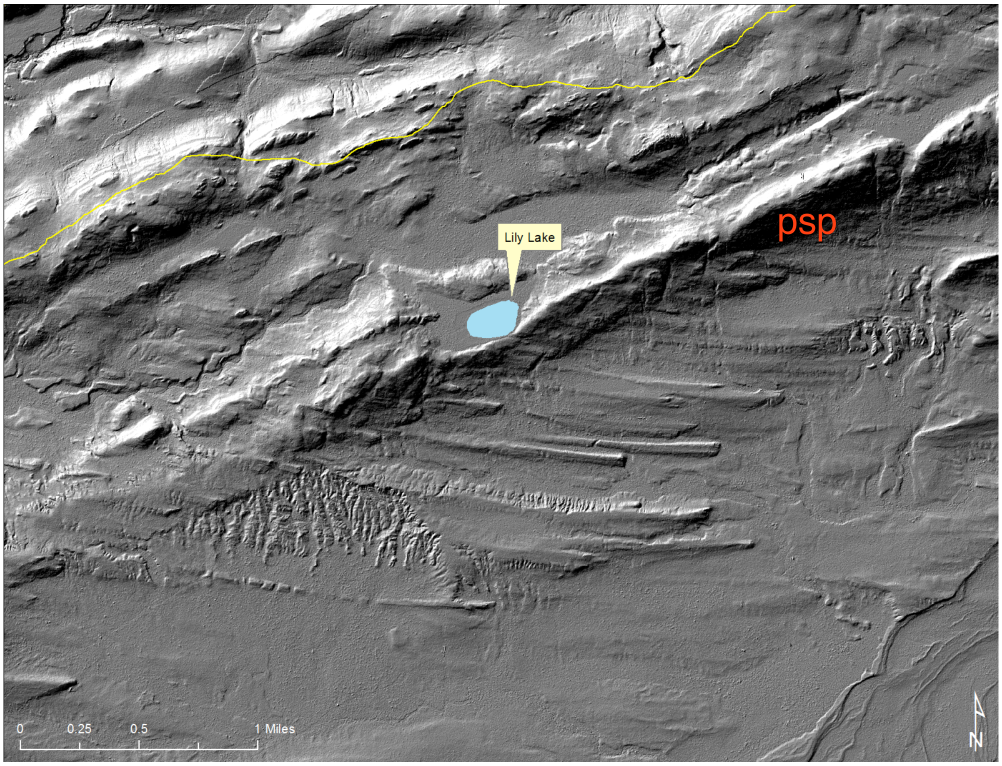
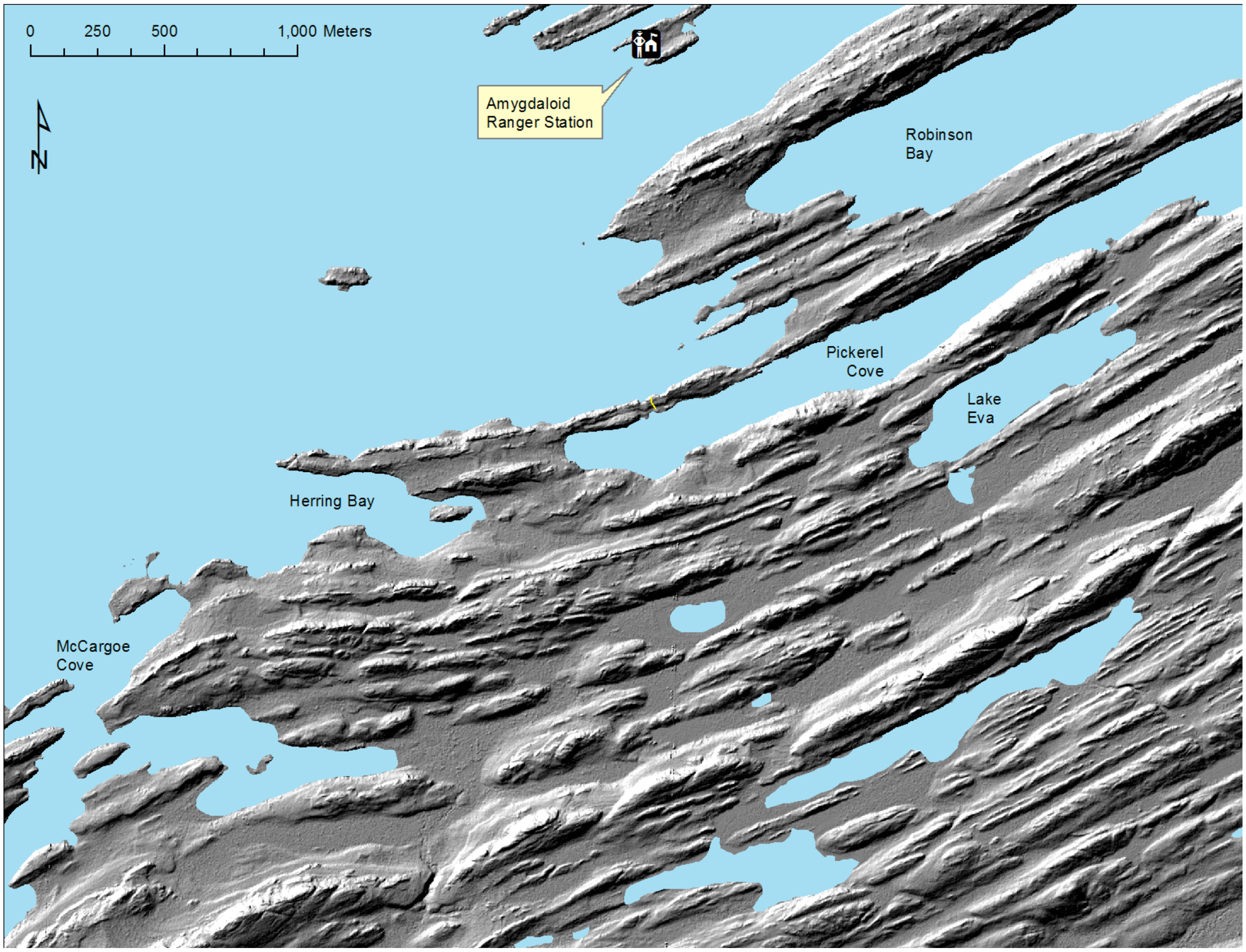


Figure 44: *LIDAR topography image of Lily Lake region, Isle Royale National Park, showing multiple drumlins.*

LIDAR is advantageous over conventional DEM (digital elevation models) for glacial features, but the good resolution of LIDAR also clarifies structural information on the lava flows. The second LIDAR image (Figure 45) shows dramatic bending of the lava flow layering that is remarkably regular in most places on Isle Royale. The bending likely reflects deformation related to faulting associated with McCargoe Cove. The LIDAR offers an opportunity to do interpretation, which will reveal details of the rift formation and its subsequent deformation.

Figure 45: *(next page) LIDAR topographic image of Pickerel Cove area, Isle Royale. The layered lava flow sequences of Isle Royale stand out clearly as resistant flow interiors resist erosion and stand up to higher levels. Faults which offset the flow layers are also detected as eroded topographic lows. Here there is apparent bending of the lava flows.*



Specific Field areas we will visit:
Washington Harbor and Windigo

The field trip starts at Grand Portage, Minnesota, where we will take the Voyageur II east to Washington Harbor and Windigo about 35 km (22 mi) offshore.

Between the Minnesota shoreline and Isle Royale, the strike of Keweenawan 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 (IRF), which the Voyageur crosses between Grand Portage and Isle Royale. This is a thrust fault which bounds the north flank of the rift, apparently associated with the inversion of the Midcontinent Rift. The IRF was detected in the GLIMPCE (Great Lakes International Multidisciplinary Program on Crustal Evolution) seismic profile (Figure 12) collected on a NS line E of the Keweenaw Peninsula, far from Isle Royale, but along the north flank of the rift zone. 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 cover and the glacial features are much more prominent (see pp. 20-21 and 41-54 in Huber 1983).

The bedrock geology of the Washington and Grace Harbor areas (Figure 46) 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 Minong Flow (pm) outcrops S of McGinty Cove, and the Scoville Point Flow (psp) outcrops near Middle Point on the S side of Grace Harbor. 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 rni) along strike. The lava flows here dip at 15-20° SE, an attitude that is similar for younger flows on Isle Royale. Vertical N-S trending fractures, with little offset, cut across the bedrock strata near Washington Harbor (Figure 46, 47, 48). Huber (1983) interprets these as structures related to the warping of the Lake Superior Syncline. South of Grace Harbor, the bedrock of the island is buried by till.

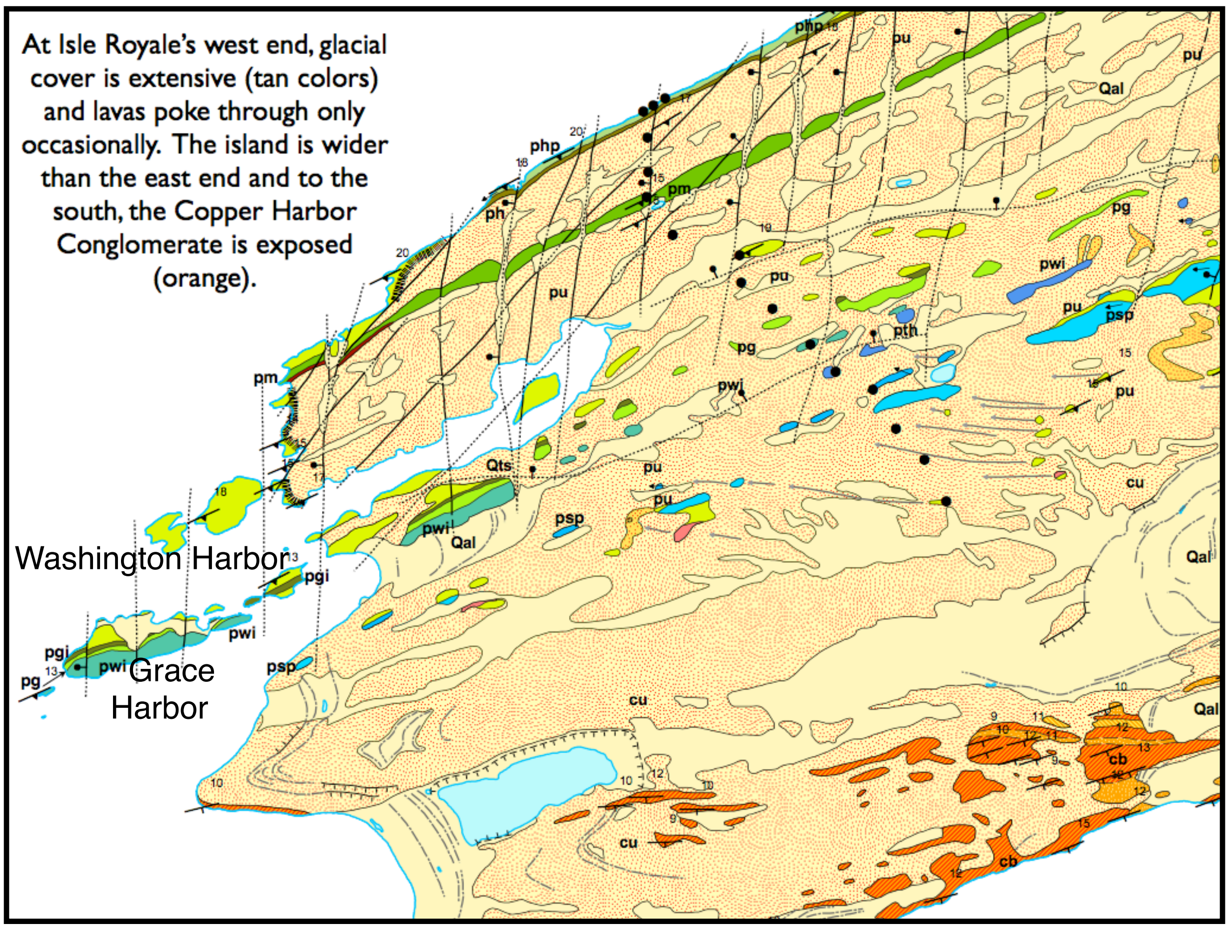


Figure 46: Portion of Figure 2 (Geologic map of Isle Royale, Huber, 1973) showing the area along the west end of Isle Royale. Most of the map indicates glacial deposits, shown in tan, which cover much of the lavas and conglomerates. The prominent locations where bedrock penetrates the glacial deposits are shown in bright colors. Most of eastern Isle Royale has little glacial cover.

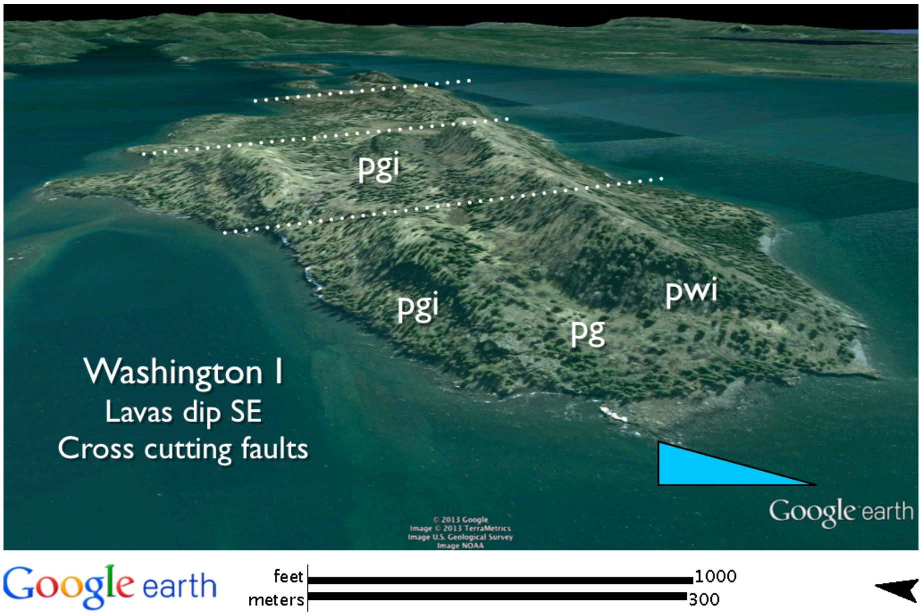


Figure 47: *Oblique Google Earth view of Washington Island, looking E, showing N-S faults and tilted lava flows. Note: the blue triangle indicates direction and angle of dip (right at about 20 deg.)*

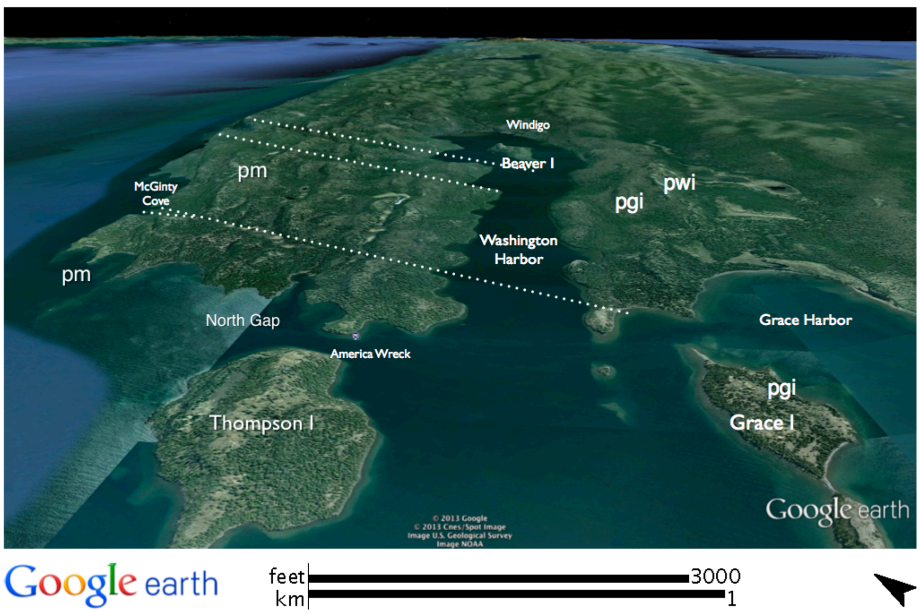


Figure 48: *Oblique Google Earth view of Washington Harbor, looking E.*

The Windigo area was the site of the last serious mining on Isle Royale, from 1890 to 1892. After failure and closure of mines farther 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, 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 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

After Windigo, we travel along a straight section of the coast following the *Hill Point Flow* (php). Muted by glacial deposits, the layered strata of lava flows shows in the geomorphology. Note the cross cutting faults (dotted lines in Figure 49), which are conspicuous in this area. These faults may have formed during deformation of the rift during its subsidence and during the Grenville Orogeny. The faults may have enhanced fluid flow, zeolite facies metamorphism, and copper mineralization. The faulted Windigo area is one place where some mining occurred.

