Revisions of Stratigraphic Nomenclature within the Keweenawan Supergroup of Northern Michigan

Geochemistry, Petrography, and Volcanology of Rhyolites of the Portage Lake Volcanics, Keweenaw Peninsula, Michigan

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Revisions of Stratigraphic Nomenclature within the Keweenawan Supergroup of Northern Michigan

By WILLIAM F. CANNON and SUZANNE W. NICHOLSON

Geochemistry, Petrography, and Volcanology of Rhyolites of the Portage Lake Volcanics, Keweenaw Peninsula, Michigan

By SUZANNE W. NICHOLSON

Chapters A and B are issued as a single volume
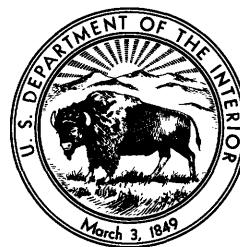and are not available separately

U.S. DEPARTMENT OF THE INTERIOR

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Chapter A

Revisions of Stratigraphic Nomenclature within the Keweenawan Supergroup of Northern Michigan

By WILLIAM F. CANNON and SUZANNE W. NICHOLSON

A new formation name (Porcupine Volcanics) and a new group
name (Bergland Group) are proposed for Middle Proterozoic
volcanic units in northern Michigan, and a sedimentary unit
(Copper Harbor Conglomerate) is recorrelated

U.S. GEOLOGICAL SURVEY BULLETIN 1970

CONTRIBUTIONS TO THE GEOLOGY AND MINERAL RESOURCES OF THE
MIDCONTINENT RIFT SYSTEM

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CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	.6214	mile (mi)

Revisions of Stratigraphic Nomenclature within the Keweenawan Supergroup of Northern Michigan

By William F. Cannon and Suzanne W. Nicholson

Abstract

The Porcupine Volcanics is here defined as a formation consisting of rhyolite, andesite, basalt, and minor interflow sedimentary rocks. It conformably overlies the Portage Lake Volcanics, and the two formations together are defined as the Bergland Group of the Keweenawan Supergroup. The Porcupine Volcanics has been recognized as a distinct unit for more than 20 years but has not been formally named; it was referred to previously as the "unnamed formation."

Also, we change the stratigraphic correlation of the Copper Harbor Conglomerate from "middle Keweenawan" of old usage to the Oronto Group. This correlation is almost universally accepted by current workers in the region.

INTRODUCTION

The Keweenawan Supergroup in the Lake Superior region of the United States and Canada is composed of a very thick sequence of subaerially deposited volcanic rocks, mostly flood basalt, and clastic sedimentary rocks. The supergroup was deposited in and near the Midcontinent rift during a period of Middle Proterozoic continental rifting. Most units of the Keweenawan Supergroup have been formally named, and a correlation of units between geographically separated areas has been generally agreed upon for many years. Some of the most recent stratigraphic summaries are presented by Green (1982), Morey and Green (1982), Ojakangas and Morey (1982), and Bergstrom and Morey (1985). In this paper, we make three revisions of U.S. Geological Survey (USGS) nomenclature for Keweenawan rocks in northern Michigan by naming a previously recognized but unnamed volcanic unit, by introducing a new group name for part of the volcanic succession, and by modifying the correlation of a long-recognized sedimentary unit to agree with the stratigraphy generally accepted by most workers in the region. Figure 1 illustrates the stratigraphic nomenclature for Keweenawan rocks as put forth by White (1972) and Hubbard (1975) and our revised nomenclature.

PORCUPINE VOLCANICS

We here define the Porcupine Volcanics as a lithostratigraphic unit of formational rank. The name comes from the Porcupine Mountains of northern Michigan. The Porcupine Volcanics consists of a sequence of rhyolites, andesites, basalts, and minor sedimentary rocks that form a distinctive stratigraphic unit in the western part of the northern peninsula of Michigan (fig. 2).

Historical Background

The Keweenawan volcanic rocks north of the Keweenaw fault in Michigan were not given formal stratigraphic names until the past few decades. Nevertheless, a detailed internal stratigraphy was recognized, and units, commonly consisting of individual flows or conglomerates, were informally named and traced over large regions as early as the late 1800's as a result of the importance of stratigraphy in the exploration for the native copper deposits for which these rocks are famous (see for instance, Lane, 1911; Butler and Burbank, 1929). The volcanic rocks on the Keweenaw Peninsula were formally named Portage Lake Volcanics by White and others (1953) for exposures near Portage Lake in Houghton County, Mich. (fig. 2). In that area, the Portage Lake Volcanics is overlain by the Copper Harbor Conglomerate. As systematic detailed mapping by the USGS proceeded to the west, it became apparent that a lenticular, westward-thickening unit of andesite and rhyolite, distinct from the basalt flows of the Portage Lake Volcanics, was a regionally significant unit beginning in the Greenland quadrangle. These rocks were first shown as a map unit in the Matchwood quadrangle by Johnson and White (1969). Their mapping clearly showed that this unit is stratigraphically above the Portage Lake Volcanics and beneath the Copper Harbor Conglomerate. They referred to the unit simply as the "unnamed formation." Hubbard (1975) correlated the volcanic rocks exposed in the Porcupine Mountains with the unnamed formation. Although the intervening area has not been mapped in detail, regional mapping and compilation (for instance, by Cannon, 1986) indicate that Hubbard's correlation is correct.

White (1972)
Hubbard (1975)
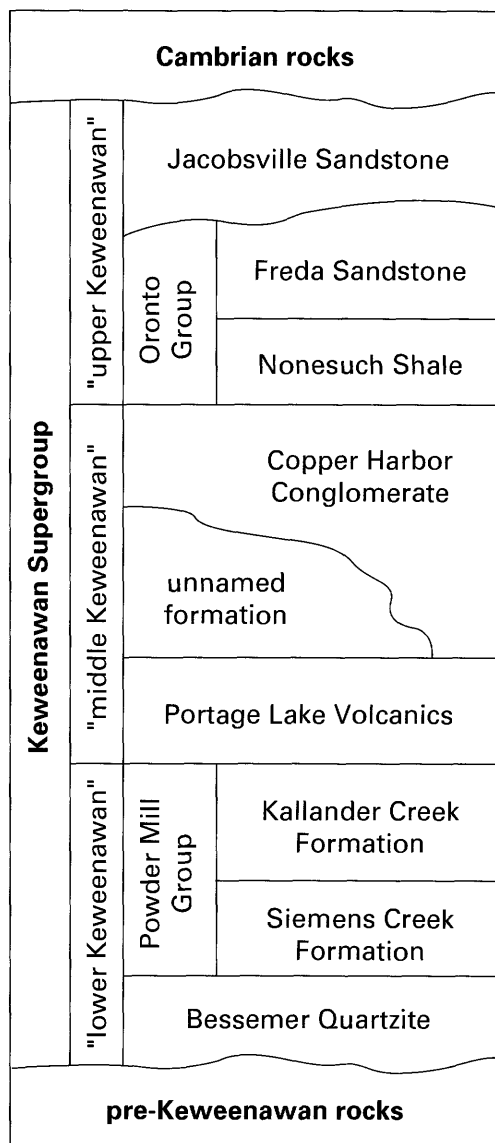
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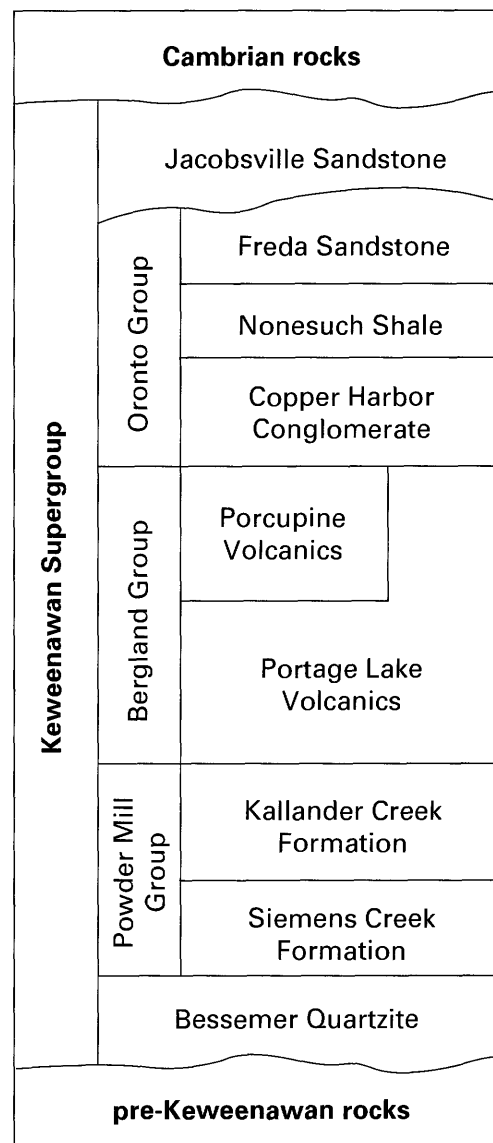
Figure 1. Comparison of the stratigraphic column of Keweenawan Supergroup rocks in northern Michigan as most recently defined by White (1972) and Hubbard (1975) and the revised lithostratigraphic column as proposed in this paper.

Since Johnson and White's (1969) recognition of this unit, the term "unnamed formation" has been widely used, and no formal designation has been proposed in the intervening years. The informal name "Oak Bluff Formation" has been used infrequently for these rocks (for instance, by Kopydlowski, 1983; Reed, 1987; Reed and Daniels, 1987). That name is derived from a topographic feature near where Johnson and White first recognized the unit. However, at Oak Bluff, exposures are sparse, consisting of only a few outcrops of andesite and minor rhyolite at the very top of the unit.

Stratigraphic Name and Type Area

The rocks here designated the Porcupine Volcanics have been recognized as a distinctive lithostratigraphic unit for more than 20 years (Johnson and White, 1969; Hubbard, 1975), but the unit has not been formally named. It has commonly been referred to as the "unnamed formation." We propose the name Porcupine Volcanics for this unit and define the type area as the Porcupine Mountains in T. 50 N., Rs. 43 and 44 W., and T. 51 N., Rs. 42 and 43 W., in Ontonagon County, Mich. (fig. 2). Although only the

Figure 2. Distribution of units within the Keweenawan Supergroup in the western part of the northern peninsula of Michigan. Geology generalized from Morey and others (1982).

EXPLANATION

Keweenawan Supergroup (Middle Proterozoic)

Jacobsville Sandstone

Oronto Group

Freda Sandstone

Nonesuch Shale

Copper Harbor Conglomerate

Bergland Group

Porcupine Volcanics

Portage Lake Volcanics

Powder Mill Group undivided

Lower Proterozoic and Archean rocks undivided

Yof

Yon

Yoc

Ybp

Ybpl

Ypu

XAu

—— Contact

—— Fault

INDEX MAP

upper part of this very thick formation is exposed in that area, all lithologies are well represented, and exposures are abundant. Specific localities where exceptionally good exposures are present are described in the following section.

Distribution and Thickness

The Porcupine Volcanics is exposed for a strike length of nearly 100 km along the main trend of the Keweenawan monocline (fig. 2) from near the town of Greenland in eastern Ontonagon County to near the Wisconsin border in western Gogebic County. The rocks are also exposed in a structural repetition of the strata in the arcuate highlands of the Porcupine Mountains. The downdip extent north of the outcrop belt is not known. The unit is as much as 2,500 m thick southeast of the Porcupine Mountains along the Keweenawan monocline. The unit is about 4,000 m thick south of the Porcupine Mountains where its total thickness is preserved. Its thickness in the Porcupine Mountains is not known because the base is not exposed. A minimum thickness of 750 m was estimated by Reed (1987) for the exposed units, but the total thickness is probably several times that figure.

Lithology

The Porcupine Volcanics is a sequence of subaerially deposited basalt, andesite, felsite, and quartz-porphyry lava flows, and minor interbedded volcaniclastic lithic sandstone, siltstone, and conglomerate (Hubbard, 1975). The abundance of felsic rocks (about 25 percent) and the predominance of andesite clearly distinguish the Porcupine Volcanics from the underlying Portage Lake Volcanics, which is dominated by flood basalt flows and contains minor (<1 percent) felsic volcanic rocks.

The following description of the Porcupine Volcanics is based on the reports of Johnson and White (1969), Hubbard (1975), and Kopydlowski (1983) and our own observations. The mafic volcanic rocks of the Porcupine Volcanics are mostly andesite flows that are dark gray to grayish red or grayish purple, are fine grained, and average about 8 m in thickness. In contrast, the Portage Lake Volcanics is dominantly ophitic basalt flows, averaging about 11–13 m in thickness (Johnson and White, 1969; Paces, 1988). Most flows in the Porcupine Volcanics contain sparse andesine phenocrysts less than 2 mm long. Flow tops are typically pahoehoe, but some are fragmented. Flow tops generally contain sparse vesicles filled with chlorite, epidote, quartz, and calcite. Andesite flows are also typically characterized by discontinuous, closely spaced banding and (or) jointing. Good exposures of typical andesite flows occur near the western edge of sec. 24, T. 50 N., R. 41 W., the area where the unit was first recognized by Johnson and White (1969).

Felsite bodies compose about a quarter of the Porcupine Volcanics, occurring as subaerially deposited domes or flows, mostly near the top of the formation. Locally, felsite bodies lie at the contact between the Porcupine Volcanics and Portage Lake Volcanics. Individual felsite bodies range from aphyric to sparsely porphyritic with feldspar and quartz phenocrysts. A particularly good exposure of multiple rhyolite flows, rhyolite breccias and debris flows, and interspersed andesite and basalt flows is near the top of the prominent hill in the SW¼ sec. 11, T. 50 N., R. 44 W., just south of the Beaver Creek Trail from Summit Peak to Little Carp River Trail in the Porcupine Mountains Wilderness State Park.

The eastern highlands of the Porcupine Mountains are underlain by a massive aphanitic rhyolite flow. The flow may be no more than about 150 m thick, but it occurs in an outcrop belt about 4 km wide because of its shallow dip and structural repetition across the crest of an anticline. The rhyolite may represent more than one flow, but no complete section is exposed through the body. Hubbard (1975) distinguished the massive lower part of the flow, exposed in the southern part of the park, especially along Lost Creek (sec. 31, T. 51 N., R. 42 W.), from the more vesicular upper part of the flow, which is exposed in many places. The massive lower part of the flow is generally pale purple to grayish purple to moderate reddish purple, whereas the vesicular part is grayish pink. Vesicular rhyolite is more abundant near the top of the flow and occurs as irregular masses or narrow layers within the more massive rhyolite, producing a banded appearance. Folds defined by the banding have variable orientations, which commonly are not consistent with regional tectonic folds. A good exposure of the layered rhyolite is on Inlet Creek near Trap Falls (NW¼ sec. 30, T. 51 N., R. 44 W.).

In the vicinity of Porcupine Peak, at least one rhyolite flow underlies the uplands and has an outcrop length of more than 10 km. The thickness is unknown. The pale-brown to grayish-orange-pink rhyolite contains numerous rounded and embayed quartz phenocrysts up to 1.5 mm in diameter and strongly altered subhedral to euhedral feldspar phenocrysts up to 3 mm long. Some phenocrysts are broken. Accessory phases include zircon and, locally, fluorite. Good exposures of this rhyolite can be found on Porcupine Peak (secs. 29 and 31, T. 50 N., R. 44 W.) and along the Little Carp River (sec. 21, T. 50 N., R. 44 W.).

Three small outcrop areas of pale-red to moderate-reddish-brown quartz latite (near Trap Falls in sec. 24, T. 51 N., R. 43 W.; sec. 32, T. 51 N., R. 43 W.; and sec. 2, T. 50 N., R. 43 W.) lie within the park (Hubbard, 1975; Kopydlowski, 1983); an additional outcrop area is south of the park in the Thomaston 7.5-min quadrangle (Hubbard, 1975). The quartz latite is massive but locally contains compressed pumice fragments. The unit also contains sparse feldspar and quartz phenocrysts.

SW   NE
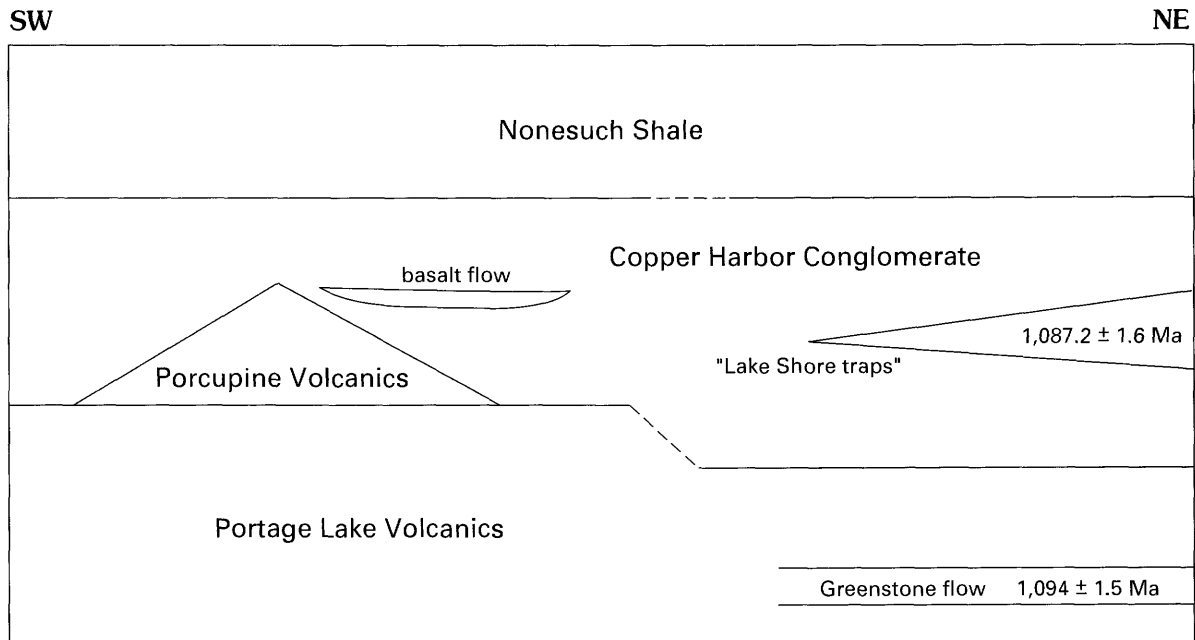
Figure 3. Schematic diagram showing the relation of the Porcupine Volcanics to surrounding units and showing radiometric ages of units determined by the U-Pb method on zircon (Davis and Paces, 1990).

Sedimentary rocks make up only a small percentage of the Porcupine Volcanics. In the Porcupine Mountains area, most of the sedimentary rocks are sandy conglomerate units, similar to the rocks of the overlying Copper Harbor Conglomerate. According to Hubbard (1975), sedimentary rocks of the Porcupine Volcanics contain more volcanic detritus and have a larger matrix component than the Copper Harbor Conglomerate. Pebbles and cobbles are generally less than 10 cm in diameter, but, locally, boulders as much as 1 m in diameter are exposed near Union Spring (sec. 22, T. 51 N., R. 42 W.). South of the Porcupine Mountains, sedimentary units are scarce and typically are siltstone (Butler and Burbank, 1929).

Stratigraphic Boundaries and Relations to Adjacent Formations

The Porcupine Volcanics is underlain by basalts and minor interflow sedimentary rocks of the Portage Lake Volcanics and probably interfingers, in places, with the overlying fluvial conglomerate and sandstone of the Copper Harbor Conglomerate. The lower contact is placed between the dominantly rhyolite-andesite volcanic sequence here defined as the Porcupine Volcanics and the dominantly basaltic volcanic sequence of the Portage Lake Volcanics. In general, the lowermost units of the Porcupine Volcanics are andesite rather than rhyolite, and so the contact generally separates basalt from andesite along most of its surface trace. Although there are no exposures of the lower contact, it appears to be essentially conformable on the basis of the

regional map pattern. No structural discordance is detectable between the two formations, and any erosional discontinuity that might be present along the contact does not appear to be greater than that expected within a sequence of intermittently erupted lava flows.

The contact with the overlying Copper Harbor Conglomerate is placed either at the abrupt change from dominantly volcanic rocks of the Porcupine Volcanics to the entirely sedimentary sequence of the Copper Harbor or, where the Copper Harbor contains some interbedded volcanic rocks, at the base of the lowermost thick (more than about 100 m) interflow conglomerate unit. Although this contact is somewhat complex, no substantial hiatus is indicated between the units. There is an inverse relation between the thickness of the two units such that the Copper Harbor Conglomerate becomes thinner along strike as the Porcupine Volcanics becomes thicker (Johnson and White, 1969); this relation suggests that the two are in part synchronous and that the Porcupine Volcanics formed a broad volcanic shield within the otherwise sediment-dominated basin into which the Copper Harbor was being deposited (fig. 3). It is likely that flows of the Porcupine Volcanics are in places interbedded with sedimentary strata of the Copper Harbor Conglomerate, but that relationship has not been definitively demonstrated in this rather poorly exposed region. In a few areas, an angular discordance appears to exist between the volcanic rocks of the Porcupine Volcanics and nearby sedimentary units probably belonging to the Copper Harbor Conglomerate. Such relations are believed to result from essentially synvolcanic erosion of

the subaerial volcanic shield of the Porcupine Volcanics followed soon after by deposition of the sediments of the Copper Harbor Conglomerate. The areas of discordance do not represent a major erosional interval.

Age

The absolute age of the Porcupine Volcanics is constrained by precise U-Pb zircon ages of nearby rock units (Davis and Paces, 1990). The relation of the Porcupine Volcanics to nearby dated units is shown schematically in figure 3. The age of the Greenstone flow, near the top of the Portage Lake Volcanics on the Keweenaw Peninsula, provides a maximum age for the Porcupine Volcanics of 1,094.0±1.5 Ma. An age of 1,087.2±1.6 Ma has been determined for the "Lake Shore traps," a series of basalt flows about 1,000 m above the base of the Copper Harbor Conglomerate near the tip of the Keweenaw Peninsula. This age is believed to approximate the time of eruption of the Porcupine Volcanics, which, like the "Lake Shore traps," postdates the final flood basalt eruptions of the Portage Lake Volcanics and is equivalent in age to the lower part of the Copper Harbor Conglomerate.

BERGLAND GROUP

For many years, the Keweenawan Supergroup in Michigan was informally divided into lower, middle, and upper parts (fig. 1). The "upper Keweenawan" included the dominantly red sedimentary rocks of the Oronto Group and younger units, whereas the "lower and middle Keweenawan" comprised the dominantly volcanic rocks of the Portage Lake Volcanics and Powder Mill Group. The boundary between the "lower Keweenawan" and "middle Keweenawan" is a horizon recording a magnetic reversal, but that boundary is everywhere covered by the younger Jacobsville Sandstone in northern Michigan. Elsewhere in the Lake Superior region, the magnetic reversal is generally exposed within the volcanic section; units such as the North Shore Volcanic Group in Minnesota and the Osler Volcanic Group and Mamainse Point Formation in Ontario span the "lower Keweenawan"-"middle Keweenawan" contact. Thus, the tripartite subdivision of the Keweenawan Supergroup as used in Michigan generally is not useful elsewhere in the region. Rather, thick volcanic successions typically have been given group rank, and the magnetic reversal has been used as a time marker to correlate groups rather than as a boundary between units. In concert with usage in other parts of the region, we no longer use lower, middle, and upper subdivisions of the Keweenawan Supergroup. Instead, we prefer to consider units as parts of formally named groups, which can be placed in their proper stratigraphic positions relative to other groups of the Keweenawan Supergroup of the Lake Superior region.

Therefore, we propose the term "Bergland Group" for the combined Portage Lake Volcanics and Porcupine Volcanics. The group is named after the town of Bergland, in Ontonagon County, Mich. (fig. 2), which is near both the formations contained in the group. A group designation for this thick volcanic succession is consistent with generally accepted stratigraphic usage in other parts of the Lake Superior region, where comparably thick units have been assigned group rank. (See Bergstrom and Morey (1985) for the most recent stratigraphic summary of Keweenawan Supergroup rocks in the region.) All rocks in the Bergland Group have normal magnetic polarity (Books, 1972).

The type area for the group is north and northeast of Bergland, where good exposures of both the Portage Lake Volcanics and Porcupine Volcanics are abundant in T. 49 N., R. 42 W. In the type area, the group is exposed in a north-facing monoclinal section about 9,000 m thick. The upper contact is the depositional surface at the base of the Copper Harbor Conglomerate described above. The basal contact is tectonic throughout the exposed length of the group. The Keweenaw fault, a thrust to high-angle reverse fault, forms the south margin of the outcrop belt of the Portage Lake Volcanics. The fault juxtaposes the Portage Lake Volcanics on the north and the younger Jacobsville Sandstone on the south.

CORRELATION OF THE COPPER HARBOR CONGLOMERATE

The Copper Harbor Conglomerate is dominantly red fluvial conglomerate and sandstone. It is the stratigraphically lowest unit in the thick postvolcanic sedimentary section that forms the upper part of the Keweenawan Supergroup. The lower part of the Copper Harbor records the transition from a dominantly volcanic regime to a dominantly sedimentary regime. Basalt flows occur intermittently in the lowest 1,500 m of the unit in some places, including the type area near the tip of the Keweenaw Peninsula (White and others, 1953), but they are volumetrically subordinate to the clastic rocks. Because of the gradual nature of the change from volcanic to sedimentary conditions in some areas, the placement of the lower contact of the Copper Harbor is somewhat arbitrary and has resulted in inconsistent stratigraphic usage over the years.

Early usage, for instance by Irving (1883), placed the base of the "upper Keweenawan" (Oronto Group of present usage) at the top of the stratigraphically highest lava flow, the "Lake Shore traps" of the Keweenaw Peninsula. The conglomerate stratigraphically above this was called the "Outer Conglomerate." Thus, some very thick conglomerates below the uppermost lava flows were included in the "middle Keweenawan." This terminology was logical and provided a readily definable contact between "upper

Keweenawan" (Oronto Group) and "middle Keweenawan" (Bergland Group) rocks on the Keweenaw Peninsula, but ultimately it created a serious stratigraphic problem as the rock sequence was traced westward into areas where the stratigraphically high flows pinch out. There the contact was left about 1,500 m up in the fluvial sedimentary section and was not marked by any distinctive unit or lithologic break. Lane and Seaman (1907) recognized this problem and proposed the name "Copper Harbor Conglomerate" to include all the thick conglomerates and interlayered flows stratigraphically between the underlying volcanic sequence (Portage Lake Volcanics of present usage) and the overlying Nonesuch Shale, but this term was not widely accepted for many years. White and others (1953) were apparently the first of the modern workers to use the name Copper Harbor Conglomerate on the Keweenaw Peninsula essentially as it had been defined earlier by Lane and Seaman. White and others also considered the Copper Harbor Conglomerate to be a part of the Oronto Group. This usage was followed by subsequent USGS mappers in the region and virtually all other workers.

Although the adoption by White and others (1953) of the Copper Harbor Conglomerate as a formational unit that contains all the major conglomerates above the Portage Lake Volcanics provided a workable and generally accepted location for the base of the unit, it caused difficulty in assigning the Copper Harbor Conglomerate to a group. Thwaites (1912) originally defined the Oronto Group from exposures near Oronto Bay in northern Wisconsin to include, from the top down, the Freda Sandstone, the Nonesuch Shale, and a lower conglomerate. Thwaites followed Irving's 1883 nomenclature and called the conglomerate at the base of the Oronto Group the Outer Conglomerate as defined on the Keweenaw Peninsula. However, in Michigan, the Outer Conglomerate correlates only with the upper conglomeratic unit of the Copper Harbor as it is now defined. Hence the base of the Oronto Group as defined by Thwaites in Wisconsin was at a medial position in the redefined Copper Harbor Conglomerate in Michigan. A group boundary may not fall within a formation.

As a solution, White (1972) proposed that the Copper Harbor be removed from the Oronto Group and be considered part of the "middle Keweenawan" sequence. He suggested that a more easily definable and relatively unambiguous contact for the base of the Oronto Group was the base of the Nonesuch Shale where the gray to black shales of the Nonesuch are in sharp contact with the mostly reddish sandstones of the upper part of the Copper Harbor. White felt that this usage was preferable because any ambiguity in placement of the basal contact of the Copper Harbor would involve only a formational contact, not the contact between groups. Although this usage was adopted by the USGS, it is a substantial departure from previously widely used terminology and has not been adopted by most of the geologic

community; most geologists continue to consider the Copper Harbor Conglomerate as the basal unit of the Oronto Group. The evolution of usage was summarized by Morey and Green (1982), and the current generally accepted usage was defined by Bergstrom and Morey (1985).

We propose that USGS stratigraphic terminology be modified so that the Copper Harbor Conglomerate as defined by White and others (1953) is considered the basal formation of the Oronto Group rather than the upper formation of the volcanic section (Bergland Group) as it now stands. The basal contact of the Oronto Group by our new definition is at the base of the stratigraphically lowest thick conglomerate overlying the dominantly basaltic flows of the Portage Lake Volcanics, the position originally specified by Lane and Seaman (1907) and White and others (1953). Although in places, particularly on the Keweenaw Peninsula, the lower 1,500 m of the Copper Harbor contains some mafic flows, the Copper Harbor is, in general, much more akin to the overlying sedimentary rocks of the Oronto Group than it is to the underlying volcanic rocks.

Since White's (1972) inclusion of the Copper Harbor Conglomerate in the "middle Keweenawan," additional mapping and work still in progress have shown that no substantial difficulties are encountered in identifying a basal contact for the Copper Harbor, even in areas where flows and sedimentary rocks are interlayered, and the placement must be somewhat arbitrary. Thus, White's principal concern that substantial difficulties would be encountered in the regional correlation of the group boundary, his main reason for placing the Copper Harbor in the "middle Keweenawan," has not materialized. We now revert to usage prior to 1972 and once again include the Copper Harbor Conglomerate in the Oronto Group.

CONCLUSIONS

We propose three changes to stratigraphic terminology for rocks of the Keweenawan Supergroup in northern Michigan.

(1) The formational name Porcupine Volcanics is introduced for a sequence of andesite, rhyolite, and basalt flows that overlies the basalt flows of the Portage Lake Volcanics. This unit, recognized and mapped for more than two decades, heretofore has not been formally named. Rather, it has been commonly referred to as the "unnamed formation."

(2) The name Bergland Group is introduced to comprise the Porcupine Volcanics and underlying Portage Lake Volcanics.

(3) The Copper Harbor Conglomerate is reassigned from the "middle Keweenawan" of old usage to the Oronto Group, a position almost universally accepted by workers in the region.

REFERENCES CITED

Bergstrom, D.J., and Morey, G.B., 1985, Correlation of Stratigraphic Units of North America (COSUNA) Project—Northern mid-continent region: Tulsa, Okla., American Association of Petroleum Geologists, 1 sheet.

Books, K.G., 1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U.S. Geological Survey Professional Paper 760, 42 p.

Butler, B.S., and Burbank, W.S., 1929, The copper deposits of Michigan: U.S. Geological Survey Professional Paper 144, 238 p.

Cannon, W.F., 1986, Bedrock geologic map of the Iron River 1°×2° quadrangle, Michigan and Wisconsin: U.S. Geological Survey Miscellaneous Investigations Map I-1360-B, scale 1:250,000.

Davis, D.W., and Paces, J.B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent rift system: Earth and Planetary Science Letters, v. 97, p. 54–64.

Green, J.C., 1982, Geology of Keweenawan extrusive rocks, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 47–56.

Hubbard, H.A., 1975, Geology of Porcupine Mountains in Carp River and White Pine quadrangles, Michigan: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 519–528.

Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.

Johnson, R.F., and White, W.S., 1969, Preliminary report on the bedrock geology and copper deposits of the Matchwood quadrangle, Ontonagon County, Michigan: U.S. Geological Survey open-file report, 31 p., 1 map, scale 1:62,500.

Kopydlowski, P.J., 1983, The Oak Bluff Volcanics, a middle Keweenawan central volcano; Porcupine Mountains region, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 88 p.

Lane, A.C., 1911, The Keweenaw Series of Michigan: Michigan Geological and Biological Survey Publication 6, Geological Series 4, v. 1, 499 p.

Lane, A.C., and Seaman, A.E., 1907, Notes on the geological section of Michigan; Part I, The pre-Ordovician: Journal of Geology, v. 15, p. 680–695.

Morey, G.B., and Green, J.C., 1982, Status of the Keweenawan as a stratigraphic unit in the Lake Superior region, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 15–26.

Morey, G.B., Sims, P.K., Cannon W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geologic map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map Series S–13, scale 1:1,000,000.

Ojakangas, R.W., and Morey, G.B., 1982, Keweenawan sedimentary rocks of the Lake Superior region; a summary, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 157–164.

Paces, J.B., 1988, Magmatic processes, evolution and mantle source characteristics contributing to the petrogenesis of Midcontinent rift basalts: Portage Lake Volcanics, Keweenaw Peninsula, Michigan: Houghton, Mich., Michigan Technological University, Ph.D. dissertation, 413 p.

Reed, R.C., 1987, Porcupine Mountains Wilderness State Park, Michigan, in Geological Society of America, North-Central Section, Centennial Field Guide, Volume 3, ed. by D.L. Biggs: Boulder, Colo., p. 269–272.

Reed, R.C., and Daniels, J.D., 1987, Bedrock geology of northern Michigan: Lansing, Mich., Michigan Department of Natural Resources, Geological Survey Division, scale 1:500,000.

Thwaites, F.T., 1912, Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geological and Natural History Survey Bulletin 25, 117 p.

White, W.S., 1972, The base of the upper Keweenawan, Michigan and Wisconsin: U.S. Geological Survey Bulletin 1354-F, p. F1–F23.

White, W.S., Cornwall, H.R., and Swanson, R.W., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–27, scale 1:24,000.

Chapter B

Geochemistry, Petrography, and Volcanology of Rhyolites of the Portage Lake Volcanics, Keweenaw Peninsula, Michigan

By SUZANNE W. NICHOLSON

This description of some rhyolites related to the Midcontinent rift summarizes previous work and presents new data within a newly revised tectonic framework for the rift

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	.6214	mile (mi)

Geochemistry, Petrography, and Volcanology of Rhyolites of the Portage Lake Volcanics, Keweenaw Peninsula, Michigan

By Suzanne W. Nicholson

Abstract

The Portage Lake Volcanics exposed on the Keweenaw Peninsula, Michigan, contains some of the youngest volcanic rocks ($\approx$1,095 Ma) erupted within the Midcontinent rift system (MRS). Recent geophysical studies in the Lake Superior region show that the Portage Lake Volcanics is the only exposed volcanic suite that was erupted at the edge of a deep ($\approx$20 kilometers), asymmetric central rift graben. Rhyolites make up less than 1 percent of the Portage Lake section, although, overall, silicic volcanic rocks make up about 10 percent of the MRS-related volcanic rocks exposed in the Lake Superior region. Rhyolite bodies are restricted to a 0.5-kilometer-thick interval near the faulted base of the Portage Lake Volcanics, an interval that also contains high-TiO_2 basalts interlayered with intermediate rocks that range from basaltic andesite to dacite. The rocks above and below this evolved interval are dominantly low-TiO_2 basalts.

Two groups of rhyolites are recognized in the Portage Lake Volcanics on the basis of mineralogy and geochemical composition. Type I rhyolite is typically dark red brown and aphyric or contains sparse feldspar microlites. This rhyolite is subalkalic, similar to rhyolites in other bimodal suites, including Icelandic rhyolites. Similarities include light rare earth element (REE) enrichment and a moderately negative europium anomaly. In contrast, Type II rhyolite is gray white and contains up to 10 percent quartz and feldspar phenocrysts. This rhyolite is chemically similar to Cenozoic topaz rhyolites in the Western United States. Like topaz rhyolites, Type II rhyolite is characterized by low REE abundances, a flat REE pattern, and enrichments in such elements as rubidium, thorium, uranium, niobium, and tantalum. All rhyolite bodies are Type I except the Copper City body, which is Type II.

The rhyolites occur as lensoidal extrusive flows and dome complexes that typically overlie thin rhyolitic pyroclastic units. Locally, carapace breccias are intact and provided debris for overlying conglomeratic units. Some delicate hydration and devitrification textures, including perlitic fractures and spherulites, are preserved. Most

extrusive rhyolite bodies exhibit strong flow foliation. Irregular subvolcanic rhyolite bodies that clearly intrude surrounding mafic flows are present stratigraphically below the extrusive rhyolite horizon. The subvolcanic bodies are massive and locally exhibit mafic inclusions and minor flow foliation around the margins.

The association of intermediate and felsic rocks in a restricted stratigraphic interval surrounded by primitive basalt flows supports an analogy with central volcanoes in the active rift zones of Iceland. Comparisons of field relations of the Portage Lake Volcanics and within-rift volcanoes in Iceland indicate that these intermediate and felsic rocks of the MRS may represent the distal part of a central volcanic complex. This analogy also probably can be applied more broadly to other areas in the MRS where rhyolite is more abundant.

As with the Icelandic rhyolites, little economic mineral potential is indicated for Type I rhyolite. Type II rhyolite offers greater mineral potential; however, the only exposed Type II rhyolite body has not evolved enough to yield economic concentrations of lithophile elements. If other, more evolved Type II rhyolite bodies, extrusive or intrusive, are present, mineralization may occur.

INTRODUCTION

Recent results of seismic-reflection profiles (Behrendt and others, 1988; Cannon and others, 1989) collected in Lake Superior by the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) have provided a tectonic framework in which to reconsider the development of the 1.1 billion-year-old (Ga) Midcontinent rift system as well as the distribution and magmatic evolution of its igneous rocks. In the Lake Superior region, a deep central rift graben contains volcanic rocks up to 15 km (kilometers) thick. Shallow basins up to 7 km deep that flank the deep central graben contain some of the earliest volcanic and sedimentary rocks associated with the Midcontinent rift system. The bimodal tholeiitic basalt-rhyolite volcanic suite has been remarkably

undeformed since rifting; thus, stratigraphic and structural relations have been preserved since 1.1 Ga. Subaerial eruption of most of 1×10^6 km^3 (cubic kilometers) of magma within less than 5 million years (m.y.) suggests that a mantle plume was the cause of the massive volume of magmatism (Cannon and others, 1989; Hutchinson and others, 1990).