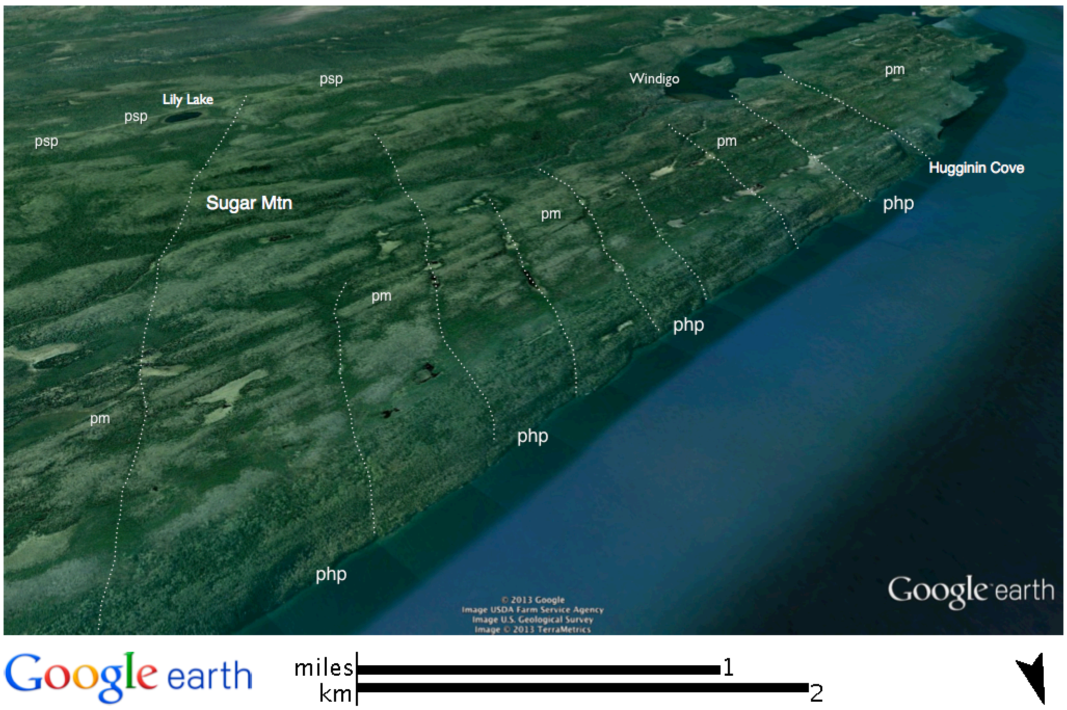


Figure 49: *Oblique Google Earth View, looking S from Hugginin Cove, directly across the stratigraphy, with flows dipping away from the view.*

With the flows dipping 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, forming imposing cliffs along the shore from Hugginin Cove all the way to Todd Harbor, a distance of about 24 km (15 mi). 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. The vertical fractures superimposed across the dipping strata are noticeable throughout the entire flow. From the west area of the flow to the east 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 Hugginin Cove.

LIDAR survey (Figure 50), from Seth De Pasqual, at Isle Royale National Park, reveals a striking topography which shows the dipping lava beds, and the prominent large lava flows, like the Hill Point Flow (php) and the Minong flow (pm) in this image of the region NE of Windigo.

Differential erosion of lava flows occurs when soft material, like what is found in the amygdaloidal flow tops and along faults is preferentially softer and evolves to a topographic low, while the massive flow interiors resist erosion and become topographic highs. The prominent N-S faulting of the lava layers is obvious, as are less extensively altered NE trending faults. Glacial deposits partially mask the lava layers, especially southward in the image, where the Grace Island (pgi) and Greenstone Flows (pg) are mostly covered, but protrude through glacial cover. Trails are plotted in yellow. This LIDAR data is advantageous for structural geology study because of its sensitivity to faults. It also reveals details of glacial (drumlins, outwash, kames, etc.) and postglacial features (shorelines, mine pits, dumps and roads).

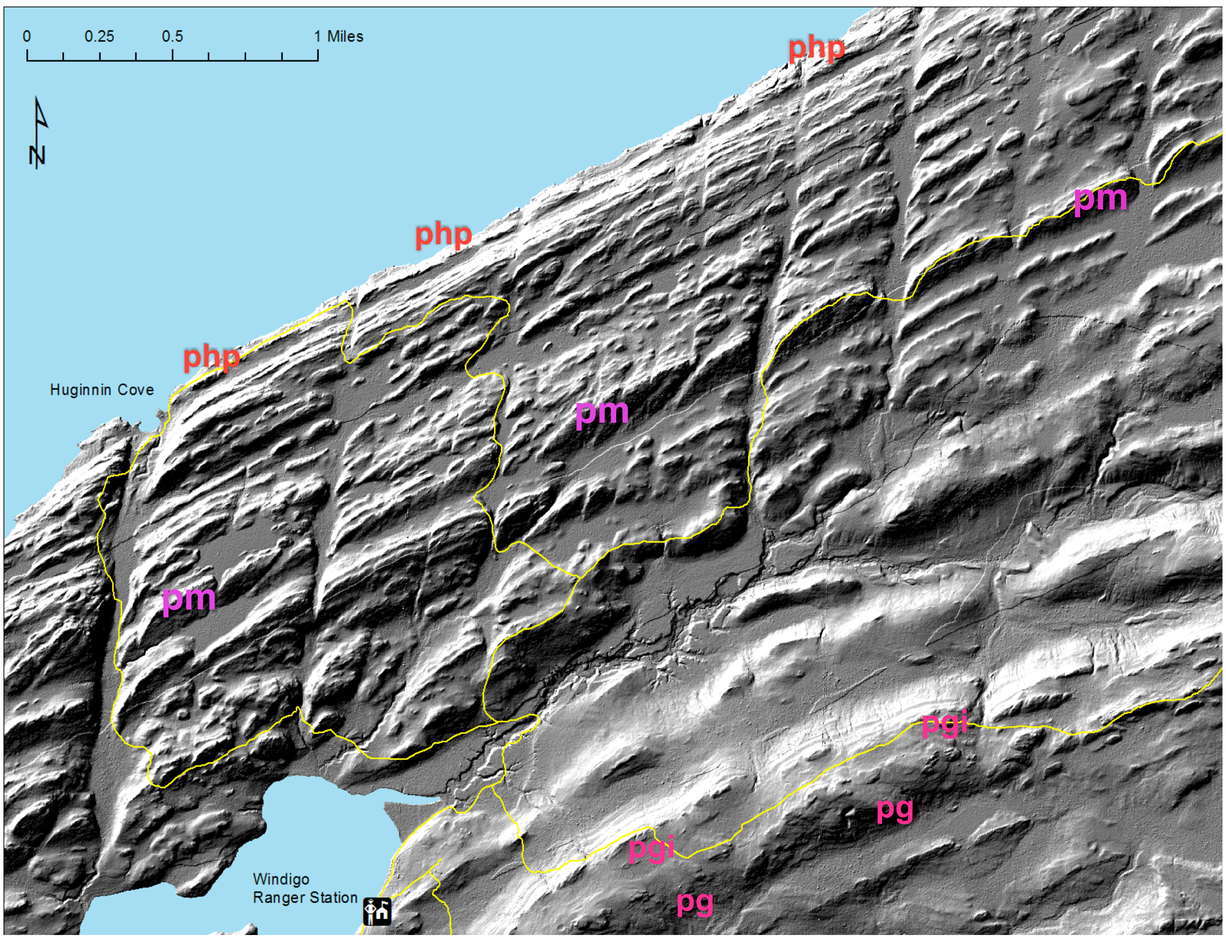


Figure 50: *LIDAR topographic image of comparable area to Figure 48, showing how LIDAR is advantageous for structural studies. (*Seth De Pasqual, NPS). *Trails in yellow.*

McCargoe Cove

At the midpoint of the island is McCargoe Cove, which is a linear, 3.2 km (2 mi) long inlet (Figure 51) that follows a large fracture zone, trending N 30º E to a campground site located along an ancient Native American portage route and near a 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).

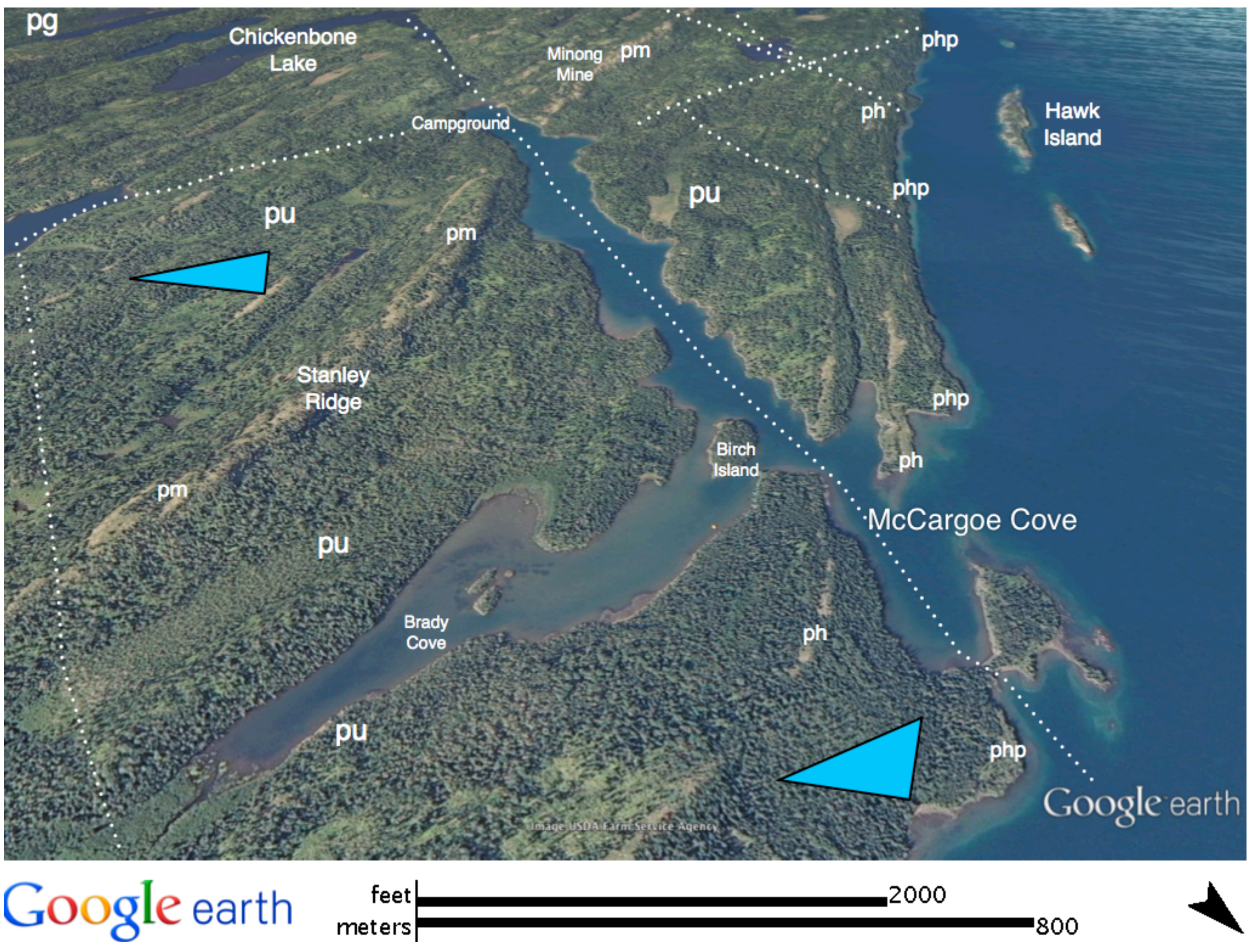


Figure 51: *Oblique Google Earth View of McCargoe Cove, looking SW. Lava layers are dipping to the left with steeper dips below and shallower ones above.*

LIDAR survey (nominal resolution of about 2 m; Figure 52), from Seth De Pasqual, at Isle Royale National Park, reveals a striking topography which shows the dipping lava beds, and the prominent large lava flows, like the the Minong Flow (pm) in this image of the region W of the McCargoe Campground.

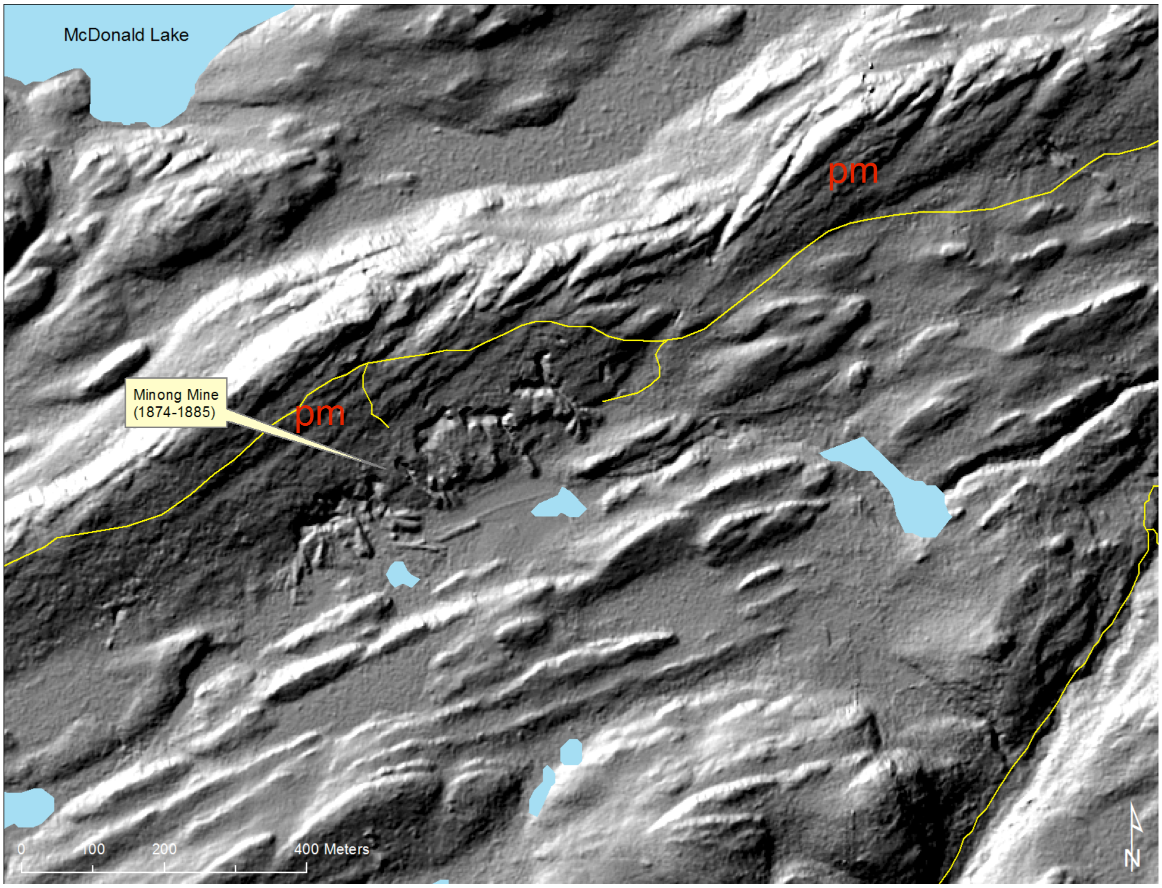


Figure 52: *LIDAR topography of the area west of the McCargoe Campground, showing the pits and dumps of the Minong Mine. These features cannot be resolved in DEM-based topo maps with lesser resolution.*

As in previous examples, increased erosion of lava flows in the amygdaloidal flow tops and along faults makes topographic lows, and flow layers and prominent NE trending faulting is obvious. Here the mine pits and dumps associated with the Minong Mine are also easily resolved, which shows how LIDAR can map topographic features that are difficult to resolve through vegetative cover. Copper mineralization in the area above a thick lava flow is common, perhaps due to the effect of channeling fluid, as the flow interiors are relatively impermeable and act as a hydrologic dam.

The Amygdaloid Channel

From McCargoe Cove, we will continue to the NE, passing through the Amygdaloid Channel (Figure 53). 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, 3.2 km (2 mi) E of the station, was, beginning in 1906, a private residence and fishery.

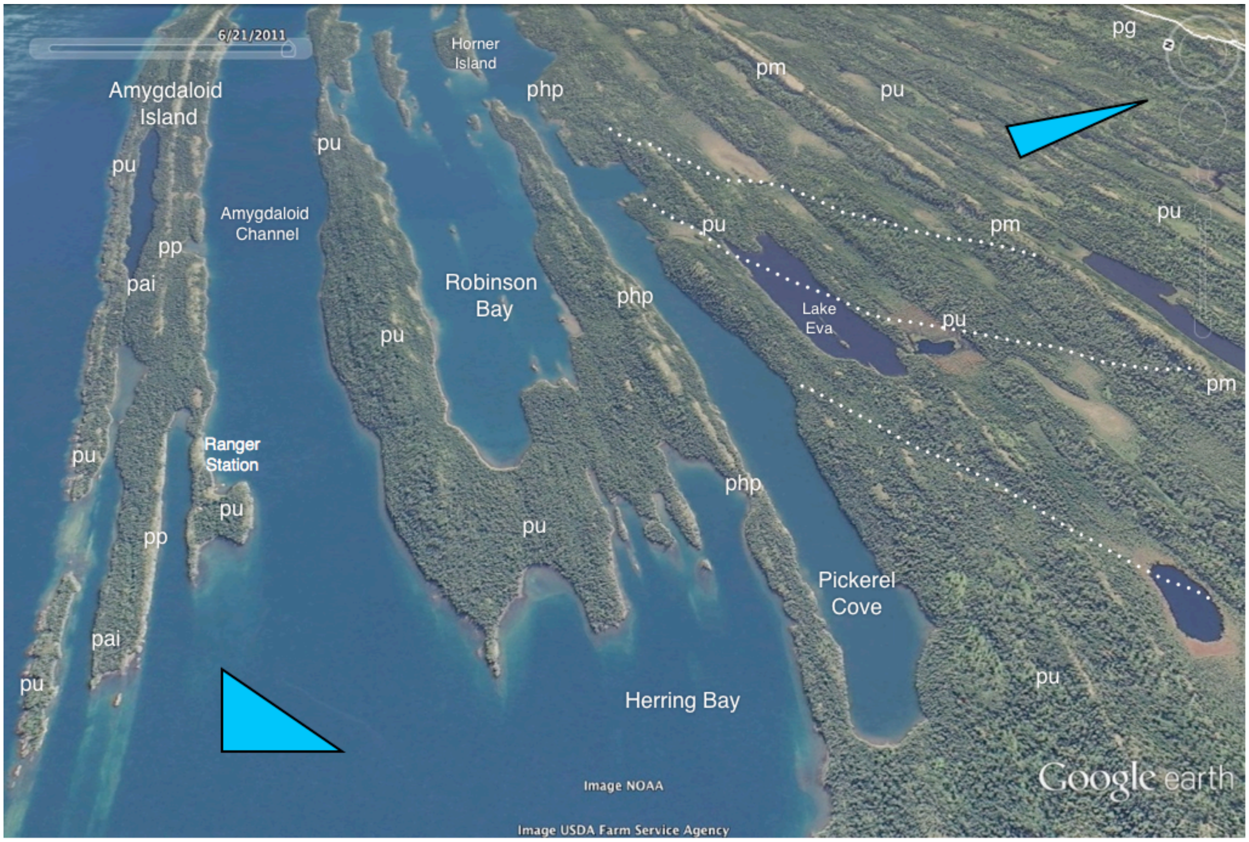
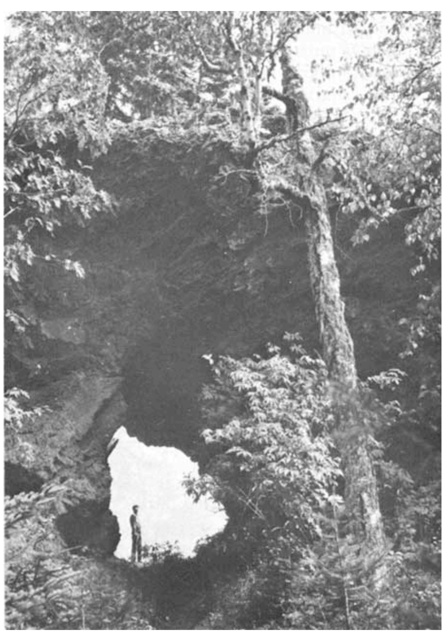


Figure 53: *Oblique Google Earth View of the Amygdaloid Channel, looking NE, with Amygdaloid Island to the left and beds dipping to the right at increasingly shallow angles.*



As we travel through the Amygdaloid Channel, drowned ridge and valley topography of Isle Royale will become very visible, with more resistant lava flows holding up linear islands. Amygdaloid Island is the site of mafic volcaniclastic deposits (pp on Amygdaloid Island in Fig 53). It also has a sea arch (left) which is located almost directly opposite the keyhole. (Fig 54). Shipwrecks are numerous on the many "reefs" found all around the NE end of Isle Royale. Opposite Crystal Cove on the south side of Amygdaloid Island is Belle Isle, a beautiful campground accessible only by boat and canoe, located on the site of a resort that operated in the 1920s, when it served the grand lake steamers of that period.

Figure 54: *Sea Arch on Amygdaloid Island.*

Blake Point—a key locality

As we round the tip of Isle Royale to Blake Point (Figure 55), we are moving up in the stratigraphic sequence. 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 Earth's largest lava flow**.

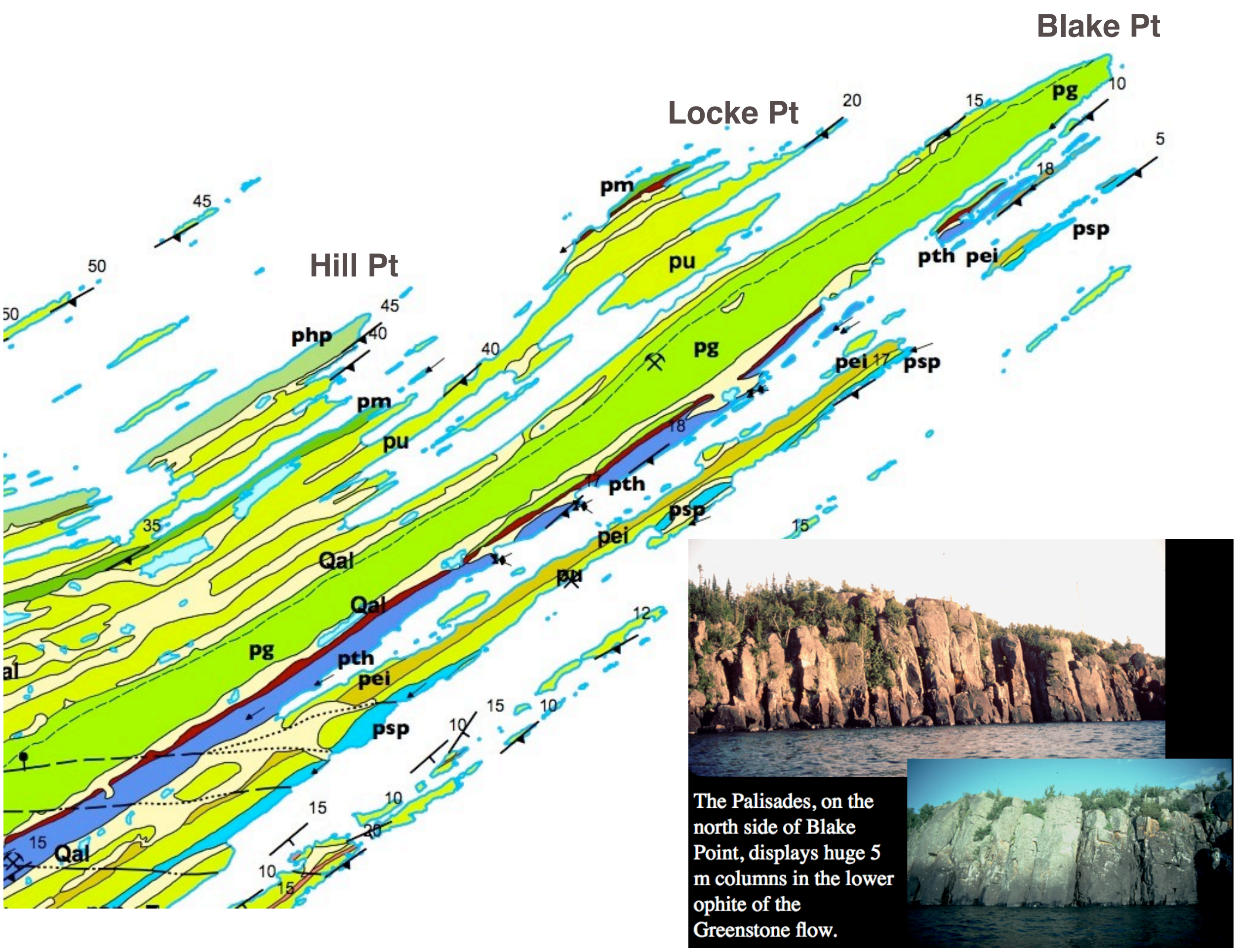


Figure 55: *Blake Point segment of Geologic Map of Isle Royale (Huber, 1973). At right, photos of columns at the Palisades on the anti-dip slope just west of Blake Point.*

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.

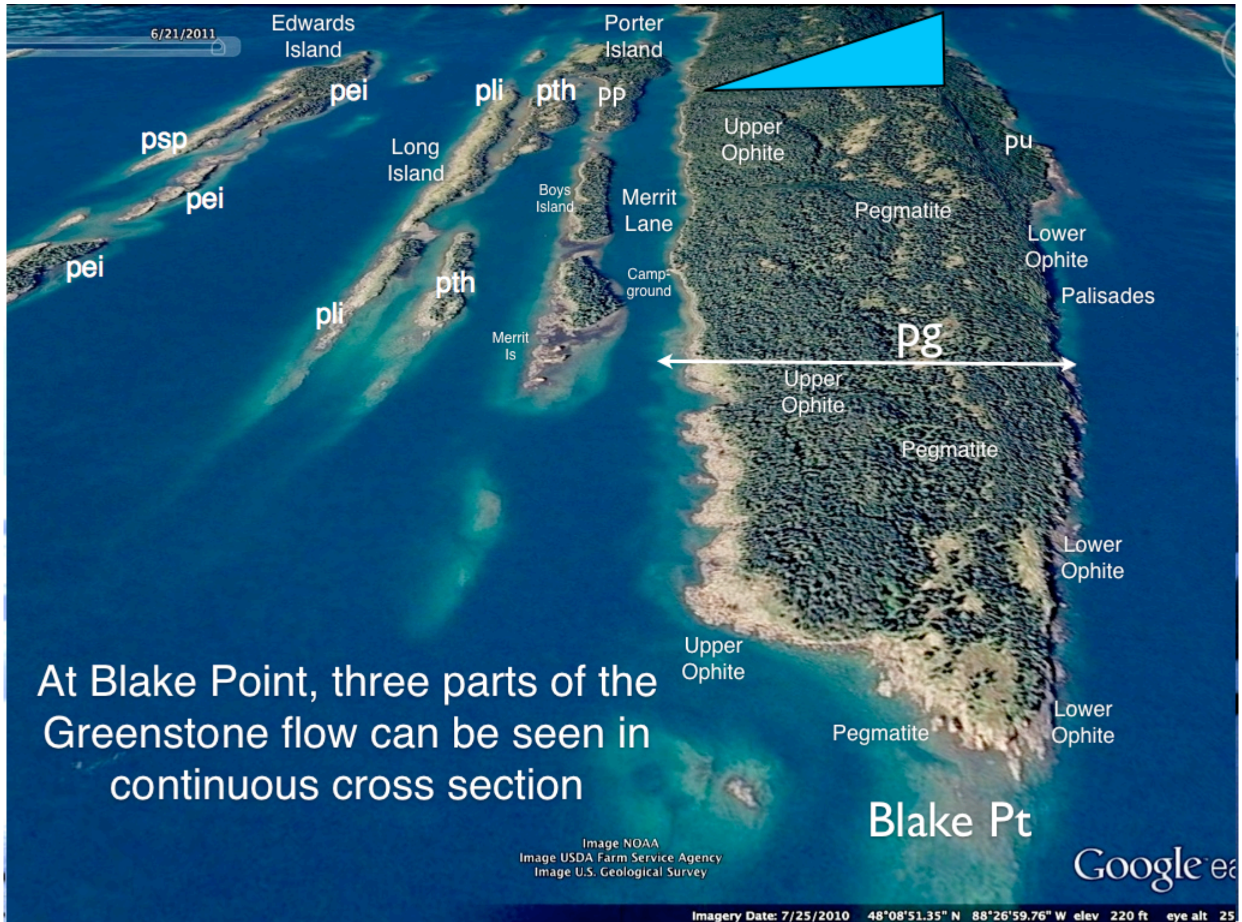
--Longo 1984

The shoreline around Blake Point offers the **best view of the Greenstone Flow**, better than any other sites at Isle Royale or the Keweenaw Peninsula (Figure 56). On the way to the campground in Merrit Lane, the starting point of our Blake Point walk, we will pass 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 poorly-developed 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 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.