Rhyolites make up a small but significant fraction of the bimodal tholeiitic basalt-rhyolite volcanic rocks associated with the rift. Most previous studies of the rift focused on basalt petrogenesis (Green, 1972, 1982; Basaltic Volcanism Study Project, 1981; Massey, 1983; Brannon, 1984; Berg and Klewin, 1988; Paces, 1988) and physical volcanology (Green, 1989). Recently, Fitz (1988) and Green and Fitz (1989) described the volcanological characteristics of several large rhyolite units in the North Shore Volcanic Group in Minnesota, rhyolites that lie within a flanking basin. Other workers (for example, Fritts, 1952; Papadakis and Raza, 1954; Browne and Haynes, 1956; Annells, 1973, 1974; McIlwaine and Wallace, 1976; Kopydlowski, 1983) have reported general descriptions of rhyolite occurrences elsewhere in the rift, but the recent geophysical models for the structure of the rift provide a newly refined tectonic framework in which to consider rhyolitic volcanism.

This report summarizes the geochemistry, petrography, and field relations of rhyolites of the Portage Lake Volcanics of the Keweenaw Peninsula, Mich., the only rhyolites that were erupted within the central rift graben in the central Lake Superior region. The volcanological characteristics of well-exposed rhyolite bodies are described and compared with those of modern rhyolites, as well as with those of other Midcontinent rift system and Icelandic rhyolites. Based on these comparisons, a model is presented for emplacement of the rhyolites within the Midcontinent rift system. Finally, the implications for mineralization associated with these rhyolites are addressed.

Acknowledgments

GEOLOGICAL SETTING

Midcontinent Rift

The 1.1 billion-year-old Midcontinent rift system (MRS) extends for about 2,000 km from Kansas north-

EXPLANATION

[: :] Flanking gravity lows
(Keweenawan clastic sedimentary rocks)

[☰] Midcontinent gravity high
(Keweenawan mafic igneous rocks)

0   200 MILES
0   200 KILOMETERS
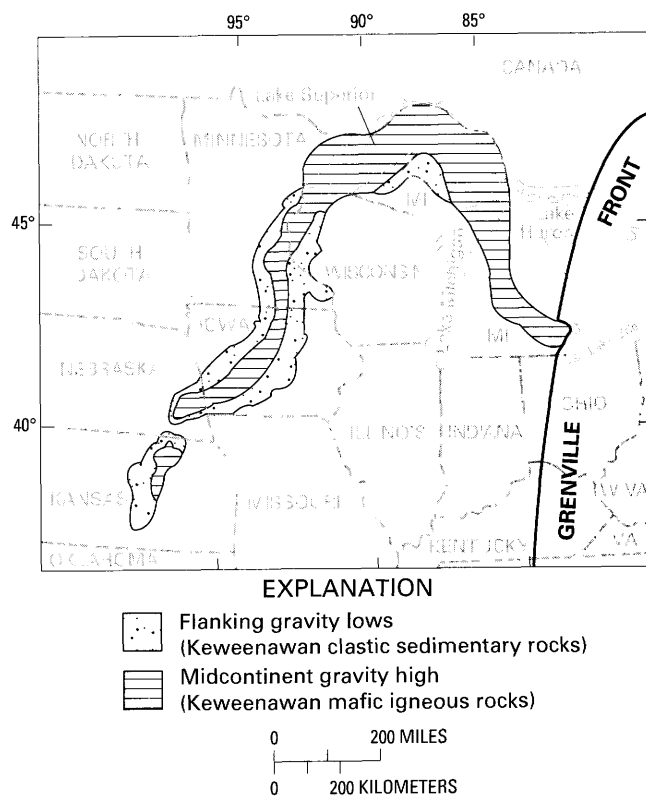
Figure 1. Midcontinent rift of North America based on gravity and magnetic anomalies (after Green, 1983). Stippled areas define regions dominated by sedimentary rocks; ruled areas define regions dominated by volcanic rocks.

northeast to Lake Superior and then southeast through Michigan (fig. 1); its position is deduced from gravity and magnetic anomalies (Lyons, 1950; Black, 1955; Thiel, 1956; Hinze and others, 1982; Van Schmus and Hinze, 1985). The only exposures of rift-related rocks are around the margin of Lake Superior (fig. 2). Rift-related rocks south of Lake Superior are obscured by Paleozoic sedimentary rocks; samples are available only from drill core. The oldest MRS rocks are exposed in several areas: in the Osler Group and Mamainse Point Formation in Ontario, at the base of the North Shore Volcanic Group in Minnesota, and in the Powder Mill Group in Michigan. Each of these basal MRS sections either conformably overlies early-rift thin quartzites or unconformably overlies Archean or Early Proterozoic basement (fig. 2). Despite some complications in the Powder Mill and Mamainse Point sequences, most of the earliest MRS rocks have reversed magnetic polarity. This characteristic has been used for stratigraphic correlation where precise ages do not exist. All igneous rocks from the Portage Lake Volcanics, as well as volcanic rocks in the Porcupine Mountains and on Michipicoten Island in Lake Superior, have normal magnetic polarity.

U-Pb zircon dating of the basal Osler Group and the related Logan diabase sills in Ontario indicates that rift-

EXPLANATION

Bayfield Group and Jacobsville Sandstone, undivided
(Middle Proterozoic) — sedimentary rocks

Oronto Group (Middle Proterozoic) — sedimentary rocks

Basalt flows and interflow sedimentary rocks
(Middle Proterozoic)

Gabbroic intrusive rocks (Middle Proterozoic)

Basalt flows and subordinate underlying sedimentary rocks (where present)
(Middle Proterozoic)

Sibley Group (Middle Proterozoic?)

Crystalline rocks (Early Proterozoic and Archean)

Figure 2. Location of major outcrops of Midcontinent rift-related volcanic and sedimentary rocks in Lake Superior region. Location of two seismic-reflection profiles (GLIMPCE lines A and C) and shot points along these profiles are shown (Cannon and others, 1989).

related magmatism began about 1,108.8+4/−2 Ma during a period of reversed magnetic polarity (Davis and Sutcliffe, 1985). The magnetic polarity shifted from reverse to normal between 1,097.6±3.7 Ma and 1,096.2±1.8 Ma (Davis and Sutcliffe, 1985; Davis and Paces, 1990). Rift-related magmatism ceased shortly after the intrusion on Michipicoten Island of a normally polarized rhyolite porphyry dated at 1,086.5+1.3/−3.0 Ma (Palmer and Davis, 1987).

Although volcanism was active for about 22 m.y. (million years), most of the activity was restricted to the 3- to 5-m.y. interval shortly after 1,098 Ma (Davis and Paces, 1990).

Seismic-reflection profiles (figs. 2, 3) collected by GLIMPCE in Lake Superior show that the Keweenaw fault and Isle Royale fault acted as major normal growth faults during crustal extension (Behrendt and others, 1988; Cannon and others, 1989). As extension continued, a deep central graben developed and ultimately accommodated more than 15 km of volcanic rocks and 7 km of sedimentary rocks (Behrendt and others, 1988). Outside the central graben, broad shallow basins about 5–7 km deep preserve some of the earliest rift-related volcanic and sedimentary rocks. Mild postrift compression reactivated the large normal growth faults as reverse faults, resulting in uplift of the Portage Lake Volcanics along the Keweenaw fault at the southern edge of a central graben segment (fig. 3). The distribution of rhyolite varies within the Lake Superior region. Flanking basins (for example, the North Shore Volcanic Group) contain up to 10–25 percent rhyolite, whereas, within the deep central grabens (for example, the Portage Lake Volcanics), rhyolites are a minor (<1 percent) component.

Portage Lake Volcanics

The Portage Lake Volcanics, located on the Keweenaw Peninsula in northern Michigan, contains some of the youngest flood basalts associated with the 1.1 billion-year-old Midcontinent rift system (fig. 4). The exposed part of the Portage Lake Volcanics consists of 3–5 km of subaerially deposited volcanic rocks. The original thickness is unknown, because the volcanic unit thickens toward the axis of the rift (Cannon and others, 1989) and is truncated at the surface by the high-angle reverse Keweenaw fault (fig. 3). Zircons from pegmatoidal zones in two large basalt flows in the Portage Lake Volcanics yield an average age of 1,095.1±1.9 Ma (Paces, 1988; Paces and Davis, 1988). On the Keweenaw Peninsula, the Portage Lake Volcanics is overlain by the basal member of the Oronto Group, the 2-km-thick Copper Harbor Conglomerate, a prograding alluvial fan complex that grades up into fluvial sandstones (Daniels, 1982; Cannon and Nicholson, this volume). To the west in the Porcupine Mountains area, the Porcupine Volcanics overlies the Portage Lake Volcanics (fig. 4).

The stratigraphy of the Portage Lake Volcanics on the Keweenaw Peninsula has been well known for more than 100 years as a result of exploration for and extensive mining of native copper deposits (see Butler and Burbank, 1929). Tholeiitic basalts make up about 95 percent of the Portage Lake Volcanics (Paces, 1988), and intermediate and felsic rocks make up less than 2 percent. Conglomerates make up the remaining 3 percent of the formation (Merk and Jirsa,

1982) and become increasingly common toward the top of the section. Laterally extensive sandstones and conglomerates were used as marker horizons by the miners. In the main native copper district of the Keweenaw Peninsula, 22 conglomerates were identified by number. Several of the most widespread conglomerates were also given informal names taken from local geographic or topographic features. These include the Allouez (No. 15), Calumet & Hecla (No. 13), Bohemia (No. 8), and St. Louis (No. 6) conglomerates (see, for example, Butler and Burbank, 1929; Cornwall, 1954a,b, 1955). These informal names remain in common usage today.

This report focuses on rhyolites of the Portage Lake Volcanics east of Calumet, Mich., and on the limited stratigraphic interval in which they occur (fig. 5). Hubbard (1898) summarized the early observations of rhyolites (or "acid rocks"), which were recognized by geologists as early as 1846, and also reported the results of his own detailed studies of felsite bodies on the Keweenaw Peninsula. Hubbard (1898) and subsequent workers identified about a dozen small intermediate to felsic bodies northeast of Houghton, Mich. Mapping during the 1950's by H.R. Cornwall, J.C. Wright, and W.S. White of the U.S. Geological Survey (USGS) and by students from Michigan Technological University resulted in detailed geologic maps for the Keweenaw Peninsula (White and others, 1953; Cornwall, 1954a,b,c, 1955; Cornwall and Wright, 1954, 1956a,b; Wright and Cornwall, 1954; Cornwall and White, 1955; Davidson and others, 1955; White, 1956; White and Wright, 1956) and detailed field and petrographic studies of several individual felsite bodies (Fritts, 1952; Papadakis and Raza, 1954; Browne and Haynes, 1956). Bornhorst (1975) examined the chemistry of the rhyolite at Fish Cove, and Grimes (1977) compiled geochemical compositions for many intermediate and felsic rocks of the Keweenaw Peninsula. On the basis of drill core that provided a vertical section through the Portage Lake Volcanics, Paces (1988) established the overall stratigraphic and geochemical characteristics of the mafic volcanic rocks on the Keweenaw Peninsula.

SAMPLING AND ANALYTICAL METHODS

More than 250 samples of rhyolites, basalts, intermediate rocks, and sedimentary rocks in the Portage Lake

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Figure 3. Seismic-reflection profiles across Lake Superior, interpreted by Cannon and others (1989). *A*, Profile along line C showing structure beneath western Lake Superior. Inferred subsurface units are projected updip to their exposed extensions on land in northern Michigan and Minnesota. *B*, Profile along line A showing subsurface geology beneath central Lake Superior. Locations of lines A and C are shown in figure 2. Vertical scale is two-way travel time; no vertical exaggeration for average velocity of 6 kilometers per second.
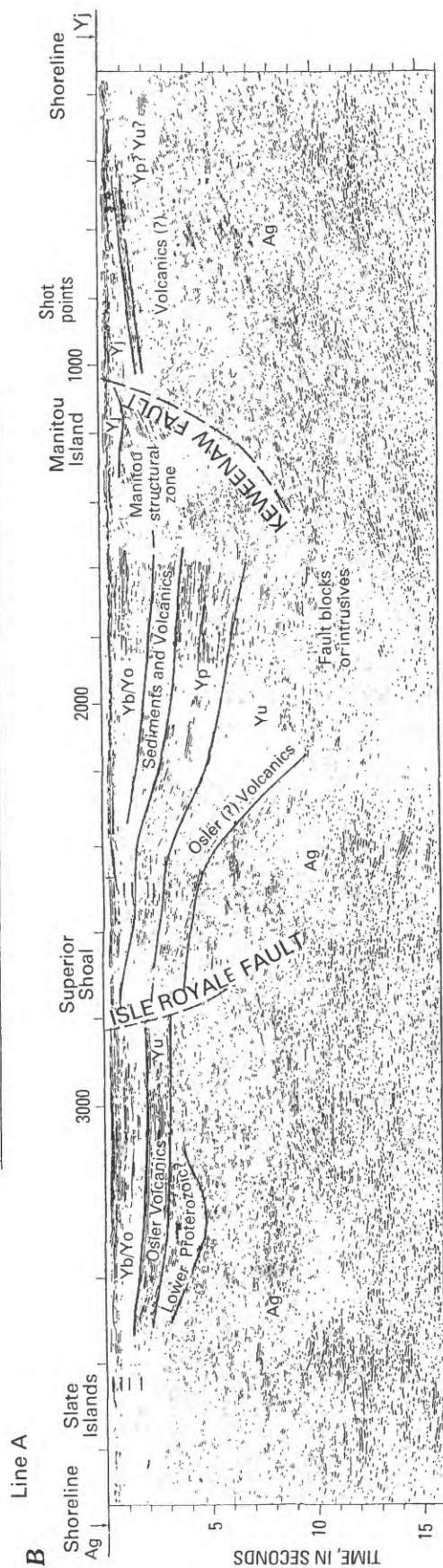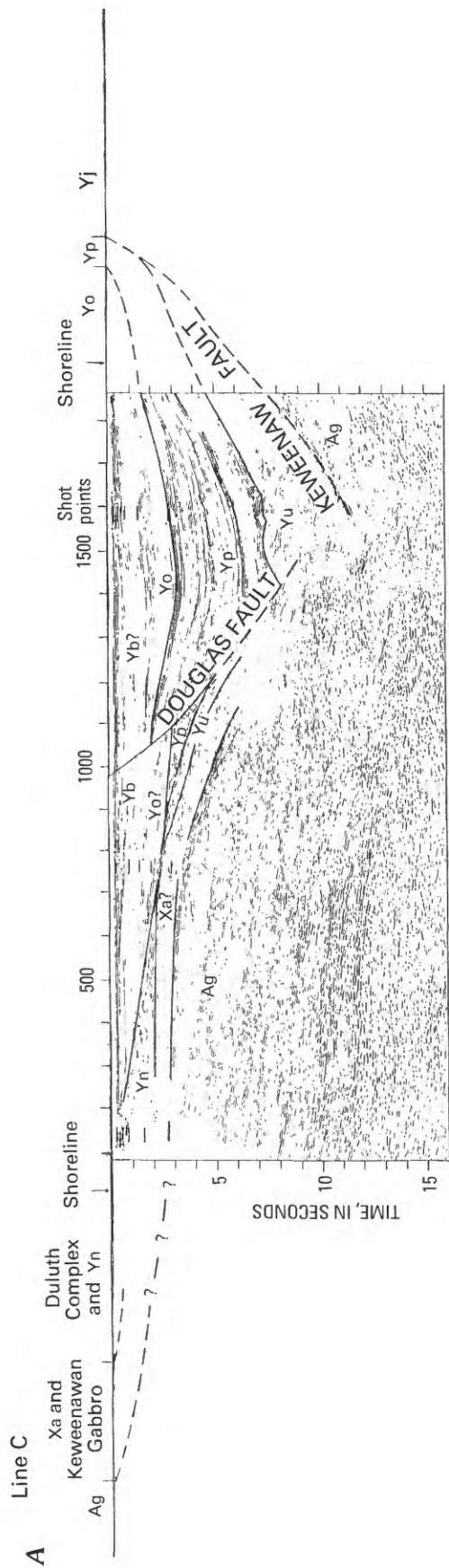
EXPLANATION

Yj Jacobsville Sandstone (Middle Proterozoic)
Yb Bayfield Group (Middle Proterozoic)
Yo Oronto Group (Middle Proterozoic)
Yp Portage Lake Volcanics (Middle Proterozoic)
Yu Undivided Middle Proterozoic rocks older than Portage Lake Volcanics
Yn North Shore Volcanic Group (Middle Proterozoic)
Xa Animikie Group (Early Proterozoic)
Ag Gneiss (Archean)

Era		Magnetic polarity	Thunder Bay area, Ontario	Minnesota	Wisconsin	Michigan	Eastern Shore, Lake Superior
MIDDLE PROTEROZOIC	KEWEENAWAN SUPERGROUP	Normal		Hinckley Sandstone	Bayfield Group	Jacobsville Sandstone	Jacobsville Sandstone
				Fond Du Lac Formation			
				Solor Church Formation	Oronto Group: Freda Sandstone; Nonesuch Shale; Copper Harbor Conglomerate	x1087 Ma[c]	x1087 Ma[b] Michipicoten Island Formation
				Chengwatana Volcanic Group	Porcupine Volcanics	Bergland Group x1094 Ma[c]	
			x1098 Ma[a]	?	Portage Lake Volcanics	x1096 Ma[c]	
		Reverse	Osler Group	North Shore Volcanic Group	Powder Mill Group: Kallander Creek Formation; Siemens Creek Formation		Mamainse Point Formation
			x1108 Ma[a] ?				
		N			Basal sandstones		
		R					
Archean and Early Proterozoic			Archean and Early Proterozoic crust				

[a] U-Pb analyses of zircon and baddeleyite reported in Davis and Sutcliffe, 1985.

[b] U-Pb analyses of zircon and baddeleyite reported in Palmer and Davis, 1987.

[c] U-Pb analyses of zircon and baddeleyite reported in Davis and Paces, 1990.

Figure 4. Stratigraphic correlation of Middle Proterozoic rocks in western and central Lake Superior region.

Volcanics were collected from surface outcrops within and near rhyolite bodies within the lowest kilometer and a half of the Portage Lake Volcanics section. An effort was made to collect samples that had little to no visible alteration, veining, or extensive fractures. From this collection, 70 volcanic rocks were chosen, on the basis of geographic distribution and minimal alteration, for major- and trace-element analysis. X-ray diffraction analyses by P.M. Okita, USGS, were conducted on eight whole-rock rhyolite samples. Sample locations and descriptions are given in appendix 1.

After the weathered surfaces were trimmed, the 70 samples were split and reduced to pea size using a steel jaw-crusher. Final grinding to −200 mesh was done using an alumina ceramic shatterbox vessel. Major and trace elements were analyzed by the U.S. Geological Survey,

using inductively coupled plasma-atomic emission spectrometry, rapid rock, X-ray fluorescence, and instrumental neutron activation techniques, as described in U.S. Geological Survey Bulletin 1770 (Baedecker, 1987). Chemical analyses are given in appendix 2.

DESCRIPTIVE GEOCHEMISTRY

Classification and Assessment of Alteration

Samples for this study were collected from rhyolite bodies and adjacent mafic flows within the lowest 1.5 km of the Portage Lake section. Rigorously classified according to SiO_2, Na_2O, and K_2O contents (Le Bas and others, 1986), this restricted suite of Portage Lake Volcanics has transi-
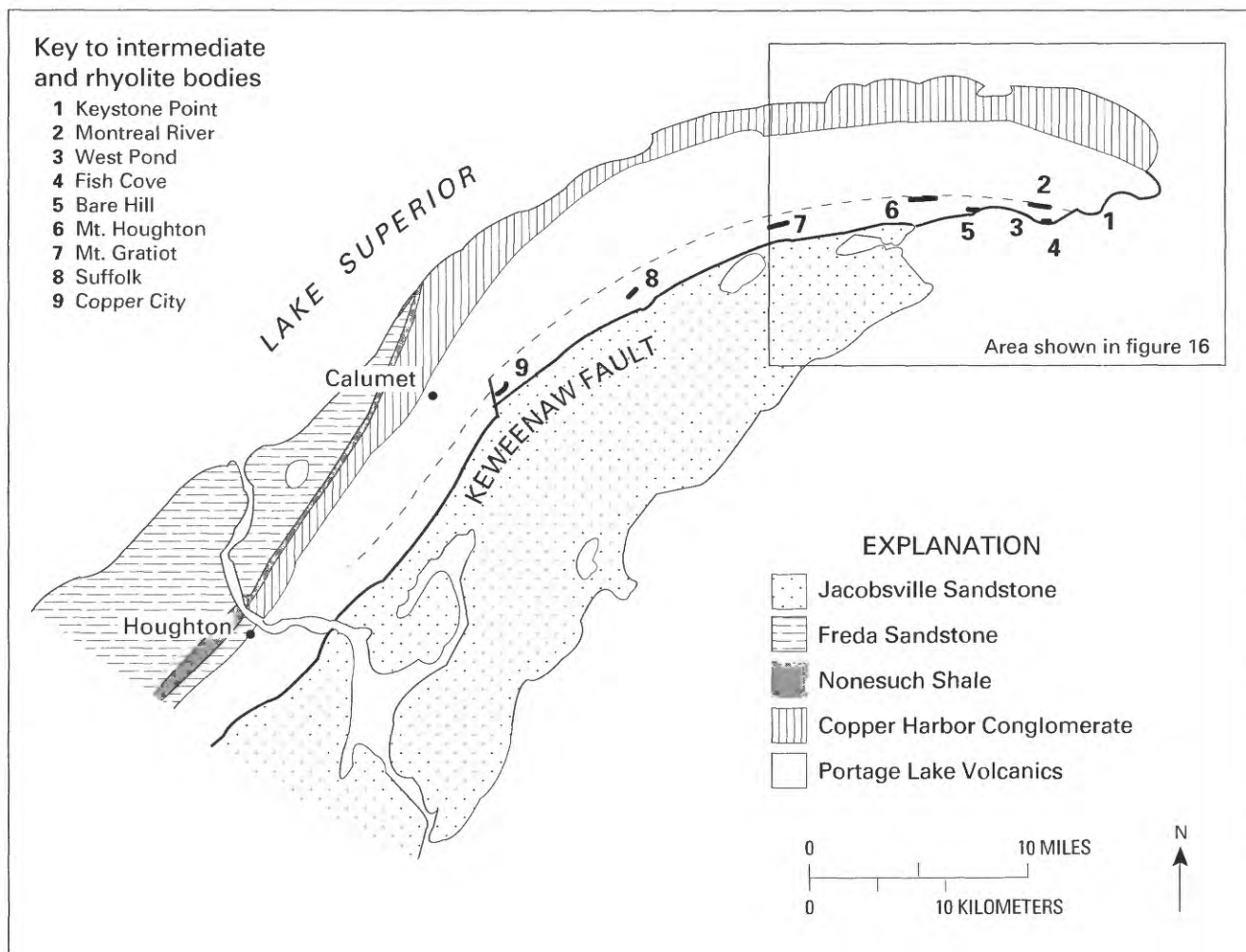
Figure 5. Location of major felsic and intermediate extrusive and subvolcanic bodies within Portage Lake Volcanics, Keweenaw Peninsula (after Grimes, 1977). Dashed line represents the stratigraphic horizon of the Bohemia conglomerate. Locations of intermediate and felsic bodies at the eastern end of the Keweenaw Peninsula are illustrated in greater detail in figure 16.

tional subalkalic to alkalic chemistry (fig. 6); mafic and intermediate rocks straddle the field boundary. However, drill core analyses chosen by Paces (1988) to reflect the freshest and most representative samples throughout the Portage Lake Volcanics lie within the subalkalic field. This suggests that the mafic volcanic rocks near the rhyolite bodies have been particularly affected by alkali metasomatism, resulting in enhanced concentration of Na_2O+K_2O. Comparison with a compilation of Na_2O and K_2O abundances for igneous rocks (Hughes, 1973) shows that this restricted suite of Portage Lake rocks has enhanced K_2O abundances relative to other Portage Lake rocks and the igneous spectrum in general (fig. 7).

On a Jensen cation plot, which relies on elements that are generally stable during secondary alteration (Jensen, 1976), basalts of the Portage Lake Volcanics in this study overlap with tholeiites reported by Brannon (1984) for the North Shore Volcanic Group in Minnesota and by Paces

(1988) for Portage Lake Volcanics (fig. 8). The few intermediate rocks lie close to the boundary between the tholeiitic and calc-alkalic fields and provide a transition from tholeiitic basalts to rhyolites.

Two corrections were applied to all major-element data to reduce the effects of postemplacement oxidation and hydration. Measured Fe_2O_3/FeO ratios for basalts to rhyolites range widely, from 0.60 to 55 (app. 2). Oxidation correction of Fe_2O_3/FeO ratios was performed according to the scheme of Middlemost (1989) in which Fe_2O_3/FeO increases from 0.15 in picrobasalts to 0.5 in rhyolites. These corrections were applied according to the location of samples in figure 6. However, a ratio of 0.15 was assigned to all samples that plotted in the basalt and trachybasalt fields in order to compare basalt analyses from this study with those from other MRS studies (Brannon, 1984; Paces, 1988) in which the normalization factor of 0.15 of Brooks (1976) was used.
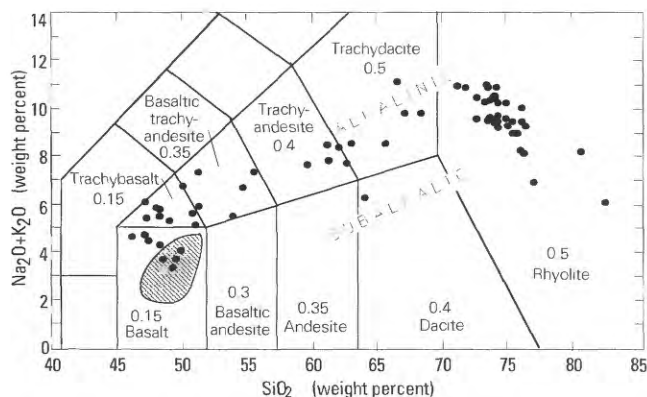
Figure 6. Classification of Portage Lake Volcanics according to Na_2O+K_2O and SiO_2 contents (Le Bas and others, 1986). Most rocks lie within the subalkalic field, according to the field boundary of Irvine and Baragar (1971). Numbers within the fields are the Fe_2O_3/FeO ratios used to correct the measured iron analyses as recommended by Middlemost (1989), with the exception of basalts, for which $Fe_2O_3/FeO=0.15$ was used as recommended by Brooks (1976). Basalts from this study (solid dots; app. 3) have higher Na_2O+K_2O contents than representative basalts of the Portage Lake Volcanics (ruled area) analyzed by Paces (1988), suggesting that the restricted suite of basalts in the present study has been affected by metasomatism more alkalic than that affecting the rest of the Portage Lake section.

Figure 7. K_2O+Na_2O and $K_2O/(K_2O+Na_2O)$ compositions of Portage Lake Volcanics. Analyses of Portage Lake rocks sampled in this study are compared with analyses of representative basalts of the Portage Lake Volcanics (ruled field) reported by Paces (1988). Most unaltered igneous rocks lie between the two field boundaries (after Hughes, 1973). This restricted suite of Portage Lake rocks shows greater K_2O contents than most other basalts of the Portage Lake Volcanics and most igneous rocks in general.

After the oxidation correction was made, major-oxide contents were normalized to 100 percent in order to reduce the effects of postemplacement hydration. All basalts collected in this study contain between 1.7 and 4.25 wt (weight) percent H_2O^+; thus, none can be considered fresh. However, normalization of these compositions allows a first-order comparison of major-oxide chemistry of MRS basalt compositions reported by Paces (1988) and Brannon (1984). A few rhyolites of the Portage Lake Volcanics contain up to 0.7 wt percent H_2O^+, but for most of them, H_2O^+ is in the range of 0.2–0.4 wt percent. Four of the seventy samples in this study contained >1 wt percent CO_2; most of the samples contained <0.1 wt percent. CIPW norms were calculated on the basis of the normalized compositions reported in appendix 3.

Because of apparent alkali metasomatism, rock names used in this study are based on SiO_2 weight percent in the normalized analyses. In this classification, SiO_2 content is <52 wt percent for basalt, 52–56 wt percent for basaltic andesite, 56–63 wt percent for andesite, 63–69 wt percent for dacite, and >69 wt percent for rhyolite. Rhyolite with SiO_2>75 wt percent is classified as high-silica rhyolite. Average normalized compositions for major Portage Lake rock types are reported in table 1. Two rhyolite samples showed excessive silicification (>80 wt percent SiO_2; app. 3) and were not included in calculating the average Type I rhyolite.

Figure 8. Cation diagram (Jensen, 1976) of Portage Lake Volcanics. Basalts, intermediate rocks, and rhyolites from this study are represented by solid dots. The basalts of Portage Lake Volcanics lie within the tholeiitic field and overlap the representative suite of basalts of the Portage Lake Volcanics (ruled field) reported by Paces (1988) and those (field defined by dashed line) reported by Brannon (1984). Intermediate rocks lie close to the tholeiitic-calc-alkalic boundary and are transitional between basalts and rhyolites.

Table 1. Average normalized major-oxide and raw trace-element compositions of major rock types in Portage Lake Volcanics, Keweenaw Peninsula, Mich.

[Average major-oxide abundances (app. 3) and 1 sigma standard deviation are reported in weight percent on an anhydrous basis, after correcting Fe_2O_3/FeO ratios according to Middlemost (1989), except for basalts, for which $Fe_2O_3/FeO=0.15$ was used. Weight percentages may not total 100.00 owing to rounding. Trace elements are reported in parts per million as analyzed (app. 2). N=number of samples averaged. $Mg\#=Mg/(Fe+Mg+Mn)$ (mole percent).]

	Low-TiO$_2$ basalt $N=11$	High-TiO$_2$ basalt $N=8$	Basaltic andesite $N=3$	Andesite $N=4$	Dacite $N=4$	Type I rhyolite $N=31$	Type II rhyolite $N=4$
Major oxides:							
SiO$_2$	48.29±1.35	49.37±1.62	54.44±0.82	61.10±1.40	65.5±1.34	73.84±1.27	75.74±0.64
TiO$_2$	1.70±0.17	2.68±0.33	2.50±0.07	1.39±0.18	0.63±0.17	0.12±0.04	0.05±0.01
Al$_2$O$_3$	16.99±0.75	15.21±0.40	15.34±0.04	15.72±0.53	15.83±0.25	13.65±0.63	13.28±0.57
Fe$_2$O$_3$	1.65±0.07	1.84±0.14	2.77±0.15	2.38±0.26	1.7±0.11	0.66±0.10	0.44±0.03
FeO	10.90±0.47	12.13±0.94	7.88±0.42	5.24±0.51	3.58±0.30	1.32±0.20	0.87±0.06
MnO	0.22±0.07	0.24±0.06	0.30±0.13	0.17±0.04	0.12±0.05	0.03±0.01	0.04±0.02
MgO	8.16±1.47	6.05±0.87	4.07±0.40	2.68±0.26	1.41±0.61	0.23±0.16	0.14±0.02
CaO	6.50±2.03	7.32±1.79	5.12±0.85	2.53±0.94	2.12±2.09	0.25±0.40	1.38±0.67
Na$_2$O	2.86±1.01	3.01±0.94	3.70±0.41	4.72±0.64	4.52±0.65	3.23±1.32	2.48±0.49
K$_2$O	2.53±1.21	1.81±1.23	2.79±1.15	3.54±0.76	4.41±2.41	6.64±1.88	5.60±0.99
P$_2$O$_5$	0.20±0.03	0.36±0.10	1.09±0.19	0.56±0.12	0.2±0.07	0.03±0.01	0.02±0.01
Mg#	0.58	0.47	0.46	0.38	0.38	0.21	0.20
Trace elements:							
Cr	163±54	76±60	1.8±0.2	6.0±3.11	<6	3.4±1.9	3.2±0.8
Ni	172±43	88±35	<80	<120	<70	<50	<40
Nb	9±3	16±3	25±2	30±2	33±2	41±8	51±8
Rb	61±59	38±17	77±32	56±27	56±22	112±30	465±30
Sr	490±399	291±187	276±23	119±59	90±39	55±30	28±2
Zr	126±54	200±37	354±6	523±72	743±55	240±41	144±4
Y	26±7.6	44±11.9	74±10	86±7	90±9	56±12	74±22
La	11.9±2.1	20.9±4.7	46.3±1.6	49.5±5.6	59±6.0	30.3±15.2	12.0±5.8
Sm	4.04±0.4	6.88±1.16	13.22±0.64	13.25±0.48	13.93±0.3	6.57±2.75	6.9±0.96
Tb	0.67±0.09	1.16±0.21	2.03±0.07	2.14±0.05	2.21±0.04	1.30±0.27	1.85±0.39
Yb	2.12±0.27	3.88±0.9	6.39±0.23	7.48±0.33	8.85±0.18	5.55±0.95	7.68±1.35
Hf	2.65±0.34	5.00±0.9	8.36±0.34	11.8±0.96	16.14±0.98	7.53±0.84	6.3±0.64
Ta	0.59±0.06	1.01±0.24	1.9±0.2	2.24±0.15	2.58±0.18	2.91±0.54	4.9±0.86
Th	1.2±0.5	2.56±0.93	5.2±0.27	7.06±0.29	9.52±0.79	15.09±1.12	63.0±5.9

Major Oxides and Trace Elements

Major-oxide compositions of rocks of the Portage Lake Volcanics in this study are illustrated in figure 9, where SiO$_2$ is used as a fractionation index. In general, FeO* (total iron as FeO), MgO, and CaO decrease as SiO$_2$ increases. Al$_2$O$_3$ remains relatively constant until quartz becomes a significant phase. The oxides of Na and K show much scatter, suggesting that they have been mobilized, but in general, K$_2$O increases with increasing SiO$_2$ and Na$_2$O remains about the same. P$_2$O$_5$ rises with increasing SiO$_2$ until about 54 wt percent SiO$_2$ and then decreases as SiO$_2$ increases further. TiO$_2$ gradually decreases with increasing SiO$_2$; however, there is a substantial range in TiO$_2$ content among the basalts.

Despite the effects of alkali metasomatism as well as secondary oxidation and hydration, major and minor elements can be used in conjunction with systematic trace-element differences to distinguish among various basalt and rhyolite groups. For general comparison, average analyses of major rock types are adequate for illustrating compositional variations.

Basalt

Two groups of basalts, low TiO$_2$ and high TiO$_2$, are recognized near the rhyolite horizon. Low-TiO$_2$ basalts contain less than 2.1 wt percent TiO$_2$; compared with high-TiO$_2$ basalts, they have lower average P$_2$O$_5$ and other incompatible trace element abundances, but higher Al$_2$O$_3$, MgO, K$_2$O, and Cr, Ni, and Rb (table 1). Low-TiO$_2$ basalts are olivine (to slightly nepheline) normative, and high-TiO$_2$ basalts are hypersthene normative (app. 3).

Comparisons of trace-element abundances for average compositions of the two basalt groups from the Portage Lake Volcanics show that high-TiO$_2$ basalts have higher incompatible trace element abundances, but that ratios among trace elements are similar; thus, the patterns for the
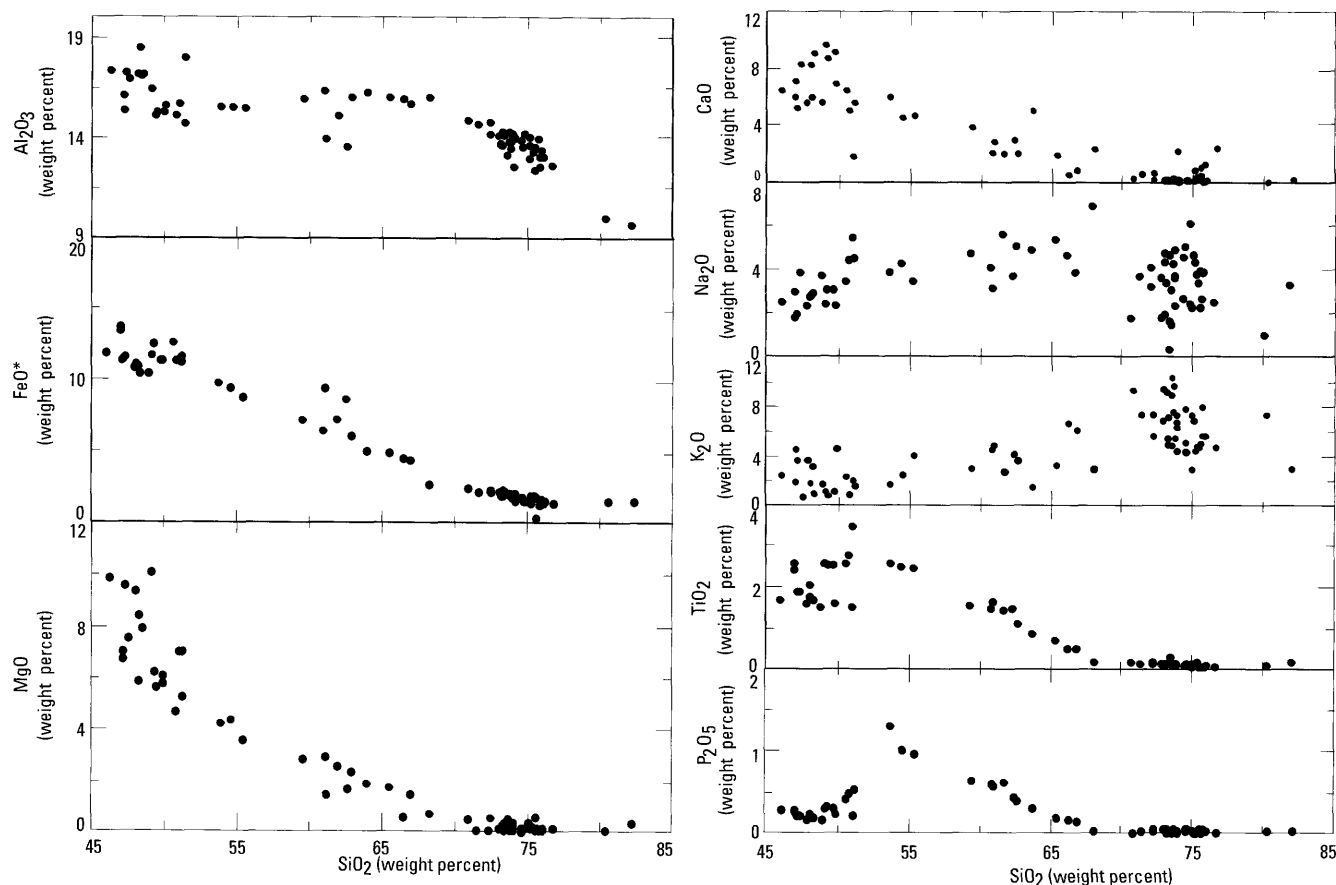
Figure 9. Major oxides of rocks of Portage Lake Volcanics analyzed using SiO_2 as a fractionation index. Because only a few intermediate rocks were analyzed, it is not clear whether compositional gaps at SiO_2=55–59 weight percent and 68–71 weight percent are real or whether rocks having these compositions simply were not sampled.

two groups yield similar slopes (fig. 10). Basalts from the Portage Lake Volcanics are enriched in large-ion-lithophile elements and other incompatible trace elements and, therefore, are distinctly different from normal midocean ridge basalts (N-MORB) and some Iceland basalts (fig. 10). Ratios of incompatible trace elements of basalts from the Portage Lake Volcanics resemble such ratios of enriched midocean ridge basalts (E-MORB) and some ocean island basalts from Iceland and Hawaii (table 2).