Figure 56 (next page): *Oblique Google Earth View of Blake Point, looking SW, with beds dipping about 25 degrees to the SE. Most of the large land mass is underlain by the Greenstone flow, and its three distinct layers can be seen and outlined here better than anywhere else. Below is a photo from just offshore at Blake Point, at the water level.*



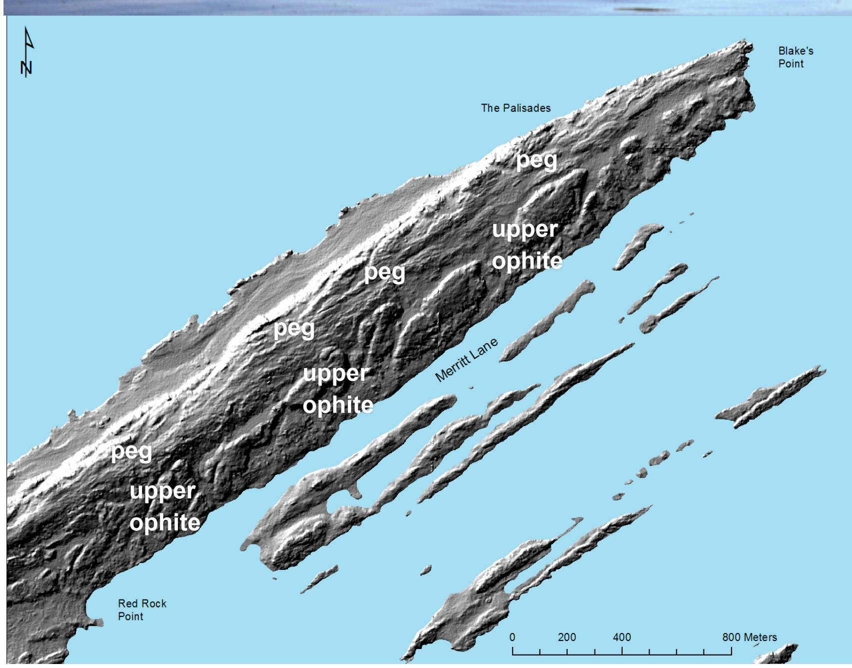


Figure 57: *LIDAR survey of Blake Point area. Most of the land imaged here is the Greenstone Flow and this image is remarkable in showing indications of layering, and also the different character of layers. On the south side of the main land body, facing Merrit Lane, are eroded remnants of the Upper Ophite layer, with its columnar jointing and dipslope aspect. On the North side there is a steep slope (Palisades) where the Lower Ophite is exposed on an antidip slope. Between these two layers lies the pegmatite of the Greenstone, which is 75 ft thick and which appears to be eroding in an irregular, wavy pattern. It is remarkable that the LIDAR shows information about these three layers. This information is valuable because we typically do not have very good exposures. Seth DePasqual, IRNP.*

Passage Island and Gull Rocks

Farther to the NE, off of Blake Point, **Passage Island**, 3.5 miles from Blake Point, and **Gull Rocks**, 8.7 miles away (Figure 58), are both built of rift lava, including the Greenstone Flow, which is found at the E end of Passage I. These are the most easterly subaerial exposures of the PLV near Isle Royale.

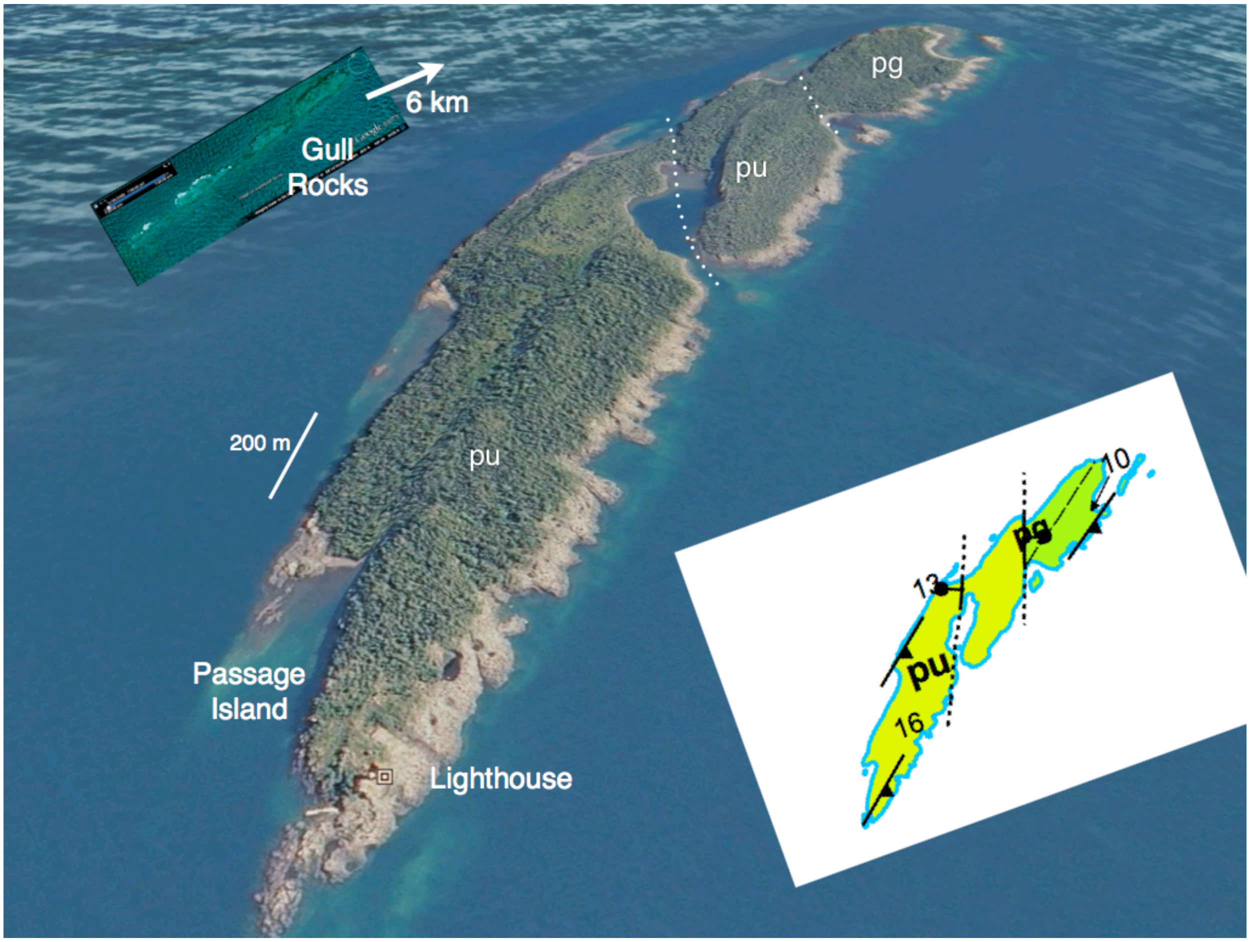


Figure 58: *Oblique Google Earth View of Passage I and Gull Rocks (same scale, but offset). To the right is a piece of the Isle Royale Geologic Map (Huber, 1973).*

Snug Harbor

At this wonderful location in Rock Harbor, the National Park Service has chosen to concentrate its Isle Royale services and concessions for visitors. The Lodge and Visitor Center is where the field trippers will sleep, catch their boat rides and have evening discussions. The location coincides with two of Huber's named lava flows: the Scoville Point (psp) porphyrite and the Edwards Island Trap (pei) (Figure 59). This location allows boat access to both Tobin and Rock Harbor, as well as foot trails to Scoville Point, Mount Franklin, and Daisy Farm, and is a safe harbor.

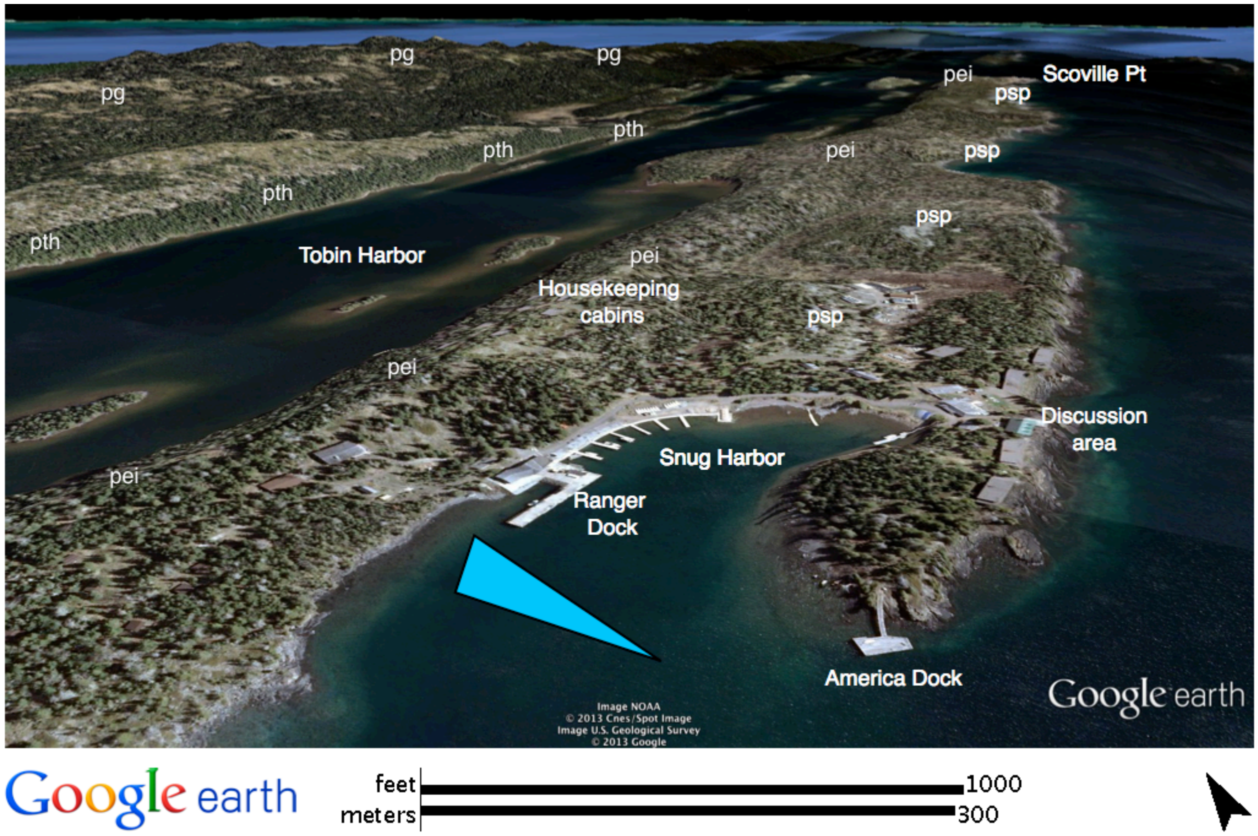


Figure 59: *Oblique Google Earth View of Snug Harbor, Looking NE.*

Scoville Point

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 (Figure 60). 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. We will take the **Stoll Trail (white line in Fig. 60)**, which goes along the shore of Rock Harbor. Along here, we will see 5000-year-old Nipissing shorelines and glacially grooved outcrops of the Scoville Point flow. Outwash cover here is meager, but kettle lakes and morainal zones occur. On the upper map in Fig. 60, GPS markers identify the points of interest/inquiry. 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 5000 yrs BP 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).

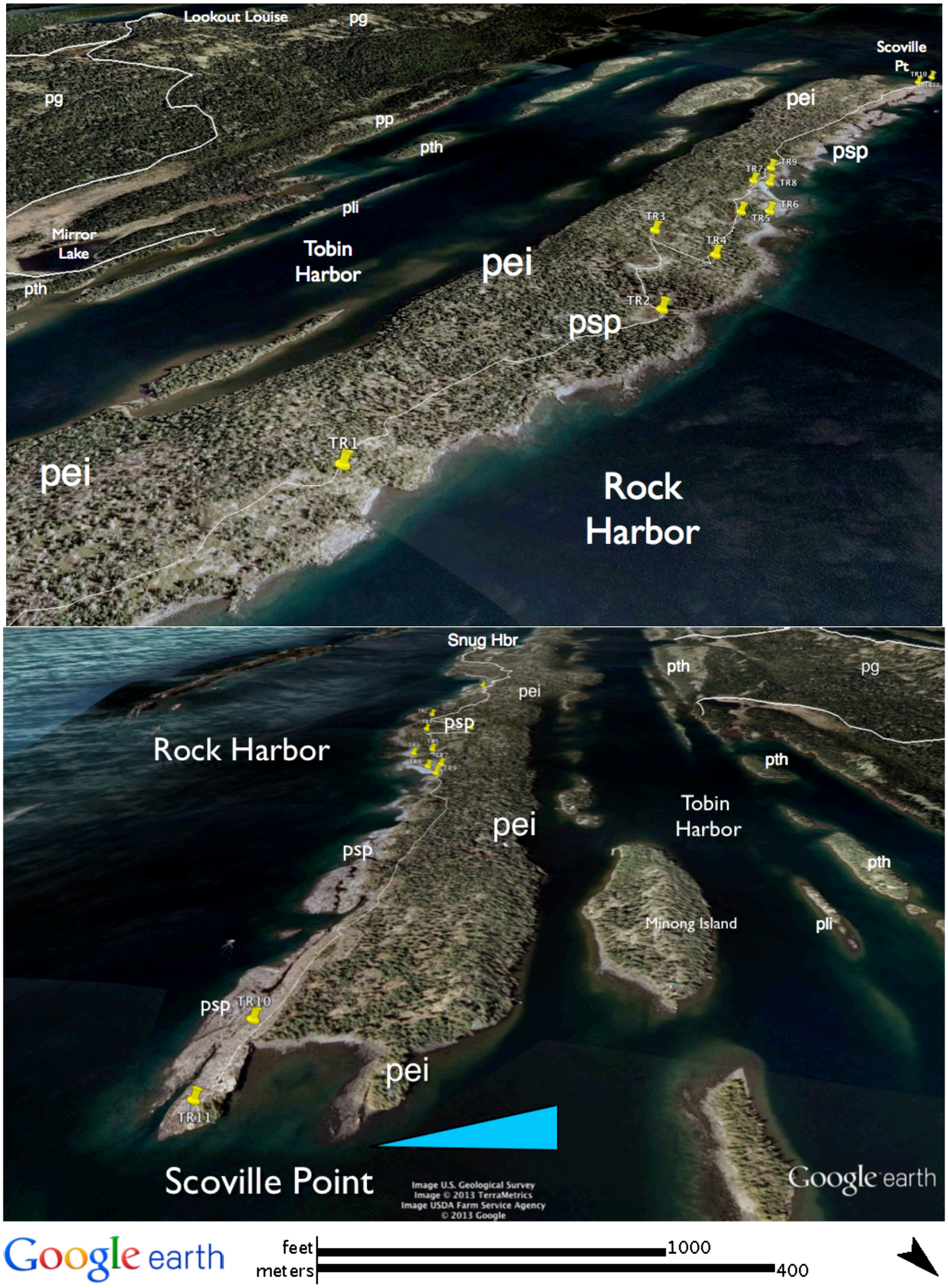


Figure 60:

Oblique Google Earth Views of Stoll Trail to Scoville Point looking N and SW. Trail is a white line, and marked points are GPS marked locations.

As we near Scoville Point, the Scoville Point flow (psp) 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* (Figures 61, 62).

Figure 61: *Shoreline exposure of Edwards Island flow near Dashler Cabin, Scoville Point (entablature joints in pei). This view shows a vertical cross section of the joints on the antidip slope.*

Figure 62: *Columnar joints in the Edwards Island Trap (pei) at the Dashler Cabin near Scoville Point. This view is perpendicular to the joints and shows their polygonal forms. The scale of the polygons is about 7-10 cm.*

While looking at the columnar joints in the Edwards Island flow (pei) at Scoville Point near the Dashler Cabin (Figs 61, 62), we should discuss whether this jointing pattern is indeed entablature jointing in the sense of Long & Wood (1986), and whether we should infer that the Edwards Island flow was indeed cooled in part by being flooded by surface water. (see also section on columnar jointing above)

We will return to the lodge 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 much ore was found (Rakestraw, 1965).

Lookout Louise and Monument Rock

From Mirror Lake to Lookout Louise, we will hike about 1.6 km (1 mi) long and 85 m (280ft.) up (Figure 63). We will begin on the Tobin Harbor flow, but after passing the Lake we will walk

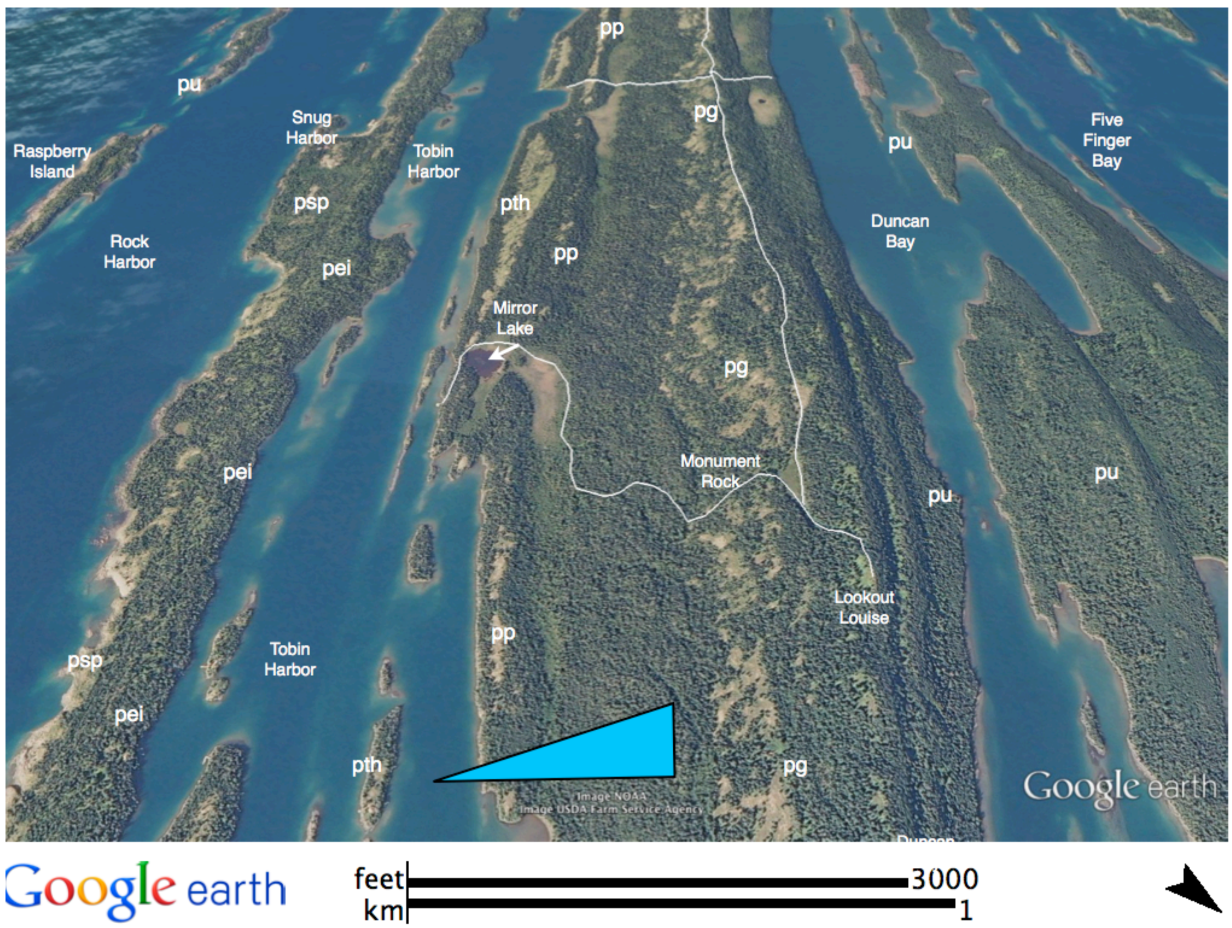


Figure 63: *Oblique Google Earth View, looking SW at Lookout Louise. Trails plotted in white.*

on the Greenstone Flow, following a dip slope up to Lookout Louise.
At about the halfway point, the trail passes Monument Rock (Figure 64), an individual column from the colonnade of the upper ophite that is exposed as an erosional remnant.

Figure 64: *Woodcut from Ackerman Lithographers, New York, showing Monument Rock in the 1840s. This old view is advantageous because the modern forest blocks an overall view like this one.*

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.

LIDAR topographic survey (Figure 65) came from Seth De Pasqual, at Isle Royale National Park. It reveals a striking topography which shows the dipping lava beds. Prominent large lava flows, like the Greenstone flow (pg) are obvious features in this image. Differential erosion of lava flows occurs when soft material, such as that found in the amygdaloidal flow tops and along faults, is preferentially removed and makes a topographic low, while the massive flow interiors resist erosion and become topographic highs. In this image we can also see the different layers of the Greenstone flow, including the Upper Ophite, the Pegmatite, and the Lower Ophite.

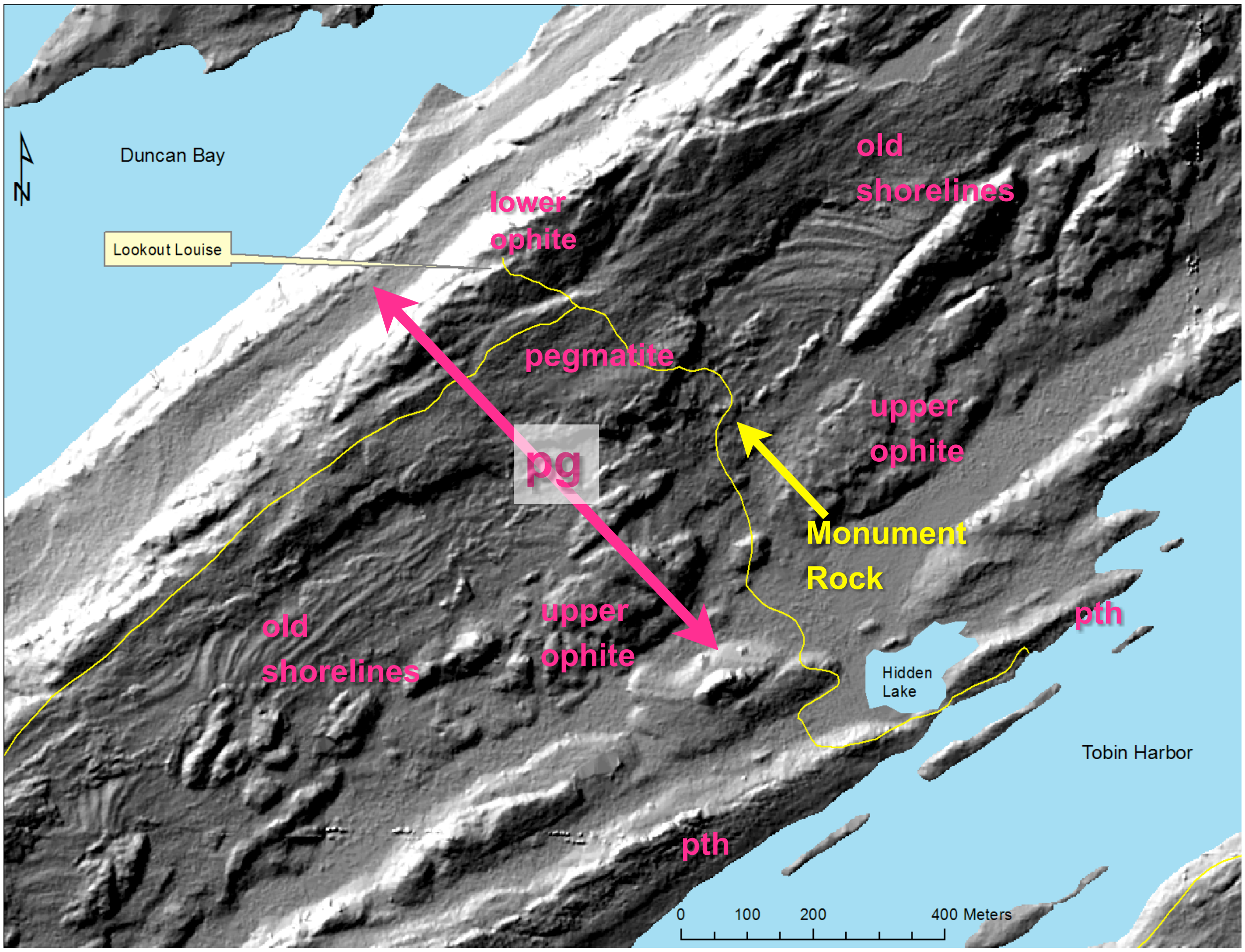


Figure 65: *Shaded LIDAR topographic map of area near Lookout Louise, Isle Royale. This image shows what are thought to be ancient lake shorelines, which demonstrate that Monument Rock, far from the shore today, was once close to the lake shore and could have had a sea stack aspect. The image also shows layering textures in the Greenstone Flow which could reflect the Upper and Lower Ophite and the Pegmatite. Image from Seth De Pasqual, IRNP. Trails are shown in yellow.*

Post glacial shorelines can be seen in parts of this image also, and including in the vicinity of Monument Rock, itself far from the current shoreline. This arrangement suggests that the freestanding form of Monument Rock is consistent with its formation as a "sea stack", and a remnant of the upper ophite of the Greenstone Flow, which is mostly eroded from this place. This interpretation was first suggested by N.K. Huber.

Red Rock Point and Porter Island

At Red Rock Point (Figure 66), we will pass excellent examples of entablature jointing of the upper part of the Greenstone flow. The basalt of the entablature is melaphyre ("trap"), very fine grained. The curvi-columnar nature of a few of the columns resembles some of the Columbia River basalt descriptions (Figure 25). Long and Wood (1986) suggest that entablature jointing results when extensive floods that are created from disrupted drainages cause dramatic quenches of solidifying flood basalts.

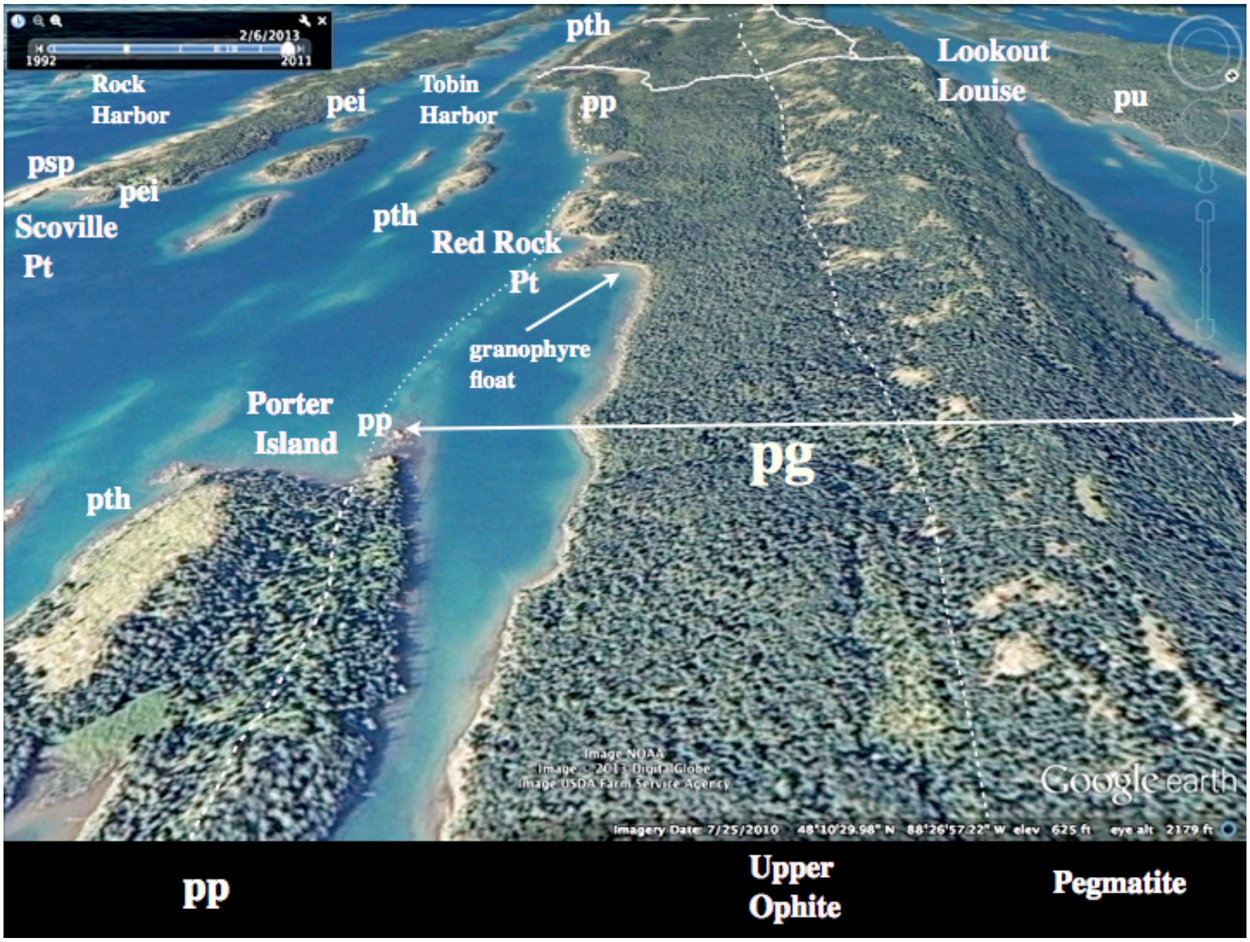


Figure 66: *Oblique Google Earth image of eastern parts of Tobin Harbor, looking SW.*

Around the corner of Red Rock Point is a feature that Longo (1984) describes as follows:
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 stratiform 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

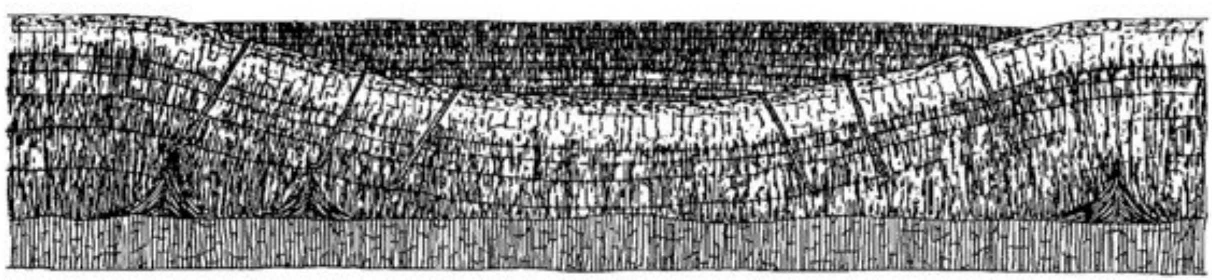


Figure 67: *Sag-Flowout structure, from McKee and Stradling (1970).*

Longo (1984) interprets the auto intrusion to be related to a sag flowout structure (Figure 67), 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 (see figure, above). 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. The origin of granophyres in sills are not well understood, and Figure 68 from Marsh *et al.*, 1991 shows some of his ideas, including existing silicic material which was carried in during intrusion.