Tholeiitic basalts exhibiting a bimodal distribution of incompatible minor and trace elements, such as TiO_2, P_2O_5, rare earth elements (REE), Hf, Ta, and Th, are common in both oceanic and continental environments. Among midocean ridge basalts, high-TiO_2 basalts tend to be localized near propagating rift tips (Sinton and others, 1983), transform faults (Bryan, 1979; Bender and others, 1984), or hotspots (Brooks and Jakobsson, 1974; Wood, 1978; Juster and others, 1989), whereas "normal" low-TiO_2 basalts are found at some distance from hotspots and transform faults. High- and low-TiO_2 basalts have also been identified in the Paraná and Karoo continental flood basalt provinces of South America and southern Africa, respectively (Cox,

1983; Bellieni and others, 1984; Marsh and Eales, 1984; Mantovani and others, 1985), as well as within the Mesozoic basins of the Eastern United States (Wiegand and Ragland, 1970; Smith and others, 1975). Although the processes thought to produce bimodal basalt suites and their bulk compositions vary from province to province, the presence of a bimodal basalt suite suggests that Keweenawan basaltic magmatism is not unique.

Intermediate Rocks

In the Portage Lake Volcanics, intermediate rocks occur only in the vicinity of the rhyolite bodies. Basaltic andesites and more evolved intermediate rocks are quartz normative; andesite and more felsic rocks are generally slightly corundum normative as well. REE concentrations for the intermediate rocks are strongly enriched compared with the basalts (fig. 11), but both basalts and intermediate rocks are enriched in light REE's, and their REE distribution patterns show similar slopes. Dacites have the highest REE, zirconium, and hafnium abundances of any Portage Lake rocks (table 1).
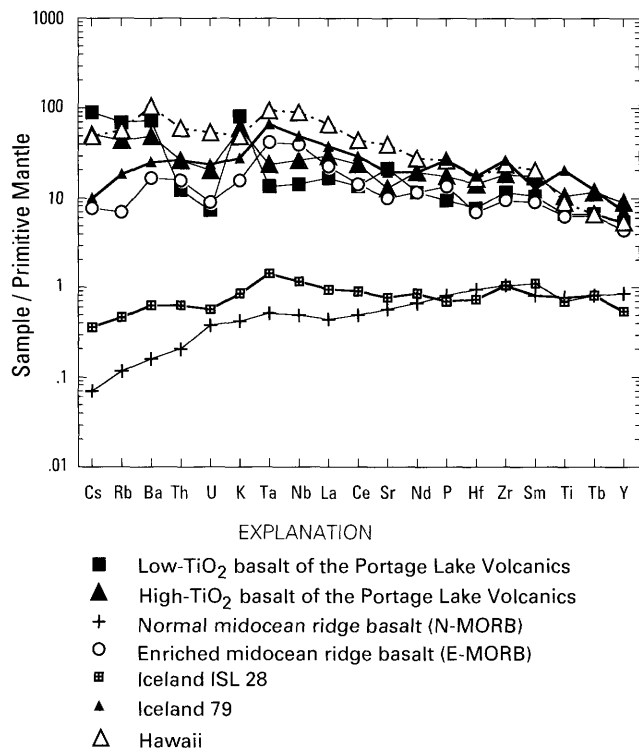
Figure 10. Average trace-element composition of low- TiO_2 and high-TiO_2 basalts of Portage Lake Volcanics and normal midocean ridge basalt (N-MORB), enriched midocean ridge basalt (E-MORB), and ocean island basalts. Basalts of the Portage Lake Volcanics are most similar to ocean island basalts and E-MORB. Data for N-MORB and Iceland from Wood and others (1979b); data for E-MORB from Wood and others (1979a), analysis 413–1; data for Hawaii from Thompson and others (1984). Primitive mantle normalizing values from Wood and others (1979b).
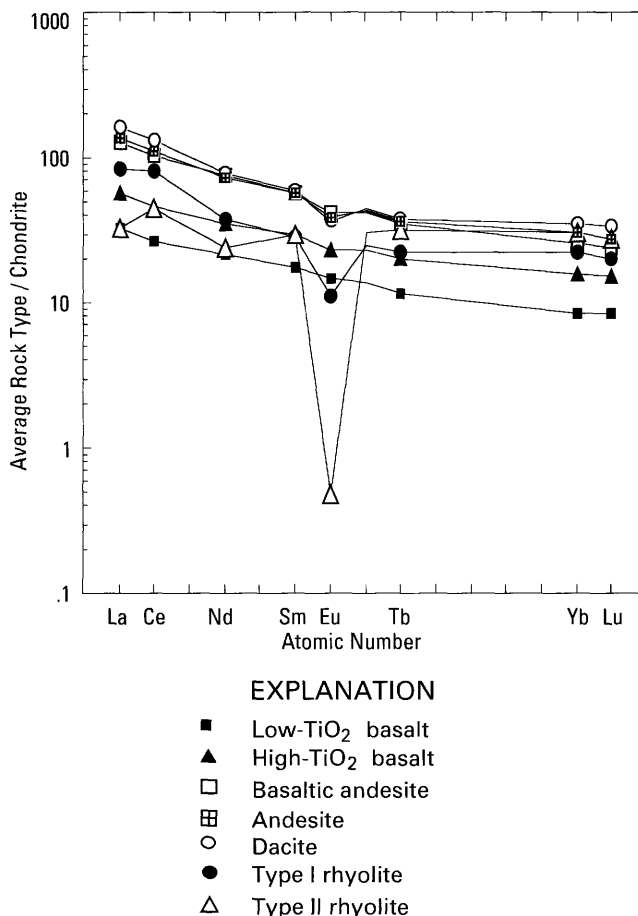
Figure 11. Chondrite-normalized rare earth element patterns for average major rock types in Portage Lake Volcanics. Normalization factors from Haskin and others (1968).

Table 2. Selected ratios of incompatible trace elements in basalts from Portage Lake Volcanics, Iceland, Hawaii, and midocean ridges

[E-MORB, enriched midocean ridge basalt; N-MORB, normal midocean ridge basalt. Dashes indicate ratio not calculated]

Ratio	Portage Lake Volcanics[1]		Iceland[2]		Hawaii[3]		Midocean ridge	
	Low-TiO$_2$	High-TiO$_2$	ISL 79	ISL 28	RTH 24	RTH 31	E-MORB[4]	N-MORB[2]
Y/Nb	2.9	2.7	1.2	3.8	1.4	0.5	0.8	13.2
Zr/Nb	14.0	12.5	9.4	15.7	9.6	4.8	3.5	36.8
Hf/Th	2.2	2.0	2.5	4.3	2.8	1.0	1.6	17.0
Zr/Y	4.8	4.5	8.1	4.2	6.8	9.9	4.2	2.8
La/Tb	17.8	18.0	21.8	8.3	—	—	25.8	3.9
La/Yb	—	—	—	—	10.3	13.7	—	—
La/Th	9.9	8.2	11.1	11.0	12.7	8.2	10.5	15.5

[1]Data from average analyses (table 1) for low-TiO$_2$ basalts ($N=11$) and high-TiO$_2$ basalts ($N=8$).
[2]Data from Wood and others (1979b).
[3]Data from Thompson and others (1984).
[4]Data from Wood and others (1979a); analysis 413–1.

Table 3. Major-oxide and normative-mineral compositions and trace-element ratios of individual rhyolite bodies in Portage Lake Volcanics, Keweenaw Peninsula, Mich.

[Major-oxide abundances are reported in weight percent on an anhydrous basis, assuming $Fe_2O_3/FeO=0.5$ (after Middlemost, 1989). Weight percentages may not total 100.00 owing to rounding. Trace-element ratios calculated for raw data reported in appendix 2. N=number of samples averaged]

	Type I rhyolite				Type II rhyolite			
	Extrusive				Intrusive			Intrusive (?)
	Mt. Houghton	Montreal River	Montreal River ashflow	Keystone Point	Bare Hill	West Pond	Fish Cove knob	Copper City
	$N=6$	$N=7$	$N=1$	$N=1$	$N=9$	$N=3$	$N=3$	$N=4$
Major oxides:								
SiO_2	74.89	73.45	73.47	75.36	74.06	73.28	73.28	75.74
TiO_2	.07	.13	.27	.17	.10	.15	.14	.05
Al_2O_3	13.16	13.64	13.00	13.41	13.58	14.24	14.15	13.28
Fe_2O_3	.56	.71	.70	.59	.61	.73	.77	.44
FeO	1.10	1.42	1.40	1.18	1.22	1.46	1.53	.87
MnO	.03	.04	.04	.03	.03	.04	.04	.04
MgO	.11	.20	.52	.07	.21	.43	.31	.14
CaO	.05	.31	.08	.20	.37	.18	.25	1.38
Na_2O	2.76	3.11	.11	4.13	3.33	4.26	4.41	2.48
K_2O	7.26	6.93	10.38	4.84	6.47	5.19	5.11	5.60
P_2O_5	.03	.03	.02	.03	.03	.03	.01	.02
CIPW norms:								
Q	30.19	27.13	31.45	31.71	28.18	26.86	26.22	36.21
Or	42.94	41.00	61.40	28.63	38.27	30.70	30.23	33.11
Ab	23.32	26.29	.93	34.91	28.14	36.01	37.27	20.95
An	.05	1.34	.27	.80	1.64	.70	1.18	6.72
C	.72	.51	1.46	1.07	.48	1.34	.92	.66
Hy	1.77	2.38	2.92	1.63	2.15	2.98	2.79	1.57
En	.27	.50	1.30	.18	.52	1.08	.78	.35
Fs	1.49	1.88	1.62	1.45	1.62	1.90	2.01	1.22
Mt	.81	1.03	1.02	.86	.88	1.06	1.12	.64
Il	.13	.25	.51	.32	.19	.29	.27	.09
Ap	.07	.07	.04	.07	.07	.07	.02	.04
Trace-element ratios:								
Rb/Sr	6.30	1.51	4.46	1.00	2.69	1.12	1.45	16.66
Zr/Nb	4.00	6.94	13.42	8.88	5.06	8.52	7.14	2.88
Nb/Rb	.35	.37	.16	.20	.47	.42	.39	.11
Ba/Rb	8.49	10.45	8.61	13.36	7.56	8.13	9.58	.87
Ba/Th	80.47	75.87	62.05	93.68	51.63	59.49	60.96	6.23
Zr/Hf	27.79	33.17	37.50	34.80	30.90	34.67	33.50	23.01
Ce/Yb	14.91	13.33	27.61	18.42	13.53	12.75	15.12	5.89

Rhyolite

Average chemical and normative compositions of eight rhyolite bodies in the Portage Lake Volcanics are reported in table 3. In modern unaltered rhyolites, Na_2O and K_2O concentrations are generally subequal (Ewart, 1979; Le Maitre, 1984). However, within individual rhyolites of the Portage Lake Volcanics, Na_2O and K_2O concentrations range from subequal (4 to 5 wt percent) to about 10 wt percent K_2O with minute quantities of Na_2O, suggesting that the degree of alkali metasomatism varies locally. In these rocks, metasomatism is almost always in the direction of increasing K_2O content and decreasing Na_2O content.

Despite the effect of alkali metasomatism, major-oxide and trace-element contents of the rhyolite at Copper City differ from those of all other rhyolite bodies at the east end of the Keweenaw Peninsula (table 3; fig. 12). For simplicity, the two compositional groups are distinguished as Type I, which includes all the rhyolite bodies except the rhyolite at Copper City, and Type II, recognized only at Copper City.

Silica content in individual Type I rhyolite samples ranges from about 71 to 76 wt percent on an anhydrous basis (app. 3), but analyses for individual bodies generally average $SiO_2 < 75$ wt percent (table 3). Type I rhyolite is mildly peraluminous to slightly metaluminous $(Al_2O_3/(Na_2O+K_2O+CaO) = 0.8-1.14$; normative corundum =

A

70

Th (parts per million)

60 — ● Type I rhyolite

△ Type II rhyolite

50

40

30

20

10

0   100   200   300   400   500

Rb (parts per million)

B

100

Nb (parts per million)

● Type I rhyolite
△ Type II rhyolite

Nb/Rb=1   Nb/Rb=0.5   Nb/Rb=0.2   Nb/Rb=0.1

Topaz
rhyolites

10

10   100   1000

Rb (parts per million)
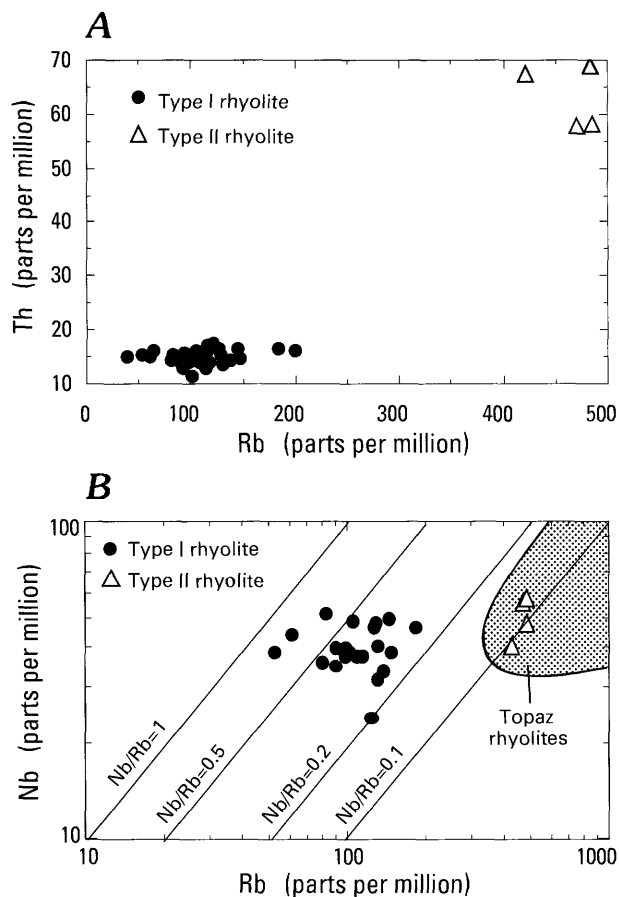
Figure 12. Selected trace-element contents for two groups of rhyolites of Portage Lake Volcanics. A, Two groups of rhyolites of Portage Lake Volcanics can be distinguished on the basis of Th and Rb abundances. B, In Portage Lake Volcanics, Type II rhyolite is similar to topaz rhyolites; both are enriched in Nb and Rb compared with Type I rhyolite. Field for topaz rhyolites from Christiansen and others (1984).

0–1.8 percent). The peraluminous nature of the rhyolite may be due in part to alteration of volcanic glass as described by Chayes (1970). Generally K_2O is greater than Na_2O. Type I rhyolite exhibits slight enrichment in light REE's ($La_N/Yb_N \approx 3$) and a moderately negative Eu anomaly (fig. 11). Type I rhyolite has higher Ba/Rb (≈ 8–13.5) and Ba/Th (≈ 50–95) ratios than Type II rhyolite (0.87 and 6.23, respectively; table 3).

Type II rhyolite has SiO_2 greater than 75 wt percent and is slightly peraluminous. Type II rhyolite can be clearly distinguished by high Th and Rb abundances compared with Type I rhyolites (fig. 12A). The Nb/Rb ratio for Type II rhyolite is 0.1, lower than that for Type I rhyolites but overlapping the range of such ratios for topaz rhyolites in the Western United States (fig. 12B). Although the data are sparse, F concentrations are somewhat higher and Cl concentrations are somewhat lower than in Type I rhyolite. Type II rhyolite has a nearly flat REE pattern ($La_N/Yb_N \approx 0.8$) and a pronounced Eu depletion (fig. 11).

The two groups of rhyolites from the Portage Lake Volcanics are chemically similar to other MRS rhyolites (table 4). Selected trace-element data for rhyolites from other MRS suites are illustrated in figure 13. Type I rhyolite of the Portage Lake Volcanics is most similar to some rhyolites from the North Shore Volcanic Group or those from Michipicoten Island with respect to ratios of incompatible trace elements, but it has lower concentrations of all incompatible trace elements. Compared with a few rhyolites from the Mamainse Point Formation and the Porcupine Volcanics, the Type II rhyolite has a similar Ba/Th ratio (table 4) but a greater concentration of Th and a lower concentration of REE's.

Rhyolites of the Portage Lake Volcanics, and MRS rhyolites in general, occur in a bimodal basalt-rhyolite province, typical of extensional tectonic settings. Type I rhyolite is similar to moderate-silica rhyolites in other bimodal basalt-rhyolite provinces, such as Iceland, the Snake River province in Idaho, and Mono Craters in California (table 5). Type II rhyolite represents the high-silica end of the rhyolite spectrum in a bimodal province. Type II rhyolite of the Portage Lake Volcanics has trace-element characteristics that are most similar to those of a small subset of high-silica rhyolites called topaz rhyolites. Topaz rhyolites are typically enriched in Rb, Th, U, and Nb and depleted in Zr, compared with other high-silica rhyolites. This style of enrichment is characteristic of F-dominated rather than Cl-dominated high-silica systems (Hildreth, 1981).

MINERALOGY AND PETROGRAPHY

Basalts and Intermediate Rocks

Paces (1988) described limited mineralogical variation among the tholeiitic olivine basalts of the Portage Lake Volcanics. His study sampled low-TiO_2 basalts almost exclusively. The basalts are characterized by early crystallization of plagioclase (An_{85-90}) and olivine ($<Fo_{84}$), followed by augite and Fe-Ti oxides, and finally by minor late-stage, Ca-poor pyroxene (Paces, 1988). Most flows display fine-grained intergranular to coarsely ophitic texture. Rare phenocrysts of olivine and plagioclase occur. Most olivine grains have been altered to varying mixtures of chlorite, serpentine, talc, Fe-Ti oxides, and quartz. Locally, intersertal volcanic "glass" is present.

Although no mineral composition data were collected for basalts sampled in this study, textural differences allow a distinction between low- and high-TiO_2 basalts near the tip of the Keweenaw Peninsula. Low-TiO_2 basalts are commonly subophitic to coarsely ophitic, as described by Paces (1988). High-TiO_2 basalts typically are finer grained, exhibiting trachytic to finely subophitic textures. This textural distinction was recognized in the field by previous workers who mapped a unit of "ophitic flows" overlain by

Table 4. Major-oxide and trace-element compositions of selected Midcontinent rift rhyolites

[Major oxides reported in weight percent on an anhydrous basis, after correcting Fe_2O_3/FeO ratios according to Middlemost (1989). Trace elements reported in parts per million as analyzed. Weight percentages may not total 100.00 owing to rounding]

	North Shore Volcanic Group[1]	Osler Group[1]	Mamainse Point Formation[1]	Michipicoten Island Formation[1]	Porcupine Volcanics[1]	Rhyolites of Portage Lake Volcanics[2]	
						Type I	Type II
	N=6	N=3	N=3	N=2	N=8	N=31	N=4
Major oxides:							
SiO_2	74.84	75.63	76.78	76.79	75.9	73.84	75.74
TiO_2	.35	.38	.11	.16	.17	.12	.05
Al_2O_3	11.64	12.80	12.38	12.29	11.61	13.65	13.28
Fe_2O_3	1.39	.66	.52	.49	.88	.66	.44
FeO	2.77	1.42	1.03	.98	1.77	1.32	.87
MnO	.03	.05	.02	.01	.01	.03	.04
MgO	.39	.31	.21	.43	.28	.23	.14
CaO	.81	2.06	2.03	.27	.11	.25	1.38
Na_2O	2.24	3.02	1.56	2.06	1.35	3.23	2.48
K_2O	5.48	3.59	5.32	6.51	7.86	6.64	5.60
P_2O_5	.06	.08	.05	.03	.06	.03	.02
Trace elements:							
Nb	35	27	130	33	36	41	51
Rb	145	60	328	250	240	112	465
Sr	57	219	38	125	58	55	28
Zr	641	559	342	266	569	240	144
Ba	1,509	573	83	1,205	285	997	402
Y	79	46	115	68	86	56	74
La	107	146	71.6	59	94.3	30.3	12.0
Sm	17.58	19.3	17.3	12.65	13.0	6.57	6.9
Yb	7.16	3.63	15.3	5.47	8.05	5.55	7.68
Hf	15.88	12.9	11	8.14	14.6	7.53	6.3
Ta	2.72	1.73	9.09	3.69	2.93	2.91	4.9
Th	14.98	9.99	31.5	26.2	35.7	15.09	63
Trace-element ratios:							
Ba/Rb	10.4	13.2	.3	4.8	1.2	8.9	.9
Ba/Th	100.7	60.3	2.7	46	8	66	6.4

[1]Unpublished data for samples collected by author.

[2]Major-oxide abundances are averages of normalized data reported in appendix 3. Trace-element abundances are averages of raw data reported in appendix 2.

"fine-grained melaphyres" (Cornwall, 1951, and references therein; Cornwall, 1955). The mapped boundary between these two textural types lies close to where the boundary would be drawn on the basis of chemical distinctions. In addition, similar textural variations have been recognized in basalts in the North Shore Volcanic Group in Minnesota (Basaltic Volcanism Study Project, 1981; Green, 1989).

The intermediate rocks, ranging from basaltic andesite to dacite, generally are dominated by plagioclase and contain lesser amounts of Fe-Ti oxide and clinopyroxene. Textures range from fine-grained subophitic to, more commonly, trachytic. Andesites and dacites typically contain a small percentage of feldspar phenocrysts. Browne and Haynes (1956) reported hornblende in the dacite of Mt. Gratiot; in one sample, they found pyroxene partly altered to chlorite. In most samples, however, mafic minerals have

been entirely altered, commonly to chlorite and opaque masses of Fe-Ti oxides. Interstitial quartz locally makes up as much as 20 percent of the dacite of Mt. Gratiot. Disseminated Fe-Ti oxides are abundant; apatite and rare zircon are accessory phases. Browne and Haynes (1956) reported pumpellyite, chlorite, carbonate, sericite, and epidote as secondary minerals.

The andesite near Suffolk (fig. 5) differs from other andesites in this study because it contains about 25 vol percent (volume percent) phenocrysts and glomerocrysts of coarse plagioclase, apatite, and Fe-Ti oxides in an aphanitic matrix and may be cumulate in part. Very fine grained disseminated Fe-Ti oxides give a reddish hue to the matrix. Plagioclase ($\approx An_{35}$) phenocrysts show minor sericitization. Any original mafic silicate phenocrysts have been altered to opaque masses of Fe-Ti oxides.

A

Sample/Primitive Mantle

□ Type I rhyolite
● Type II rhyolite

Cs Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

B

Sample/Primitive Mantle

Cs Rb Ba Th U K Ta Nb La Ce Sr Nd P Hf Zr Sm Ti Tb Y

EXPLANATION

□ Michipicoten Island Formation
▲ North Shore Volcanic Group
○ Mamainse Point Formation
■ Rhyolite of South Mirror Lake
● Rhyolite of Osler Group
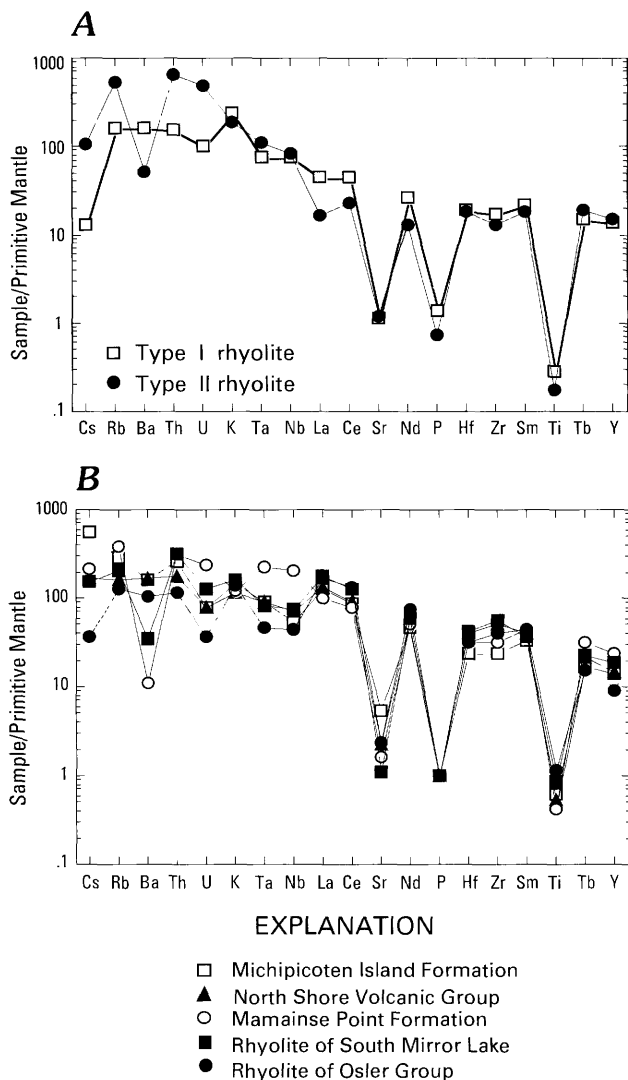
Figure 13. Selected trace-element contents for two groups of rhyolites. *A*, Incompatible trace elements for average Type I and Type II rhyolites of Portage Lake Volcanics. *B*, Incompatible trace elements for average rhyolites from several localities within the Midcontinent rift. Normalization to primitive mantle using the normalizing values of Wood and others (1979b).

Rhyolites

The two types of rhyolites distinguished geochemically also can be distinguished macroscopically. Type I rhyolite samples are dark-red-brown aphyric rocks in which phenocrysts are absent or make up no more than 2 vol percent of the rock. Where present, the phenocrysts are typically small (<1.5 mm (millimeters)), euhedral to subhedral feldspars locally associated with very rare subhedral quartz phenocrysts. In comparison, the Type II rhyolite is gray white and distinctly porphyritic, containing up to 10 vol percent phenocrysts of euhedral to anhedral quartz and euhedral to subhedral feldspar ranging in size from 0.5 to

2.5 mm. Detailed mineral composition data are not available for either rhyolite type.

Type I Rhyolite

In Type I rhyolite, both alkali and plagioclase feldspar are intergrown with quartz in a very fine grained devitrified matrix. The rhyolite of Mt. Houghton contains feldspar microlites of about 0.2 mm size that are generally aligned parallel to the direction of flow foliation and are slightly larger than the groundmass feldspar. All other Type I rhyolite bodies also have sparse andesine to oligoclase phenocrysts and glomerocrysts, in addition to the groundmass and microlite feldspars (Papadakis and Raza, 1954). Locally, plagioclase phenocrysts are mildly sericitized. Widespread, finely disseminated Fe-Ti oxides impart the characteristic red color to the Type I rhyolite. No mafic minerals are preserved, but some concentrations of Fe-Ti oxides may represent the sites of original mafic silicate minerals. Fe-Ti oxide microphenocrysts about 0.2–0.3 mm long are common. Whole-rock X-ray spectra collected during this study by P.M. Okita for several Type I rhyolite samples show the presence of quartz, orthoclase, and plagioclase, with local minor carbonate minerals in some samples.

Quartz is an essential groundmass constituent but rarely occurs as a phenocryst phase in Type I rhyolites. Where rare quartz phenocrysts are present (such as in the rhyolites of Montreal River and Bare Hill), the grains are anhedral, commonly embayed, and small (<1 mm). Secondary quartz fills vesicles, lithophysae, and small fractures and acts as a cement among breccia fragments. Zircon is a sparse but ubiquitous accessory mineral. Carbonate and epidote locally fill veins and cavities.

Type II Rhyolite

Feldspar phenocrysts in Type II rhyolite are both plagioclase and an alkali feldspar, most likely sanidine. The alkali feldspar phenocrysts are commonly altered and have been replaced by clay minerals, oxides, and (or) carbonate. Sparse albite phenocrysts show minor alteration to sericite. Quartz is a common phenocryst phase in the Type II rhyolite, typically making up about half the volume of phenocrysts. Quartz phenocrysts are subhedral to anhedral and show resorbed margins. No mafic silicate minerals are preserved in the Type II rhyolite, although, as is the case for the Type I rhyolites, it is possible that some Fe-Ti oxide concentrations represent sites of original mafic phases. Fe-Ti oxides also occur as sparse phenocrysts. Zircon is a common accessory phase, and, locally, carbonate has flooded the quartz-feldspar groundmass. Whole-rock X-ray spectra for Type II rhyolite samples show the presence of quartz, orthoclase, plagioclase, carbonate minerals, and illite; illite is not in the Type I rhyolite.

Table 5. Average major-oxide and trace-element compositions of rhyolites of Portage Lake Volcanics and representative bimodal, calc-alkalic, peralkalic, and topaz rhyolites

[Major oxides in weight percent; trace elements in parts per million. Empty cells, no data; n.d., not determined; N, number of samples in average analysis reported in table]

| | Bimodal basalt-rhyolite | | | Calc-Alkalic | Peralkalic | | Topaz rhyolite[6] | | Midcontinent rift rhyolites of Portage Lake Volcanics[7] | |
| | Iceland[1] | Yellowstone and Snake River[2] | Mono Craters and Glass Mountain[3] | Taupo[4] | Kenya Rift Valley[5] | | Spor Mountain | Thomas Range | Type I | Type II |
	$N{=}4$	$N{=}21/15$	$N{=}24/3{-}19$	$N{=}25/35$	$N{=}1$	$N{=}1$	$N{=}11$	$N{=}7$	$N{=}31$	$N{=}4$
Major oxides:										
SiO_2	73.91	76.59	76.61	74.22	75.2	72.5	74.2	76.46	73.84	75.74
TiO_2	.20	.16	.06	.28	.17	.23	.05	.13	.12	.05
Al_2O_3	12.79	12.36	12.77	13.27	12.11	10.44	13.5	12.53	13.65	13.28
Fe_2O_3	.96	1.08	.4	.88	.83	1.9	[8]1.29	.91	.66	.44
FeO	1.82	.56	.56	.92	1.06	2.21		.24	1.32	.87
MnO	.05	.03	.05	.05	.04	.06	.06	.04	.03	.04
MgO	.26	.14	.08	.28	.07	.02	.11	.18	.23	.14
CaO	1.00	.54	.57	1.59	.44	.15	.61	.96	.25	1.38
Na_2O	4.01	3.47	4.04	4.24	4.59	5.54	3.95	3.34	3.23	2.48
K_2O	3.54	5.04	4.82	3.18	4.73	4.36	4.86	4.91	6.64	5.60
P_2O_5	.59	.02	.04	.05	n.d.	n.d.	0	.02	.03	.02
Total	99.13	99.99	100.00	98.96	99.24	97.44	98.63	99.72	100.00	100.04
Trace elements:										
Nb	71	41	17	5.6	200	590	109	53	41	51
Rb	90		185	108	290	637	1,010	423	112	465
Sr	82	27	121	125	6.15	1.25	6	28	55	28
Zr	451	203	111	160	439	2,018	110	129	240	144
Y	140	54	25	27.5	108	296	116	58	56	74
La	77.2	97	39	28.4	74	153	38	59.5	30.3	12.0
Sm	20.74			5.5	12.3	36.8	6.5	15.6	6.57	6.9
Yb	1.82	6.5	3	3.55	10.1	34.6	8	15.6	5.55	7.68
Hf	14.8			4.5	14.9	60.5	6.7	5.5	7.53	6.3
Ta	5.35			n.d.	14.4	49.4	26	5.6	2.91	4.9
Th	11.2			11.3	38.8	124	67	54.8	15.09	63.0

[1]Wood (1978).

[2]Ewart (1979). $N{=}21$ for major oxides, 15 for trace elements.

[3]Ewart (1979). $N{=}24$ for major oxides, 3 for Yb, 10 for La, 18 for Rb, 19 for Nb, Sr, Zr, and Y.

[4]Ewart and others (1968). $N{=}25$ for major oxides, 35 for trace elements.

[5]Macdonald and others (1987a).

[6]Christiansen and others (1984, 1986).

[7]This report.

[8]Total iron as Fe_2O_3.

Hydration and Devitrification Textures

Devitrification textures, developed in formerly glassy material, are common in silicic volcanic rocks and are present in all rhyolites of the Portage Lake Volcanics. Glass is extremely rare in silicic volcanic rocks older than Cretaceous age (Lofgren, 1971b). However, the presence of glassy material in Midcontinent rift volcanic rocks from the North Shore Volcanic Group and the Michipicoten Island Formation (Roedder and Weiblen, 1971; Palmer and others, 1988) attests to remarkable preservation due to the lack of extensive alteration, posteruptive deformation, or deep burial of Midcontinent rift rocks. No pristine glass has been identified in the Portage Lake Volcanics, but the original presence of glass is demonstrated by delicate hydration and incomplete devitrification textures preserved in these rhyolites for more than a billion years.

Lofgren (1971a,b) successfully produced common devitrification textures by varying conditions of temperature, pressure, time, and fluid composition in subsolidus experimental runs with natural rhyolite obsidians. He defined two devitrification stages—an initial glassy stage followed by a spherulitic stage. In addition to intergrown spherulites, the spherulitic stage is characterized by the presence of micropoikilitic quartz enclosing spherulites and feldspar grains, the so-called snowflake texture (Lofgren, 1971b). In older volcanic rocks, the fibrous minerals in spherulites typically are recrystallized, resulting in a fine-grained equidimensional or felsitic texture of quartz and feldspar (Cas and Wright, 1987).

Textures produced experimentally by Lofgren (1971a,b) duplicate textures in modern rhyolite bodies (for example, Christiansen and Lipman, 1966; Bonnichsen and Kauffman, 1987; Cas and Wright, 1987; Manley and Fink,
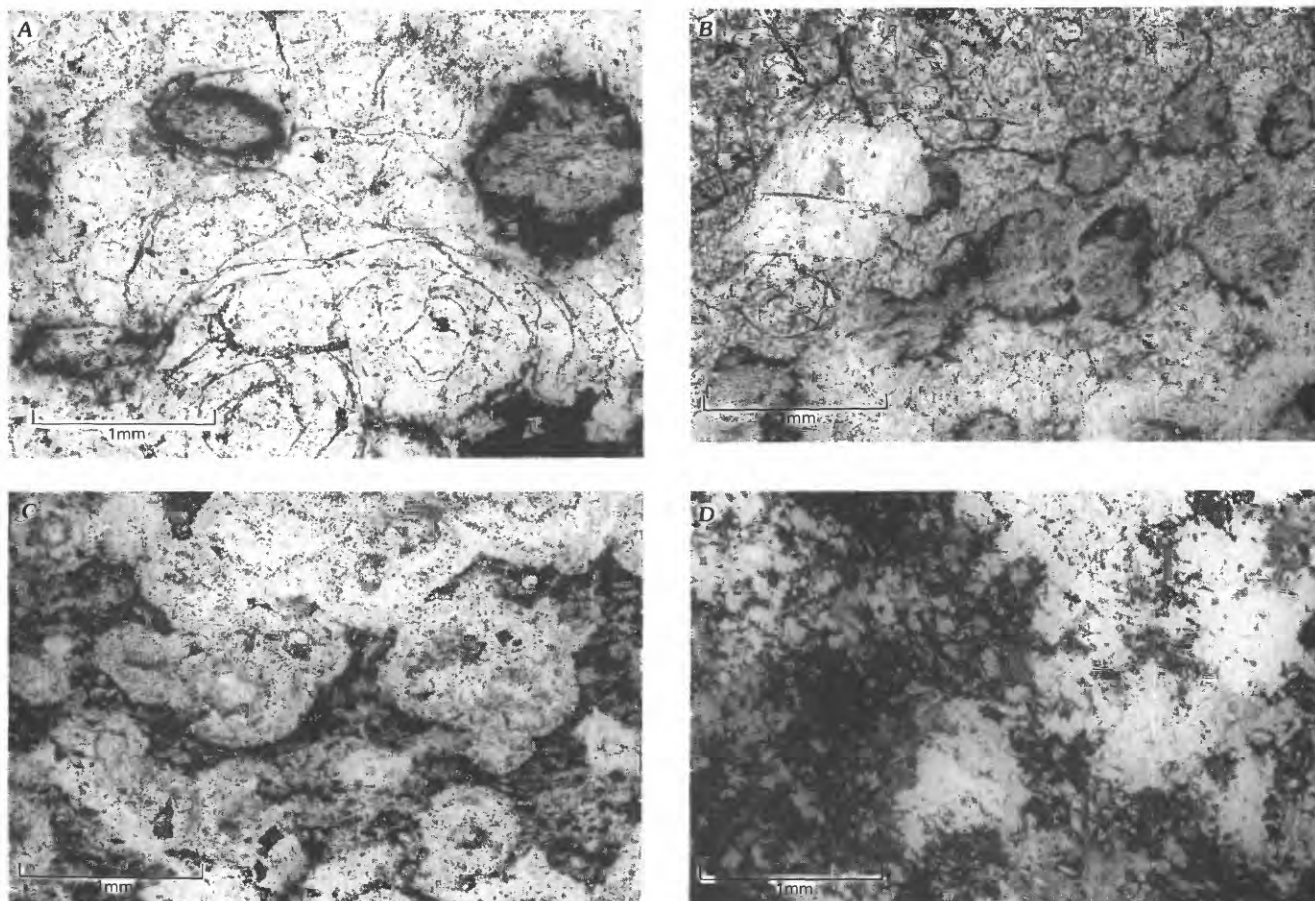
Figure 14. Photomicrographs of rhyolitic textures. *A*, Thin section (plane-polarized light) of perlitic texture and isolated spherulites preserved in rhyolite breccia fragment from Keystone Point. *B*, Thin section (plane- polarized light) of bow-tie spherulites in perlitic matrix in rhyolite breccia fragment from Keystone Point. *C*, Thin section (plane-polarized light) of coalescing spherulites from north side of rhyolite of Mt. Houghton. *D*, Thin section (x-nicols) of snowflake texture preserved near top of south side of rhyolite of Mt. Houghton.