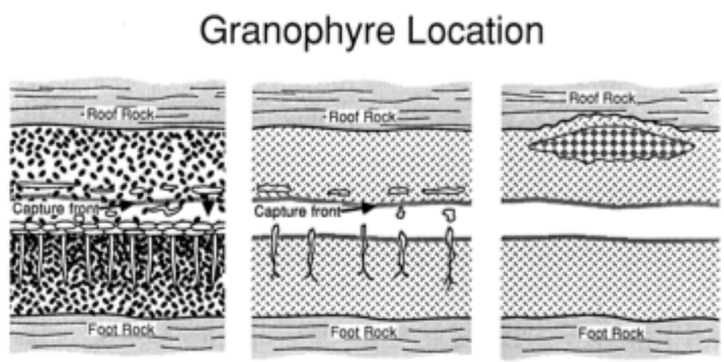


Figure 68: *Some possible positions of granophyre within sheet-like intrusions. the left two panels show residual fluids forming lenses. The panel at right shows an accumulation of granophyre at the upper contact which may have existed upon emplacement (Marsh et al., 1991).*

We will also pass Porter's Island, which includes exposures of a fragmental rock that Huber (1973a) interprets as pyroclastic (pp). The same unit can be found on the Tobin Harbor shoreline opposite Newman Island. However, according to Longo (1984), these exposures may represent the fragmental top of the greenstone flow. The breccia unit, which is about 1-5 m (3.3-16.4 ft.) thick, contains rounded and semirounded fragments of the Greenstone flow set in a finer matrix that has amoeboid-shaped, agate amygdules. Longo did an extensive petrographic 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 undercooled 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).

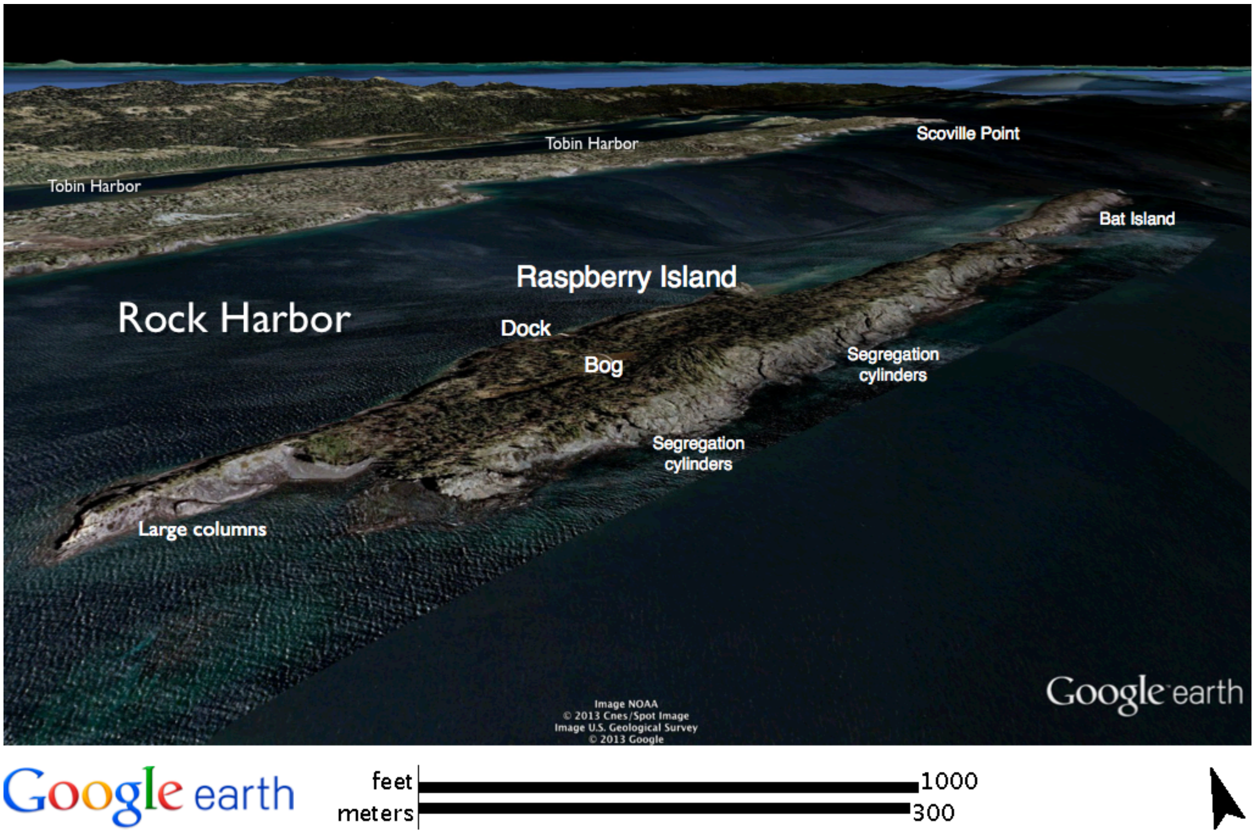


Figure 69: *Oblique Google Earth Image of Raspberry Island, looking N.*

Raspberry Island

At Raspberry Island (Fig 69), about 0.5 km (0.3 mi) SE of Rock Harbor Lodge, we spend the 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). At least since 2000, and in increasing amounts, low lake levels have made these exposures more numerous and accessible. One of many small islands along the S side of Rock Harbor, Raspberry Island is three ophitic flows of the undivided PLV (**pu**) dipping 15° SE. The uppermost of these flows is extensively exposed on a wave-washed dip slope. This shoreline receives strong storm waves and, fortunately has wave-washed exposures about 1 km (0.6 mi) long. They expose the flow interior, with the top of the flow eroded away and the base buried. 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 W end 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 (Fig 70).

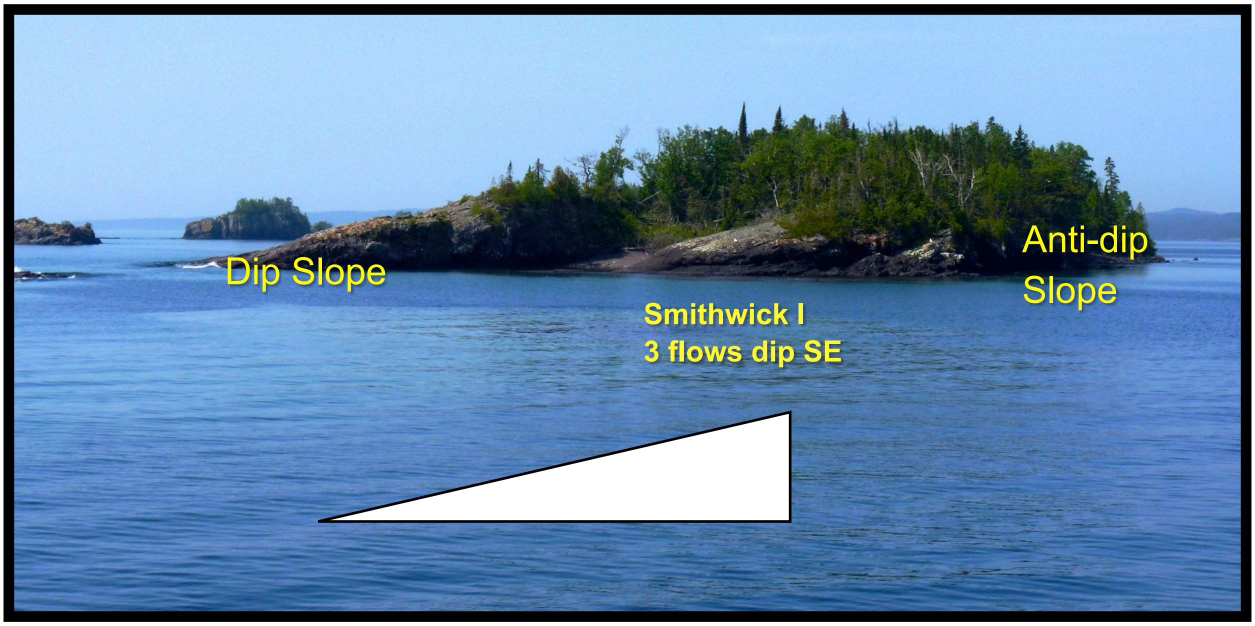


Figure 70: *Photo of Smithwick Island taken from Raspberry Island, showing a gently dipping sequence of three lava flows with obvious dip and anti-dip slopes. The dip of 20-25 degrees to the SE is typical of Isle Royale.*

The point on Raspberry Island facing the Channel is underlain by the oldest of the three flows on the island. We will walk on a dip slope that shows some of the jointing pattern we will also observe on the SE sides of Davidson and Smithwick Islands. Next, we will head to the SE corner of the island to observe some poorly-developed columns in the uppermost Raspberry Island flow, before looking at vesicle and segregation cylinders, and vesicle sheets or pegmatites.

On the wave-washed SE shore are two zones of exposures of vesicle cylinders. Paces (1988) describes *vesicle cylinders* (Goff 1996) in the PLV:

Vesicle pipes are elongated, tube-like structures, 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

Figure 71: *Segregation cylinders standing up as resistant to wave washing, forming small mounds separated by a few feet. The flow is tilted about 20 degrees to the left in this view.*

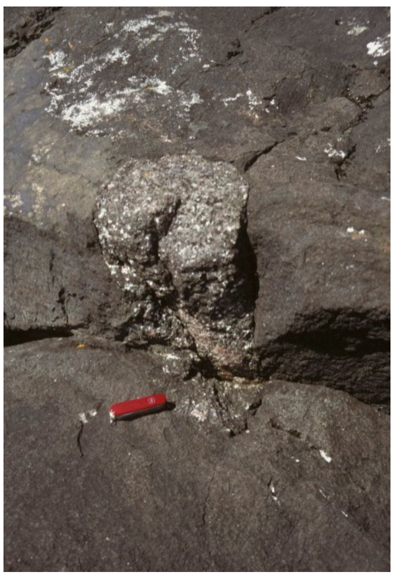


Figure 72: *Vesicle cylinder or segregation cylinder from Raspberry Island, showing its cylindrical shape in 3 dimensions.*

Here at Raspberry Island, exposures of vesicle cylinders (Figures 71, 72) show a fairly regular spacing, 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 diminished by the proximity to the vesicle cylinder.

Vesicle cylinders (Goff, 1996) 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, by Paces (1988) of the PLV on the Keweenaw, by Marsh *et al.* (1991) of solidification in sheet-like basaltic bodies, and those from Hon *et al.* (1994) and Self *et al*. (1998), are illuminating.

Also featured conspicuously along the E shore of Raspberry Island are *slickenside surfaces*. A study of the fault slickenfibers allowed Witthuhn-Rolf (1997) to use geometrical and statistical methods to define the kinematics of the closing of the rift (Figure 73). In Witthuhn-Rolf's study,

Figure 73: Equal area rose diagrams of the trend of slickensides on reverse faults on island along Rock Harbor, Isle Royale National Park (Witthuhn-Rolf, 1997).

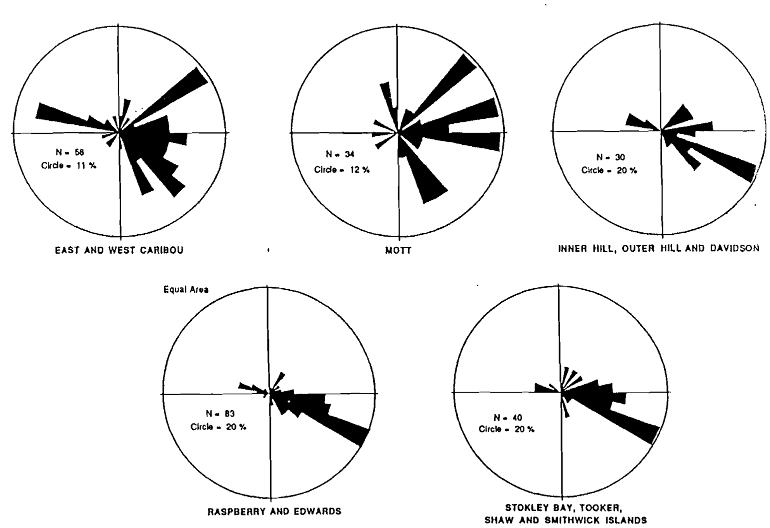


***Figure 74:** Epidote-coated slickenside surfaces along faults exposed in Raspberry Island lava flows.*

Raspberry and Edwards Islands offered one of the largest populations of measurements. 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 predominately N-S trending structures measured in the PLV on the Keweenaw Peninsula.

Figure 75: *4 cm thick vesicle sheet or pegmatoid layer within horizontally fractured section of basaltic lava flow at Raspberry Island.*

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 (vesicle sheets: Figure 75) occur.

Paces (1988) describes them:

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 upperflow surface. Both vesicle cylinders and pegmatoid layers contain significant void space in the form of vesicles and gas pockets and contribute to the permeability of the lava flows.*

--Paces 1988

The origin of the pegmatoids is likely 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 75).

It is possible that Keweenawan flows preserve the inflated nature of ponded flood basalts well because runout of inflated flows, such as can occur on sloping volcanoes, is prevented by the rift-filling geometry.