1987) and have been documented at least locally in some rhyolites of the Portage Lake Volcanics, despite their Proterozoic age. Some of the most delicate textures representing the earliest stages of devitrification are preserved in silicified breccia fragments from northern margins of the rhyolites of Mt. Houghton and Keystone Point. In a breccia sample from Keystone Point (fig. 14*A*), delicate perlitic texture and isolated spherulites are preserved, representing very low temperature hydration. Such marginal breccias are only locally preserved; more commonly, rhyolite at the present margins of the stratiform bodies contains small spherulites, indicative of devitrification at temperatures lower than 400 °C.

Larger and more widely spaced spherulites are typical of samples closer to the interior of the rhyolite bodies. Well-preserved bow-tie spherulites at Keystone Point (fig. 14*B*) and coalescing spherulites or axiolites (fig. 14*C*) near the margins of the rhyolites of Mt. Houghton and Montreal River suggest that these samples underwent devitrification at intermediate temperatures, resulting from slower cooling

rates than encountered at the margins of the bodies. The most common devitrification textures are "snowflake" and felsitic textures characteristic of large parts of the rhyolites of Bare Hill, West Pond, and Fish Cove as well as the stony cores of the rhyolites of Mt. Houghton (fig. 14*D*) and the Montreal River. Recrystallization to felsitic textures obliterates earlier textural features of silicic glass and is common in many older rhyolites (Green, 1970, 1977).

In summary, the stratiform rhyolite bodies show a wide range of devitrification textures, from perlitic and (or) spherulitic at their margins to felsitic in their interiors. The discordant rhyolite bodies are dominated by felsitic texture and only locally show spherulites near their margins.

Alteration around Vesicles and Fractures

Numerous small vesicles and fractures are present near the margins of some Type I rhyolite bodies. They are generally aligned subparallel to the dominant foliation in the rhyolite (fig. 15*A*). Strings of rounded to slightly flattened
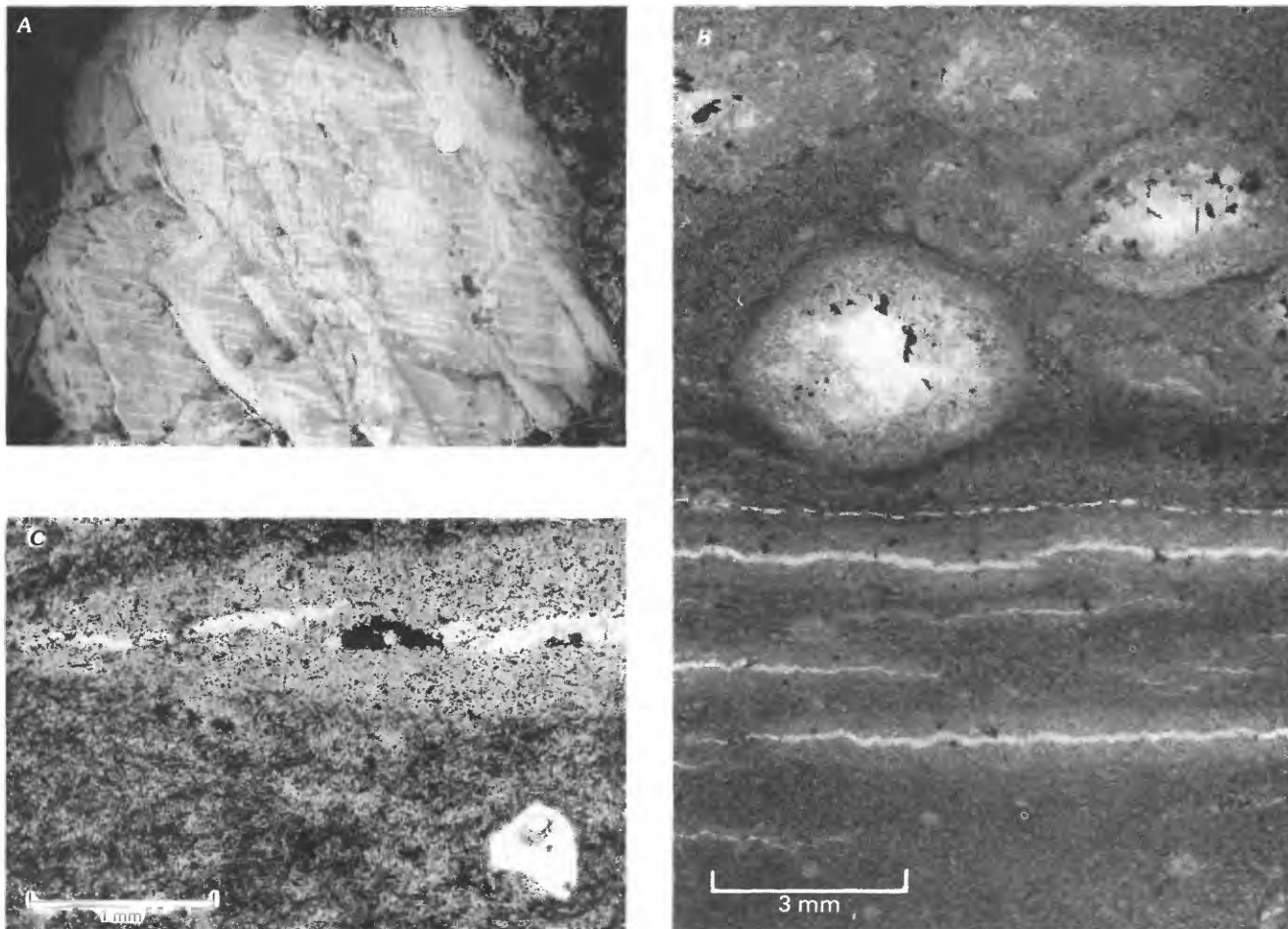
Figure 15. Photograph and photomicrographs of en echelon fractures in rhyolite. *A*, Field shot of en echelon fractures (low dip, light color due to local alteration) at Mt. Houghton. Coin is 2.2 centimeters in diameter. *B*, Thin section (plane-polarized light) of vesicles and tension fractures. Interiors of vesicles filled with quartz, Fe-Ti oxides, and some feldspar. From rhyolite sample from Mt. Houghton. C, Thin section (plane-polarized light) of zoning around quartz-filled fracture. Phenocryst is a rare quartz grain; rhyolite of Montreal River.

vesicles commonly occur in the same area as discontinuous en echelon fractures (fig. 15*B*). Some fractures may be collapsed vesicles that became elongated during flowage as the rhyolite cooled (Fink, 1983; Bonnichsen and Kauffman, 1987; Hausback, 1987); most, however, probably resulted from shearing as the flow advanced, providing avenues for vapor migration through the flow (Manley and Fink, 1987). Equant vesicles commonly are a few millimeters to 1 cm (centimeter) in diameter, whereas the fractures typically range up to 5 cm or more in length and 1–2 mm in width and are spaced about 0.5 cm to several centimeters apart.

Both vesicles and fractures are typically filled by coarse euhedral quartz and lesser Fe-Ti oxides. Surrounding individual vesicles and fractures is a light-colored zone several millimeters wide that resulted from an abrupt decrease in Fe-Ti oxide concentration in the rhyolite groundmass (fig. 15*C*). This zone near the fracture is dominated by potassium feldspar, and by fewer and coarser disseminated oxides compared with unaffected rhyolite.

Locally within this zone, there is a slight increase in size of the potassium feldspar grains, suggesting that locally higher contents of volatile elements may have affected grain size.

FIELD RELATIONS OF RHYOLITES OF PORTAGE LAKE VOLCANICS

Early workers recognized that several stratiform rhyolite bodies occur along nearly the same horizon and exhibit features that suggest an extrusive origin, whereas several other rhyolite bodies occur stratigraphically below the stratiform rhyolite horizon and appear to be "intrusive," disrupting adjacent basalt flows (Hubbard, 1898). The conclusions of these early observers remain valid. Recent work in young rhyolite fields (for example, Christiansen and Lipman, 1966; Benson and Kittleman, 1968; Fink, 1983; Bonnichsen and Kauffman, 1987; Fink and Manley, 1987; Manley and Fink, 1987; Sampson, 1987) has docu-
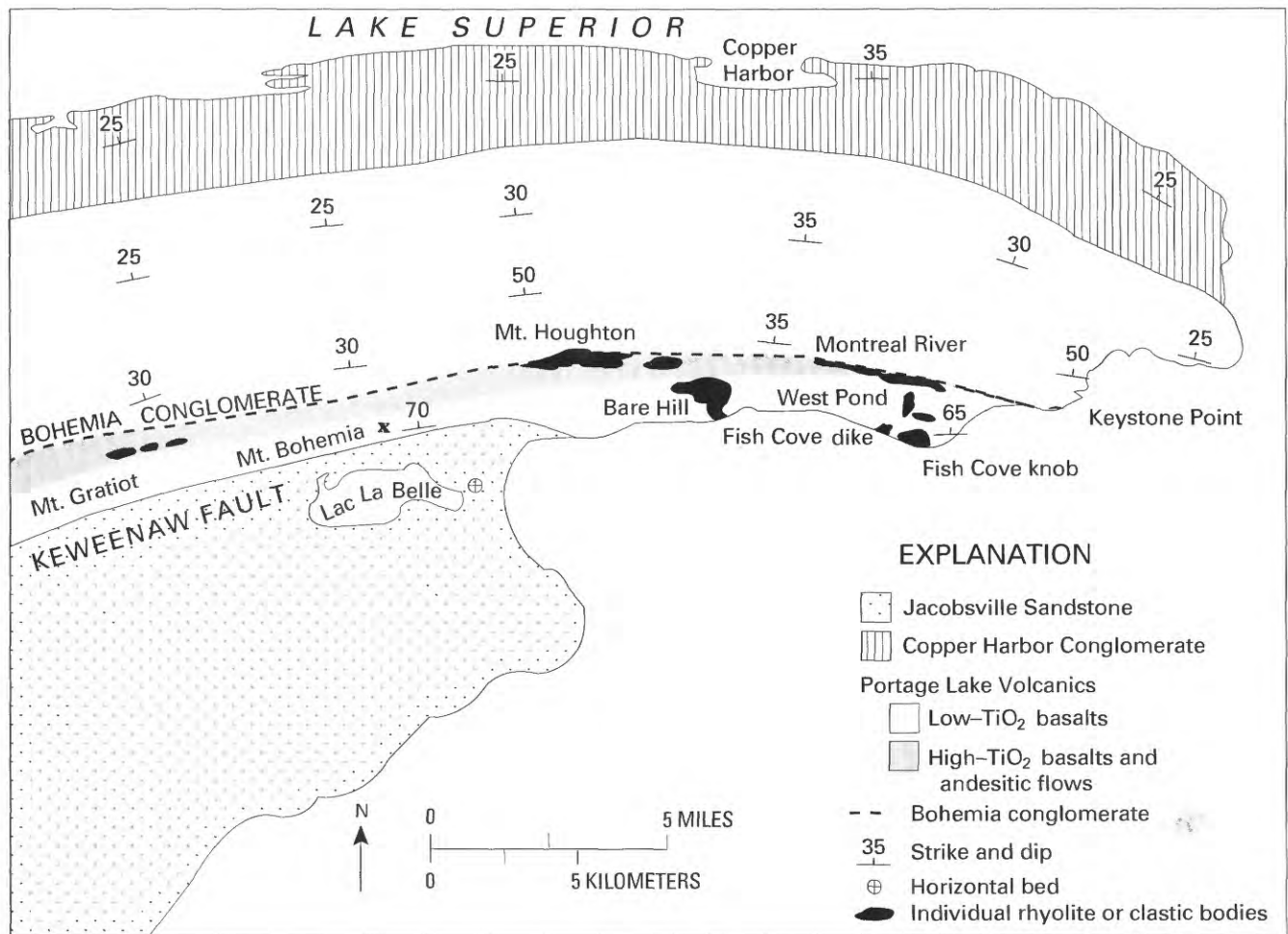
Figure 16. Location of Type I rhyolite bodies and some andesite and dacite bodies, and the regional dips of the Portage Lake Volcanics and surrounding units, on the eastern tip of Keweenaw Peninsula.

mented the characteristics typical of modern rhyolite extrusive flows and has led to a more complete understanding of the relation between rhyolitic pyroclastic and lava flows. It is clear, from comparison with these studies, that many features of modern flows are preserved in the rhyolites of the Portage Lake Volcanics, despite their Middle Proterozoic age.

This section summarizes the field relations of rhyolites of the Portage Lake Volcanics, compares modern rhyolite systems with these rhyolites, and discusses the relation of the rhyolite bodies to the associated "conglomerates."

Stratigraphy

The Portage Lake Volcanics dips to the north beneath Lake Superior, is 3–5 km thick, and is faulted, but the unit has not been penetratively deformed. Dips are steepest (about 60°–80° N.) near the Keweenaw fault and become more shallow near the lake, where the upper part of the

Portage Lake Volcanics and the overlying Copper Harbor Conglomerate dip about 20°–30° N. (fig. 16). The Portage Lake Volcanics is at the margin of a central graben segment of the rift adjacent to the Keweenaw fault, which acted as a major normal growth fault during extension. Subsidence was greatest within the central graben, and volcanism became focused there. When flows of the Portage Lake Volcanics were extruded, rapid subsidence resulted in early flows tilting into the graben and succeeding flows erupting on a surface that continued to subside. Thus, the fanning of dips in the Portage Lake section is in part a primary feature, steepened by later compression.

Because the rhyolite bodies are near the base of the section where dips are steep, the map view (Cornwall, 1954b, 1955) is essentially a cross section through the bodies. Individual rhyolite bodies are resistant to erosion, and the larger bodies form hills above the erosional level of the basalts. For this reason, the rhyolite hills and associated conglomerate were called the "Bohemian Range" by Irving (1883) and earlier workers.
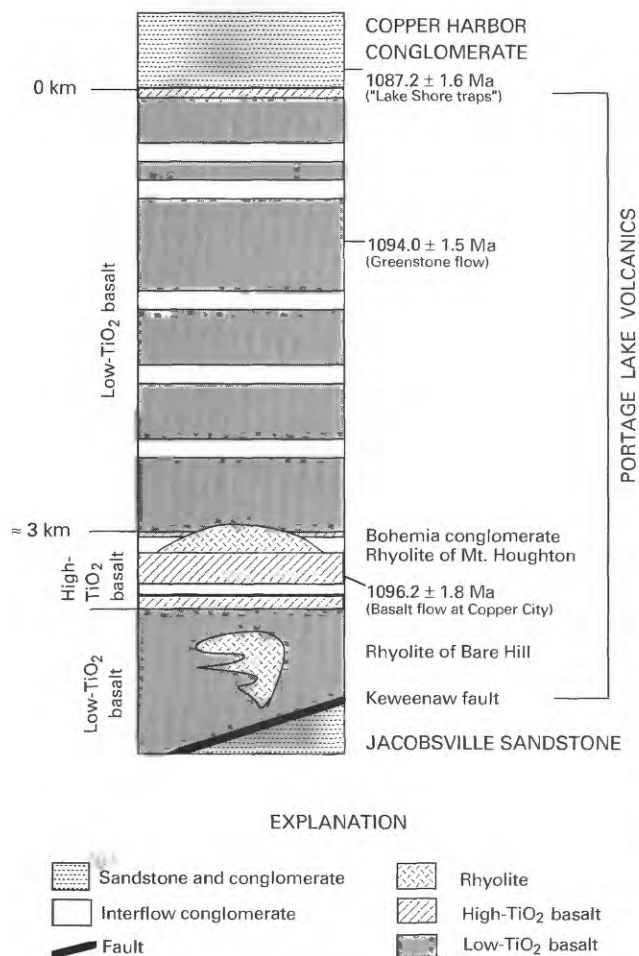
Figure 17. Generalized stratigraphic section of Portage Lake Volcanics in vicinity of rhyolite of Mt. Houghton, illustrating the location of high-TiO$_2$ basalt intervals and the location of associated felsic extrusive and subvolcanic bodies. Ages for the Copper City basalt flow, the Greenstone flow, and the "Lake Shore traps" (within the Copper Harbor Conglomerate) from Davis and Paces (1990).

The general stratigraphy in the vicinity of the rhyolite bodies at the eastern end of the Keweenaw Peninsula is as follows (fig. 17). Low-TiO$_2$ ophitic basalts are the lowest unit of the Portage Lake Volcanics, and their base is faulted. About 1 km above the Keweenaw fault, a 0.5-km interval of high-TiO$_2$ basalts and more evolved rocks overlies the low-TiO$_2$ basalts. Stratiform or extrusive rhyolite bodies occur near the top of this interval of high-TiO$_2$ basalt, basaltic andesite, and andesite. Andesite commonly underlies the pyroclastic units, which typically underlie the stratiform rhyolite bodies. Discordant or "intrusive" rhyolite bodies occur below the stratiform rhyolite horizon. The Bohemia conglomerate, a distinctive felsic pebble conglomerate associated with the stratiform rhyolite horizon, has been traced laterally for tens of kilometers (Stoiber and Davidson, 1959a,b). Overlying the stratiform rhyolite horizon and Bohemia conglomerate are about 3 km of basalt and minor interlayered sedimentary rocks. In the Mt. Houghton

area, the first basalt flows to extrude after deposition of the Bohemia conglomerate were high-TiO$_2$ basalts. Subsequently, low-TiO$_2$ basalts were extruded and thereafter dominated the volcanism. High-TiO$_2$ basalts recur only near the top of the Portage Lake Volcanics (Paces, 1988). No rhyolite bodies are exposed above the Bohemia conglomerate.

Twenty-two interflow conglomerates have been mapped within the Portage Lake Volcanics and used extensively for correlation (Butler and Burbank, 1929). Two types of conglomerates are recognized: amygdaloidal basaltic conglomerates are more common in the lower part of the formation, and dominantly felsic conglomerates are common in the upper part (above the felsic Bohemia conglomerate). Where the two types occur together, amygdaloidal basalt conglomerate generally underlies felsic conglomerate; their positions suggest that local erosion of basalt flows was followed by stream deposition of debris from more distant sources (Butler and Burbank, 1929).

Despite the restricted exposure of rhyolite bodies in the Portage Lake Volcanics, felsite and granophyric pebbles account for nearly 70 percent of the clastic material that makes up the numerous interflow conglomerates above the Bohemia conglomerate (Merk and Jirsa, 1982). Such a large volume implies a larger felsic source than can be accounted for by the presently exposed rhyolite bodies. In addition, some of the rhyolite pebbles contain abundant quartz and feldspar phenocrysts, an assemblage that is absent from the outcrop at the east end of the Keweenaw Peninsula. The presence of this distinctive rhyolite type in conglomerates above the observed rhyolite exposures (which lack this rhyolite type) has been a puzzle. Paleocurrent studies suggest northwestward flow from sources, now eroded or buried, that were located to the south-southeast of the present exposure of the Portage Lake Volcanics (Merk and Jirsa, 1982) and, thus, outside the central rift graben.

The major rhyolite and intermediate bodies, from east to west, are described below.

Keystone Point

At Keystone Point, a southern point near the eastern tip of the Keweenaw Peninsula, felsic rocks crop out at the shore of Lake Superior along strike with the stratiform Montreal River bodies to the west (fig. 16). Because the felsic rocks extend into the water, the dimensions of the body are indeterminate, and the body is at most less than a meter above the lake level. Hubbard (1898) described two small promontories as banded and jointed felsite masses that locally contain spherulites. Contact relations are obscure, but to the north of these promontories, altered and brecciated felsic rock is overlain by a breccia containing fragments of felsic and mafic rocks. Similar breccia crops out at the lake's edge just to the east of Hoar Creek, less than 2 km west of Keystone Point.

Montreal River Area

Rhyolite of Montreal River

Outcrop of three small stratiform rhyolite bodies in the vicinity of the Montreal River is nearly 3 km long (fig. 16). This group of rhyolite bodies lies along strike about 3 km west of Keystone Point and strikes N. 70° W. to east-west. In map view, the widest area of outcrop is 200 m (meters), but generally the width is less than about 20 m. Outcrop is scattered, but small ridges and glaciated northern slopes afford reasonable exposure. Present-day relief is at most 25 m. Hubbard (1898), Papadakis and Raza (1954), and Cornwall (1955) mapped and described the rhyolites of Montreal River and associated conglomerates.

Hubbard (1898) considered this series of felsite bodies to be extrusive. The main mass of each Montreal River body is maroon rhyolite containing sparse feldspar phenocrysts. The most striking field characteristic is a well-developed foliation that generally parallels the margins of the body. This foliation is defined by maroon to gray laminae several millimeters thick interlayered on a scale of a few millimeters to centimeters. Adjacent layers vary in degree of crystallinity and devitrification, grain size, and content of spherulites and vesicles. Trails of spherulites are noticeable throughout the outcrops. Folding of interbanded layers is visible. Closely spaced parallel or en echelon fractures that are aligned with the flow foliation typically are filled with secondary quartz and feldspar as well as some carbonate minerals and epidote.

A coarse felsic pebble conglomerate overlying the Montreal River bodies has been correlated with the laterally extensive Bohemia conglomerate. Blocks within the felsic conglomerate become increasingly coarse and angular adjacent to the rhyolite, indicating that the breccia along the northern margin of the bodies was a local source of detritus.

Pyroclastic Units and Associated Conglomerate of Montreal River

Previous workers mapped at least three felsic fragmental units that they termed "conglomerates" adjacent to the rhyolites of Montreal River (Hubbard, 1898; Papadakis and Raza, 1954). West of the Montreal River, the "conglomerates" coalesce (Hubbard, 1898) and are correlated laterally with the Bohemia conglomerate (Cornwall, 1955). However, these three "conglomerates" are not identical; two are pyroclastic units. The coarse felsic pebble conglomerate that directly overlies the rhyolites of Montreal River is the most similar to the Bohemia conglomerate to the west.

The "conglomerate" directly underlying the rhyolite bodies, and in some places underlying the Bohemia conglomerate, is a lavender, partly welded pyroclastic unit (fig. 18A). The unit contains small fragments of rhyolite and basalt as well as rounded and broken feldspar phenocrysts and collapsed pumice fragments visible in hand sample and thin section (fig. 18B). This distinctive unit can be traced
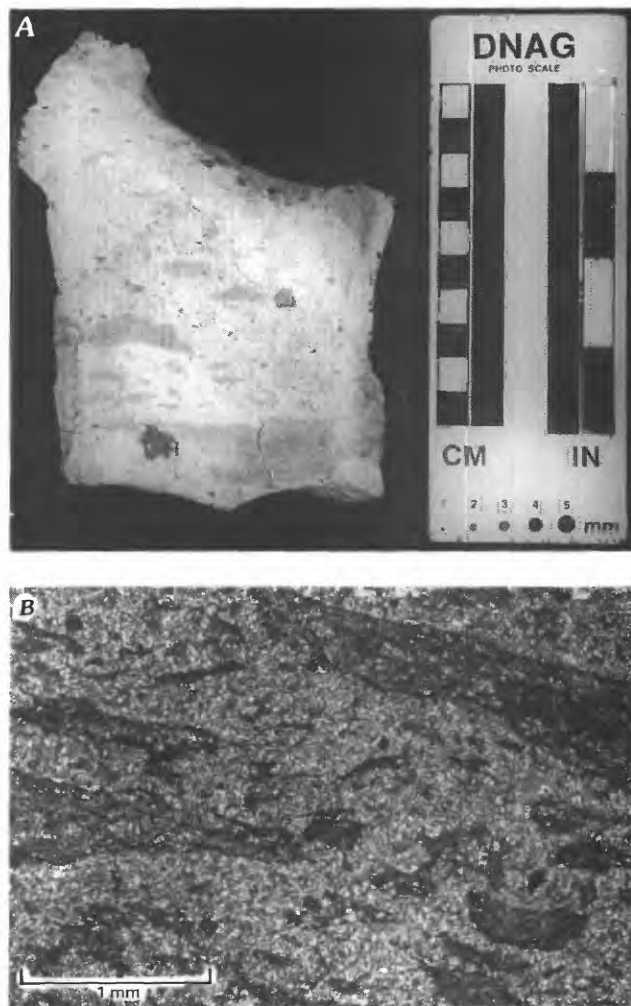
Figure 18. A, Hand specimen of ashflow tuff that underlies the rhyolite domes of Montreal River, showing partly flattened pumice and angular lithic fragments. B, Photomicrograph of thin section (plane-polarized light) of tuff showing fiamme.

beneath the rhyolite bodies near the Montreal River itself, but it is poorly exposed away from the river. Directly beneath this lavender pyroclastic unit is a coarse breccia whose angular blocks are dominantly mafic. Another lavender pyroclastic unit is exposed in limited outcrops between Mt. Houghton and Bare Hill (fig. 16). Although this unit is on strike with the lavender unit beneath the rhyolites of the Montreal River to the east, correlation of the two is equivocal.

Fish Cove Knob, Fish Cove Dike, and West Pond

The rhyolites at Fish Cove and West Pond, described by Hubbard (1898), Papadakis and Raza (1954), and Cornwall (1955), are considered to be intrusive. Two rhyolite exposures east of West Pond may be part of a single body, but their junction is covered. One exposure trends east-west, the other north-south, clearly cutting across the regional strike of the adjacent basalt units. Papadakis and

Raza (1954) described a few basalt inclusions at the margin of one West Pond body.

Fish Cove knob is an irregular body rising about 30 m above Lake Superior. The orientations of basalt flows adjacent to both the West Pond and Fish Cove knob bodies have been disrupted locally, suggesting displacement during intrusion of the bodies. Fish Cove dike is a small outcrop that cuts across the regional strike of the flows at a high angle and extends into the lake about 300 m west of Fish Cove knob. This brecciated outcrop is cemented by carbonate and contains small amounts of native copper.

The rhyolites of Fish Cove and West Pond have sparse feldspar and rare quartz phenocrysts and thus are similar to the rhyolite of Montreal River. Flow foliation is present only near contacts. The interiors typically are massive and are brecciated locally. Small quartz-filled vesicles are present in some areas. Spherulitic texture is preserved locally at the margin of Fish Cove knob. The two rhyolite bodies of West Pond and the two of Fish Cove are directly south of the rhyolite domes of Montreal River and may represent feeders to the overlying domes. However, no direct connection among the bodies is traceable in the field.

Bare Hill Area

Bare Hill is named for its steep, unvegetated, south-facing cliffs, which rise nearly 300 m above Lake Superior and more than 100 m above the erosional level of the surrounding basalts. Hubbard (1898) and more recent workers (Papadakis and Raza, 1954) recognized that several sills make up this body, although there is no obvious connection between the rhyolite visible on the lake shore and the main mass of several sills that underlie Bare Hill itself. The upper sill is the largest, nearly 1 km long and up to 0.5 km wide (fig. 16).

Emplacement of the Bare Hill sills resulted in a flexure in the orientations of the overlying basalt flows and conglomerates, both above and below the Bohemia conglomerate (Papadakis and Raza, 1954). The eastern contacts of the upper and lower rhyolite bodies of Bare Hill trend about N. 25° W., clearly crosscutting the regional east-west strike of the adjacent basalts and interflow conglomerates. Along the southern margin of the uppermost sill, small basalt fragments are included in the rhyolite and clearly have reacted with the rhyolite. Flow foliation is common throughout the lowermost sill but is present only at the margins of the upper sills. The rhyolite sills of Bare Hill contain sparse feldspar phenocrysts and rare quartz phenocrysts, similar to the West Pond and Fish Cove bodies.

Four small, closely spaced outcrops of strongly brecciated, carbonate-cemented rhyolite lie on the lake shoreline just west of the stream immediately west of Bare Hill (Cornwall, 1954b). The largest outcrop trends N. 80° E. (Cornwall, 1954b), but it may be truncated by a fault (Papadakis and Raza, 1954). These outcrops, called the "western felsite" by Papadakis and Raza (1954), are mineralogically similar to the rhyolite of Bare Hill.

Mt. Houghton Area

Rhyolite of Mt. Houghton

Mt. Houghton is a prominent topographic feature rising about 150 m above the current erosional level of the surrounding basalts. Mapped by Hubbard (1898), Fritts (1952), and Cornwall (1954b), the lenticular rhyolite body of Mt. Houghton is more than 2 km long and strikes east-west. This stratiform extrusive body is 300 m wide at its widest point, but it pinches out to the east and west (fig. 16). Steep slopes along the north and south sides of Mt. Houghton afford good rock exposures.

Along the northern flank of Mt. Houghton near the contact with the overlying basalts, a fine-grained breccia is locally preserved (see fig. 20). This breccia grades laterally into felsic conglomerates that adjoin the Mt. Houghton body at several places. Most of the conglomerates pinch out within a kilometer of the rhyolite body, but the Bohemia conglomerate, which adjoins the rhyolite body near its base, has been correlated laterally with extensive conglomerate exposures east and west of Mt. Houghton. Also on the northern flank, abundant lithophysae as large as 2–3 cm in diameter are well exposed (fig. 19A). The cavities generally are spherical, but locally vesicles and lithophysae coalesce.

The main mass of Mt. Houghton is composed of maroon aphyric rhyolite, which has a well-developed foliation that generally parallels the margins. Interbedded maroon to gray laminae several millimeters to centimeters thick define the foliation (fig. 19B). Adjacent layers vary in degree of crystallinity and devitrification, grain size, and content of spherulites and vesicles. Locally, some layers have been pulled apart, forming boudins (fig. 19C), and folding of interbanded layers is common. Near the summit of Mt. Houghton, foliation orientations define a roughly concentric pattern (fig. 20). Closely spaced parallel or en echelon fractures commonly are filled with secondary quartz and feldspar and are aligned with the flow foliation. Along the northern contact, the fractures and flow foliation generally become less regular and more widely spaced.

A steep face on the south side of Mt. Houghton provides an oblique cross section of the stony foliated interior of the rhyolite body, its southern contact, and part of the underlying pyroclastic unit. The upper part of the pyroclastic unit has been welded, rendering the contact between the pyroclastic unit and the overlying rhyolite body indistinct. Numerous internal zones of fine-grained breccia can be traced throughout the basal section of the rhyolite body. Flow foliation generally parallels the southern margin of the body, but locally it defines small folds and boudins. Spherulites are also present near the base. No xenoliths were observed, and none has been reported from this body.
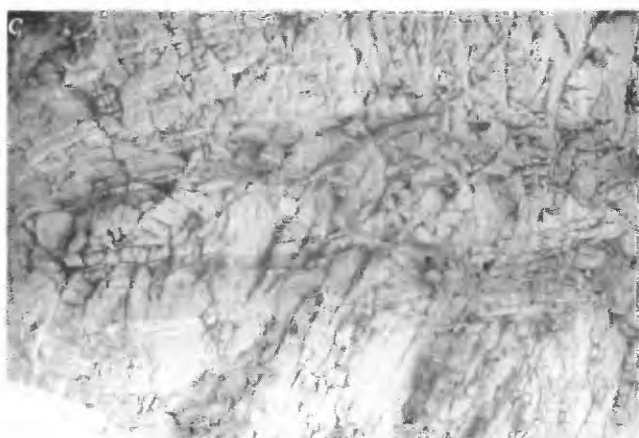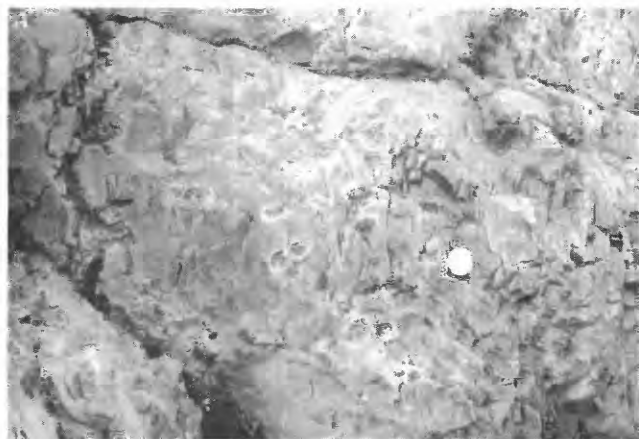
Figure 19. Features in the rhyolite of Mt. Houghton. *A,* Lithophysae on the north flank of Mt. Houghton range up to several centimeters in size. Coin is 2.2 centimeters in diameter. *B,* Foliation defined by alternating layers of varying crystallinity, vesicularity, color, and texture. Hammer for scale. *C,* Vesicular layers forming boudins, with foliation flowing around the boudins. Coin is 2.2 centimeters in diameter.
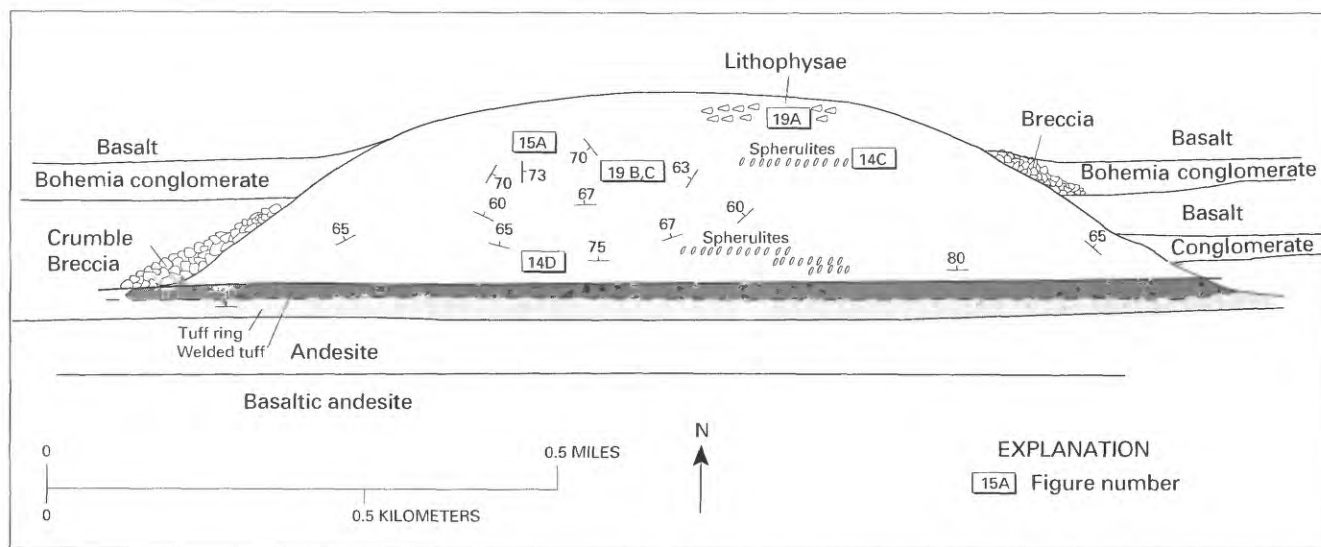
Figure 20. Plan view of rhyolite of Mt. Houghton showing location of diagnostic features, orientations of foliations, and adjacent rock units. Numbers correspond to thin-section photographs in figure 14, and to field photographs in figures 15 and 19. The Mt. Houghton body most likely represents a rhyolite lava dome or flow.

Along the western margin of the main rhyolite mass, a coarse silicified breccia overlies the pyroclastic unit. Perlitic texture is visible within the brecciated rhyolite fragments.

Pyroclastic Unit of Mt. Houghton

Immediately underlying the rhyolite body of Mt. Houghton is a pyroclastic unit that was mapped as a

"conglomerate" by previous workers (Hubbard, 1898; Fritts, 1952). This unit appears to be a local feature preserved directly beneath Mt. Houghton itself; beyond the margins of the rhyolite body, preservation and outcrop exposure of the pyroclastic unit are poor to nonexistent. The thickness of the unit ranges from 0 to 30 m. In one locality, beneath the eastern half of Mt. Houghton, a coarse mafic-clast-dominated breccia is present and the fine-grained pyroclastic unit is not exposed, being either absent or very thin.

Glass shards and basaltic and rhyolitic fragments are aligned parallel to the regional strike in this pyroclastic unit. The unit shows little welding at its base, but the upper several meters are welded where the unit is in direct contact with the overlying rhyolite body (fig. 20). Although exposures of the unit are poor, clastic fragments appear to become generally finer up-section. Beneath the west end of the rhyolite of Mt. Houghton, the coarsest fragments decrease in size from about 5–20 cm near the base to 2–4 cm near the top of the unit. Beneath the eastern end of the body, the coarsest fragments, about 3–6 cm, are near the top. Foliated rhyolite fragments and glass shards dominate the clasts, but mafic fragments are present, though they commonly are smaller than the rhyolite fragments. Although the pyroclastic unit underlies Mt. Houghton, it is not possible to correlate it directly with a similar unit that crops out beneath the Montreal River bodies. No chemical analyses that would aid in correlation have been done on this unit, outcrop is discontinuous, and the pyroclastic unit of Mt. Houghton contains a larger proportion of mafic and intermediate fragments than the unit beneath the Montreal River domes.

Suffolk and Mt. Gratiot Areas

Other small, discordant bodies have been mapped to the west of Mt. Houghton, including the bodies at Mt. Gratiot (Cornwall, 1954a) and Suffolk (Wright and Cornwall, 1954) (fig. 5). These small, irregular bodies occur below the Bohemia conglomerate in a stratigraphic position similar to that of the rhyolites of Bare Hill and Fish Cove to the east (fig. 16). The dacite at Mt. Gratiot occurs as discontinuous exposures at the top of Mt. Gratiot (Cornwall, 1954a). Browne and Haynes (1956) described flow foliation in the lower part and abundant vesicles and brecciation near the upper contact. The interior is massive felsite with sparse feldspar phenocrysts.

The Suffolk intrusion, originally called the Praysville porphyry (Irving, 1883), is a dark-reddish-brown andesite containing feldspar phenocrysts (fig. 5). Contacts with surrounding basalts are covered, but its dimensions are estimated at 500 m long and 100 m wide (Wright and Cornwall, 1954).
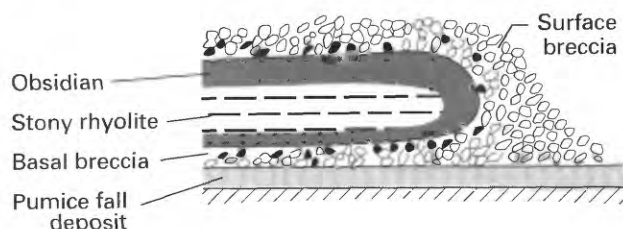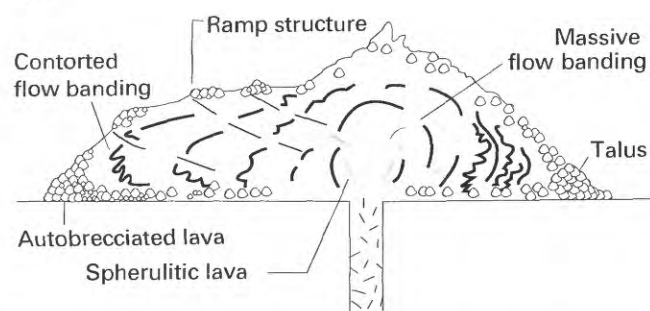
Figure 21. *A*, Schematic cross section of a typical rhyolite lava flow illustrating distribution of lithologies (after Cas and Wright, 1987). *B*, Schematic cross section of a typical small rhyolite dome and short flow illustrating distribution of internal and surficial features (after Self, 1982). See text for discussion.

Copper City Area

The rhyolite of Copper City occurs below the Bohemia conglomerate but significantly to the west of the other rhyolite bodies near the tip of the Keweenaw Peninsula (fig. 5) (White and others, 1953; Davidson and others, 1955). It is the only rhyolite body on the Keweenaw Peninsula that is gray white in outcrop and has abundant quartz phenocrysts. One or two additional small occurrences of gray quartz-bearing rhyolite in the vicinity of the rhyolite of Copper City were noted by Hubbard (1898), but they have not been located by more recent workers.

Although internal breccia zones are numerous, flow foliation is not common. The contacts are not exposed; thus, it is difficult to determine whether the body was extrusive or subvolcanic. Because of poor outcrop in the area, it is also not known whether a pyroclastic phase is present. However, the body occurs below the Bohemia conglomerate and appears to crosscut the strike of the basalt units. Until further evidence is found, it is considered to be subvolcanic.

Comparison of a Modern Rhyolite Lava Flow with Extrusive Rhyolites of Portage Lake Volcanics

A comparison of a typical modern rhyolite lava flow and a well-exposed example of an extrusive rhyolite body of

the Portage Lake Volcanics, such as at Mt. Houghton, reveals that original lithologies and delicate textures are remarkably well preserved despite the ancient age of the rhyolites of Portage Lake. An idealized cross section (fig. 21A) illustrates the spatial distribution of lithologies within a typical recent rhyolite lava flow. The vertical stratigraphy upward in a rhyolite flow begins with pyroclastic material from a coeruptive pumice fall deposit that precedes the eruption of the lava flow itself (Christiansen and Lipman, 1966; Fink, 1983). As the rhyolite lava extrudes, its surface quenches and fractures, and blocks slide off the flow front and are overridden by the advancing lava (Fink, 1983), producing a basal breccia and brecciated flow margins. If the rhyolite flow is sufficiently thick, then a quenched obsidian margin forms an envelope around the stony foliated interior of the flow. The glassy marginal envelope may be somewhat thicker at the top of the flow than beneath it and may show evidence of hydration, vesiculation, interbanding of lithologies, flow foliation, and upon cooling, incipient development of spherulites (Cas and Wright, 1987). The stony interior retains heat, allowing devitrification, spherulite development, and crystallization. Thicker flows commonly have disproportionately thicker devitrified cores than thinner flows, owing to the exponential increase in heat retention with increasing flow thickness (Manley and Fink, 1987). Overlying the upper obsidian zone is an upper vesicular and brecciated glassy zone.

Flow foliation or flow banding is the primary internal feature within a rhyolite flow or dome (fig. 21B). This foliation is typically defined by laminae a few millimeters to a few centimeters thick that show variations in color, texture, lithology, vesicularity, or phenocryst content (Christiansen and Lipman, 1966; Benson and Kittleman, 1968; Fink, 1983; Cas and Wright, 1987). Phenocrysts and microlites commonly are aligned with their long axes approximately parallel to the direction of flow foliation (Benson and Kittleman, 1968). Studies of modern rhyolite flows and domes (Christiansen and Lipman, 1966; Benson and Kittleman, 1968; Fink, 1980, 1983) have used orientations of surficial ridges, folds, diapirs, and ramp structures to constrain the geometry and emplacement history of the flows.

In modern rhyolite flows, the location of the vent ideally can be determined from the orientation of flow foliations. Where the vent is a pipelike conduit, such as in the obsidian Inyo domes of California, foliations measured on the upper surface of the flow commonly dip shallowly away from the vent in a concentric pattern (Sampson, 1987); at some distance from the vent, foliations locally may steepen and overturn. Within the conduit itself, steep flow foliations parallel the sides of the conduit. A radial fracture pattern may occur around a pipe vent in addition to the concentric foliation pattern (Sampson, 1987). Not all rhyolite flows emanate from pipelike vents; some are

extruded along fissures. Fink (1983) and Fink and Pollard (1983) documented rhyolitic fissure eruptions in the Medicine Lake Highland area of California. The strike of flow foliations is parallel to the strike of the fissure, and flow foliations dip steeply away from the fissure on either side. Fractures in the rhyolite tend to parallel the orientation of the fissure.

Comparison of the distribution of lithologies within the Mt. Houghton body with an ideal lava flow reveals remarkable similarities (figs. 20, 21). The rhyolite of Mt. Houghton most likely represents a small rhyolite dome, or a lava flow lobe associated with a dome. The glassy carapace is still intact locally along the northern contact. Well-developed spherulites and lithophysae are evident stratigraphically just below the carapace. The core is stony and generally exhibits noticeable flow foliation. At the west end of the dome, a fragmental unit representing a probable marginal flow-front breccia has been silicified at the toe of the dome. The dome itself probably has relatively steep sides, but the breccia apron surrounding it softens the marginal slope. The relatively complete internal stratigraphy of the rhyolite of Mt. Houghton suggests that the present exposure represents a cross section near the middle of the body, whereas the abundance of spherulitic rhyolite with a strong flow foliation in the rhyolites of Montreal River suggests that these outcrops represent a cross section through the thinning margins of several domes or flows.

The concentrically zoned flow foliation pattern near Mt. Houghton's summit (fig. 20) suggests that it could represent the site of a vent; however, there is no direct evidence for the location of a vent, such as a feeder dike or localization of coarse pyroclastic material beneath the rhyolite body. Although the origin of the concentric fracture pattern is unknown, it may be analogous to the cross-sectional concentric fracture pattern illustrated in figure 21B above the vent area. Orientations of surficial ridges and folds could be helpful in determining the flow direction; however, rhyolites of the Portage Lake Volcanics are exposed only in cross section, and where the upper surface of a body is exposed, erosion typically has stripped away many surficial features.

Although mineral composition data are not available to constrain the original temperatures and volatile compositions of rhyolites of the Portage Lake Volcanics, the aphyric to sparsely porphyritic character of the rhyolites suggests that temperatures were high. No hydrous or anhydrous mafic phenocrysts have been recognized in rhyolites of the Portage Lake Volcanics. In addition, the preservation of glass (or the minor degree of devitrification of glass) and the small volume of pyroclastic material associated with the rhyolitic eruptions are characteristics that have been used as evidence of high temperature and low volatile contents of rhyolite lava flows in the Snake River Plain (Bonnichsen and Kauffman, 1987).

Comparison of Modern and Portage Lake Volcanics Pyroclastic Deposits

Many modern rhyolitic lava flows are preceded by phases of explosive activity. Three types of pyroclastic deposits, called fall, flow, and surge deposits, can be distinguished on the basis of mode of transport and deposition (Cas and Wright, 1987). Pyroclastic fall deposits result from particles settling out of an eruption column and being deposited downwind. Typically, the ash and lithic fragments mantle the topography, are generally better sorted than other pyroclastic deposits, and locally may be stratified. Walker (1973) described a classification of pyroclastic fall deposits that related the eruption style to the dispersal area and the degree of fragmentation. Pyroclastic flow deposits result from collapse of a lava dome, a flow, or an eruption column, causing the emplacement of multiple high-temperature dense mixtures of solids and gases that are gravity controlled and typically fill topographic depressions. Poor sorting is characteristic, although inverse grading of pumice fragments and normal grading of lithic fragments are observed locally. Pyroclastic surge deposits are well stratified and result from turbulent, low-density mixtures of solids, gases, and water associated with a variety of pyroclastic events.

All exposed extrusive rhyolites of the Portage Lake Volcanics clearly overlie pyroclastic units. However, studies of the areal distribution of the pyroclastic units are precluded by the present near-vertical orientation and limited lateral exposure. At Mt. Houghton, the progressive welding in the underlying pyroclastic unit toward the overlying lava suggests that the pyroclastic unit is a tuff ring produced by a small pyroclastic eruption that preceded the extrusion of the rhyolite flow itself. Pyroclastic activity probably was confined to the earliest stages of rhyolite eruption, as no pyroclastic units overlie the rhyolite of Mt. Houghton (or the rhyolite of Montreal River). The pyroclastic unit is poorly sorted and has an ash matrix. Locally, some internal stratification and inverse grading of glass shards may be present. The unit is matrix supported, and the abundance of glass shards relative to lithic fragments varies over several centimeters. Lithic fragments range from rhyolitic to basaltic but are dominated by rhyolite.

Underlying the Montreal River bodies are several pyroclastic units that may or may not be related to each other or to the overlying rhyolite domes. Outcrop exposure is poor, but these pyroclastic units do not appear to be laterally persistent; they may reflect irregular topography at the time of deposition. The basal unit, which is inferred to be pyroclastic, is exposed west of the Montreal River and overlies an andesite flow. The basal pyroclastic unit is characterized by coarse, angular mafic blocks in an ashy matrix and probably represents a block-and-ash flow. Overlying this basal unit is a lavender to maroon pyroclastic unit that contains abundant angular lithic fragments ranging from rhyolite to basalt. Feldspar phenocrysts, commonly broken, and flattened fiamme are visible in outcrop and thin section. Sorting is poor, and the outcrop is generally massive. The distribution of this unit appears to reflect topographic valleys. In different localities, it is overlain by the Bohemia conglomerate, by the extrusive rhyolite flow, and by a coarse rhyolite breccia that may represent the flow-front breccia of an adjacent dome or flow. These characteristics suggest that the lavender pyroclastic unit is a welded ash-flow tuff, and that the basal mafic breccia unit may represent an early phase of the same eruptive event.

Correlation of pyroclastic units from area to area is difficult owing to poor exposure. Nonetheless, it is clear that several local pyroclastic events preceded rhyolite lava extrusion and the formation of the domes or flows. Because the outcrop exposure is limited to a cross section, there is no record of other rhyolite domes that may have been updip and are now completely eroded or that may be buried downdip. Thus, not all exposed ash flows are necessarily related to the few domes that are exposed.

Summary of Field Relations

An analogy with modern rhyolites indicates that the rhyolites of Mt. Houghton, the Montreal River, and Keystone Point were erupted subaerially as domes or flows on a basalt plain. Characteristics of the extrusive domes include lithophysae, spherulites, flow foliation, the absence of xenoliths, and the presence of underlying rhyolitic pyroclastic units and associated felsic conglomerates bearing locally derived rhyolite fragments. Adjacent basalt units are not disrupted by emplacement of these lens-shaped rhyolite bodies. In contrast, rhyolites in the Bare Hill, West Pond, Fish Cove, and Copper City areas have all been emplaced stratigraphically below the Bohemia conglomerate and the extrusive rhyolite horizon. Some rhyolite contacts are at high angles to the regional strike of the basalts, adjacent basalt units above the rhyolite bodies are bowed, no pyroclastic or conglomeratic units are consistently associated with these bodies, and basalt inclusions are found locally at the margins. Flow foliation is minor or absent, and lithophysae do not occur in these bodies, but vesicles may be present locally.

Thus, the rhyolites associated with the Bohemia conglomerate most likely were extrusive, whereas rhyolites occurring below the conglomerate were emplaced as "cryptodomes" or subvolcanic bodies. The two rhyolite bodies of West Pond and the two at Fish Cove are directly south of the rhyolite domes of Montreal River and may represent feeders to the overlying domes, although no direct connection can be traced in the field.

Interflow conglomerates become increasingly abundant in the upper part of the Portage Lake Volcanics. Amygdaloidal basaltic conglomerates are most common near the base of the section. Above the extrusive rhyolite

A

North   South

B

C

D

E

                                    PLV

EXPLANATION

Sedimentary rocks

Volcanic rocks

Pre-Keweenawan basement

Mantle
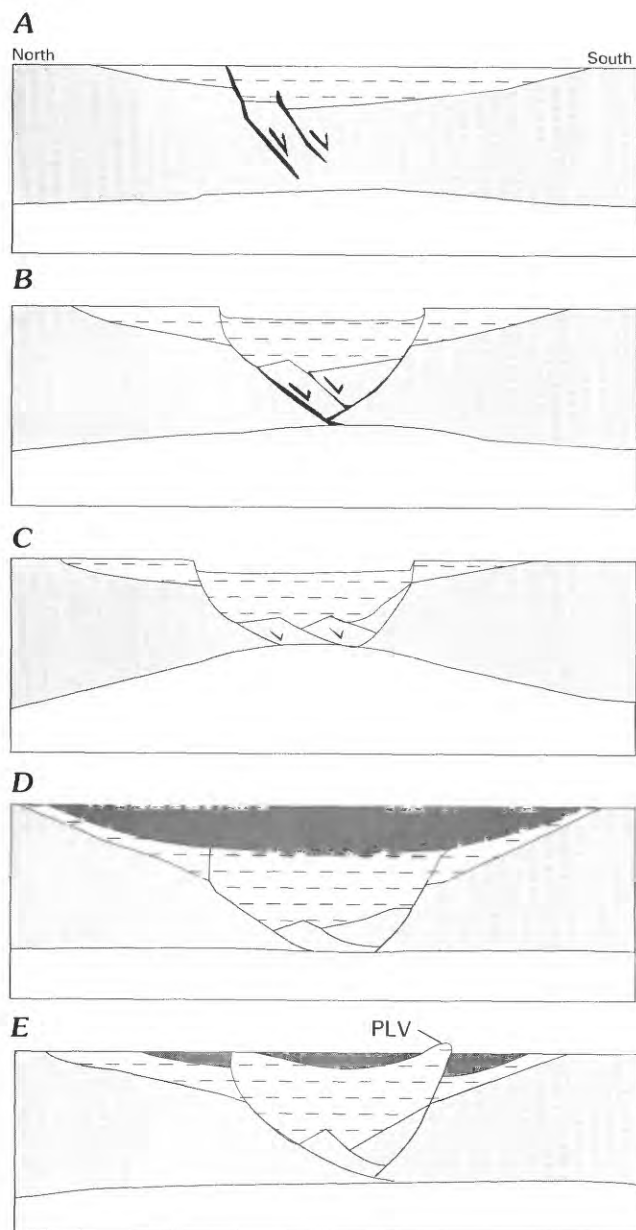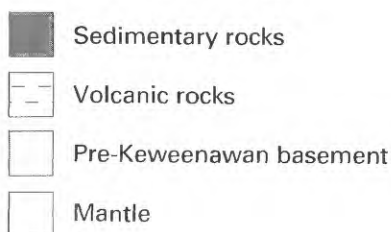
Figure 22. Interpretation of development of Midcontinent rift in Lake Superior region (from Cannon and others, 1989). *A,* A broad crustal sag develops in the early stage. Volcanic rocks are erupted into the basin, and minor normal faults develop. *B,* Extension continues, resulting in large normal growth faults and continued eruption of volcanic material. *C,* Extension continues as the central graben fills with an enormous amount of volcanic material. *D,* After the thermal anomaly wanes, the entire system subsides, creating a basin, which is filled by sediments. *E,* Postrift compression reactivates the normal growth faults as large reverse faults, resulting in uplift of the central rift graben and exposure of Portage Lake Volcanics (PLV).

DISCUSSION

Decompression melting above anomalously hot mantle plumes has been postulated as the cause of enormous volumes of basalt associated with major continental flood basalt provinces and volcanic continental margins (White and McKenzie, 1989). Such a plume may have caused volcanism in the Midcontinent rift system (MRS) (Hutchinson and others, 1990; Nicholson and Shirey, 1990). Active plume-related rifting that produces tholeiitic basaltic to rhyolitic rocks in Iceland provides a modern analog for the environment in which Keweenawan volcanic rocks were erupted. Green (1977, 1989) compared North Shore Volcanic Group basalts with Tertiary basalts from eastern Iceland, citing such similarities as subaerial eruption from fissures, compositional range, abundances of rock types, and volcanological characteristics. Although Icelandic rhyolitic centers have received much study (for example, Walker, 1963; Carmichael, 1964; Blake, 1970, 1984; Sigvaldason, 1974; Sigurdsson and Sparks, 1981; Macdonald and others, 1987b; Gústafsson and others, 1989), MRS rhyolites are only now being integrated into our understanding of the magmatic evolution of the Midcontinent rift.

The following discussion reviews the tectonic development of the MRS, examines the occurrence of rhyolitic volcanic rocks in the Portage Lake Volcanics within the rift, and compares rhyolites of the Portage Lake Volcanics with other MRS rhyolites. Finally, MRS rhyolitic volcanic rocks are compared with rhyolite from Icelandic central volcanoes to evaluate the hypothesis that plume-related rifting in Iceland can be viewed as a modern analog for Midcontinent rifting.

Development of the Midcontinent Rift

The following summary of the tectonic evolution of the Midcontinent rift (fig. 22) is based on an interpretation of GLIMPCE seismic-reflection data by Cannon and others (1989). The rift was initiated by a broad crustal sag in which thin quartz sandstones were deposited. Early widespread flood basalts erupted, thickening toward the middle of the

horizon, felsite clasts dominate the interflow conglomerates. However, the volume and, locally, the composition of the rhyolite clasts cannot be accounted for solely by the currently exposed rhyolite bodies of the Portage Lake Volcanics.
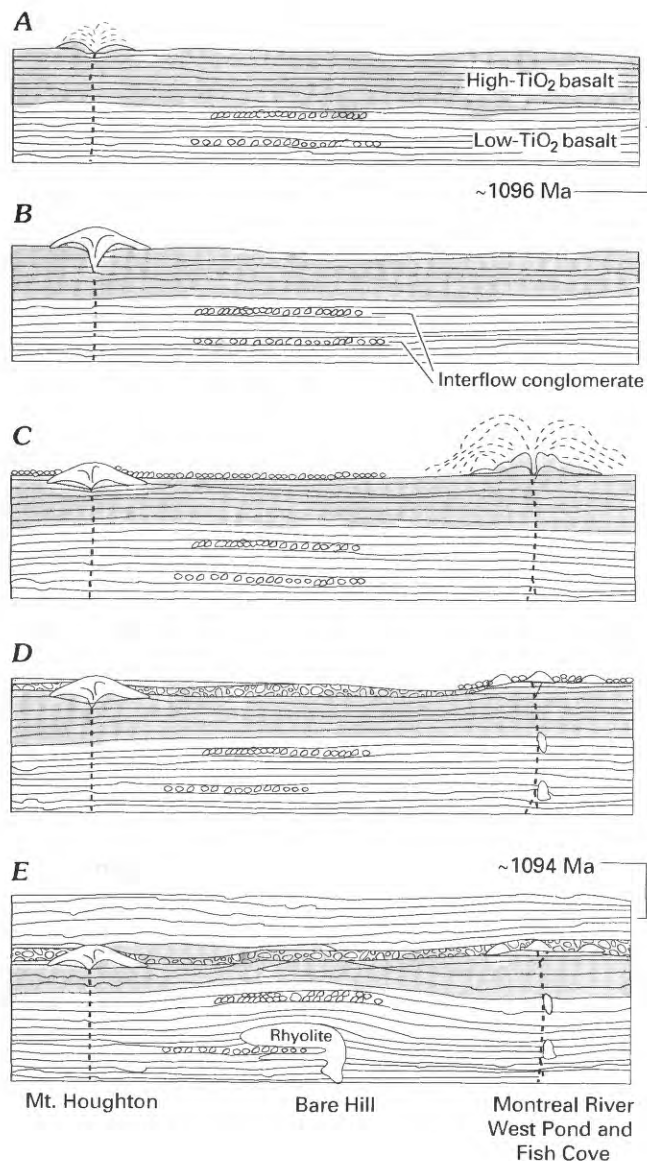
Figure 23. Schematic representation of emplacement of Type I rhyolites of Portage Lake Volcanics. *A*, Low-TiO$_2$ basalts erupt from fissures, followed by a localized group of high-TiO$_2$ basalts and intermediate rocks. Near the end of this interval, a pyroclastic rhyolitic eruption forms the initial tuff ring of the Mt. Houghton center. *B*, Rhyolite of Mt. Houghton is extruded to overlie the tuff ring. *C*, Local sedimentation of clasts, in part derived from erosion of the rhyolite dome, results in deposition of the Bohemia conglomerate. Pyroclastic eruptions at Montreal River center. *D*, The three rhyolite lobes or domes are erupted at Montreal River. Small subvolcanic bodies (West Pond and Fish Cove) are emplaced along the feeder system for the overlying domes. Erosion of the domes contributes to sedimentation. Basalts continue to erupt. High-TiO$_2$ basalt erupts above the Bohemia conglomerate and then is covered by fissure-fed low-TiO$_2$ basaltic flows. *E*, Fissure eruptions of low-TiO$_2$ basalt continue, ultimately covering the rhyolite extrusions and conglomerate. Subvolcanic emplacement of the Bare Hill rhyolite sills disrupts the overlying basalts and Bohemia conglomerate. End of rhyolitic activity.

sag, the area that ultimately became the rift axis. The Archean basement was thinned; minor normal faulting near the rift axis probably occurred in addition to mild subsidence (fig. 22A). As crustal extension and subsidence continued, large normal growth faults developed, resulting in an asymmetric central rift valley within which most of the magmatism and sedimentation became focused (fig. 22B). Within the central graben, at least 15 km of basalt were deposited before extension ceased and volcanism diminished. The earliest volcanic rocks were preserved at the margins of shallow flanking basins, whereas voluminous later eruptions were focused within the central graben and locally may have spilled out into the flanking basins (fig. 22C). Sedimentary rocks up to 7 km thick were deposited during subsidence of the entire area as the thermal anomaly waned (fig. 22D). After the rifting event, the area underwent mild compression, resulting in the transposition of large normal growth faults into reverse faults and the surficial exposure of rocks that were originally deposited in the central graben (fig. 22E).

Rhyolitic Volcanism of Portage Lake Volcanics

Volcanism that led to the formation of the Portage Lake Volcanics occurred near the margin of a deep central graben during the main phase of rifting; a large volume of magma was extruded rapidly under subaerial conditions (Cannon and others, 1989; Hutchinson and others, 1990). At the margin of a central graben segment, eruption kept pace with subsidence so that streams deposited sediments only intermittently. Escarpments must have been present locally, certainly while the Keweenaw fault was active, shedding volcanic debris into alluvial fans. Figure 23 illustrates the emplacement of rhyolites of the Portage Lake Volcanics. Extrusion of low-TiO$_2$ basaltic flows gave way to extrusion of high-TiO$_2$ basalts and intermediate rocks. Near the end of this interval, pyroclastic eruptions preceded the extrusion of small-volume rhyolite domes (figs. 23A, 23B). These domes were rapidly eroded; the erosion provided material for alluvial fan conglomerates and extensive stream deposits such as the Bohemia conglomerate (fig. 23C). Rhyolitic subvolcanic bodies were emplaced into basalts below the rhyolite domes, causing some disruption of the overlying units. Basaltic flows, most likely erupted from fissures, lapped up against the rhyolite domes and ultimately covered the domes with additional low-TiO$_2$ basalt more than 3 km thick. As basaltic volcanism waned, interflow conglomerates became more common, until conglomerates were deposited with only minor associated basalt flows (for example, the "Lake Shore traps" in the Copper Harbor Conglomerate).

Rhyolite bodies and intermediate rocks do not crop out above the Bohemia conglomerate. However, the large volume of rhyolitic clastic material that constitutes the interflow conglomerates above the Bohemia conglomerate

suggests that other rhyolite complexes may occur stratigraphically higher elsewhere in the formation and are not currently exposed, or may have formed in flanking basins outside the central graben and shed debris into the graben. The Porcupine Mountains area (summarized below) may represent such a complex southwest of the Keweenaw Peninsula.

Midcontinent Rift Rhyolites

Rhyolites make up about 10 percent of the exposed MRS volcanic rocks, but as noted above, their distribution is not uniform. Rhyolites make up 10–25 percent of the volcanic rocks in the flanking basins, whereas they make up less than 1 percent of the exposed Portage Lake Volcanics at the margin of the central graben. Although the central graben setting of these rhyolites differs from the settings of other MRS rhyolites, a comparison of stratigraphy and emplacement styles among MRS rhyolites reveals several common characteristics.

Within the flanking basins, some rhyolites occur without associated intermediate rocks. For example, the early volcanic sequences of the Mamainse Point Formation and the Osler Group are characteristically bimodal (Annells, 1973; McIlwaine and Wallace, 1976). Mafic rocks are restricted to picritic to tholeiitic basalt and basaltic andesites, and rhyolites are the only silicic rocks; no intermediate rocks occur in these two suites. Locally, some rhyolites were extrusive, but most rhyolites of the Mamainse Point Formation and the Osler Group probably were intruded as sills or plugs (McIlwaine and Wallace, 1976; Green, 1977).

Most MRS rhyolite bodies of somewhat younger age in the flanking basins (and in the central graben) are associated with accumulations of intermediate rocks, and the rhyolites themselves are more commonly extrusive. For example, in the northeast limb of the North Shore Volcanic Group, near the top of the basal Grand Portage sequence, a trachyandesite underlies a porphyritic rhyolite flow, and the overlying Hovland Lava includes a range of basaltic, intermediate, and rhyolitic units (Green, 1972; Green and others, 1980). Younger rhyolite units of the North Shore Volcanic Group range from about 150 to 1,000 m in thickness and commonly overlie intermediate rocks (Green, 1972). These rhyolites exhibit a variety of emplacement styles and include large lava flows, ash flows, and rheoignimbrites (Green, 1972, 1977, 1989; Fitz, 1988; Green and Fitz, 1989): a few rheoignimbrites can be traced 40 km along strike (Fitz, 1988). There is some evidence of local mixing of basaltic and rhyolitic magmas near Duluth, Minn.

In Michigan, the Kallander Creek Formation of the Powder Mill Group consists of at least 1,200 m of mostly intermediate to rhyolitic rocks that overlie the predominantly basaltic basal unit, the Siemens Creek Formation (Hubbard, 1975b). Emplacement style of these silicic rocks is not well described, but Cooper (1973) suggested that the rhyolites are extrusive.

Thick sections of intermediate to rhyolitic rocks on Michipicoten Island (Annells, 1974) and in the Porcupine Volcanics of the Porcupine Mountains area in Michigan (Leonardson, 1966; Hubbard, 1975a,b; Kopydlowski, 1983) constitute up to 25 percent of these volcanic sections. Emplacement styles of these rhyolites are poorly described in the literature, but the rhyolites occur near the top of the sections as both extrusive and subvolcanic bodies.

Recognition of the characteristic association of intermediate and rhyolitic rocks in the Porcupine Mountains area, on Michipicoten Island, and in the North Shore Volcanic Group led White (1972), Annells (1974), Green (1977, 1989), and Kopydlowski (1983) to postulate that the large accumulations of intermediate and rhyolitic rocks represent central volcanoes, similar to those found in eastern Iceland. Detailed stratigraphic studies have not been conducted for most MRS rhyolite occurrences, but it is the contention of this study that the analogy to Iceland's central volcanoes can be applied more broadly than previously postulated.

Iceland: A Modern Volcanological Analog

Active plume-related rifting that produced and is still producing tholeiitic basaltic to rhyolitic rocks in Iceland provides a likely modern analog for the environment in which Keweenawan volcanic rocks were erupted. In Iceland, basalts make up about 85 percent of the Tertiary and postglacial series; intermediate and acidic rocks make up another 3 percent and 12 percent, respectively (Sigurdsson and Sparks, 1981). These proportions are similar to proportions for MRS volcanic rocks.

Silicic rocks and intermediate rocks in Iceland are confined to major Tertiary and neovolcanic central volcanic complexes (Walker, 1966; Saemundsson, 1978). The composition and form of these volcanic centers differ between within-rift and off-rift settings. Within-rift volcanic centers typically erupt tholeiitic basalts, whereas off-rift centers erupt alkalic or transitional tholeiitic basalts (Oskarsson and others, 1982). Within-rift central volcanoes tend to be low-relief shield volcanoes only a few hundred meters high (Saemundsson, 1978) or clusters of low hills interspersed with basaltic shields (Walker, 1966). In some, a central caldera may develop. The low relief of within-rift central volcanoes may be due in part to high tectonic subsidence rates. In contrast, off-rift central volcanoes are commonly cone-shaped stratovolcanoes with summit craters. Less tectonic subsidence in the off-rift regions in part accounts for the higher relief of the stratovolcanoes. Off-rift central volcanoes have higher proportions of silicic rocks and pyroclastic rocks than their counterparts in the active rift zone (Saemundsson, 1978).

Although central volcanic complexes occur in both within-rift and off-rift settings in Iceland, within-rift vol-

EXPLANATION

Thin basic and intermediate lava flows ⎫
Rhyolitic lava flows and welded   ⎬ Breiddalur
   tuffs, felsic tuffs, and agglomerates ⎮ volcano
Intrusions, mainly felsic   ⎭

Flood basalts forming envelope enclosing
   central volcanic complex

Length of section approximately 35 kilometers

Vertical scale approximately twice the horizontal scale
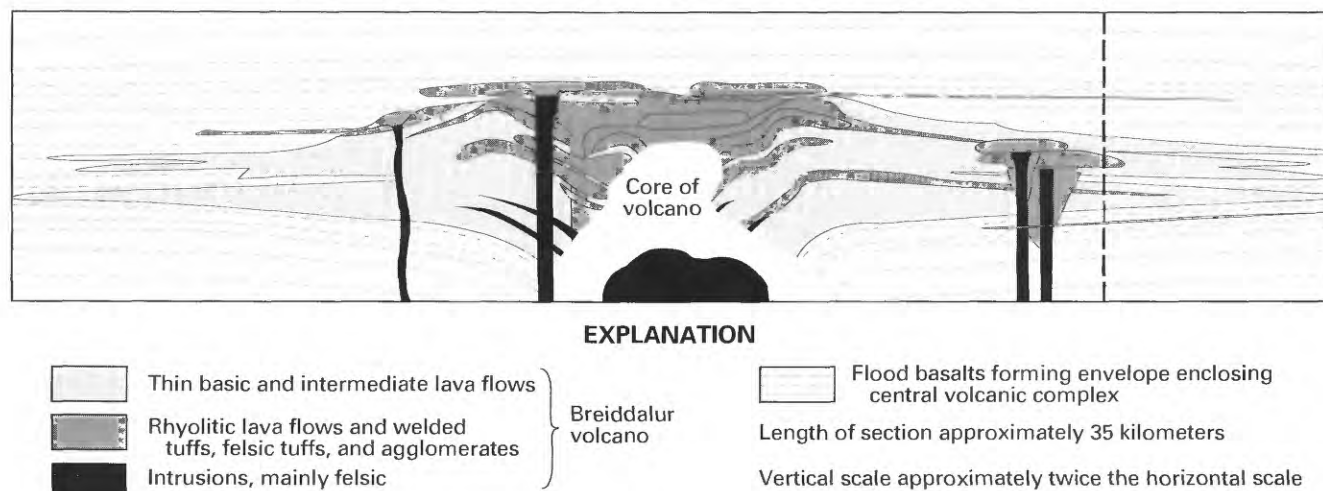
Figure 24. Stratigraphy in a cross section of the Breiddalur central volcano in Iceland, modified from Walker (1963). A localized accumulation of basalts and intermediate rocks is surrounded by an envelope of fissure-erupted basalt flows. Rhyolites occur near the top of the volcano, emplaced as both extrusive and subvolcanic bodies. The small parasitic rhyolite bodies at Breiddalur provide a good analog for the emplacement of rhyolites of Portage Lake Volcanics.

canism provides the stronger analogy to MRS volcanism. Fracturing in Icelandic axial rift zones is concentrated into fissure swarms up to 20 km broad and more than 100 km long. Most fissure swarms are focused on a central volcano, together constituting a volcanic system between 50–100 km long and 10–30 km wide. Basalt flows dip gently on a regional scale toward the center of the active rifting zone (Saemundsson, 1979); this regional tilt is imparted to the pile by subsidence during growth, but eruption rates are rapid enough to allow eruption to occur subaerially. In the well-exposed eroded Tertiary central volcanoes of eastern Iceland, the ratio of basalts to intermediate and rhyolitic rocks is about 3:1 (Walker, 1966). Volumes of central volcanoes can range from 200 to 600 km^3 (Walker, 1966).

Icelandic within-rift shield-type central volcanoes (fig. 24) are characterized by accumulations of intermediate and silicic rocks, high eruption rates of tholeiitic basalt, and the presence of dikes, shallow intrusions, and localized hydrothermal alteration that is not characteristic of the surrounding flood basalts (Saemundsson, 1978). Central volcanoes are interpreted to overlie shallow magma chambers (Saemundsson, 1979; Oskarrson and others, 1982) that fill episodically. When lithostatic pressure is overcome by magmatic pressure, eruption occurs (Saemundsson, 1979). As these major volcanic centers are being built, fissure-fed basaltic lava flows may erupt simultaneously. Once a volcanic center wanes, it is partially or completely buried by later basalts (Walker, 1966). The lifespan of a volcanic center is on the order of 1 million years or less (Saemundsson, 1979).

Comparison of Icelandic and Midcontinent Rift Rhyolites

Green (1977, 1989), Green and others (1980), and White (1972) have argued that areas of abundant rhyolite such as parts of the North Shore Volcanic Group and those of the Porcupine Volcanics and the Michipicoten Island Formation are comparable to Icelandic central volcanoes. It is argued here that this analogy can be more broadly applied to other MRS rhyolite occurrences, including the occurrence of Type I rhyolite bodies of the Portage Lake Volcanics.

The stratigraphy within the vicinity of the extrusive rhyolite horizon of the Portage Lake Volcanics is relatively simple: extrusive rhyolites occur only near the top of a stratigraphically restricted group of high-TiO$_2$ basalts, intermediate, and rhyolitic rocks near the faulted base of the Portage Lake Volcanics. This interval is completely enclosed by low-TiO$_2$ basalts. Alteration appears to be localized around this area. Rhyolitic extrusive rocks typically overlie pyroclastic deposits and subvolcanic rhyolite bodies are present below the extrusive rhyolite horizon. Interflow conglomerates contain much felsitic material above the Bohemia conglomerate and very little below the extrusive rhyolite horizon.

Specific characteristics of Icelandic central volcanoes in active rift zones include (1) abundant quartz tholeiites and more evolved rocks, (2) thinner basalt flows within the volcanoes than outside the volcanoes, (3) angular discordance between basalts within and outside the volcanic center,

(4) emplacement of abundant dikes near the core of the volcano, (5) gabbroic to granophyric intrusions near the volcanic core, and (6) localized alteration in the core of the volcanic center (fig. 24). Each of these features is comparable to features of the group of intermediate and rhyolitic rocks of the Portage Lake Volcanics.

The restricted association of intermediate rocks and rhyolites of the Portage Lake Volcanics surrounded by olivine tholeiites initially prompted the analogy to Icelandic central volcanoes. High-TiO_2 basalts and intermediate rocks are interlayered over a 0.5-km-thick interval; similar rocks occur again only as a few high-TiO_2 basalt flows at the top of the Portage Lake section. In general for the Portage Lake section, the thickness of basalt flows is about 10–30 m for subophitic to ophitic basalts (which are commonly low- TiO_2 basalts) and about 5 m for melaphyric basalts (Paces, 1988). A group of melaphyric basalts was recognized in outcrop just below the Bohemia conglomerate at the east end of the Keweenaw Peninsula (Cornwall, 1954a,b; 1955; Davidson and others, 1955). This group of melaphyric, high-TiO_2 basalts pinches out east of the rhyolite of Montreal River but thickens to an outcrop width of about 0.5 km west of Mt. Houghton. This field contact closely corresponds to the boundary between low-TiO_2 basalts and high-TiO_2 basalts inferred on geochemical grounds. Thus, there is at least circumstantial evidence that flows of intermediate composition are thinner than underlying and overlying fissure-fed basalts.

There is little field evidence for a discordance in dips between low-TiO_2 basalts and high-TiO_2 basalts, that is, between flows outside and within the inferred volcanic center. Careful examination of drill core may resolve this point. If little discordance exists, it may indicate that the present-day exposures of the Portage Lake Volcanics cut through a distal edge of a volcanic center, where angular discordance should be minimal. The lack of a high density of dikes and intrusive rocks also suggests that the exposed section is not through the core of a volcanic center. Hydrothermal alteration, in the form of alkali metasomatism, has affected these rocks and may reflect localized hydrothermal cells near shallow intrusions that are not exposed.

If rhyolites of the Portage Lake Volcanics do represent the distal facies of a central volcano, it is fortuitous that the volcano is exposed at all, given the steep dip of the Portage Lake Volcanics in this area. Thus, there may have been numerous central volcanoes that were emplaced updip and then eroded away, or that were emplaced farther out in the central rift graben and are now buried, or that were emplaced in the flanking basins and were covered by sediment during the waning stages of rifting. If several volcanic centers existed at different times, they could have produced a steady supply of felsic material, including the exotic rhyolite and granophyric pebbles that are observed in conglomerates in the upper parts of the Portage Lake Volcanics.

The association of intermediate and rhyolitic rocks in many localities of the MRS suggests that detailed stratigraphic analysis of these areas may allow recognition of volcanic centers that have been eroded to different levels. The abundance of intermediate and intrusive felsic rocks in the Porcupine Mountains and Michipicoten Island areas implies that the present outcrop may expose the cores of volcanic centers. Likewise, intrusions of rhyolites in the oldest sequences, the Osler Group and the Mamainse Point Formation, and intrusions of granophyres in the North Shore Volcanic Group may have been feeders to overlying rhyolites that have been eroded away. Thus, it is likely that juxtaposition of primitive and evolved volcanic rocks throughout the MRS occurred in a manner analogous to the development of silicic central volcanoes in Iceland. Further documentation of stratigraphic and structural relations is needed to fully evaluate this hypothesis, however.

IMPLICATIONS FOR MINERAL RESOURCES

Precious- and base-metal mineralization associated with rhyolites occurs in several tectonic environments (Anderson, 1969; Hutchinson, 1973; Sillitoe, 1977), including extensional environments related to hotspot activity beneath continents (Sawkins, 1976, 1984, 1986). Although the hotspot-related Midcontinent rift system hosts some exceptional mineral deposits, including the world's largest native copper deposits (see, for example, Butler and Burbank, 1929; White, 1968) and very large copper-nickel deposits (Nicholson and others, in press), most MRS-related mineral deposits are associated with mafic and sedimentary rift rocks, not with intermediate to felsic rocks. The only exception is the copper-molybdenum deposit in rhyolite-hosted breccia pipes, believed to be Keweenawan in age, in the Tribag area of Ontario (Blecha, 1965; Armbrust, 1969; Norman, 1978; Norman and Sawkins, 1985; Richards and Spooner, 1989).