Tookers and Davidson Islands

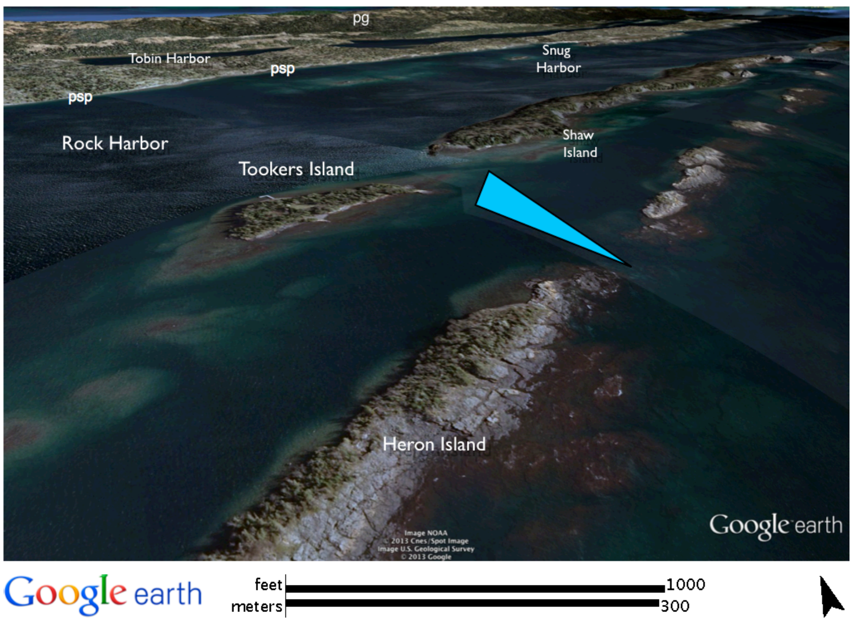


***Figure 76**: Oblique Google Earth Image of Tookers I looking N.*

One of many small islands strung out along the south side of Rock Harbor, Tookers (Fig 76) has some nice exposures of lava flow tops on its south side. Flow tops are amygdaloidal and less resistant to weathering. Flow interiors are massive and featureless, except they nearly always have at least poorly-developed columns.

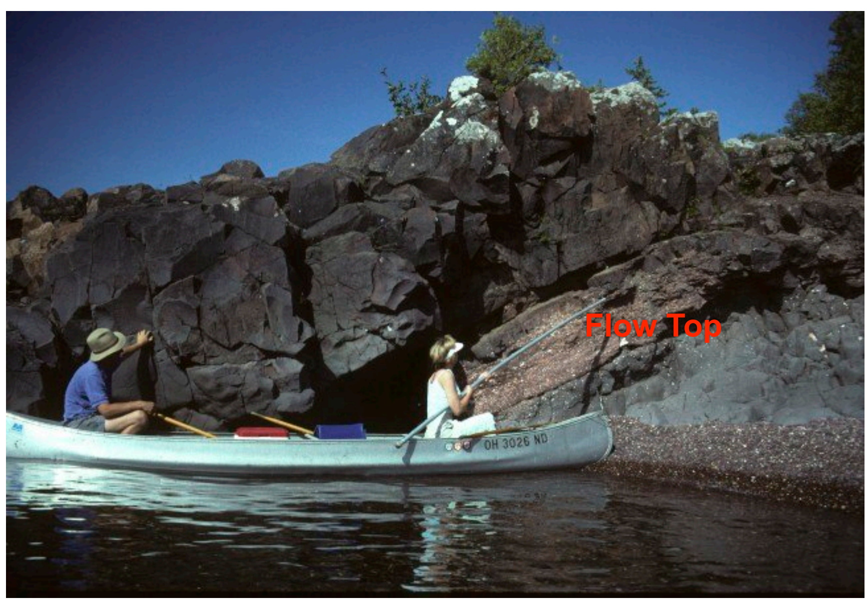


***Figure** 77: Exposure of contact between two lava flows, showing a black massive, relatively fresh upper flow, in contact with a reddish altered amygdaloidal flow top. Photo from 7 Mile Point, Keweenaw Peninsula.*

Figure 78: *Wave-washed lava surface on SE corner of Davidson Island showing polygonal jointing pattern with 2-4 m diameter polygons. Such patterns may be seen on many ophitic flows on Isle Royale.*

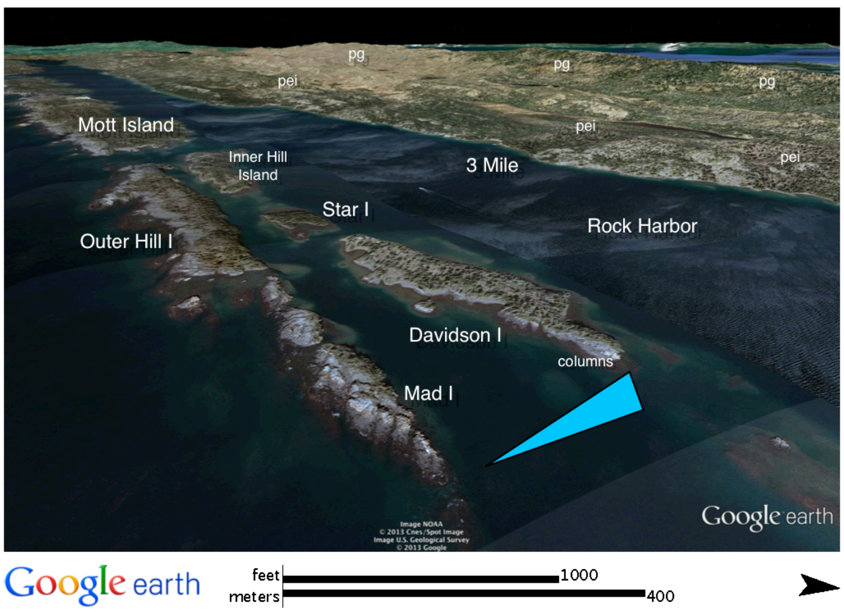


Figure 79: *Oblique Google Earth Image of Davidson I looking W.*

On Davidson Island (Fig 79) is the Boreal Research Center, a residence for researchers at Isle Royale. 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 (Figure 78).

The wave-washed shoreline has exposed a surface perpendicular to the columns, which are 2-3 m (6-10 ft.) across. Large columns seem to be a regular feature of ophitic flows at Isle Royale.

Mott Island

We will stop at Mott Island (Figures 79, 80) 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.

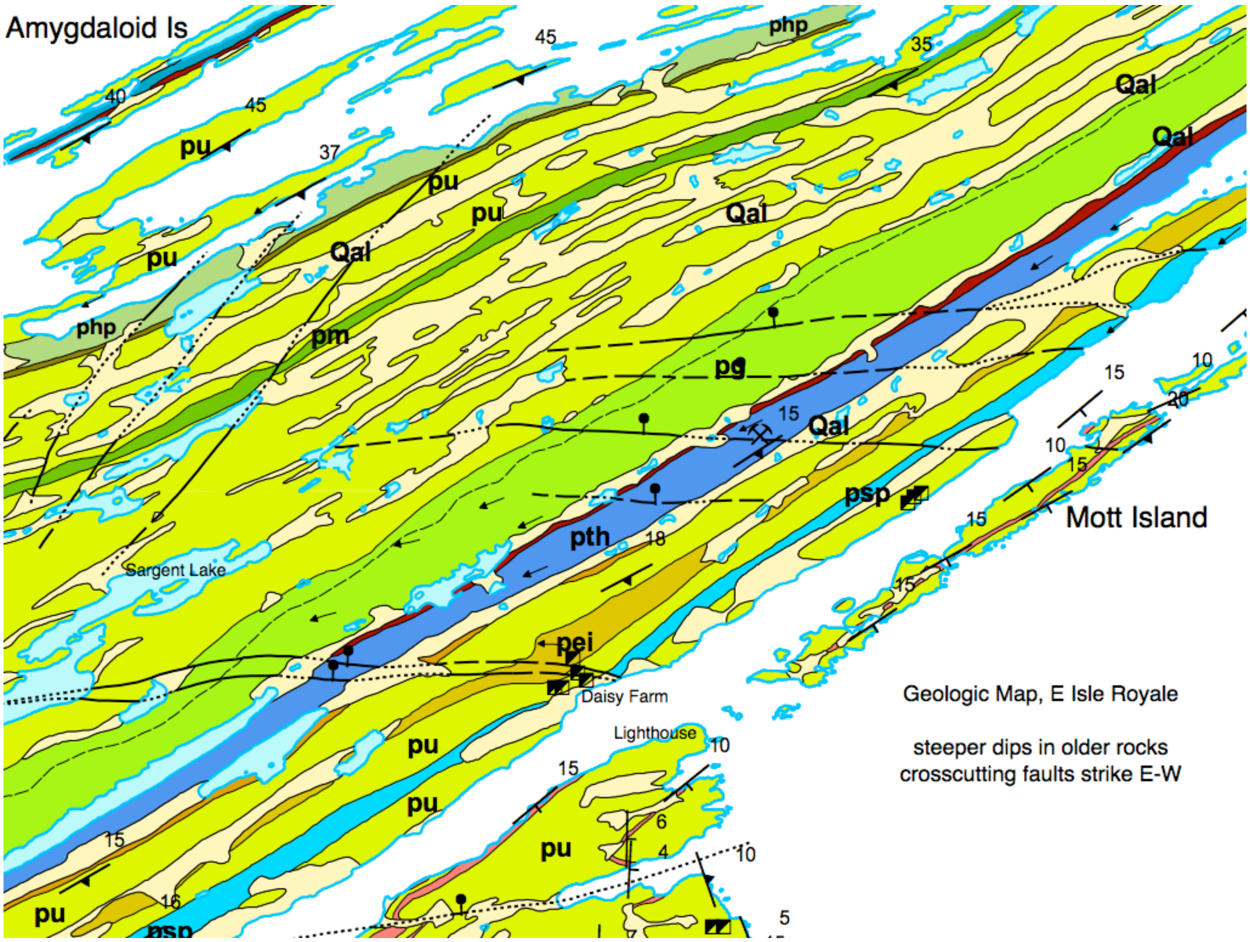


Figure 80 *: Detail of Isle Royale Geologic Map (Huber, 1973) which shows part of Eastern Isle Royale including Mott Island. The brown colored unit is the interflow sediment we will visit.*

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).

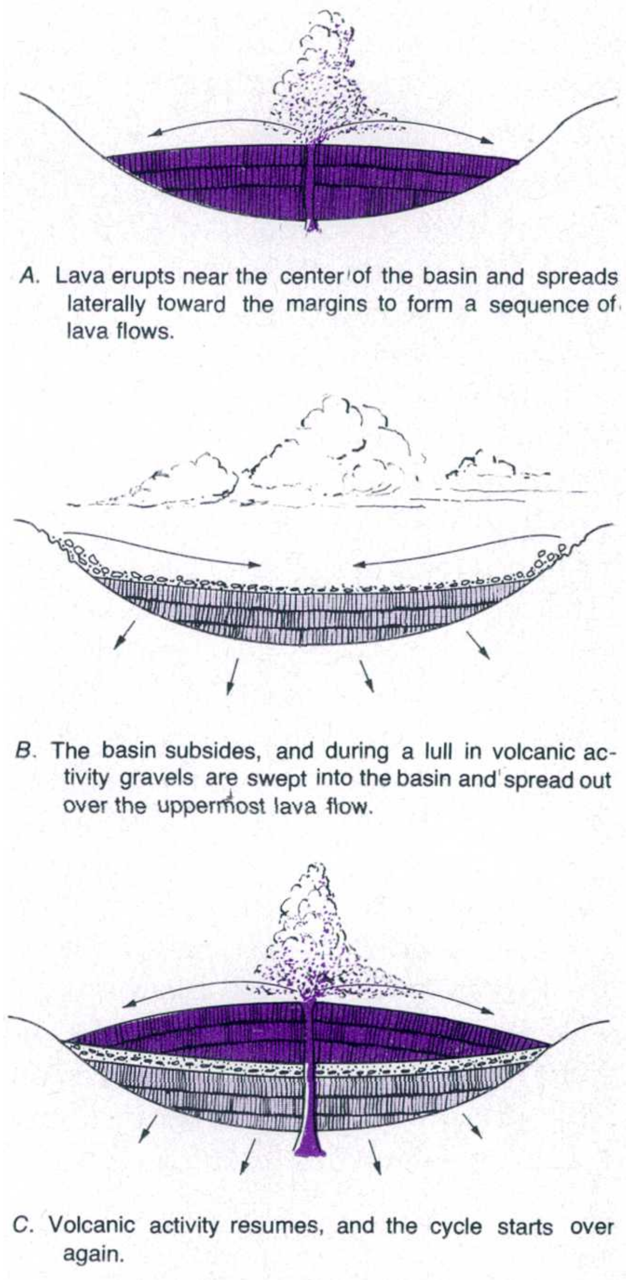


Figure 81 *: Cross section of rift valley showing accumulation of lava from fissure vents in the Center of the rift, sometimes alternating with infilling sediments from outside the rift (Huber, 1973).*

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 or 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

*this quote refers to the Keweenaw, where Paces worked--on Isle Royale directions are reversed.

Edison Fishery and the Lighthouse

The Fishery (Figure 82) 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.

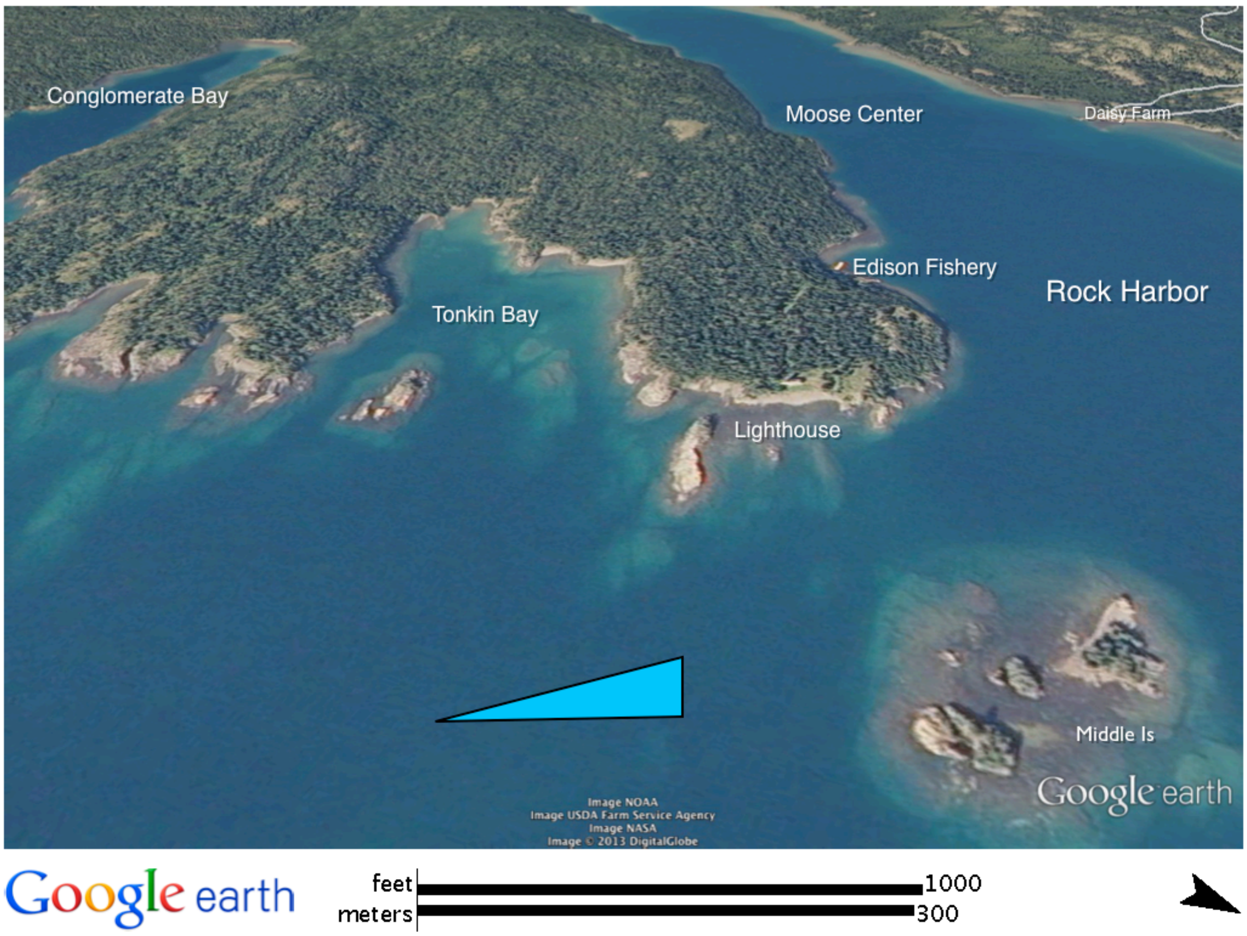


Figure 82 *Oblique Google Earth View of Edison Fishery and the Lighthouse looking SW.*

The lavas that underlie the site of the fishery and the lighthouse are a sequence of 45-50 ophitic flows, which occur between the Scoville 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 (but not to collect!) Isle Royale 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. 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 (chlorastrolite or “greenstone”), quartz (agate), and thomsonite (see section on Amygdaloid). 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 lower mineralization temperature may partially explain the lower abundances of native copper on Isle Royale than those found on the Keweenaw Peninsula. This metamorphic event reflects a large hydrothermal (hot, geothermal brine which was pumped through the porous flow tops and conglomerates of the Portage Lake Volcanics for years after the volcanism ended (Jolly, 1972).

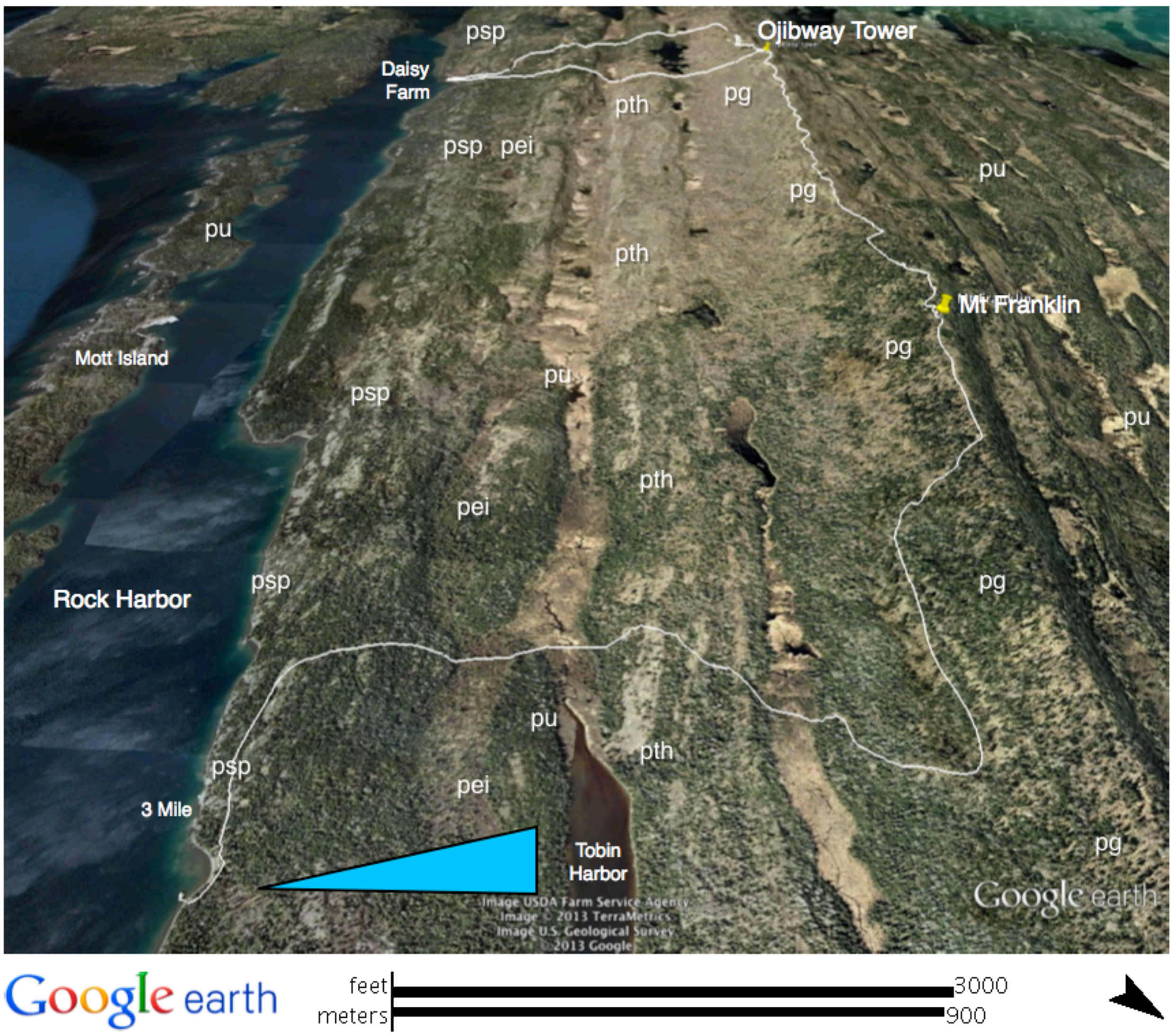


Figure 83: *Oblique Google Earth View of Mt Franklin and Ojibway tower, looking SW. The view looks directly along the strike of the lava flows, which are dipping gently to the east.*

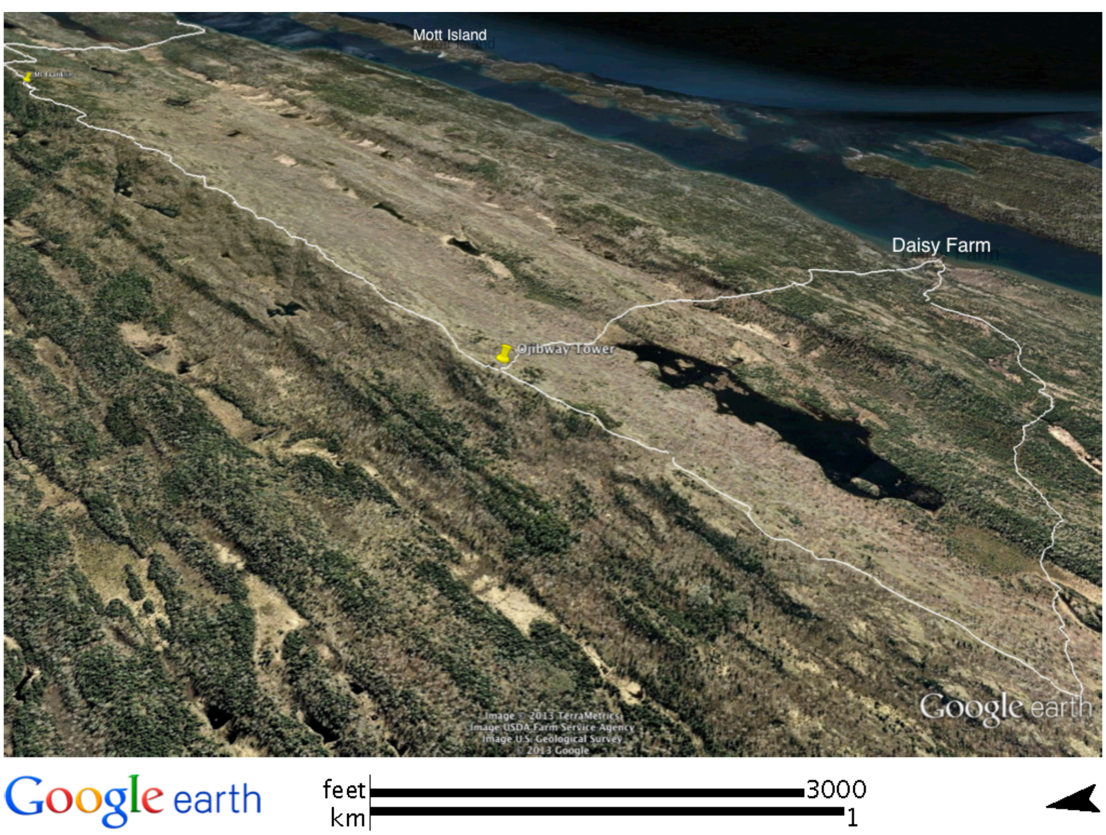
Franklin and Ojibway

The Mount Franklin Trail begins 0.3 km (0.2 mi) W of Three Mile Campground (Figure 83).

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 (l080 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.

Figure 84: *Oblique Google Earth view of Ojibway Tower and Daisy Farm, looking E.*



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.

From the tower we will descend to the Daisy Farm Campground via the Mount Ojibway Trail. (Figure 84). 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) slope 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).

What to take home

After a journey of several days, what are the Earth sciences messages that stick with you? What are the globally significant issues that stand out? What is uniquely interesting about the place and time that is recorded in rocks here? What big ideas emerge from this geology?

1. Rodinia, a Proterozoic supercontinent, blanketed Earth's mantle, and the higher heat flow of 1.1 billion years ago triggered huge volumes of hot magmatism from the mantle, first giving rise to ultramafic dike swarms, then basalts in huge quantities. These dikes split the great supercontinent, but a nearby continental collision (Grenville) was apparently what prevented the formation of an ocean basin.

2. Large Scale Flood basalts occurred for a brief period, lasting only a few million years in the Keweenaw and Isle Royale. These eruption rates, much higher than average, apparently were driven by a mantle plume. They are similar to other continental flood basalts and mafic large igneous provinces (LIPs) in these respects. There are volcanic, plutonic, and sedimentary elements to the mantle plume and rifting (see map, below).

3. Ponding of magma happened in a great crack—the midcontinent rift basin, locally called the Keweenaw Rift. Because lava solidifies by heat loss from the lower surface where it is contact with the cold ground and the upper surface where it is in contact with the air, thick lava flows cool much more slowly than thin ones, because the massive flow interiors, far

from the top and bottom of the flow, are shielded from heat loss. The Keweenaw Rift has flows as thick as 1200 ft, thicker than those found in other mafic LIPs.

4. The *in situ* differentiation within the largest lava flows may have occurred because of the existence of a large ponded magma body (not unlike a magma ocean) within the rift valley for perhaps up to a millennium. This results in pegmatite or dolerite horizons within the large flows, features that are not common in younger flood basalts. Vesicle cylinders and segregation cylinders are also conspicuous features of these ponded flows which occur in the lower parts of the flows, reflecting compaction of a dendritic mush consisting of ophitic crystals.

5. The hotspot (mantle plume head), along with the rifting it caused, created a big, elongate hole in the continent, that was partially filled with basalt and redbed sediments. This hole has persisted until now and it is this hole that coincides very closely to the position of Lake Superior.

6. An unexplained unique aspect of this rift situation is native copper mineralization. Though other rifts have all of the other mineral deposit types of the 1.1 Ga Lake Superior area, none has native copper. We are puzzled by this cosmic geochemical oddity. What happened to the sulfur usually found with chalcophile elements?

7. Fossils are difficult to find in Keweenawan rocks, generally, but cyanobacteria are conspicuous. Stromatolites within the rift basin here are associated with an oxidized ocean and an atmosphere that was holding at least some free oxygen. Following the redbeds of the rift were the multiple Snowball Earth events.

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Lat-Long Locations of this field trip

You have noticed there is no road log for this trip. This is because there are no roads! Download all the locations from the web here: www.geo.mtu.edu/~raman/IsleRoyalekmz.zip
These files will be readily ingested by Google Earth software or GPS software and provide precise locations for all the sites described here.

A table of the Latitude and Longitude of all these sites is listed here so it can be used to manually transfer this information if needed. These values may be entered manually into GPS or Google Earth.

Name	Longitude	Latitude
3 Mile CG	-88.52960447	48.12410194
Amygdaloid Island Ranger St	-88.65598008	48.13570657
Arch Amgd I	-88.62558448	48.14889669
Belle Isle CG	-88.58562501	48.15234621
Big Cols Davidson	-88.51062061	48.1249503
Big Cols Rasp I	-88.47841662	48.14023711
Big Cols Rasp	-88.48350224	48.13787684
Blake Pt	-88.42229232	48.19082848
Caribou Arch	-88.56108894	48.09705948
Caribou CG	-88.57214509	48.09498673
Cop Harb Cong RC	-89.23205406	47.85168084
Crystal Cove	-88.58980015	48.15869417
Daisy Farm CG	-88.59552193	48.09214022
Davidson I	-88.51535972	48.12257809
Duncan Bay CG	-88.52185527	48.150598
Edison Fishery	-88.58317221	48.08946992
Edwards Is	-88.43527441	48.17172245
Gull Rocks East	-88.26162826	48.26236504
Hill Pt	-88.52528802	48.1655558
Johnson Is	-88.58571927	48.14731944
Keyhole	-88.61806043	48.14501207
L Louise	-88.47250078	48.16924628

Name	Longitude	Latitude
Lane Cove CG	-88.5570814	48.14486573
Lighthouse	-88.57937109	48.08979679
Little Todd CG	-88.92697185	48.02005966
Locke Pt	-88.45901399	48.18450616
McCargoe CG	-88.7082605	48.08740121
Merrit Lane CG	-88.42972709	48.18442853
Minong Mine	-88.72005096	48.08347491
Moose Skulls	-88.59063351	48.08709128
Mott I Dock	-88.54739095	48.10720599
Mott Sediment	-88.55002491	48.10429157
Ollies Rocks	-88.71228558	48.11692273
Ophite php Wash Hbr	-89.17944981	47.93491098
Ophite pwi Wash Hbr	-89.23071872	47.87582894
Passage Island Dock	-88.35571791	48.23122681
Passage Light	-88.36567255	48.22354584
Pickerel Cove	-88.65241933	48.12402173
Pine Mountain	-88.72816055	48.08439633
Porphyrite pgi Wash Hbr	-89.21618244	47.88214454
Porphyrite pmp Wash Hbr	-89.21962318	47.8702359
Porphyrite ph Wash Hbr	-89.18438864	47.93089216
Porter I	-88.44598813	48.17423934
Rasp I Dock	-88.47534021	48.14220455
Rasp Seg Cyls	-88.47477863	48.1405457
Raspberry Pegs	-88.46879695	48.14351368

Name	Longitude	Latitude
Red Rock Pt	-88.45413695	48.17139189
Rock of Ages Light	-89.313	47.867
Scoville Pt	-88.44940521	48.16322165
Snug Harbor	-88.4852324	48.14576228
South Rock	-89.27218772	47.86125303
Susie Islands	-89.5736758	47.96604403
Suzy's Cave	-88.51477842	48.13207674
Todd Harbor CG	-88.8219923	48.05083223
Tookers I	-88.50329307	48.12941722
Trap pm Wash Hbr	-89.2212717	47.90837977
Trap2 pm Wash Hbr	-89.14971047	47.93373916
Voyaguer II Dock	-89.65254479	47.96263767
Wendigo Mine	-89.15127391	47.93227937
Wilson I	-88.83672187	48.05654853
Windigo Dock	-89.15820212	47.91194955