No mineralization is known to be directly associated with rhyolites of the Portage Lake Volcanics on Keweenaw Peninsula. However, an understanding of modern volcanic facies and cyclicity has been a useful mineral exploration tool in ancient volcanic terranes (Easton and Johns, 1986; Thurston, 1986) and can be applied to this terrane. For example, based on alteration mineralogy, major- and trace-metal content, and associated igneous rock types, three major categories of modern rhyolite-hosted epithermal precious-metal deposits have been reviewed by Bonham (1988). The first is a low-sulfur epithermal deposit characterized by adularia in the alteration assemblage, a high Ag/Au ratio, and varying amounts of base-metal sulfides. A second type of epithermal deposit is dominated by argillic alteration, enargite mineralization, high total sulfur, and a

spatial and temporal relationship to calc-alkalic inter-mediate-composition rocks. The third type is also a low-sulfur type, with a low Ag/Au ratio and a genetic relation-ship to alkalic rocks. The tholeiitic igneous association of rhyolites of the Portage Lake Volcanics and the generally low sulfur content of MRS rocks suggest that within Bonham's broad classification of epithermal deposits, only the first type is a possibility for rhyolites of the Portage Lake Volcanics.

Type I Rhyolite

Type I rhyolite bodies occur as small subaerial flows or domes and subvolcanic bodies within the dominantly basaltic Portage Lake Volcanics. These rhyolites and under-lying intermediate rocks most likely represent the distal facies of an Icelandic-style silicic volcanic complex. If this interpretation is correct, it is possible that a caldera existed in the central part of the silicic volcanic complex. However, there is no direct evidence of subsidence of a caldera or of ring fractures in the cross section through the Portage Lake Volcanics that is preserved. Thus, it is assumed that the Type I rhyolites formed as domes and flows away from or independent of other major volcanic edifices.

Sillitoe and Bonham (1984) correlated the occurrence of specific mineral deposits with the volcanic landform with which the deposits are associated. Flow-dome complexes similar to those formed by Type I rhyolite of the Portage Lake Volcanics can develop in three environments: (1) near the summit or as parasitic domes on a stratavolcano, (2) along ring fractures or within the core of resurgent calderas, or at the eruptive sites of ignimbrite shields, and (3) in domes that may have formed without benefit of preexisting volcanic edifices (Sillitoe and Bonham, 1984). Shallow-level mineralization accompanying flow-dome complexes may produce precious- and base-metal stockworks, veins, and breccia fillings (fig. 25) as well as replacement bodies; thus, it usually occurs late in the evolution of the dome. Additionally, hot-spring-type deposits of mercury and pre-cious metals may occur locally in and near silicic domes (White, 1981).

The Midcontinent rift is dominated by tholeiitic rocks; less abundant rhyolites are compositionally similar to rhyolites in bimodal suites elsewhere (table 6). Type I rhyolite has been shown to be derived by partial melting of MRS-related mafic rocks (Nicholson, 1990), but this rhy-olite type occurs stratigraphically within an interval of high-TiO_2 basaltic to intermediate-composition subaerial flows that are related to each other by fractional crystalli-zation. The magmatic system in general is deficient in sulfur, and so models for possible mineralization must be consistent with low-sulfur compositions. Features that might indicate the presence of mineralization related to flow domes are not observed in the Type I rhyolite bodies. Despite the fact that the feeders to some extrusive rhyolite
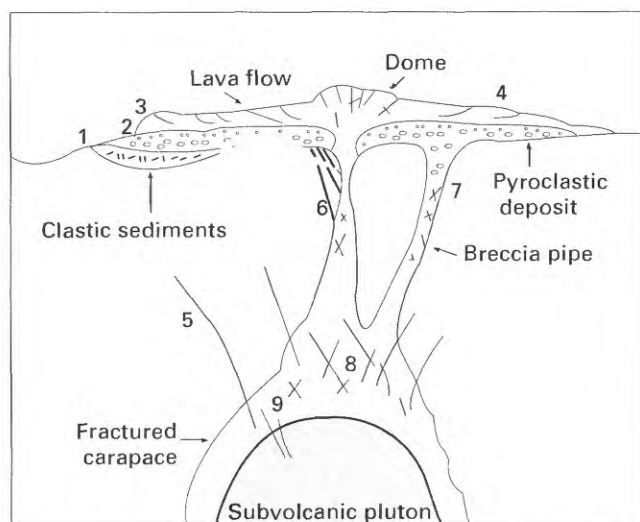
Figure 25. Schematic cross section of a hypothetical flow-dome complex, independent of other volcanic edifices (after Sillitoe and Bonham, 1984; Christiansen and others, 1986). Possible sites for mineralization include the crum-ble breccia forming a talus apron around the dome, sinters if hot springs are associated with the dome, and veins, breccia pipes, or stockwork fractures that may underlie the dome. Topaz rhyolite volcanism may repre-sent the surficial expression of mineralized porphyry sys-tems at depth. Based on a summary by Christiansen and others (1986), possible sites and types of mineralization are keyed by number and include (1) preexisting clastic sediments beneath tuffs (U); (2) mineralized pyroclastic deposits (Be, Li, F, U, Cs); (3) hot-spring deposits within rhyolite (Ag, Au, W, Mn); (4) fractured and flow-banded lavas (Sn); (5) base- and precious-metal veins (Ag, Pb, Zn, Au, Sn, W); (6) vent and contact breccias (F, U); (7) mineralized breccia pipes (Mo, Ag, Au, F); (8) stockwork porphyry deposits (Mo, Sn, W); and (9) greisen-bordered veins in subvolcanic environment (Sn, W, Cu, Zn, Be).

flows are exposed locally, there is no evidence of adularia in alteration zones, stockwork vein systems, breccia pipes, or sinters on the Keweenaw Peninsula. In addition, gold in Type I rhyolites is generally below the detection limit (≈ 6 parts per billion; table 6). For comparison, there is no reported metallic mineralization associated with the active central volcanoes in Iceland, despite numerous high-temperature geothermal fields, some of which occur with silicic rocks (Sigurdsson and Torfason, 1989).

Although mineralization directly related to rhyolite emplacement is lacking, stratiform copper sulfide mineral-ization (dominantly chalcocite) has been identified in a zone about 30 km long and 3 km wide (fig. 26) between the Bohemia conglomerate and the Keweenaw fault; the min-eralization is associated with the interval of intermediate and basaltic flows (Robertson, 1975; Michigan Copper Company, 1989). The sulfides occur as open-space fillings and replacements in amygdaloidal flow tops. Low-angle dacite dikes may be related to the mineralization (Robert-son, 1975). The copper sulfide mineralization does not

Table 6. Chemical analyses of rhyolites of Portage Lake Volcanics and barren and productive Cenozoic topaz rhyolites in the Western United States

[In parts per million, except as noted. b.d., below detection limit; empty cells, no data. Data from Christiansen and others, 1984, 1986]

Element	Portage Lake Volcanics (1,095 Ma)		Cenozoic topaz rhyolites	
	Type I rhyolite	Type II rhyolite	Thomas Range (barren)	Spor Mountain (productive)
Nb	41	51	53	109
Rb	112	465	423	1,010
Sr	55	28	28	6
Zr	240	144	129	110
Y	56	74	58	116
Cs	1.2	2.0	11.3	56
Ta	2.9	4.9	5.6	56
Th	15.1	63.0	55	67
U	2.5	13	22	37
Cl	b.d.	<.0045	≈600	1,370
F	.01	<.03	≈2,000–4,000	10,000
Cu	83	22		
Zn	43	30.3		
As	4.4	61.5		
Sb	.27	.47		
Sn	2.6	5.8	≈2	≈30
Mo	.4	<1		
Au[1]	b.d.	<6		

[1]In parts per billion.

appear to be directly related to observed rhyolite units. Crosscutting relations and the low-temperature gangue minerals associated with the sulfides (Robertson, 1975) indicate that the sulfide mineralization is slightly younger than the native copper deposits of the area. Grade and tonnage estimates are about 7 million tons of 2.3 percent copper ore (Michigan Copper Company, 1989).

Type II Rhyolite

The incompatible trace element content of Type II rhyolite is consistent with that of topaz rhyolite, a subclass of high-silica rhyolites. Cenozoic topaz or rare-metal rhyolites in the Western United States occur in extensional environments in areas underlain by Precambrian crust. Topaz rhyolites typically are enriched in Li, Rb, Cs, U, Th, Nb, Ta, and Sn. These rhyolites have been linked spatially and genetically to several types of ore deposits: (1) volcanogenic deposits of Be, Li, U, and F such as those found at Spor Mountain, Utah, (2) subvolcanic breccia, porphyry, and greisen deposits of Mo, W, and Sn such as those found at the Climax deposit in Colorado, and (3) fluorite- and manganese-rich San Juan-type base- and precious-metal veins in volcanic rocks, or fluorite-rich skarn replacements in carbonate rocks (Burt and others, 1982). Where other types of mineralization, such as Hg and Au-Ag, are associated with topaz rhyolites, the common denominators may not be compositional but tectonic (thermal regime and (or) style of emplacement) (Christiansen and others, 1986).

Most topaz rhyolites are not associated with volcanogenic mineralization, but those topaz rhyolites that do contain productive deposits have common characteristics. These include a massive or blocky texture, few miarolitic cavities, 10–40 percent phenocrysts, >1.0 wt percent fluorine, and extreme enrichment in lithophile elements. In contrast, nonproductive topaz rhyolites are commonly flow banded and have abundant lithophysal cavities, few phenocrysts, 0.1–0.3 wt percent fluorine, and more moderate enrichment in lithophile elements.

The Spor Mountain beryllium deposit is the most important ore deposit directly associated with topaz rhyolite (Christiansen and others, 1986). Beryllium, uranium, and fluorine mineralization is contained within a rhyolitic tuff that underlies rhyolite flows; the mineralization is believed to result from vapor-phase crystallization accompanied by redistribution by meteoric water (Burt and Sheridan, 1981; Burt and others, 1982). Topaz rhyolites may also represent the surface expression of fluorine-rich intrusions, which, if there is little venting, may host porphyry molybdenum-tungsten mineralization. Mineralization in the form of base and precious metals also could occur in fractures and veins emanating from the top of an intrusion, in breccia pipes, and in stockworks, as illustrated in a schematic cross section of a small rhyolite complex and its possible mineralization (fig. 25).

The small-volume Type II rhyolite near Copper City is most similar in composition to barren topaz rhyolites such
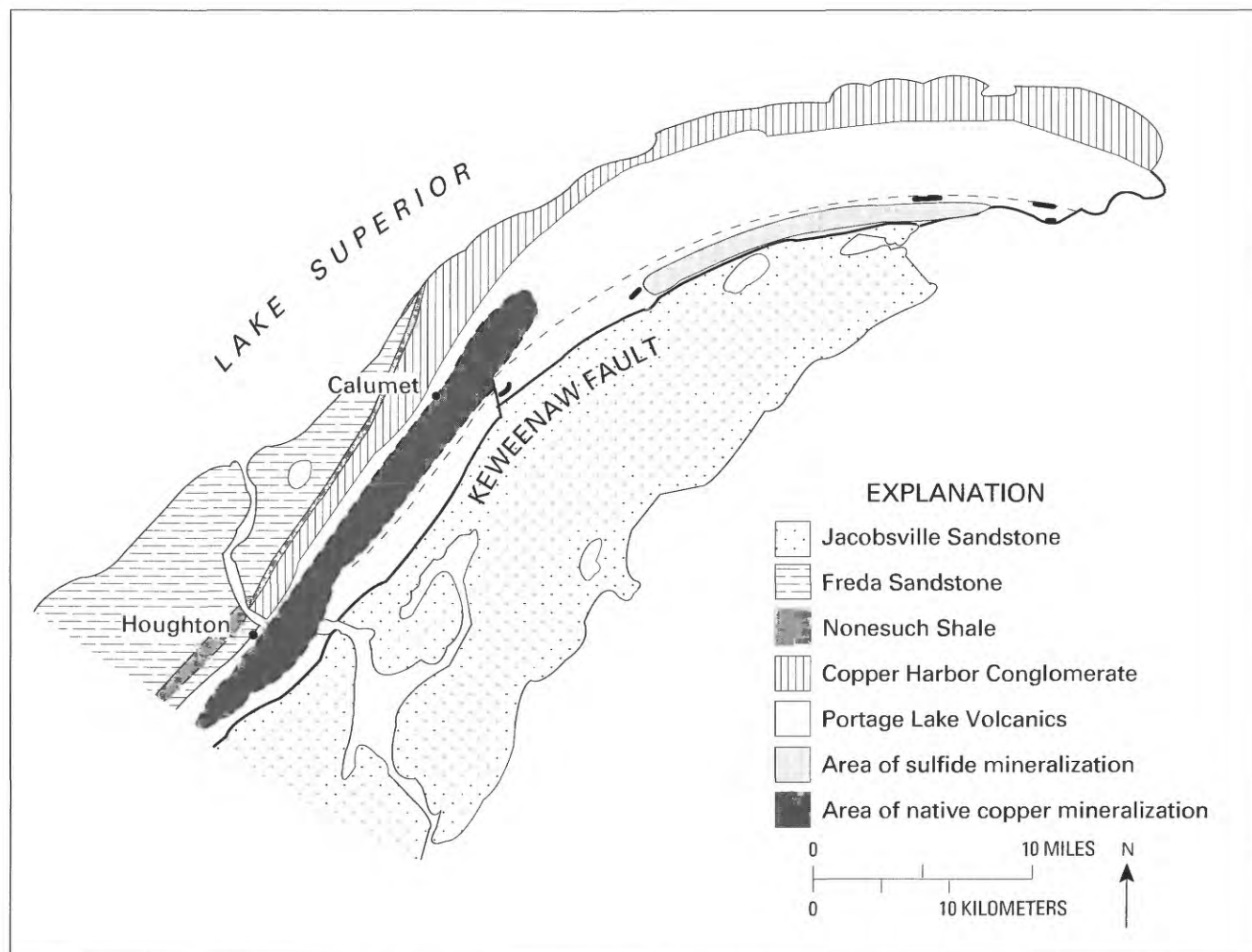
Figure 26. Location of disseminated massive sulfide deposits associated with intermediate rocks, and the major native copper deposits, on east end of Keweenaw Peninsula (Michigan Copper Company, 1989). Dashed line represents the stratigraphic horizon of the Bohemia conglomerate.

as those of the Thomas Range, Utah, having only moderate enrichment in lithophile elements, a low fluorine content, and no recognized topaz (although the sample suite is small) compared with the productive rhyolite of Spor Mountain (table 6). Compared with Type I rhyolites, Type II rhyolites are enriched in Sn, As, U, Th, and Sb and are depleted in Mo, Zn, and Cu (table 6); apparent depletions may result from inconclusive analyses.

Many barren topaz rhyolites may have simply lost much of their metal content during volatile loss accompanying eruption, and this could be the case for the Type II rhyolite of the Portage Lake Volcanics. It is not clear from the field relations what the margins of the body are like and whether there is an associated pyroclastic phase. If the Type II rhyolite was extrusive, tin (and topaz) may have been concentrated in the upper brecciated parts of the flow as a result of vapor-phase crystallization (Christiansen and others, 1986).

Type II rhyolite could have been emplaced as a shallow intrusion. There is no field evidence for vent breccias or breccia pipes, although such features could be obscure because exposure is poor and the dip of the units provides only a single cross section through the body. Topaz rhyolites have not been recognized elsewhere in the rift, but there is no reason the rhyolite of Copper City should be the only occurrence of rhyolite enriched in lithophile elements. Deeper intrusions of Type II rhyolites could have retained more of the elements for mineralization.

CONCLUSIONS

The exposed rhyolites extruded within the central rift graben in central Lake Superior during the main stage of rifting account for less than 1 percent of the Portage Lake

Volcanics. The rhyolites are restricted to a stratigraphic interval also characterized by high-TiO_2 basalts and by intermediate rocks. Small-volume rhyolite domes near the top of this interval typically overlie thin pyroclastic units. Subvolcanic bodies were emplaced within the pile of basaltic and intermediate lavas beneath the extrusive rhyolite horizon. Due to lack of alteration and extensive postrift deformation, delicate hydration and devitrification textures are still preserved after 1 billion years.

The setting and field relations of intermediate and felsic rocks in the Portage Lake Volcanics are similar to those of central volcanoes in the active rift zone of Iceland. Similarities include a well-defined, chemically evolved group of basalts and intermediate rocks capped by rhyolites and associated with localized alteration, and burial of this group of rocks by more primitive fissure-erupted basalts. By analogy with well-described Icelandic central volcanoes, these characteristics suggest that the rhyolites of the Portage Lake Volcanics may represent the distal facies of a central volcano complex. The large proportion of silicic clasts in conglomerates adjacent to and overlying the extrusive rhyolite bodies suggests that rhyolitic centers are present elsewhere in the Portage Lake Volcanics or in an adjacent flanking basin but are not currently exposed. Although other workers have postulated a similarity between some MRS rhyolites and those of Iceland, a broad application of this analogy awaits detailed stratigraphic studies of additional rhyolite occurrences in the Midcontinent rift.

Type I rhyolite is a subalkalic rhyolite derived by partial melting of MRS-related rocks. Chemical analyses and field relations indicate that metallic mineralization potential related to this rhyolite type is limited. The lack of observed adularia in alteration assemblages and the lack of structural ground preparation (stockwork, veins, breccia) beneath the rhyolite flow domes would decrease the number of possible suitable sites for mineralization directly related to rhyolite emplacement. However, it is intriguing that late-stage copper sulfide mineralization underlies the extrusive rhyolite horizon and is intimately associated with the intermediate rocks of the Portage Lake Volcanics. It is possible that the rhyolitic horizon acted as a cap for percolating hydrothermal fluids.

Type II rhyolite is compositionally similar to some unmineralized Cenozoic topaz rhyolites in the Western United States. The small volume and geochemical characteristics of Type II rhyolite suggest that it is unlikely to contain mineralization. However, this rhyolite could represent the surficial expression of an intrusive system that may contain mineralization at depth.

REFERENCES CITED

Anderson, C.A., 1969, Massive sulfide deposits and volcanism: Economic Geology, v. 64, p. 129–146.

Annells, R.N., 1973, Proterozoic flood basalts of eastern Lake Superior: The Keweenawan volcanic rocks of the Mamainse Point area, Ontario: Geological Survey of Canada Department of Energy, Mines and Resources Paper 72–10, 51 p.
———1974, Keweenawan volcanic rocks of Michipicoten Island, Lake Superior, Ontario; An eruptive centre of Proterozoic age: Geological Survey of Canada Department of Energy, Mines and Resources Bulletin 218, 141 p.

Armbrust, G.A., 1969, Hydrothermal alteration of a breccia pipe deposit, Tribag mine, Batchawana Bay, Ontario: Economic Geology, v. 64, p. 551–563.

Baedecker, P.A., ed., 1987, Methods for geochemical analysis: U.S. Geological Survey Bulletin 1770, 129 p.

Basaltic Volcanism Study Project, 1981, Pre-Tertiary continental flood basalts, in Basaltic volcanism on the terrestrial planets: New York, Pergamon Press, p. 60–77.

Behrendt, J.C., Green, A.G., Cannon, W.F., Hutchinson, D.R., Lee, M.W., Milkereit, Bernd, Agena, W.F., and Spencer, Carl, 1988, Crustal structure of the Midcontinent rift system: Results from GLIMPCE deep seismic reflection profiles: Geology, v. 16, p. 81–85.

Bellieni, Giuliano, Comin-Chiaramonti, P., Marques, L.S., Melfi, A.J., Piccirillo, E.M., Nardy, A.J.R., and Roisenberg, Ari, 1984, High- and low-TiO_2 flood basalts from the Paraná plateau (Brazil): Petrology and geochemical aspects bearing on their mantle origin: Neues Jahrbuch für Mineralogische Abhandlungen, v. 150, p. 273–306.

Bender, J.F., Langmuir, C.H., and Hanson, G.N., 1984, Petrogenesis of basalt glasses from the Tamayo region, East Pacific Rise: Journal of Petrology, v. 25, p. 213–254.

Benson, G.T., and Kittleman, L.R., 1968, Geometry of flow layering in silicic lavas: American Journal of Science, v. 266, p. 265–276.

Berg, J.H., and Klewin, K.W., 1988, High-MgO lavas from the Keweenawan midcontinent rift near Mamainse Point, Ontario: Geology, v. 16, p. 1003–1006.

Black, W.A., 1955, Study of the marked positive gravity anomaly in the northern Midcontinent region of the United States [abs.]: Geological Society of America Bulletin, v. 66, p. 1531.

Blake, D.H., 1970, Geology of Alftafjordur volcano, a Tertiary volcanic centre in south-eastern Iceland: Scientia Islandica, v. 2, p. 43–63.

Blake, Stephen, 1984, Magma mixing and hybridization processes at the alkalic, silicic, Torfajökull central volcano triggered by tholeiitic Veidivötn fissuring, south Iceland: Journal of Volcanology and Geothermal Research, v. 22, p. 1–31.

Blecha, Matthew, 1965, Geology of the Tribag mine: Canadian Institute of Mining and Metallurgy Transactions, v. 68, p. 321–326.

Bonham, H.F., Jr., 1988, Models for volcanic-hosted epithermal precious metal deposits, in Scafer, R.W., Cooper, J.J., and Vikre, P.G., eds., Bulk mineable precious metal deposits of the Western United States: Symposium proceedings: Reno, Nev., Geological Society of Nevada, p. 259–271.

Bonnichsen, Bill, and Kauffman, D.F., 1987, Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho: Geological Society of America Special Paper 212, p. 119–145.

Bornhorst, T.J., 1975, Petrochemistry of the Fish Cove rhyolite, Keweenaw Peninsula, Michigan, U.S.A.: Chemical Geology, v. 15, p. 295–302.

Brannon, J.C., 1984, Geochemistry of successive lava flows of the Keweenawan North Shore Volcanic Group: St. Louis, Mo., Washington University, Ph.D. dissertation, 312 p.

Brooks, C.K., 1976, The Fe_2O_3/FeO ratio of basalt analyses: An appeal for a standard procedure: Bulletin of the Geological Society of Denmark, v. 25, p. 117–120.

Brooks, C.K., and Jakobsson, S.P., 1974, Petrochemistry of the volcanic rocks of the North Atlantic ridge system. in Kristjansson, Leo, ed., Geodynamics of Iceland and the North Atlantic area: Dordrecht-Holland, D. Reidel Pub. Co., p. 139–154.

Browne, J.L., and Haynes, C.W., 1956, Geology of the Mount Gratiot area, Keweenaw County, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 44 p.

Bryan, W.B., 1979, Regional variations and petrogenesis of basalt glasses from the FAMOUS area, mid-Atlantic ridge: Journal of Petrology, v. 20, p. 293–325.

Burt, D.M., and Sheridan, M.F., 1981, Model for the formation of uranium/lithophile element deposits in fluorine-rich volcanic rocks, in Goodell, P.C., and Waters, A.C., eds., Uranium in volcanic and volcaniclastic rocks: American Association of Petroleum Geologists Studies in Geology 13, p. 99–109.

Burt, D.M., Sheridan, M.F., Bikun, J.V., and Christiansen, E.H., 1982, Topaz rhyolites—Distribution, origin and significance for exploration: Economic Geology, v. 77, p. 1818–1836.

Butler, B.S., and Burbank, W.S., 1929, The copper deposits of Michigan: U.S. Geological Survey Professional Paper 144, 238 p.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M.W., Milkereit, Bernd, Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, Richard, and Spencer, Carl, 1989, The North American Midcontinent rift beneath Lake Superior from GLIMPCE seismic reflection profiling: Tectonics, v. 8, p. 305–332.

Carmichael, I.S.E., 1964, The petrology of Thingmuli, a Tertiary volcano in eastern Iceland: Journal of Petrology, v. 5, p. 435– 460.

Cas, R.A.F., and Wright, J.V., 1987, Volcanic successions: Modern and ancient: London, Allen and Unwin, 528 p.

Chayes, Felix, 1970, Experimentation in the electronic storage and manipulation of large numbers of rock analyses: Carnegie Institution of Washington Yearbook, v. 68, p. 174–196.

Christiansen, E.H., Bikun, J.V., Sheridan, M.F., and Burt, D.M., 1984, Geochemical evolution of topaz rhyolites from the Thomas Range and Spor Mountain, Utah: American Mineralogist, v. 69, p. 223–236.

Christiansen, E.H., Sheridan, M.F., and Burt, D.M., 1986, The geology and geochemistry of Cenozoic topaz rhyolites from the Western United States: Geological Society of America Special Paper 205, 82 p.

Christiansen, R.L., and Lipman, P.W., 1966, Emplacement and thermal history of a rhyolite lava flow near Fortymile Canyon, southern Nevada: Geological Society of America Bulletin, v. 77, p. 671–684.

Cooper, R.W., 1973, Middle Precambrian and Keweenawan rocks north of the Gogebic Range in Wisconsin: Madison, Wis., University of Wisconsin, M.S. thesis, 83 p.

Cornwall, H.R., 1951, Differentiation in lavas of the Keweenawan Series and the origin of the copper deposits of Michigan: Geological Society of America Bulletin, v. 62, p. 159–202.

———1954a, Bedrock geology of the Delaware quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–51, scale 1:24,000.

———1954b, Bedrock geology of the Lake Medora quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–52, scale 1:24,000.

———1954c, Bedrock geology of the Phoenix quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–34, scale 1:24,000.

———1955, Bedrock geology of the Fort Wilkins quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–74, scale 1:24,000.

Cornwall, H.R., and White, W.S., 1955, Bedrock geology of the Manitou Island quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–73, scale 1:24,000.

Cornwall, H.R., and Wright, J.C., 1954, Bedrock geology of the Eagle Harbor quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–36, scale 1:24,000.

———1956a, Geologic map of the Hancock quadrangle, Michigan: U.S. Geological Survey Mineral Investigations Map MF–46, scale 1:24,000.

———1956b, Geologic map of the Laurium quadrangle, Michigan: U.S. Geological Survey Mineral Investigations Map MF–47, scale 1:24,000.

Cox, K.G., 1983, The Karoo province of southern Africa: origin of trace element enrichment patterns, in Hawkesworth, C.J., and Norry, M.J., eds., Continental basalts and mantle xenoliths: Cheshire, United Kingdom, Shiva Pub. Ltd., p. 139–157.

Daniels, P.A., Jr., 1982. Upper Precambrian sedimentary rocks: Oronto Group, Michigan-Wisconsin, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 107–133.

Davidson, E.S., Espenshade, G.H., White, W.S., and Wright, J.C., 1955, Bedrock geology of the Mohawk quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–54, scale 1:24,000.

Davis, D.W., and Paces, J.B., 1990, Time resolution of geologic events on the Keweenaw Peninsula and implications for development of the Midcontinent rift system: Earth and Planetary Science Letters, v. 97, p. 54–64.

Davis, D.W., and Sutcliffe, R.H., 1985, U-Pb ages from the Nipigon plate and northern Lake Superior: Geological Society of America Bulletin, v. 96, p. 1572–1579.

Easton, R.M., and Johns, G.W., 1986, Volcanology and mineral exploration: The application of physical volcanology and facies studies, in Wood, John, and Wallace, Henry, eds., Volcanology and mineral deposits: Ministry of Northern Development and Mines, Ontario Geological Survey, Miscellaneous Paper 129, p. 2–40.

Ewart, Anthony, 1979, A review of the mineralogy and chemistry of Tertiary-Recent dacitic, latitic, rhyolitic and related salic volcanic rocks, in Barker, Fred, ed., Trondhjemites, dacites and related rocks: New York, Elsevier Scientific Pub., p. 13–121.

Ewart, Anthony, Taylor, S.R., and Capp, A.C., 1968, Trace and minor element geochemistry of the rhyolitic volcanic rocks, central North Island, New Zealand: Contributions to Mineralogy and Petrology, v. 18, p. 76–104.

Fink, J.H., 1980, Surface folding and viscosity of rhyolite flows: Geology, v. 8, p. 250–254.

———1983, Structure and emplacement of a rhyolitic obsidian flow: Little Glass Mountain, Medicine Lake Highland, northern California: Geological Society of America Bulletin, v. 94, p. 362– 380.

Fink, J.H., and Manley, C.R., 1987, Origin of pumiceous and glassy textures in rhyolite flows and domes, in Fink, J.H.,

ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 77–88.

Fink, J.H., and Pollard, D.D., 1983, Structural evidence for dikes beneath silicic domes, Medicine Lake Highland Volcano, California: Geology, v. 11, p. 458–461.

Fitz, T.J., 1988, Large felsic flows in the Keweenawan North Shore Volcanic Group in Cook County, Minnesota: Duluth, Minn., University of Minnesota, M.S. thesis, 181 p.

Fritts, C.E., 1952, A petrologic study of the Mount Houghton felsite, Keweenaw Peninsula: Houghton, Mich., Michigan Technological University, M.S. thesis, 42 p.

Green, J.C., 1970, Snowflake texture not diagnostic of devitrified ash-flow tuffs: Geological Society of America Bulletin, v. 81, p. 2527–2528.

———1972, North Shore Volcanic Group, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: St. Paul, Minn., Minnesota Geological Survey, p. 294–332.

———1977, Keweenawan plateau volcanism in the Lake Superior region, in Baragar, W.R.A., Coleman, L.C., and Hall, K.M., eds., Volcanic regimes in Canada: Geological Society of Canada Special Paper 16, p. 407–422.

———1982, Geology of Keweenawan extrusive rocks, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 47–55.

———1983, Geologic and geochemical evidence for the nature and development of the Middle Proterozoic (Keweenawan) midcontinent rift of North America: Tectonophysics, v. 94, p. 413–437.

———1989, Physical volcanology of mid-Proterozoic plateau lavas: The Keweenawan North Shore Volcanic Group, Minnesota: Geological Society of America Bulletin, v. 101, p. 486–500.

Green, J.C., and Fitz, T.J., 1989, Large rhyolites in the Keweenawan midcontinent rift plateau volcanics of Minnesota— Lavas or rheoignimbrites? [abs.], in Continental magmatism, Abstracts of a meeting of the International Association of Volcanology and Chemistry of the Earth's Interior: New Mexico Bureau of Mines and Mineral Resources Bulletin 131, p. 113.

Green, J.C., Haskin, L.A., and Brannon, J.C., 1980, Geochemistry and stratigraphy of the northeast limb of the Keweenawan North Shore Volcanics, Minnesota [abs.]: Eos, v. 61, p. 1192.

Grimes, J.G., 1977, Geochemistry and petrology of Keweenawan rhyolites and associated rocks, Portage Lake Volcanics, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 80 p.

Gústafsson, L.E., Lapp, Bernhard, Thomas, Lutz, and Lapp, Manuel, 1989, Tertiary silicic rocks in the area of the Kaekjuskörd rhyolitic volcano, eastern Iceland: Jökull, no. 39, p. 75–89.

Haskin, L.A., Haskin, M.A., Frey, F.A., and Wildeman, T.R., 1968, Relative and absolute terrestrial abundances of the rare earths, in Ahrens, L.H., ed., Origin and distribution of the elements: Oxford, Pergamon, p. 889–911.

Hausback, B.P., 1987, An extensive, hot, vapor-charged rhyodacite flow, Baja California, Mexico, in Fink, J.H., ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 111–118.

Hildreth, Wes, 1981, Gradients in silicic magma chambers: Implications for lithospheric magmatism: Journal of Geophysical Research, v. 86, p. 10153–10192.

Hinze, W.J., Wold, R.J., and O'Hara, N.W., 1982, Gravity and magnetic anomaly studies of Lake Superior, geology and tectonics of the Lake Superior basin, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 203–222.

Hubbard, H.A., 1975a, Geology of Porcupine Mountains in Carp River and White Pine quadrangles, Michigan: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 519–528.

———1975b, Lower Keweenawan volcanic rocks of Michigan and Wisconsin: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 529–541.

Hubbard, L.L., 1898, Keweenaw Point with particular reference to the felsites and their associated rocks: Michigan Geological Survey Report 6, pt. 2, 155 p.

Hughes, C.J., 1973, Spilites, keratophyres, and the igneous spectrum: Geological Magazine, v. 109, p. 513–527.

Hutchinson, D.R., White, R.S., Cannon, W.F., and Schulz, K.J., 1990, Keweenaw hot spot: Geophysical evidence for a 1.1 Ga mantle plume beneath the Midcontinent rift system: Journal of Geophysical Research, v. 95, p. 10869–10884.

Hutchinson, R.W., 1973, Volcanogenic sulfide deposits and their metallogenic significance: Economic Geology, v. 68, p. 1223–1246.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 527–548.

Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.

Jensen, L.S., 1976, A new cation plot for classifying subalkalic volcanic rocks: Ontario Division of Mines, Ministry of Natural Resources, Miscellaneous Paper 66, 22 p.

Juster, T.C., Grove, T.L., and Perfit, M.R., 1989, Experimental constraints on the generation of FeTi basalts, andesites and rhyodacites at the Galapagos spreading center, 85°W and 95°W: Journal of Geophysical Research, v. 94, p. 9251–9274.

Kopydlowski, P.J., 1983, The Oak Bluff volcanics, a middle Keweenawan central volcano: Porcupine Mountains region, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 88 p.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A.L., and Zanettin, Bruno, 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Le Maitre, R.W., 1984, A proposal by the IUGS subcommission on the systematics of igneous rocks for a chemical classification of volcanic rocks based on the total alkali-silica (TAS) diagram: Australian Journal of Earth Sciences, v. 31, p. 243–255.

Leonardson, R.W., 1966, Petrology of the Bergland rhyolite, the Firetower rhyolite, and associated rocks, Ontonagon County, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 121 p.

Lofgren, Gary, 1971a, Experimentally produced devitrification textures in natural rhyolitic glass: Geological Society of America Bulletin, v. 82, p. 111–124.

———1971b, Spherulitic textures in glassy and crystalline rocks: Journal of Geophysical Research, v. 76, p. 5635–5648.

Lyons, P.L., 1950, A gravity map of the United States: Tulsa Geological Society Digest, v. 18, p. 33–43.

Macdonald, Raymond, Davies, G.R., Bliss, C.M., Leat, P.T., Bailey, D.K., and Smith, R.L., 1987a, Geochemistry of high-silica peralkaline rhyolites, Naivasha, Kenya rift valley: Journal of Petrology, v. 28, p. 979–1008.

Macdonald, Raymond, Sparks, R.S.J., Sigurdsson, Haraldur, Mattery, D.P., McGarvie, D.W., and Smith, R.L., 1987b, The 1875 eruption of Askja volcano, Iceland: Combined

fractional crystallization and selective contamination in the generation of rhyolitic magma: Mineralogical Magazine, v. 51, p. 183–202.

Manley, C.R., and Fink, J.H., 1987, Internal textures of rhyolite flows as revealed by research drilling: Geology, v. 15, p. 549– 552.

Mantovani, M.S.M., Marques, L.S., De Sousa, M.A., Civetta, Lucia, Atalla, L., and Innocenti, F., 1985, Trace element and strontium isotope constraints on the origin and evolution of Parana continental flood basalts of Santa Catarina State (southern Brazil): Journal of Petrology, v. 26, p. 187–209.

Marsh, J.S., and Eales, H.V., 1984, The chemistry and petrogenesis of igneous rocks of the Karoo central area, southern Africa, in Erlank, A.J., ed., Petrogenesis of the volcanic rocks of the Karoo province: Geological Society of South Africa Special Publication 13, p. 27–67.

Massey, N.W.D., 1983, Magma genesis in a Late Proterozoic proto-oceanic rift: REE and other trace-element data from the Keweenawan Mamainse Point Formation, Ontario, Canada: Precambrian Research, v. 21, p. 81–100.

McIlwaine, W.H., and Wallace, Henry, 1976, Geology of the Black Bay Peninsula area, district of Thunder Bay: Ontario Division of Mines, Ministry of Natural Resources Geoscience Report 133, 54 p.

Merk, G.P., and Jirsa, M.A., 1982, Provenance and tectonic significance of the Keweenawan interflow sedimentary rocks, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior basin: Geological Society of America Memoir 156, p. 97–105.

Michigan Copper Company, 1989, Michigan Copper Sulfide Project, Keweenaw Peninsula: Lansing, Michigan, Michigan Copper Company report to the State of Michigan, 21 p. (On file at Michigan Geological Survey, Michigan Department of Natural Resources, Lansing, Mich.).

Middlemost, E.A.K., 1989, Iron oxidation ratios, norms and the classification of volcanic rocks: Chemical Geology, v. 77, p. 19–26.

Nicholson, S.W., 1990, Portage Lake rhyolites of the Midcontinent rift system, Keweenaw Peninsula, Michigan: Geology, petrogenesis and implications for rift magmatism and mineralization: Minneapolis, University of Minnesota, Ph.D. dissertation, 268 p.

Nicholson, S.W., Cannon, W.F., and Schulz, K.J., in press, Metallogeny of the Midcontinent rift system of North America: Precambrian Research.

Nicholson, S.W., and Shirey, S.B., 1990, Midcontinent rift volcanism in the Lake Superior region: Sr, Nd and Pb isotopic evidence for a mantle plume origin: Journal of Geophysical Research, v. 95, p. 10851–10868.

Norman, D.I., 1978, Ore deposits related to the Keweenawan rift, in Neumann, E.-R., and Ramberg, I.B., eds., Petrology and geochemistry of continental rifts: Dordrecht-Holland, D. Reidel Pub. Co., p. 245–253.

Norman, D.I., and Sawkins, F.J., 1985, The Tribag breccia pipes: Precambrian Cu-Mo deposits, Batchawana Bay, Ontario: Economic Geology, v. 80, p. 1593–1621.

Oskarsson, Niels, Sigvaldason, G.E., and Steinthorsson, Sigurdur, 1982, A dynamic model of rift zone petrogenesis and the regional petrology of Iceland: Journal of Petrology, v. 23, p. 28–74.

Paces, J.B., 1988, Magmatic processes, evolution and mantle source characteristics contributing to the petrogenesis of Midcontinent rift basalts: Portage Lake basalts, Keweenaw Peninsula, Michigan: Houghton, Mich., Michigan Technological University, Ph.D. dissertation, 413 p.

Paces, J.B., and Davis, D.W., 1988, Duration of Midcontinent Rift volcanism with estimates of subsidence rates, repose periods and magma production rates [abs.]: Eos, v. 69, p. 1479.

Palmer, H.C., and Davis, D.W., 1987, Paleomagnetism and U-Pb geochronology of Michipicoten Island: Precise calibration of the Keweenawan polar wander track: Precambrian Research, v. 37, p. 157–171.

Palmer, H.C., Tazaki, Kazue, Fyfe, W.S., and Zhou, Z.H., 1988, Precambrian glass: Geology, v. 16, p. 221–224.

Papadakis, James, and Raza, S.N., 1954, Geology of the Bare Hill and Montreal River areas, Keweenaw County, Michigan: Houghton, Mich., Michigan Technological University, M.S. thesis, 83 p.

Richards, J.P., and Spooner, E.T.C., 1989, Evidence for Cu-(Ag) mineralization by magmatic-meteoric fluid mixing in Keweenawan fissure veins, Mamainse Point, Ontario: Economic Geology, v. 84, p. 360–385.

Robertson, J.M., 1975, Geology and mineralogy of some copper sulfide deposits near Mount Bohemia, Keweenaw County, Michigan: Economic Geology, v. 70, p. 1202–1224.

Roedder, Edwin, and Weiblen, P.W., 1971, Petrology of silicate melt inclusions, Apollo 11 and Apollo 12 and terrestrial equivalents, in Proceedings of the Second Lunar Science Conference: Geochimica et Cosmochimica Acta, Supp. 2, v. 1, p. 507–538.

Saemundsson, Kristjan, 1978, Fissure swarms and central volcanoes of the neovolcanic zones of Iceland, in Bowes, D.W., and Leake, B.E., eds., Crustal evolution in northwestern Britain and adjacent regions: Liverpool, Seel House Press, p. 415–431.

———1979, Outline of the geology of Iceland: Jökull, v. 29, p. 7–27.

Sampson, D.E., 1987, Textural heterogeneities and vent area structures in the 600-year-old lavas of the Inyo volcanic chain, eastern California, in Fink, J.H., ed., The emplacement of silicic domes and lava flows: Geological Society of America Special Paper 212, p. 89–101.

Sawkins, F.J., 1976, Metal deposits related to intracontinental hotspot and rifting environments: Journal of Geology, v. 84, p. 653–671.

———1984, Metal deposits in relation to plate tectonics: Berlin, Springer-Verlag, 325 p.

———1986, The recognition of paleorifting in mid- to late-Proterozoic terranes: Implications for the exploration geologist: Transactions of the Geological Society of South Africa, v. 89, p. 223–232.

Self, Stephen, 1982, Lava flows and domes, in Ayres, L.D., ed., Pyroclastic volcanism: Geological Association of Canada Short Course Notes, v. 2, p. 53–57.

Sigurdsson, Freysteinn, and Torfason, Helgi, 1989, Iceland, in Notholt, A.J.G., ed., Mineral deposits of Europe: Volume 4/5: Southwest and Eastern Europe, with Iceland: London, Institution of Mining and Metallurgy and the Mineralogical Society, p. 421–431.

Sigurdsson, Haraldur, and Sparks, R.S.J., 1981, Petrology of rhyolitic and mixed magma ejecta from the 1875 eruption of Askja, Iceland: Journal of Petrology, v. 22, p. 41–84.

Sigvaldason, G.E., 1974, The petrology of Hekla and origin of silicic rocks in Iceland: Societas Scientiarum Islandica, v. 5, p. 1–44.

Sillitoe, R.H., 1977, Metallic mineralization affiliated to subaerial volcanism: A review, in Volcanic processes in ore genesis: Institution of Mining and Metallurgy and the Geological Society of London Special Paper 7, p. 99–116.

Sillitoe, R.H., and Bonham, H.F., Jr., 1984, Volcanic landforms and ore deposits: Economic Geology, v. 79, p. 1286–1298.

Sinton, J.M., Wilson, D.S., Christie, D.M., Hey, R.N., and Delaney, J.R., 1983, Petrologic consequences of rift propagation on oceanic spreading ridges: Earth and Planetary Science Letters, v. 62, p. 193–207.

Smith, R.C., II, Rose, A.W., and Lanning, R.M., 1975, Geology and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943–955.

Stoiber, R.E., and Davidson, E.S., 1959a, Amygdule mineral zoning in the Portage Lake Lava Series, Michigan Copper District—Part I: Economic Geology, v. 54, p. 1250–1277.

————1959b, Amygdule mineral zoning in the Portage Lake Lava Series, Michigan Copper District—Part II: Economic Geology, v. 54, p. 1444–1460.

Thiel, E.C., 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota: Geological Society of America Bulletin, v. 67, p. 1079–1100.

Thompson, R.N., Morrison, M.A., Hendry, G.L., and Parry, S.J., 1984, An assessment of the relative roles of crust and mantle in magma genesis: An elemental approach: Philosophical Transactions of the Royal Society of London, Series A, v. 310, p. 549–590.

Thurston, P.C., 1986, Volcanic cyclicity in mineral exploration; The caldera cycle and zoned magma chambers, in Wood, John, and Wallace, Henry, eds., Volcanology and mineral deposits: Ministry of Northern Development and Mines, Ontario Geological Survey, Miscellaneous Paper 129, p. 104–123.

Van Schmus, W.R., and Hinze, W.J., 1985, The Midcontinent rift system: Annual Reviews of Earth and Planetary Sciences, v. 13, p. 345–383.

Walker, G.P.L., 1963, The Breiddalur central volcano, eastern Iceland: Quarterly Journal of the Geological Society of London, v. 119, p. 29–63.

————1966, Acid volcanic rocks in Iceland: Bulletin Volcanologique, v. 29, p. 375–402.

————1973, Explosive volcanic eruptions—A new classification scheme: Geologische Rundschau, v. 62, p. 431–446.

Weigand, P.W., and Ragland, P.C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, no. 3, p. 195–214.

White, D.E., 1981, Active geothermal systems and hydrothermal ore deposits: Economic Geology, 75th anniv. volume, p. 392–423.

White, R.S., and McKenzie, D.P., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

White, W.S., 1956, Geologic map of the Chassell quadrangle, Michigan: U.S. Geological Survey Mineral Investigations Map MF–43, scale 1:24,000.

————1968, The native-copper deposits of northern Michigan, in Ridge, J.D., ed., Ore deposits of the United States, 1933–1967 (Graton-Sales volume): New York, American Institute of Mining, Metallurgy and Petroleum Engineers, v. 1, p. 303–325.

————1972, The base of the upper Keweenawan, Michigan and Wisconsin: U.S. Geological Survey Bulletin 1354–F, 23 p.

White, W.S., Cornwall, H.R., and Swanson, R.W., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–27, scale 1:24,000.

White, W.S., and Wright, J.C., 1956, Geologic map of the South Range quadrangle, Michigan: U.S. Geological Survey Mineral Investigations Map MF–48, scale 1:24,000.

Wood, D.A., 1978, Major and trace element variations in the Tertiary lavas of eastern Iceland and their significance with respect to the Iceland geochemical anomaly: Journal of Petrology, v. 19, p. 393–436.

Wood, D.A., Joron, J.L., Treuil, Michel, Norry, M.J., and Tarney, John, 1979a, Elemental and Sr isotope variations in basic lavas from Iceland and the surrounding ocean floor: Contributions to Mineralogy and Petrology, v. 70, p. 319–339.

Wood, D.A., Tarney, John, Varet, Jacques, Saunders, A.D., Bougault, Henri, Joron, J.L., Treuil, Michel, and Cann, J.R., 1979b, Geochemistry of basalts drilled in the North Atlantic by IPOD leg 49: Implications for mantle heterogeneity: Earth and Planetary Science Letters, v. 42, p. 77–97.

Wright, J.C., and Cornwall, H.R., 1954, Bedrock geology of the Bruneau Creek quadrangle, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–35, scale 1:24,000.

APPENDIXES 1–3

APPENDIX 1 — Sample Locations and Descriptions

Mt. Houghton area: Lake Medora, Mich., 7.5-minute quadrangle

85KE74: *Location:* NE¼SW¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, mottled dark-gray, medium-grained ophitic texture.

86KE215: *Location:* NW¼E¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, olive-gray to olive-black, fine-grained massive ophitic texture.

88KE308: *Location:* NE¼SE¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, dusky-yellowish-brown, medium-grained ophitic texture with stringers of chlorite.

86KE230: *Location:* NE¼SW¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, olive-black, massive fine-grained ophitic texture.

88KE309: *Location:* NE¼SE¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, brownish-black, medium-grained ophitic texture.

88KE305 *Location:* SE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Basalt, dark-gray, fine-grained, massive.

86KE218: *Location:* NE¼SW¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, overall color is dusky yellowish brown, but close inspection reveals fine-grained feldspar and pyroxene grains. Fine-grained massive ophitic texture.

86KE217: *Location:* SW¼SE¼ sec. 24, T. 58 N., R. 29 W. *Description:* Basalt, dark-gray, fine-grained massive texture.

88KE303: *Location:* SE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Basalt, grayish-red, fine-grained, massive, sparse amygdules filled with carbonate minerals and chlorite.

88KE306: *Location:* SE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Basalt, brownish-black, fine-grained, massive.

88KE304: *Location:* SE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Basaltic andesite, dusky-yellowish-brown, fine-grained, massive.

88KE311: *Location:* NE¼SW¼ sec. 19, T. 58 N., R. 28 W. *Description:* Andesite, strongly banded; black bands (0.5–3 cm wide) containing many minute feldspar microlites and sparse feldspar phenocrysts are interlayered with dark-red aphanitic bands (0.1–1.5 cm wide) containing very sparse feldspar phenocrysts; small angular to subangular xenoliths also present.

88KE310: *Location:* NE¼SW¼ sec. 19, T. 58 N., R. 28 W. *Description:* Andesite, grayish-red, aphanitic, massive, thinly jointed.

85KE167: *Location:* SW¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Andesite, very dusky red, massive, fine-grained.

88KE307: *Location:* SW¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Dacite, grayish-brown, fine-grained, massive.

85KE83: *Location:* NE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Rhyolite, dull grayish-red aphanitic matrix. Massive, spherulitic texture, locally contains small (1–5 mm wide) vugs, typically filled with feldspar and (or) quartz.

85KE64: *Location:* NE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Rhyolite, massive, dark-reddish-brown aphanitic matrix. Breakage occurs along joint surfaces.

85KE65: *Location:* NE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Rhyolite, dull grayish-red aphanitic matrix with a few discontinuous en echelon subparallel fractures typically 1–2 mm wide, filled by quartz and potassium feldspar. Fractures are typically spaced 0.5–1 cm apart and are symmetrically zoned: a narrow black selvage occurs at the margin of the fracture, a red feldspar-rich zone occurs within the fracture, and the center of the fracture is filled with white feldspar and quartz.

86KE224: *Location:* NW¼SW¼ sec. 24, T. 58 N., R. 29 W. *Description:* Rhyolite, dull grayish-red aphanitic matrix. Massive, with mottled texture due to elongated spherulites. Dark oxides appear to be preferentially located around the spherulites. One large fracture is 5 mm wide and is symmetrically zoned with red feldspar lining the walls of the fracture and a mixture of red and white feldspar and quartz filling the center of the fracture.

86KE219: *Location:* NE¼SW¼ sec. 24, T. 58 N., R. 29 W. *Description:* Rhyolite, massive, moderate-red aphanitic matrix, conchoidal fracture.

85KE63: *Location:* NW¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Rhyolite, dull grayish-red aphanitic matrix with discontinuous en echelon subparallel fractures typically 1–2 mm wide and several centimeters long, filled by quartz and potassium feldspar. Fractures are typically spaced 0.3–1 cm apart and are symmetrically zoned: a narrow black selvage occurs at the margin of the fracture, a red feldspar-rich zone occurs within the fracture, and the center of the fracture is filled with feldspar and quartz.

85KE67A: *Location:* NE¼SE¼ sec. 23, T. 58 N., R. 29 W. *Description:* Rhyolite, dull grayish-red aphanitic matrix with relict spherulitic texture. Conchoidal fracture.

Montreal River area: Fort Wilkins, Mich., 7.5-minute quadrangle

88KE302: *Location:* NE¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Basalt, mottled grayish-red, fine-grained, plagioclase and chlorite grains visible, diabasic texture.

86KE255: *Location:* SE¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Basalt, dusky-yellowish-brown, fine-grained massive basalt.

86KE261: *Location:* SE¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Basaltic andesite, very dusky red, massive, very fine grained groundmass in which a faint foliation is defined by changes in grain size.

86KE256: *Location:* SE¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Basaltic andesite, very dusky red, massive texture.

85KE101: *Location:* NW¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Rhyolite breccia, coarse spherulitic brecciated rhyolite fragments in a fine-grained, red aphanitic volcanic matrix with incipient spherulitic texture. Breccia pieces are up to 6 cm in diameter; few fragments are smaller than 0.5 cm. Breccia fragments make up at least 50 percent of the rock; the aphanitic rhyolitic matrix makes up the remainder.

85KE107: *Location:* SW¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, grayish-red massive aphanitic groundmass containing small sparse feldspar phenocrysts.

85KE105: *Location:* SW¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red aphanitic groundmass with small sparse feldspar phenocrysts, conchoidal fracture.

85KE104: *Location:* SE¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Rhyolite, lavender, partly welded ash flow containing small fragments of layered rhyolite, elongated and flattened fiamme, and very small fragments of probable mafic volcanic material; massive texture.

86KE259: *Location:* SW¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, grayish-red, massive aphanitic groundmass containing small sparse feldspar phenocrysts, conchoidal fracture.

85KE108: *Location:* SW¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, grayish-brown aphanitic groundmass containing small sparse feldspar phenocrysts. Widely spaced (3–4 cm apart, 0.5 cm wide) discontinuous fractures are common, filled with quartz and feldspar. Alteration has affected the surrounding rhyolite, producing a narrow black selvage which encloses a bright-red zone surrounding the fracture.

85KE98: *Location:* NE¼NE¼ sec. 27, T. 58 N., R. 28 W. *Description:* Rhyolite, very dark red massive aphanitic matrix with sparse small (1–2 mm) feldspar phenocrysts. Local internally brecciated zones are filled with feldspar and quartz.

85KE106: *Location:* SW¼NW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, dark-reddish-brown aphanitic matrix containing small sparse feldspar phenocrysts. Locally, small joints have been filled with carbonate minerals.

Bare Hill area: Lake Medora, Mich., 7.5-minute quadrangle

86KE241: *Location:* SE¼NE¼ sec. 30, T. 58 N., R. 28 W. *Description:* Basalt, dark-gray, coarsely ophitic texture.

86KE236: *Location:* NW¼SW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Basalt, dark-gray, coarsely ophitic texture.

86KE242: *Location:* SE¼NE¼ sec. 30, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red apahanitic groundmass containing small sparse feldspar phenocrysts, minor alteration along secondary fractures.

86KE240: *Location:* SW¼NE¼ sec. 30, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red aphanitic groundmass containing small sparse feldspar phenocrysts, conchoidal fracture.

85KE154: *Location:* SE¼SE¼ sec. 25, T. 58 N., R. 29 W. ("western felsite") *Description:* Rhyolite, grayish-red aphanitic massive groundmass, internally brecciated zones with minor carbonate infilling.

85KE173: *Location:* NW¼NW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red aphanitic groundmass containing small sparse feldspar phenocrysts, massive with fractures filled by feldspar and quartz.

85KE172: *Location:* NE¼NE¼ sec. 30, T. 58 N., R. 28 W. *Description:* Rhyolite, dark-reddish-brown aphanitic massive groundmass containing small sparse feldspar phenocrysts.

86KE244: *Location:* NE¼NW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red apahanitic groundmass containing small sparse feldspar phenocrysts; sample strongly fractured, breaking into small pieces.

85KE176: *Location:* NW¼NW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red aphanitic groundmass containing small sparse feldspar phenocrysts, massive.

85KE175: *Location:* NW¼NW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red aphanitic groundmass containing small sparse feldspar phenocrysts, massive.

85KE156: *Location:* SE¼NW¼ sec. 29, T. 58 N., R. 28 W. *Description:* Rhyolite, dusky-red, massive aphanitic groundmass containing small sparse feldspar phenocrysts, locally brecciated with minor feldspar and quartz infilling.

West Pond area: Fort Wilkins, Mich., 7.5-minute quadrangle

85KE132: *Location:* NW¼SE¼ sec. 27, T. 58.N., R. 28 W. *Description:* Basalt, dark-gray, medium-grained ophitic texture.

85KE129: *Location:* NE¼SW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, grayish-red aphanitic groundmass containing small sparse feldspar phenocrysts; massive texture.

85KE128: *Location:* NE¼SW¼ sec. 26, T. 58 N., R. 28 W. *Description:* Rhyolite, grayish-red aphanitic groundmass containing small sparse feldspar phenocrysts; massive texture. Local alteration along secondary fractures, resulting in bleaching of color.

85KE130: *Location:* NE¼SW¼ sec. 26, T. 58 N., R. 28 W.

Description: Rhyolite, grayish-red aphanitic ground-mass containing small sparse feldspar phenocrysts; massive texture.

Keystone Point area: Fort Wilkins, Mich., 7.5-minute quadrangle

85KE135: *Location:* SW¼SE¼ sec. 30, T. 58 N., R. 27 W.
Description: Rhyolite, dusky-red, strongly spheru-litic texture with small sparse feldspar phenocrysts.

85KE136: *Location:* SW¼SE¼ sec. 30, T. 58 N., R. 27 W.
Description: Rhyolite, dusky-red, strongly spheru-litic texture with small sparse feldspar phenocrysts.

85KE137: *Location:* SW¼SE¼ sec. 30, T. 58 N., R. 27 W.
Description: Rhyolite, dusky-red, strongly spheru-litic texture with small sparse feldspar phenocrysts.

Copper City area: Ahmeek, Mich., 7.5-minute quadrangle

88KE301: *Location:* SW¼SW¼ sec. 4. T. 56 N., R. 32 W.
Description: Rhyolite, light-gray aphanitic ground-mass containing sparse feldspar and quartz pheno-crysts, massive.

85KE150: *Location:* SW¼SW¼ sec. 4, T. 56 N., R. 32 W.
Description: Rhyolite, light-gray aphanitic ground-mass containing feldspar and quartz phenocrysts, massive.

85KE147: *Location:* SE¼SW¼ sec. 4, T. 56. N., R. 32 W.
Description: Rhyolite, light-gray aphanitic ground-mass containing feldspar and quartz phenocrysts, massive.

85KE151: *Location:* NE¼SW¼ sec. 4, T. 56 N., R. 32 W.
Description: Rhyolite, light-gray aphanitic ground-mass containing feldspar and quartz phenocrysts, massive but with secondary fractures, some of which have been filled by carbonate minerals.

Suffolk area: Bruneau Creek, Mich., 7.5-minute quadrangle

85KE37: *Location:* SW¼SW¼ sec. 10, T. 57 N., R. 31 W.
Description: Andesite, very dusky red aphanitic groundmass containing abundant elongated feldspar phenocrysts.

85KE39: *Location:* SW¼SW¼ sec. 10, T. 57 N., R. 31 W.
Description: Andesite, very dusky red aphanitic groundmass containing abundant elongated feldspar phenocrysts.

Mt. Gratiot area: Delaware, Mich., 7.5-minute quadrangle

85KE49: *Location:* SE¼SW¼ sec. 26, T. 58 N., R. 30 W.
Description: Andesite, grayish-red, massive apha-nitic groundmass, with small concentrations of oxide minerals (<2 percent of specimen).

85KE45: *Location:* NE¼NW¼ sec. 34, T. 58 N., R. 30 W.
Description: Dacite, grayish-red aphanitic ground-mass containing small sparse feldspar phenocrysts; massive texture.

85KE48: *Location:* SW¼SW¼ sec. 26, T. 58 N., R. 30 W.
Description: Dacite, very dusky red, fine-grained massive texture.

85KE50: *Location:* SE¼SW¼ sec. 26, T. 58 N., R. 30 W.
Description: Dacite, grayish-red aphanitic ground-mass, with small elongated vugs. Vugs are filled, entirely or partially, by quartz and feldspar.

Fish Cove area: Fort Wilkins, Mich., 7.5-minute quadrangle

85KE122: *Location:* NE¼NW¼ sec. 35, T. 58 N., R. 28 W.
Description: Basalt, grayish-brown, fine-grained groundmass containing abundant feldspar pheno-crysts (up to 1 cm long). Small vugs, many of which are filled with chlorite.

85KE113: *Location:* SW¼SW¼ sec. 26, T. 58 N., R. 28 W. ("Fish Cove dike")
Description: Rhyolite, grayish-red aphanitic ground-mass containing small sparse feldspar phenocrysts. Sample is brecciated, with minor alteration and carbonate minerals occurring along secondary frac-tures; small vugs are filled with quartz.

85KE119: *Location:* NE¼NW¼ sec. 35, T. 58 N., R. 28 W.
Description: Rhyolite, grayish-red aphanitic ground-mass containing small sparse feldspar phenocrysts; sparse small vugs are filled with quartz.

85KE117: *Location:* NE¼NW¼ sec. 35, T. 58 N., R. 28 W.
Description: Rhyolite, grayish-red aphanitic ground-mass containing small sparse feldspar phenocrysts; sparse small vugs are filled with quartz.

85KE118: *Location:* NE¼NW¼ sec. 35, T. 58 N., R. 28 W.
Description: Rhyolite, grayish-red aphanitic ground-mass containing sparse small to medium feldspar phenocrysts, most of which are altered; sparse small vugs are filled with quartz.

Mt. Bohemia area: Delaware and Lake Medora, Mich., 7.5-minute quadrangle

88KE313: *Location:* SE¼NW¼ sec. 27, T. 58 N., R. 29 W.
Description: Basalt, dark-gray, finely ophitic, mas-sive.

88KE312: *Location:* NW¼SE¼ sec. 27, T. 58 N., R. 29 W.
Description: Basalt, dark-gray, coarsely ophitic, massive.

85KE51: *Location:* NW¼SE¼ sec. 29, T. 58 N., R. 29 W.
Description: Basalt, dark-gray, coarsely ophitic, massive.

APPENDIX 2—Major-oxide and trace-element data for 70 samples of Portage Lake Volcanics

[All major oxides and volatile elements are in weight percent. All trace elements are in parts per million except Au, which is reported in parts per billion, and Na and Fe, which are reported in weight percent. XRF, X-ray fluorescence; INAA, instrumental neutron activation analyses; ppm, parts per million; ppb, parts per billion; n.d., not determined. Totals are rounded to the nearest 0.01. USGS chemical analyses conducted by A.J. Bartel, E. Brandt, J.H. Christie, W.B. Crandell, M.W. Doughten, J. Evans, J. Grossman, J.S. Kane, M.G. Kavulak, B.J. Libby, J.W. Marinenko, J.S. Mee, M. Pickering, N. Rait, E. Robb, J. Sharkey, D.F. Siems, C.J. Skeen, H. Smith, J. Taggert, and G.A. Wandless]

	Mt. Houghton area										
	85KE74	86KE215	88KE308	86KE230	88KE309	88KE305	86KE218	86KE217	88KE303	88KE306	88KE304
SiO_2	43.90	44.80	45.10	45.50	46.30	47.80	48.40	48.90	49.00	49.30	53.50
TiO_2	1.60	2.29	2.48	1.52	1.97	2.52	2.63	2.49	3.31	2.51	2.38
Al_2O_3	16.43	15.20	14.60	16.20	17.70	14.60	14.80	14.90	14.00	14.60	14.80
Fe_2O_3	10.20	10.54	8.10	7.02	8.98	6.31	7.68	8.19	9.91	8.85	5.39
FeO	3.50	5.18	7.72	5.10	3.80	7.10	5.14	5.13	3.50	5.80	4.60
MnO	.22	.18	.35	.20	.18	.23	.21	.21	.22	.25	.36
MgO	9.40	6.44	6.76	8.89	5.66	6.07	6.69	5.66	5.05	4.53	3.50
CaO	6.20	6.83	5.81	5.36	8.04	9.63	4.88	9.17	5.44	6.35	4.55
Na_2O	2.20	2.65	1.48	2.03	2.40	2.71	4.04	2.84	4.14	3.14	3.19
K_2O	2.30	1.86	4.35	3.51	1.77	1.07	.85	1.15	1.55	2.31	3.91
P_2O_5	0.27	.25	.27	.16	.21	.28	.46	.29	.51	.40	.93
Subtotal	96.22	96.22	97.02	95.49	97.01	98.32	95.78	98.93	96.63	98.04	97.11
H_2O^+	3.5	3.08	3.3	4.40	2.7	1.9	3.71	1.47	2.7	1.7	1.8
H_2O^-	.63	.80	.32	.43	.60	.26	.44	.25	.78	.24	.57
CO_2	.03	.02	.06	.03	.08	.08	.02	.16	.19	.03	.21
Cl	.018	<.01	n.d.	<.01	n.d.	n.d.	.01	.01	n.d.	n.d.	n.d.
F	0.022	.03	n.d.	<.01	n.d.	n.d.	.04	.03	n.d.	n.d.	n.d.
Total	100.42	100.15	100.70	100.35	100.39	100.56	100.00	100.85	100.30	100.01	99.69
XRF analyses (ppm):											
Nb	10	13	14	<10	11	13	14	17	21	17	26
Rb	33	39	53	132	58	35	24	27	24	72	107
Sr	477	235	744	781	239	205	274	272	163	226	290
Zr	101	152	153	97	125	192	198	193	253	246	355
Y	24	33	27	20	29	44	32	51	52	60	84
Ba	176	549	269	1300	580	278	190	282	660	536	3190
Other analyses (ppm):[1]											
Cu	28	79	145	100	58	9	41	110	26	20	22
Sn	<1	2.7	n.d.	<1	n.d.	n.d.	<1	<1	n.d.	n.d.	n.d.
Mo	<1	<1	n.d.	<1	n.d.	n.d.	<1	<1	n.d.	n.d.	n.d.
INAA (ppm):											
Na (%)	1.62	2.02	1.14	1.21	1.86	2.05	3.15	2.11	3.19	2.34	2.41
Sc	28.0	32.2	33.0	26.4	28.2	34.7	22.4	34.6	30.5	31.2	23.9
Cr	152	100.9	101.9	154	117	73.5	189	73	5.4	5.4	<.4
Fe (%)	9.7	11.57	11.13	8.96	9.67	9.86	9.70	9.68	9.7	10.60	7.5
Co	53.0	49.9	53.8	55.6	45.5	47.2	45.8	44.6	38.5	43.5	18.1
Ni	162	116	98	185	88	53	156	64	<50	51	<60
Zn	118	136	138	116	111	110	208	116	206	152	173
As	<2	<5	<.9	3.4	<.9	<.9	<4	<4	2.2	1.9	2.1
Se	<12	<2	n.d.	<3	n.d.	n.d.	<3	<2	n.d.	n.d.	n.d.
Sb	<.7	<.6	<.09	<.4	<.1	<.1	<.5	<.6	.18	.19	.229
Cs	1.54	.63	2.20	1.01	1.04	.45	.52	.84	.44	1.76	.89
La	10.40	16.5	18.2	10.7	15.1	20.6	15.2	20.7	29.5	25.5	46.3
Ce	23.0	36.0	38.7	22.9	33.5	43.2	35.4	43.1	63.5	53.9	98.0
Nd	13.6	24.2	23.2	14.0	17.9	26.6	23.5	21	34.1	28.2	53.3
Sm	3.73	5.66	6.05	3.67	4.98	6.38	6.16	6.41	9.02	8.12	12.94
Eu	1.25	1.70	1.90	1.25	1.63	1.89	1.88	1.87	2.52	2.29	3.67
Tb	.58	.939	1.02	.609	.84	1.09	.99	1.04	1.50	1.45	1.99
Yb	2.08	3.02	3.24	1.83	2.65	3.89	2.82	3.70	4.84	5.23	6.66
Lu	.305	.457	.477	.27	.404	.559	.46	.59	.693	.731	.912
Hf	2.3	3.78	4.24	2.45	3.41	4.82	4.77	4.63	6.43	6.11	8.74
Ta	.524	.814	.91	.60	.72	.93	.81	.843	1.50	1.23	1.87
Th	.80	1.64	1.79	1.07	1.60	2.76	1.26	2.58	3.56	3.85	5.50
U	.36	<1	.87	<.9	.34	.66	<.9	.40	.82	.99	1.20
Au (ppb)	n.d.	13	<4	14	<4	<10	<25	<22	<3	<2	<9

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

	Mt. Houghton area—Continued										
	88KE311	88KE310	85KE167	88KE307	85KE83	85KE64	85KE65	86KE224	86KE219	85KE63	85KE67A
SiO_2	57.60	60.10	61.40	62.00	73.80	74.30	74.30	74.90	75.20	75.90	78.60
TiO_2	1.50	1.39	1.10	.82	.09	.08	.09	.05	.05	.08	.07
Al_2O_3	15.30	14.60	15.60	15.70	13.40	13.40	13.90	12.80	12.40	12.90	9.70
Fe_2O_3	7.68	8.20	5.90	3.72	1.70	1.40	1.80	1.72	1.62	1.50	1.50
FeO	.76	.36	1.20	1.90	.20	.16	.12	.06	.05	.20	.08
MnO	.17	.13	.15	.17	.03	.02	.02	.01	.01	.04	.04
MgO	2.79	2.52	2.30	1.87	.08	.20	.09	.05	.05	.06	.06
CaO	3.83	2.00	2.00	4.98	.05	.07	.04	.05	.03	.06	.03
Na_2O	4.47	5.32	4.80	4.58	1.20	2.40	3.50	3.72	2.01	3.70	.72
K_2O	2.94	2.82	3.60	1.52	9.70	7.80	6.80	5.63	7.97	5.60	7.30
P_2O_5	0.62	.59	.37	.29	.02	.02	.02	.03	.03	.02	.02
Subtotal	97.66	98.03	98.42	97.55	100.27	99.85	100.68	99.02	99.42	100.06	98.12
H_2O^+	2.0	1.3	1.7	2.0	.26	.40	.41	.26	.32	.43	.37
H_2O^-	.04	.12	.49	.17	.13	.16	.15	.096	.07	.11	.1
CO_2	.06	<.01	.02	.01	.06	.06	.06	<.01	<.01	.06	.08
Cl	n.d.	n.d.	.015	n.d.	.0050	0.0037	0.0042	<.01	.01	.011	.0060
F	n.d.	n.d.	.084	n.d.	<.008	<.008	<.008	<.01	<.01	<.008	<.008
Total	99.76	99.45	100.73	99.73	100.73	100.47	101.30	99.38	99.82	100.67	98.67
XRF analyses (ppm):											
Nb	28	31	32	35	52	47	50	49	51	41	34
Rb	44	27	60	24	200	183	145	105	117	131	101
Sr	98	77	95	137	16	53	21	35	18	24	16
Zr	468	467	620	813	196	207	216	186	170	180	167
Y	94	88	84	101	76	68	80	62	72	61	46
Ba	626	938	919	446	1260	2290	1070	981	814	1110	967
Other analyses (ppm):[1]											
Cu	<2	19	12	19	27	60	21	13	31	9.6	6.6
Sn	n.d.	n.d.	2.9	n.d.	1.6	3.2	1.2	1.3	<1	3.0	1.2
Mo	n.d.	n.d.	<1	n.d.	<1	<1	<1	<1	<1	<1	<1
INAA (ppm):											
Na (%)	3.35	4.10	3.35	3.43	.797	1.79	2.50	2.78	1.50	2.69	.53
Sc	18.1	16.9	15.1	13.57	2.53	2.43	2.39	2.48	2.20	2.26	1.560
Cr	9.4	4.2	7.8	3.4	4.3	3.9	<4	1.5	1.8	2.5	2.2
Fe (%)	5.88	6.17	4.80	3.97	1.30	1.145	1.276	1.333	1.20	1.164	1.087
Co	8.76	9.25	5.38	3.59	.34	1.06	<.7	.219	.143	<.7	<.6
Ni	<9	<29	<120	<7	<60	<50	<50	<30	<30	<50	<40
Zn	115	119	222	144	13.2	270	18.6	24.4	8.7	21.1	19.1
As	4.6	3.3	2.7	2.4	29.3	2.01	2.11	2.4	19.6	2.51	5.00
Se	n.d.	n.d.	<4	n.d.	<3	<4	<3	<1	<2	<3	<6
Sb	<.1	.28	<.6	.087	.42	.24	.24	.33	.84	.33	<.3
Cs	.2	.19	<1	.3	.31	.47	.28	.15	.15	.19	.208
La	47.2	43.1	51.8	60.0	27.6	39.9	64.1	34.5	15.8	58.5	12.0
Ce	100.2	99.7	112	124.0	132	55.6	98	76.5	52.0	144	27.2
Nd	51.6	50.8	50.8	57.0	35.2	35.6	51.2	30.9	15.4	55.4	11.7
Sm	12.90	13.33	12.87	13.80	11.0	8.0	10.7	7.09	5.69	12.4	3.28
Eu	3.33	3.63	3.11	3.14	1.16	.767	.98	.72	.688	1.13	.289
Tb	2.09	2.16	2.19	2.19	1.89	1.42	1.50	1.46	1.51	1.77	.79
Yb	7.25	7.23	7.93	8.70	7.02	7.04	6.77	6.53	5.60	5.28	4.70
Lu	1.017	1.008	1.11	1.25	.980	.954	.939	.899	.797	.732	.64
Hf	10.84	11.26	13.0	17.6	7.34	7.50	7.22	7.02	6.23	6.27	5.39
Ta	2.11	2.10	2.38	2.34	3.36	3.55	3.37	3.49	3.14	3.07	2.43
Th	6.80	6.90	7.46	8.90	16.0	16.3	16.4	16.0	14.1	14.0	11.4
U	1.84	1.49	1.56	2.24	2.76	2.97	2.59	2.50	1.98	2.86	3.61
Au (ppb)	<1	<2	n.d.	<2	n.d.	n.d.	n.d.	<20	<16	n.d.	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

	Montreal River area											
	88KE302	86KE255	86KE261	86KE256	85KE101	85KE107	85KE105	85KE104	86KE259	85KE108	85KE98	85KE106
SiO_2	45.90	47.90	52.00	52.80	71.40	71.40	72.80	72.90	73.40	73.70	75.20	75.40
TiO_2	1.56	2.45	2.50	2.40	.14	.13	.04	.27	.11	.13	.13	.16
Al_2O_3	15.90	14.70	14.90	14.90	14.60	14.00	14.00	12.90	13.60	14.10	12.90	12.30
Fe_2O_3	10.36	10.19	7.93	8.23	2.40	2.20	2.30	2.20	1.96	2.20	2.00	2.10
FeO	2.20	3.47	3.39	2.76	.08	.16	.12	.04	.04	.08	.20	.08
MnO	.16	.17	.15	.37	.05	.06	.04	.04	.02	.03	.04	.04
MgO	7.72	5.49	4.13	4.22	.08	.08	.17	.52	.05	.06	.35	.57
CaO	7.10	8.61	5.90	4.42	.55	.67	.19	.08	.09	.10	.11	.46
Na_2O	2.60	2.78	3.58	3.99	3.50	3.00	3.40	.11	2.86	3.20	2.20	3.60
K_2O	2.65	.82	1.72	2.48	7.40	7.40	6.90	10.30	7.61	7.20	7.30	4.70
P_2O_5	0.16	.31	1.27	.98	.02	.04	.04	.02	.03	.02	.03	.04
Subtotal	96.31	96.89	97.47	97.55	100.22	99.14	100.00	99.38	99.77	100.82	100.46	99.45
H_2O^+	3.2	1.76	2.42	2.49	.17	.26	.26	.68	.23	.43	.51	.55
H_2O^-	.79	.70	.46	.39	.18	.12	.18	.42	.08	.12	.15	.20
CO_2	.02	.03	.02	.04	.33	.45	.06	.04	<.01	.07	.04	.06
Cl	n.d.	<.01	.02	.01	.0065	.0090	.011	.0085	<.01	.0050	.0070	.010
F	n.d.	.02	.09	.09	.008	.010	.009	.031	<.01	.010	<.008	.021
Total	100.32	99.40	100.48	100.57	100.91	99.99	100.52	100.56	100.08	101.46	101.17	100.29
XRF analyses (ppm):												
Nb	8.0	20	26	22	38	38	39	19	40	36	34	31
Rb	38	33	44	79	109	98	101	116	99	81	138	91
Sr	1340	207	250	288	62	51	116	26	66	45	75	103
Zr	92	215	348	359	266	244	253	255	247	263	259	234
Y	15	52	72	65	47	45	45	38	59	51	49	46
Ba	173	266	410	576	975	931	1470	999	895	585	1310	1310
Other analyses (ppm):[1]												
Cu	46	210	6	100	12	14	26	190	14	52	180	84
Sn	n.d.	1.5	1.9	1.9	2.3	2.3	1.6	<1	1.9	3.2	3.8	2.5
Mo	n.d.	<1	1.4	1.2	<1	<1	<1	<1	1.3	<1	<1	<1
INAA (ppm):												
Na (%)	2.07	2.11	2.75	3.03	2.45	2.05	2.51	.085	2.21	2.29	1.552	2.69
Sc	27.3	34.2	23.9	23.3	2.18	2.20	2.35	3.25	2.31	2.22	2.82	2.86
Cr	158	17.1	2.6	2.9	2.7	2.4	8.3	5.1	1.7	<3	2.9	4.4
Fe (%)	9.17	10.6	8.82	7.81	1.63	1.62	1.73	1.51	1.469	1.56	1.483	1.580
Co	56.1	46.0	18.1	17.9	.74	.72	1.72	3.82	1.14	.67	1.08	3.40
Ni	181	65	<80	<80	<50	<50	<50	24	<30	<50	<50	<50
Zn	99	126	133	192	25.1	25.9	25.2	22.4	23.4	16	37.7	52.4
As	<1	<5	<5	<5	4.2	4.6	1.83	3.02	6.2	4.2	3.1	6.0
Se	n.d.	<3	<.3	<2	<2	<3	<3	<2	<1	<2	<4	<3
Sb	<.2	<.6	<.5	<.5	.23	.24	.21	.33	1.01	<.4	.263	.14
Cs	1.72	.83	1.27	1.25	.38	.33	.44	.72	.27	.24	.61	.64
La	11.3	21.3	47.9	44.7	22.0	20.9	15.3	8.62	47.3	27.7	17.1	24.8
Ce	24.5	44.4	101.9	94.1	52.8	56.9	64	90	97.4	64	75.8	72
Nd	14.0	21.7	56	52.6	17.6	18.4	16.1	<12	35.8	21.3	16.0	24.0
Sm	3.98	7.23	13.96	12.77	4.37	4.67	4.53	3.84	7.90	4.72	4.53	5.98
Eu	1.34	1.95	3.69	3.47	.516	.506	.578	.65	1.020	.67	.570	.850
Tb	.629	1.23	2.11	1.98	1.04	1.01	.98	1.11	1.51	1.20	1.09	1.24
Yb	2.26	4.28	6.30	6.22	5.00	4.97	5.09	3.26	5.71	5.32	5.00	4.98
Lu	.311	.67	.940	.88	.688	.673	.734	.457	.799	.734	.718	.693
Hf	2.71	5.24	8.09	8.24	7.55	7.32	7.71	6.8	8.16	7.72	7.87	6.97
Ta	.55	1.07	1.82	1.76	2.81	2.65	2.67	1.55	3.00	2.80	2.71	2.44
Th	1.03	3.04	5.09	5.00	14.1	13.8	14.32	16.1	15.25	14.4	14.4	12.9
U	.25	.73	1.36	1.27	2.00	1.97	2.46	2.30	2.89	2.06	2.49	2.12
Au (ppb)	<4	<27	<20	<13	n.d.	n.d.	n.d.	n.d.	<16	n.d.	n.d.	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

APPENDIX 2—Major-oxide and trace-element data for 70 samples of Portage Lake Volcanics—Continued

	Bare Hill area										
	86KE241	86KE236	86KE242	86KE240	85KE154	85KE173	85KE172	86KE244	85KE176	85KE175	85KE156
SiO_2	44.60	45.40	72.30	72.40	72.60	73.60	73.80	74.00	75.00	75.20	75.40
TiO_2	1.77	1.80	.08	.08	.09	.10	.10	.09	.11	.11	.10
Al_2O_3	16.20	16.10	13.50	13.40	12.20	13.70	13.90	13.70	14.20	14.00	13.20
Fe_2O_3	8.69	9.97	2.11	1.96	1.50	1.70	2.00	1.84	1.60	1.70	2.00
FeO	4.23	3.44	.06	.11	.16	.36	.12	.04	.08	.12	.12
MnO	.32	.16	.01	.01	.06	.03	.03	.01	.02	.02	.02
MgO	9.07	7.20	.18	.30	.23	.20	.29	.16	.16	.14	.19
CaO	4.98	8.13	.05	.07	2.20	.06	.15	.07	.10	.12	.39
Na_2O	1.65	3.56	1.55	1.68	2.10	1.40	3.40	4.41	4.90	6.00	4.50
K_2O	3.49	.75	9.39	9.08	7.20	9.00	6.30	5.09	4.40	3.00	4.50
P_2O_5	0.19	.19	.03	.03	.01	.02	.02	.03	.04	.03	.01
Subtotal	95.19	96.70	99.26	99.12	98.35	100.17	100.11	99.44	100.61	100.44	100.43
H_2O^+	4.25	3.01	.42	.34	.24	.46	.35	.29	.50	.50	.17
H_2O^-	.92	.95	.19	.06	.13	.23	.18	.05	.17	.10	.35
CO_2	.02	.04	<.01	<.01	.08	.03	.02	<.01	.04	.03	.22
Cl	.01	<.01	<.01	<.01	<.003	.0055	.0030	<.01	.0030	.0030	.0045
F	.01	.01	<.01	<.01	.008	<.008	<.008	<.01	<.008	<.008	<.008
Total	100.40	100.71	99.87	99.52	98.81	100.90	100.66	99.78	101.32	101.07	101.17
XRF analyses (ppm):											
Nb	<10	13	45	49	38	39	47	48	51	44	40
Rb	58	21	94	104	114	109	126	129	83	61	90
Sr	1060	399	27	30	41	36	72	41	49	28	32
Zr	119	115	218	233	193	218	234	230	258	236	230
Y	18	28	62	77	52	53	56	66	81	57	59
Ba	143	130	655	725	924	1010	1030	939	542	438	568
Other analyses (ppm):[1]											
Cu	150	29	24	58	20	29	13	11	77	13	54
Sn	1.5	<1	2.9	2.9	2.7	2.5	3.3	2.6	2.5	2.8	2.2
Mo	<1	<1	1.5	1.2	<1	<1	<1	<1	<1	<1	<1
INAA (ppm):											
Na (%)	1.27	2.69	1.13	1.29	1.56	1.11	2.62	3.34	3.45	4.28	3.18
Sc	28.9	29.2	2.48	2.58	2.03	2.26	2.49	2.50	2.50	2.16	1.95
Cr	186	224	1.50	2.8	6.3	<4	3.1	2.1	8.7	4.2	6.0
Fe (%)	9.40	9.53	1.62	1.50	1.16	1.45	1.49	1.368	1.101	1.177	1.35
Co	55.6	55.8	.72	.79	1.09	.54	.74	.67	.56	.54	.91
Ni	185	216	<40	<30	<50	<50	<50	<30	<50	<50	<40
Zn	113	98	44.8	37.1	45	64	61	38.8	22.7	22	23.1
As	<4	<4	2.1	<1	5.9	3.2	3.9	<3	<3	<2	2.4
Se	<2	<3	<3	<2	<3	<2	<3	<2	<2	<4	<4
Sb	<.5	<.5	.232	.15	.12	.24	<.3	.108	.136	<.2	.18
Cs	1.16	1.26	.250	.20	.27	.68	1.21	.30	.24	.26	.17
La	13.1	11.8	22.9	28.0	20.8	70.8	38.3	49.8	66.4	35.2	23.7
Ce	27.6	25.0	47.8	100.1	54.5	48	106	108.5	137	59.5	39.5
Nd	17.7	15.3	20.1	23.9	25.8	60	33	44.4	58.4	28.5	20.1
Sm	4.30	4.10	4.87	6.87	6.4	11.8	8.3	9.27	12.7	6.5	5.13
Eu	1.35	1.35	.550	.828	.82	1.13	.88	.982	1.31	.73	.60
Tb	.70	.68	1.25	1.67	1.12	1.49	1.24	1.60	1.86	1.16	1.17
Yb	2.03	2.10	6.90	6.98	4.90	6.07	6.21	6.20	6.06	5.51	5.66
Lu	.348	.34	.957	.905	.672	.839	.866	.881	.844	.737	.774
Hf	2.84	2.65	7.58	7.63	6.1	7.70	7.7	7.43	7.44	7.39	6.88
Ta	.626	.59	3.25	3.15	2.65	3.18	3.43	3.18	3.25	3.16	2.93
Th	1.19	1.05	15.59	15.59	12.9	15.7	16.3	15.4	15.3	15.1	14.1
U	<.9	<.9	3.83	2.29	2.08	2.99	2.88	2.46	2.59	2.12	2.90
Au (ppb)	<19	<26	<15	<14	n.d.	n.d.	n.d.	<19	n.d.	n.d.	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

	West Pond area				Keystone Point area			Copper City area			
	85KE132	85KE129	85KE128	85KE130	85KE135	85KE136	85KE137	88KE301	85KE150	85KE147	85KE151
SiO_2	47.00	71.90	73.00	73.80	66.50	74.70	82.00	74.30	74.30	74.40	74.80
TiO_2	1.50	.18	.14	.13	.18	.17	.16	.03	.06	.04	.05
Al_2O_3	14.60	14.60	13.80	14.10	15.50	13.30	9.60	13.00	13.40	13.60	12.20
Fe_2O_3	13.60	2.40	2.20	1.90	3.00	1.80	1.60	1.31	1.40	1.20	1.40
FeO	2.50	.24	.12	.12	.04	.08	.08	.06	.04	.04	.04
MnO	.09	.04	.04	.03	.05	.03	.03	<.02	.04	.05	.04
MgO	5.70	.60	.39	.30	.72	.07	.34	.15	.11	.14	.14
CaO	6.60	.20	.20	.15	2.30	.20	.19	1.23	.86	1.00	2.30
Na_2O	2.00	3.90	4.70	4.10	6.60	4.10	3.10	2.43	2.00	3.10	2.20
K_2O	4.40	5.60	4.40	5.50	3.00	4.80	3.00	5.52	6.90	5.00	4.60
P_2O_5	0.21	.03	.03	.03	.02	.03	.02	<.05	.01	.01	.01
Subtotal	98.20	99.69	99.02	100.16	97.91	99.28	100.12	98.03	99.12	98.58	97.78
H_2O^+	2.7	.65	.57	.38	.57	.23	.45	.72	.60	.55	.85
H_2O^-	.21	.35	.24	.23	.21	.23	.19	.05	.19	.17	.25
CO_2	.85	.07	.06	.08	1.6	.04	.02	.88	.64	.74	1.7
Cl	.0055	.0045	.010	<.003	<.003	.0045	.013	n.d.	.0045	<.003	.0030
F	0.041	.014	.010	.009	.023	<.008	.010	n.d.	.015	.017	.032
Total	101.97	100.76	99.91	100.86	100.31	99.78	100.80	99.68	100.57	100.06	100.62

XRF analyses (ppm):

	85KE132	85KE129	85KE128	85KE130	85KE135	85KE136	85KE137	88KE301	85KE150	85KE147	85KE151
Nb	14	32	39	39	26	24	21	41	48	58	56
Rb	35	130	53	147	65	122	38	421	483	486	471
Sr	238	105	69	108	102	122	49	28	30	26	28
Zr	107	386	268	258	193	213	178	139	142	146	148
Y	22	41	47	48	36	38	31	59	52	92	94
Ba	340	859	510	1200	711	1630	594	460	622	248	276

Other analyses (ppm):[1]

	85KE132	85KE129	85KE128	85KE130	85KE135	85KE136	85KE137	88KE301	85KE150	85KE147	85KE151
Cu	240	150	150	51	1200	99	140	n.d.	12	50	26
Sn	<1	9.4	3.5	3.2	2.0	2.5	1.6	n.d.	4.6	6.9	6.0
Mo	<1	<1	<1	<1	<1	<1	<1	n.d.	<1	<1	<1

INAA (ppm):

	85KE132	85KE129	85KE128	85KE130	85KE135	85KE136	85KE137	88KE301	85KE150	85KE147	85KE151
Na (%)	1.46	2.77	3.42	3.03	4.86	3.02	2.24	1.8	1.50	2.27	1.60
Sc	24.8	3.01	2.33	2.35	1.79	1.65	1.37	.921	.947	.492	.770
Cr	194	3.5	2.7	<3	7.6	3.1	3.6	3.6	3.0	3.9	2.2
Fe (%)	9.3	1.80	1.59	1.374	2.17	1.31	1.15	.958	1.000	.797	.947
Co	37.0	1.34	1.94	.89	2.98	.66	1.01	.177	<.6	<.4	<.5
Ni	180	<50	<50	<50	<50	<40	<40	<9	<40	<40	<40
Zn	72	32	52	36.6	60	3.5	12.6	30.1	29.3	30.9	30.9
As	<3	4.4	2.21	1.59	4.3	4.7	3.1	70.7	73.2	82.9	19.3
Se	<9	n.d.	<5	<2	<3	<3	<2	n.d.	<4	3.8	<5
Sb	<.5	.60	.55	.26	.15	.28	.26	.485	.65	.76	<1
Cs	1.09	19.9	.307	1.90	.38	.68	.52	1.49	1.77	3.58	1.22
La	9.57	14.5	16.4	22.6	10.9	16.9	26.4	18.7	14.4	9.48	5.32
Ce	20.3	34.6	87	75.0	19.7	62.8	83	43.8	49.9	26.1	53.4
Nd	13.9	9.1	12.2	18.5	10.0	15.2	19.2	18.6	20.4	17.8	12.3
Sm	3.76	2.93	3.36	4.49	2.42	4.64	5.08	7.43	6.64	7.85	5.68
Eu	1.06	.54	.489	.600	.541	.787	.72	.050	.037	.038	.041
Tb	.60	.98	1.00	1.09	.71	.98	.79	1.31	1.92	2.25	1.91
Yb	1.90	4.94	5.20	5.17	3.87	3.41	3.05	6.75	6.47	9.39	8.12
Lu	.327	.725	.724	.761	.595	.494	.422	.906	.934	1.270	1.15
Hf	2.45	10.2	8.0	7.90	5.56	6.12	5.15	6.37	6.35	7.03	5.46
Ta	.53	2.54	2.92	2.79	1.84	.93	1.68	4.77	4.59	6.12	4.11
Th	1.01	13.6	15.4	14.6	16.2	17.4	14.9	67.4	68.8	58.1	57.7
U	<.6	2.61	2.17	2.31	2.93	3.07	2.37	5.05	4.54	8.72	35.1
Au (ppb)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<6	n.d.	n.d.	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

	Suffolk area		Mt. Gratiot area				Fish Cove area				
	85KE37	85KE39	85KE49	85KE45	85KE48	85KE50	85KE122	85KE113	85KE119	85KE117	85KE118
SiO_2	58.60	59.00	58.80	63.70	65.40	65.50	47.90	69.20	72.00	72.20	72.20
TiO_2	1.58	1.40	1.40	.13	.48	.49	1.40	.16	.13	.14	.14
Al_2O_3	13.30	12.70	15.70	15.50	15.20	15.60	16.70	14.40	13.90	14.00	13.90
Fe_2O_3	8.86	7.80	5.80	5.00	3.60	5.00	10.20	2.60	2.00	2.50	2.30
FeO	2.10	2.40	1.60	.68	1.40	.36	2.60	.16	.16	.12	.16
MnO	.12	.15	.20	.13	.12	.06	.34	.03	.04	.03	.04
MgO	1.43	1.60	2.80	1.70	1.40	.54	6.60	.47	.30	.30	.33
CaO	2.75	2.80	2.00	1.90	.81	.57	1.70	.32	.27	.24	.23
Na_2O	2.84	3.30	3.80	5.10	3.60	4.40	5.00	1.50	4.40	4.50	4.10
K_2O	4.67	4.00	4.40	3.20	6.00	6.60	1.90	9.20	4.80	4.80	5.40
P_2O_5	0.56	.42	.57	.18	.14	.16	.19	.01	.01	.01	.01
Subtotal	96.81	95.57	97.07	97.22	98.15	99.28	94.53	98.05	98.01	98.84	98.81
H_2O^+	1.50	1.7	1.6	1.6	.61	.43	3.9	.72	.66	.52	.64
H_2O^-	.12	.15	.50	.18	.20	.50	.72	.10	.23	.29	.23
CO_2	1.37	1.6	.09	.07	.08	.08	.28	.17	.03	.08	.04
Cl	.01	.018	.019	0.012	.011	.005	.006	.005	.005	.005	.005
F	0.05	.082	.090	.070	.050	.044	.13	.016	.013	.010	.014
Total	99.86	99.12	99.37	99.15	99.10	100.34	99.57	99.06	98.95	99.75	99.74
XRF analyses (ppm):											
Nb	32	30	28	35	31	31	11	43	39	35	40
Rb	143	100	91	57	74	67	21	115	100	91	99
Sr	109	100	206	103	72	46	161	35	70	65	65
Zr	549	552	537	756	720	684	133	293	271	267	274
Y	82	81	77	91	86	81	32	64	48	51	44
Ba	1720	1390	1320	762	882	858	134	1090	900	886	990
Other analyses (ppm):[1]											
Cu	110	130	8	12	16	24	160	490	390	67	130
Sn	2.9	3.7	2.1	2.8	3.8	2.3	4.1	2.7	2.0	2.1	2.3
Mo	1.6	1.2	1.2	1.2	1.0	<1	<1	1.5	1.8	2.5	1.5
INAA (ppm):											
Na (%)	2.17	2.52	2.89	3.84	2.78	3.28	3.75	1.12	3.38	3.31	3.02
Sc	20.0	19.7	17.5	12.33	10.46	10.37	27.0	2.75	2.34	2.19	2.48
Cr	2.5	<7	2.7	4.0	<4	<6	39.6	5.5	5.5	2.7	2.9
Fe (%)	7.91	7.62	5.47	3.93	3.67	3.83	9.61	1.99	1.579	1.89	1.80
Co	11.5	11.81	6.69	2.57	2.09	1.50	45.2	1.46	1.07	1.09	1.011
Ni	<70	<100	<90	<70	<70	<70	95	<50	<40	<40	<50
Zn	225	278	220	108	122	58	288	50.0	82	62.8	73
As	8.0	4.1	2.8	<3	1.6	2.4	<7	<3	2.4	7.9	3.1
Se	<3	<6	<5	<3	<2	<2	<4	<3	<2	<2	<2
Sb	1.48	.83	<.4	<.3	.31	.20	.59	.26	.16	.099	.145
Cs	1.58	1.13	.47	.63	.4	<.6	1.4	1.28	.57	1.87	.87
La	90.7	83.6	55.9	51.5	66.0	58.5	15.7	24.7	36.6	33.5	24.4
Ce	179	166	116.2	128	135	127.1	29.1	48.3	97.4	78	51.6
Nd	82	73.3	55	53	59	56.5	15	20.1	24.5	27.0	16.3
Sm	17.9	17.9	13.9	13.6	14.0	14.3	4.16	4.52	5.88	6.74	3.95
Eu	4.00	4.03	3.38	3.34	2.96	3.11	1.22	.75	.847	.95	.555
Tb	2.33	2.39	2.11	2.27	2.17	2.19	.76	1.41	1.17	1.33	.914
Yb	7.59	7.55	7.51	8.7	8.90	9.08	2.34	6.59	5.26	5.06	4.51
Lu	1.07	1.07	1.07	1.26	1.26	1.30	.38	.93	.718	.73	.690
Hf	12.9	12.83	12.1	15.8	15.65	15.5	2.84	9.29	8.09	8.0	8.15
Ta	2.31	2.36	2.35	2.56	2.72	2.71	.64	3.41	3.01	2.79	2.99
Th	11.7	11.53	7.09	8.78	10.2	10.2	2.65	17.2	15.4	14.8	15.33
U	2.04	2.19	1.82	2.04	2.62	2.66	<2	2.45	2.36	1.21	1.86
Au (ppb)	<12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

APPENDIX 2—Major-oxide and trace-element data for 70 samples of Portage Lake Volcanics—Continued

	Mt. Bohemia area		
	88KE313	88KE312	85KE51
SiO_2	46.10	46.10	46.40
TiO_2	1.42	1.67	1.60
Al_2O_3	15.40	16.20	16.40
Fe_2O_3	6.31	8.55	5.20
FeO	5.30	4.00	6.50
MnO	.22	.19	.18
MgO	9.49	8.09	7.60
CaO	5.35	5.83	8.90
Na_2O	3.31	2.53	2.60
K_2O	1.69	3.05	.94
P_2O_5	0.15	.18	.17
Subtotal	94.74	96.39	96.49
H_2O^+	4.3	3.3	2.2
H_2O^-	.61	.17	.54
CO_2	.50	.16	.34
Cl	n.d.	n.d.	.014
F	n.d.	n.d.	.036
Total	100.15	100.02	99.62
XRF analyses (ppm):			
Nb	6.4	7.7	15
Rb	41	213	26
Sr	259	127	310
Zr	92	282	118
Y	27	43	27
Ba	369	2590	218
Other analyses (ppm):[1]			
Cu	3	9	71
Sn	n.d.	n.d.	<1
Mo	n.d.	n.d.	<1
INAA (ppm):			
Na (%)	2.47	1.93	1.97
Sc	22.1	26.9	27.7
Cr	122	177	226
Fe (%)	8.28	9.35	9.05
Co	54.6	56.8	53.1
Ni	177	198	220
Zn	111	109	101
As	1.5	2.9	<4
Se	n.d.	n.d.	<3
Sb	<.1	<.01	<.6
Cs	.75	6.56	1.04
La	8.8	12.6	11.9
Ce	19.3	27.3	24.7
Nd	13.0	16.7	15.6
Sm	3.28	4.19	4.14
Eu	1.06	1.34	1.30
Tb	.539	.694	.71
Yb	1.69	2.29	2.12
Lu	.239	.329	.306
Hf	2.09	2.74	2.63
Ta	.501	.613	.63
Th	.68	1.22	.89
U	.21	1.00	<1
Au (ppb)	<3	<6	n.d.

[1]Cu concentrations were determined by flame atomic absorption, Sn concentrations were determined by graphite furnace atomic absorption, and Mo concentrations were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

APPENDIX 3—Major-oxide and CIPW normative compositions of Portage Lake Volcanics

[Major-oxide compositions from appendix 2 recalculated on an anhydrous basis after correcting Fe_2O_3/FeO ratios of all rocks except basalts, according to Middlemost (1989). Basalt analyses were corrected using $Fe_2O_3/FeO=0.15$ (after Brooks,1976). Mg $\#=Mg/(Fe+Mg+Mn)$ (mole percent)]

	Mt. Houghton area												
	85KE74	86KE215	88KE308	86KE230	88KE309	88KE305	86KE218	86KE217	88KE303	88KE306	88KE304	88KE311	88KE310
SiO_2	46.05	46.98	47.04	47.92	48.10	49.17	50.85	49.75	51.15	50.65	55.26	59.31	61.66
TiO_2	1.68	2.40	2.59	1.60	2.05	2.59	2.76	2.53	3.45	2.58	2.46	1.54	1.43
Al_2O_3	17.20	15.94	15.23	17.06	18.39	15.02	15.55	15.16	14.61	15.00	15.29	15.75	14.98
Fe_2O_3	1.77	2.05	2.02	1.61	1.65	1.75	1.69	1.70	1.73	1.89	2.60	2.37	2.74
FeO	11.70	13.53	13.30	10.59	10.86	11.57	11.15	11.20	11.41	12.45	7.42	5.76	5.48
MnO	.23	.19	.37	.21	.19	.24	.22	.21	.23	.26	.37	.18	.13
MgO	9.86	6.75	7.05	9.36	5.88	6.24	7.03	5.76	5.27	4.65	3.61	2.87	2.59
CaO	6.50	7.16	6.06	5.65	8.35	9.80	5.13	9.33	5.68	6.52	4.70	3.94	2.05
Na_2O	2.31	2.78	1.54	2.14	2.49	2.23	4.24	2.89	4.32	3.23	3.29	4.60	5.46
K_2O	2.41	1.95	4.54	3.70	1.84	1.10	.89	1.17	1.62	2.37	4.04	3.03	2.89
P_2O_5	.28	.26	.28	.17	.22	.29	.48	.30	.53	.41	.96	.64	.61
Mg#	.60	.47	.49	.61	.49	.49	.53	.48	.45	.40	.47	.47	.46
CIPW norms:													
Q											4.68	7.59	9.76
Or	14.26	11.54	26.86	21.89	10.88	6.51	5.27	6.92	9.59	14.02	23.92	17.94	17.10
Ab	17.29	32.51	12.23	16.30	21.05	18.85	35.86	24.43	36.53	27.31	27.84	38.91	46.17
An	29.41	25.22	21.18	25.96	33.52	27.69	20.75	24.91	15.67	19.40	14.99	13.35	6.20
Ne	1.21		.42	.97									
C													.59
Di	.86	7.18	5.87	.80	5.39	15.78	1.32	16.13	7.53	8.64	1.73	1.69	
Wo	.44	3.61	2.95	.41	2.71	7.96	.67	8.12	3.79	4.30	.88	.86	
En	.24	1.66	1.40	.23	1.30	3.87	.35	3.87	1.80	1.73	.45	.44	
Fs	.18	1.92	1.52	.16	1.37	3.95	.30	4.13	1.94	2.61	.40	.39	
Wo													
Hy		.75			7.94	21.21	17.61	13.84	11.36	14.25	16.28	12.75	12.15
En		.35			3.86	10.49	9.53	6.70	5.46	5.69	8.59	6.74	6.48
Fs		.40			4.08	10.72	8.08	7.14	5.90	8.56	7.69	6.01	5.67
Ol	30.60	23.70	24.97	28.34	14.46	1.86	10.44	5.83	9.09	7.84			
Fo	17.09	10.41	11.36	16.22	6.68	.87	5.39	2.68	4.15	2.95			
Fa	13.51	13.29	13.61	12.12	7.78	.99	5.05	3.15	4.94	4.89			
Mt	2.57	2.97	2.93	2.33	2.39	2.54	2.45	2.47	2.51	2.74	3.77	3.44	3.98
Il	3.19	4.56	4.92	3.04	3.90	4.92	5.25	4.81	6.56	4.90	4.68	2.93	2.72
Ap	.61	.57	.61	.37	.48	.63	1.05	.66	1.16	.90	2.10	1.40	1.33

	Mt.Houghton area—Continued									Montreal River area				
	85KE167	88KE307	85KE83	85KE64	85KE65	86KE224	86KE219	85KE63	85KE67A	88KE302	86KE255	86KE262	86KE256	85KE101
SiO_2	62.62	63.70	73.68	74.48	73.89	75.67	75.66	75.93	80.19	48.10	49.34	53.63	54.43	71.36
TiO_2	1.12	.84	.09	.08	.09	.05	.05	.08	.07	1.63	2.52	2.58	2.47	.14
Al_2O_3	15.91	16.13	13.38	13.43	13.82	12.93	12.48	12.90	9.90	16.66	15.14	15.37	15.36	14.59
Fe_2O_3	2.29	1.62	.59	.49	.60	.56	.56	.57	.50	1.61	1.88	2.90	2.80	.77
FeO	4.58	3.93	1.19	.98	1.19	1.12	1.05	1.07	1.01	10.62	12.40	8.25	7.97	1.54
MnO	.15	.17	.03	.02	.02	.02	.02	.04	.04	.17	.18	.15	.38	.05
MgO	2.35	1.92	.08	.20	.09	.10	.10	.06	.06	8.09	5.65	4.26	4.35	.08
CaO	2.04	5.12	.05	.07	.04	.05	.03	.06	.03	7.44	8.87	6.09	4.56	.55
Na_2O	4.90	4.71	1.20	2.41	3.48	3.76	2.02	3.70	.73	2.72	2.86	3.69	4.11	3.50
K_2O	3.67	1.56	9.68	7.82	6.76	5.69	8.02	5.60	7.45	2.78	.84	1.77	2.56	7.40
P_2O_5	.38	.30	.02	.02	.02	.05	.05	.02	.02	.17	.32	1.31	1.01	.02
Mg#	.48	.47	.11	.27	.12	.14	.15	.09	.10	.58	.45	.48	.49	.08
CIPW norms:														
Q	11.05	16.32	28.74	29.88	26.55	31.20	32.42	32.18	46.69			6.04	3.29	20.61
Or	21.72	9.23	57.26	46.34	39.85	33.66	47.45	33.11	44.07	16.45	4.97	10.49	15.16	43.77
Ab	41.43	39.82	10.14	20.41	29.32	31.78	17.08	31.26	6.17	18.00	24.18	31.24	34.78	29.58
An	7.65	18.24	.12	.22	.07			.17	.02	25.00	25.97	20.14	15.88	2.19
Ne										2.71				
C	1.06		.86	.90	.73	.57	.45	.67	.61					
Di		4.33								8.89	13.32	1.30	.16	.36
Wo		2.18								4.52	6.68	.66	.08	.17
En		1.07								2.45	2.98	.35	.04	.02
Fs		1.07								1.91	3.66	.29	.03	.17
Wo														
Hy	10.82	7.46	1.80	1.35	2.40	1.80	1.70	1.58	1.55		19.06	18.80	19.76	2.06
En	5.88	3.73	.20	.05	.22	.25	.25	.15	.15		8.55	10.32	10.85	.18
Fs	4.94	3.73	1.60	1.30	2.17	1.55	1.45	1.43	1.40		10.51	8.48	8.91	1.88
Ol										23.16	4.29			
Fo										12.45	1.82			
Fa										10.71	2.47			
Mt	3.32	2.35	.86	.71	.87	.81	.75	.83	.73	2.34	2.73	4.21	4.07	1.12
Il	2.13	1.60	.17	.15	.17	.10	.10	.15	.13	3.10	4.79	4.91	4.70	.27
Ap	.83	.66	.04	.04	.04	.08	.05	.04	.04	.37	.70	2.86	2.21	.04

	Montreal River area—Continued							Bare Hill area					
	85KE107	85KE105	85KE104	86KE259	85KE108	85KE98	85KE106	86KE241	86KE236	86KE242	86KE240	85KE154	85KE173
SiO_2	72.21	72.85	73.47	73.62	73.21	74.95	75.93	47.20	47.35	72.92	73.12	73.89	73.55
TiO_2	.13	.12	.27	.11	.13	.13	.16	1.87	1.88	.08	.08	.09	.10
Al_2O_3	14.10	14.01	13.00	13.64	14.01	12.86	12.39	17.14	16.79	13.62	13.53	12.42	13.69
Fe_2O_3	.74	.75	.70	.62	.70	.69	.68	1.70	1.73	.68	.65	.53	.65
FeO	1.49	1.51	1.40	1.25	1.41	1.38	1.37	11.23	11.40	1.37	1.30	1.06	1.30
MnO	.06	.04	.04	.02	.03	.04	.04	.34	.17	.02	.02	.06	.03
MgO	.08	.17	.52	.10	.06	.35	.57	9.60	7.51	.18	.30	.23	.20
CaO	.67	.19	.08	.09	.10	.11	.46	5.27	8.48	.05	.07	2.24	.06
Na_2O	3.02	3.40	.11	2.87	3.18	2.19	3.63	1.75	3.71	1.56	1.70	2.14	1.40
K_2O	7.45	6.91	10.38	7.63	7.15	7.28	4.73	3.69	.78	9.47	9.17	7.33	8.99
P_2O_5	.04	.04	.02	.05	.02	.03	.04	.20	.20	.05	.05	.01	.02
Mg#	.09	.17	.40	.13	.07	.31	.43	.60	.54	.19	.29	.28	.22
CIPW norms:													
Q	23.83	25.18	31.45	26.79	26.27	32.85	34.21			26.48	26.88	29.44	29.83
Or	44.07	40.88	61.40	45.13	42.29	43.06	27.98	21.83	4.61	56.02	54.25	43.36	53.18
Ab	25.53	28.74	.93	24.26	26.88	18.51	30.68	14.79	25.46	13.19	14.37	18.09	11.83
An	2.86	.68	.27	.12	.37	.35	2.02	24.87	26.83		.02	2.58	.17
Ne									3.20				
C		.67	1.46	.59	.89	1.23	.54	1.14		.78	.78		1.57
Di	.18								11.51			4.00	
Wo	.09								5.83			1.96	
En	.01								3.00			.58	
Fs	.09								2.67			1.47	
Wo												1.58	
Hy	2.12	2.45	2.92	1.89	2.00	2.70	3.19	4.35		2.31	2.50		2.24
En	.19	.43	1.30	.25	.15	.87	1.43	2.56		.45	.75		.50
Fs	1.93	2.03	1.62	1.64	1.85	1.82	1.76	1.79		1.86	1.75		1.74
Ol								26.57	21.88				
Fo								15.01	11.04				
Fa								11.55	10.83				
Mt	1.07	1.09	1.02	.90	1.02	1.00	.99	2.47	2.51	.99	.94	.77	.94
Il	.25	.23	.51	.21	.25	.25	.30	3.55	3.57	.15	.15	.17	.19
Ap	.09	.09	.04	.11	.04	.07	.09	.44	.44	.08	.11	.02	.04

	Bare Hill area—Continued					West Pond area				Keystone Point area		
	85KE172	86KE244	85KE176	85KE175	85KE156	85KE132	85KE129	85KE128	85KE130	85KE135	85KE136	85KE137
SiO_2	73.82	74.42	74.63	74.97	75.18	49.84	72.24	73.83	73.78	68.06	75.33	81.99
TiO_2	.10	.09	.11	.11	.10	1.59	.18	.14	.13	.18	.17	.16
Al_2O_3	13.90	13.78	14.13	13.96	13.16	15.48	14.67	13.96	14.10	15.86	13.41	9.60
Fe_2O_3	.66	.59	.52	.56	.66	1.70	.83	.73	.63	.97	.59	.52
FeO	1.32	1.17	1.04	1.12	1.32	11.23	1.66	1.47	1.26	1.93	1.18	1.05
MnO	.03	.02	.02	.02	.02	.10	.04	.04	.03	.05	.03	.03
MgO	.29	.16	.16	.14	.19	6.04	.60	.39	.30	.74	.07	.34
CaO	.15	.17	.10	.12	.39	7.00	.20	.20	.15	2.35	.20	.19
Na_2O	3.40	4.43	4.88	5.98	4.49	2.12	3.92	4.75	4.10	6.76	4.13	3.10
K_2O	6.30	5.12	4.38	2.99	4.49	4.67	5.63	4.45	5.50	3.07	4.84	3.00
P_2O_5	.02	.05	.04	.03	.01	.22	.03	.03	.03	.02	.03	.02
Mg#	.28	.20	.21	.18	.20	.49	.39	.32	.30	.40	.10	.37
CIPW norms:												
Q	28.45	27.92	28.57	27.76	30.02		25.70	27.40	27.48	11.47	31.71	51.06
Or	37.27	30.29	25.91	17.69	26.56	27.63	33.30	26.32	32.53	18.16	28.63	17.75
Ab	28.74	37.44	41.24	50.54	37.94	14.62	33.13	40.15	34.65	57.14	34.91	26.20
An	.61	.52	.24	.40	1.87	18.88	.80	.80	.55	3.84	.80	.81
Ne						1.79						
C	1.25	.75	1.26	.73	.21		1.82	1.02	1.19		1.07	.95
Di						11.98				6.55		
Wo						6.03				3.21		
En						2.82				1.36		
Fs						3.13				1.86		
Wo												
Hy	2.49	1.95	1.73	1.80	2.22		3.64	2.91	2.38	1.16	1.63	2.14
En	.73	.40	.40	.35	.47		1.50	.98	.75	.49	.18	.85
Fs	1.77	1.55	1.33	1.45	1.75		2.14	1.94	1.63	.67	1.45	1.29
Ol						19.12						
Fo						8.60						
Fa						10.53						
Mt	.96	.86	.75	.81	.96	2.47	1.20	1.06	.91	1.41	.86	.75
Il	.19	.17	.21	.21	.19	3.02	.34	.27	.25	.34	.32	.30
Ap	.04	.11	.09	.07	.02	.48	.07	.07	.07	.04	.07	.04

	Copper City area				Suffolk area		Mt. Gratiot area				Fish Cove area		
	88KE301	85KE150	85KE147	85KE151	85KE37	85KE39	85KE49	85KE45	85KE48	85KE50	85KE122	85KE113	85KE119
SiO_2	75.83	75.03	75.53	76.57	60.90	62.30	60.81	65.32	66.77	66.20	51.14	70.70	73.56
TiO_2	.03	.06	.04	.05	1.64	1.48	1.45	.70	.49	.50	1.49	.16	.13
Al_2O_3	13.27	13.53	13.81	12.49	13.82	13.41	16.24	15.89	15.52	15.77	17.83	14.71	14.20
Fe_2O_3	.44	.45	.39	.46	3.14	3.28	2.12	1.85	1.63	1.69	1.68	.88	.69
FeO	.87	.91	.78	.92	7.64	6.57	5.15	3.71	3.27	3.39	11.07	1.76	1.38
MnO	.01	.04	.05	.04	.12	.16	.21	.13	.12	.06	.36	.03	.04
MgO	.15	.11	.14	.14	1.49	1.69	2.90	1.74	1.43	.55	7.05	.48	.31
CaO	1.26	.87	1.02	2.35	2.86	2.96	2.07	1.95	.83	.58	1.81	.33	.28
Na_2O	2.48	2.02	3.15	2.25	2.95	3.48	3.93	5.23	3.68	4.45	5.34	1.53	4.50
K_2O	5.63	6.97	5.08	4.71	4.85	4.22	4.55	3.28	6.13	6.67	2.03	9.40	4.90
P_2O_5	.03	.01	.01	.01	.58	.44	.59	.18	.14	.16	.20	.01	.01
Mg#	.24	.18	.24	.22	.26	.31	.50	.46	.44	.22	.53	.33	.28
CIPW norms:													
Q	36.48	34.03	34.90	40.00	14.49	15.76	9.86	14.13	16.55	11.33		23.38	26.76
Or	33.30	41.23	30.05	27.86	28.71	24.98	26.93	19.41	36.26	39.45	12.01	55.61	29.04
Ab	20.96	17.07	26.62	19.02	24.95	29.43	33.23	44.22	31.10	37.61	44.85	12.93	38.03
An	6.06	4.25	5.00	10.02	10.10	8.47	6.43	8.51	3.21	1.84	7.68	1.57	1.32
Ne													
C	.86	1.08	1.28				2.48	.61	1.64	.54	.16	1.42	.98
Di				1.36	.27	2.83					4.02		
Wo				.66	.13	1.40							
En				.15	.04	.53							
Fs				.55	.10	.90							
Wo													
Hy	1.58	1.55	1.49	.95	12.53	10.00	12.95	8.72	7.64	5.48		3.49	2.60
En	.38	.28	.35	.20	3.69	3.70	7.25	4.35	3.58	1.37		1.20	.77
Fs	1.20	1.27	1.14	.75	8.84	6.30	5.69	4.36	4.07	4.11		2.29	1.82
Ol											25.27		
Fo											12.34		
Fa											13.23		
Mt	.64	.65	.57	.67	4.56	4.76	3.08	2.68	2.36	2.45	2.44	1.28	1.00
Il	.06	.11	.08	.10	3.12	2.81	2.76	1.33	.93	.95	2.83	.30	.25
Ap	.07	.02	.02	.02	1.27	.96	1.29	.39	.31	.35	.44	.02	.02

APPENDIX 3—Major-oxide and CIPW normative compositions of Portage Lake Volcanics—Continued

	Fish Cove area—Continued		Mt. Bohemia area		
	85KE117	85KE118	88KE313	88KE312	85KE51
SiO_2	73.10	73.18	48.91	48.17	48.38
TiO_2	.14	.14	1.51	1.75	1.66
Al_2O_3	14.17	14.09	16.34	16.93	17.03
Fe_2O_3	.83	.78	1.55	1.63	1.55
FeO	1.66	1.56	10.25	10.76	10.21
MnO	.03	.04	.23	.20	.19
MgO	.30	.33	10.07	8.45	7.89
CaO	.24	.23	5.68	6.09	9.24
Na_2O	4.56	4.16	3.51	2.64	2.70
K_2O	4.96	5.47	1.79	3.19	.98
P_2O_5	.01	.01	.16	.19	.18
Mg#	.25	.28	.64	.58	.58
CIPW norms:					
Q	25.70	26.18			
Or	29.34	32.36	10.59	18.87	5.80
Ab	38.54	35.16	28.11	19.28	22.82
An	1.13	1.08	23.51	24.88	31.41
Ne			.85		
C	.87	.92		1.65	
Di			2.97	3.38	10.88
Wo			1.52	1.72	5.54
En			.90	.95	3.03
Fs			.55	.71	2.31
Wo					
Hy	2.93	2.89			6.52
En	.75	.83			3.70
Fs	2.18	2.06			2.82
Ol			28.51	25.84	16.77
Fo			17.00	14.13	9.10
Fa			11.51	11.71	7.67
Mt	1.20	1.13	2.25	2.36	2.25
Il	.27	.27	2.87	3.33	3.15
Ap	.02	.02	.35	.41	.39

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