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THE PETROLOGY AND GEOCHEMISTRY OF KEWEENAWAN DIABASE DIKES IN ONTONAGON, GOGEBIC, IRON AND DICKINSON COUNTIES, MICHIGAN

By

James J. Hahnenberg

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
Requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
August, 1981

THE PETROLOGY AND GEOCHEMISTRY OF KEWEENAWAN DIABASE DIKES IN ONTONAGON, GOGEBIC, IRON AND DICKINSON COUNTIES, MICHIGAN

James J. Hahnenberg, M.S.

Western Michigan University, 1981

Petrographic and chemical studies of Keeweenawan-age diabase dikes in Michigan's Upper Peninsula show two major groupings, Procupine Mountain dikes and Lower Keweenawan dikes. Lower Keweenawan dikes consist of two major rock types, fine-grained smaller dikes and the coarse-grained central portions of larger dikes. Major minerals are subophitic plagioclase and pyroxene. The rocks, as compared to "average" basalts, are low in Al_2O_3, high in TiO_2, K_2O, P_2O_5 and contain moderate amounts of FeO_t. They are classified as quartz tholeiites. Several parental magma sources that would account for these and other Keweenawan igneous units are presented; the most acceptable is derived from 1-1.5% partial melting of pyrolite at a depth of 50-75 km. The Keweenawan basalts were derived from a tectonic environment similar to a plume-generated oceanic island such as Iceland. The Porcupine Mountain dikes are more alkalic than the Lower Keweenawan dikes and show greater secondary alteration.

ACKNOWLEDGEMENTS

I would like to express appreciation and thanks to my thesis committee, Drs. John Grace, Lloyd J. Schmaltz, and Ronald B. Chase. First mention of appreciation should go to my advisor Dr. Chase for the time he spent with me in the field, helping to set up the study, and knowledgeable advice regarding sampling and petrographic analysis. Additionally, his critical readings of the initial drafts and aid in obtaining grants for the research and seminar presentation are all greatly appreciated. I am also grateful to Drs. John Grace and William B. Harrison, III for their help during the geochemical laboratory analysis. Were it not for their efforts, this study might not have been completed. Thanks are extended also to Bob Gorman who provided a strong back, patience, and good companionship during the field work. I would also like to acknowledge the late Dr. W. David Kuenzi for his inspiring and illuminating discussions during the early phases of the project. Others who have helped in various aspects of this project are my wife Colette, Robert Havira, Kevin Prochaska, and John Fowler.

James J. Hahnenberg

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INTRODUCTION

Purpose of Study

The Lower Keweenawan dikes of this study in the Upper Peninsula of Michigan may correlate in age and composition with each other as well as other Keweenawan igneous units (Figure 1). Geochemical correlations are also made with basalts of other tectonic environments. It is hoped that this study will reveal whether or not Keweenawan igneous activity fits a rifting model such as that of the Red Sea. Additionally, significant geochemical information will be added to the present knowledge of Keweenawan age rocks in the Lake Superior region.

General Geologic Setting

The study area is in the western Upper Peninsula of Michigan (Figure 2), within the Southern Province of the Canadian Shield (Figure 3). Most of the dikes sampled are located in metamorphic terrane (Morey, 1978).

The age of most correlative lava flows is 1000 to 1200 m.y. Green (1977) has narrowed the period of most Keweenawan volcanic activity to 1120-1140 m.y. based on U-Pb ages of zircons from intermediate to felsic rocks ranging from the lowermost lavas (magnetically reversed) to the top of the "upper normal" magnetic rocks in Michigan. The paleomagnetic data (Pesonen, 1979) suggest that most dike intrusion occurred just prior to most of the extrusion of massive lava flows, the dikes being about 1150-

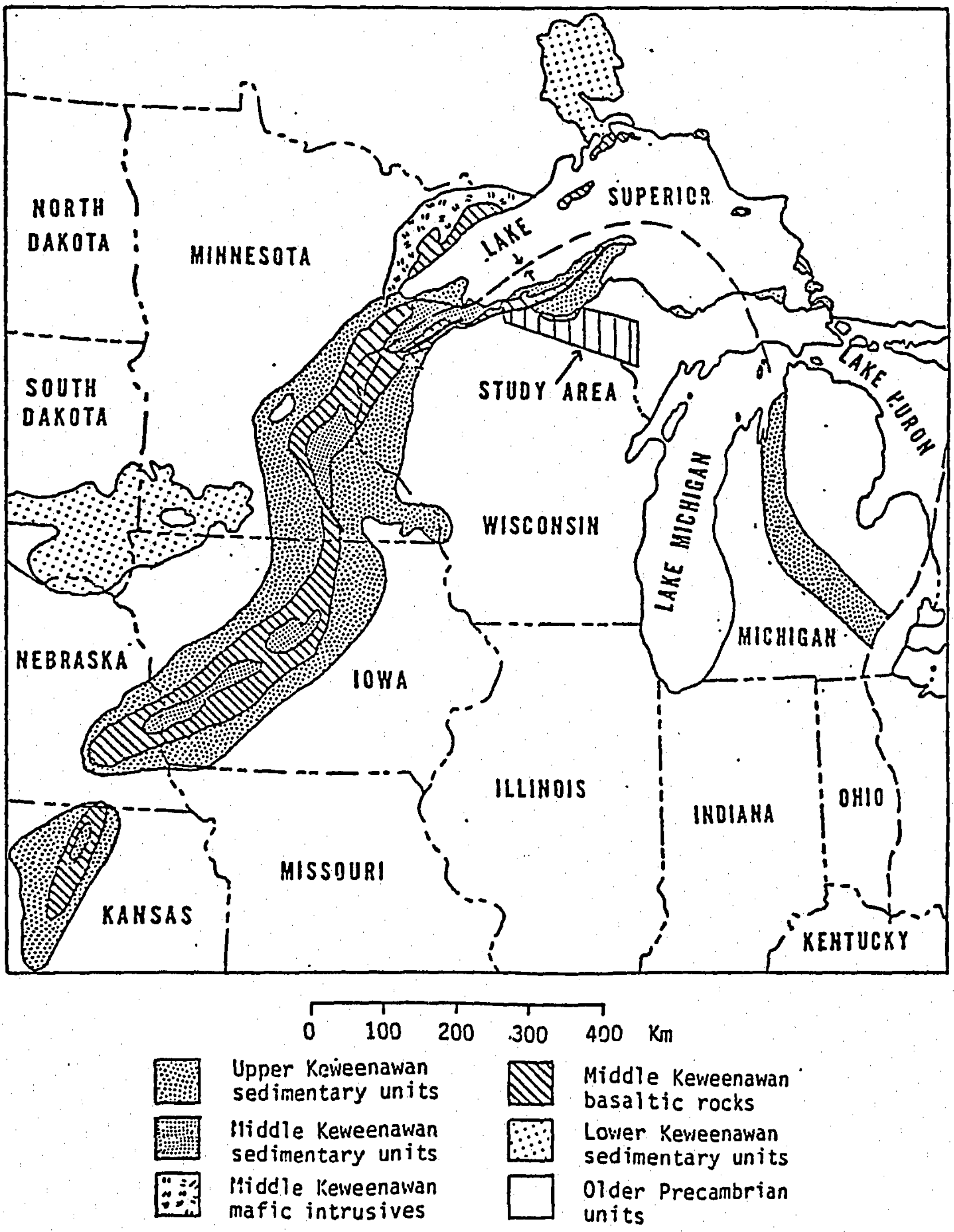


Figure 1. Geology of Keweenawan-age rocks in north-central United States (from King, 1976).

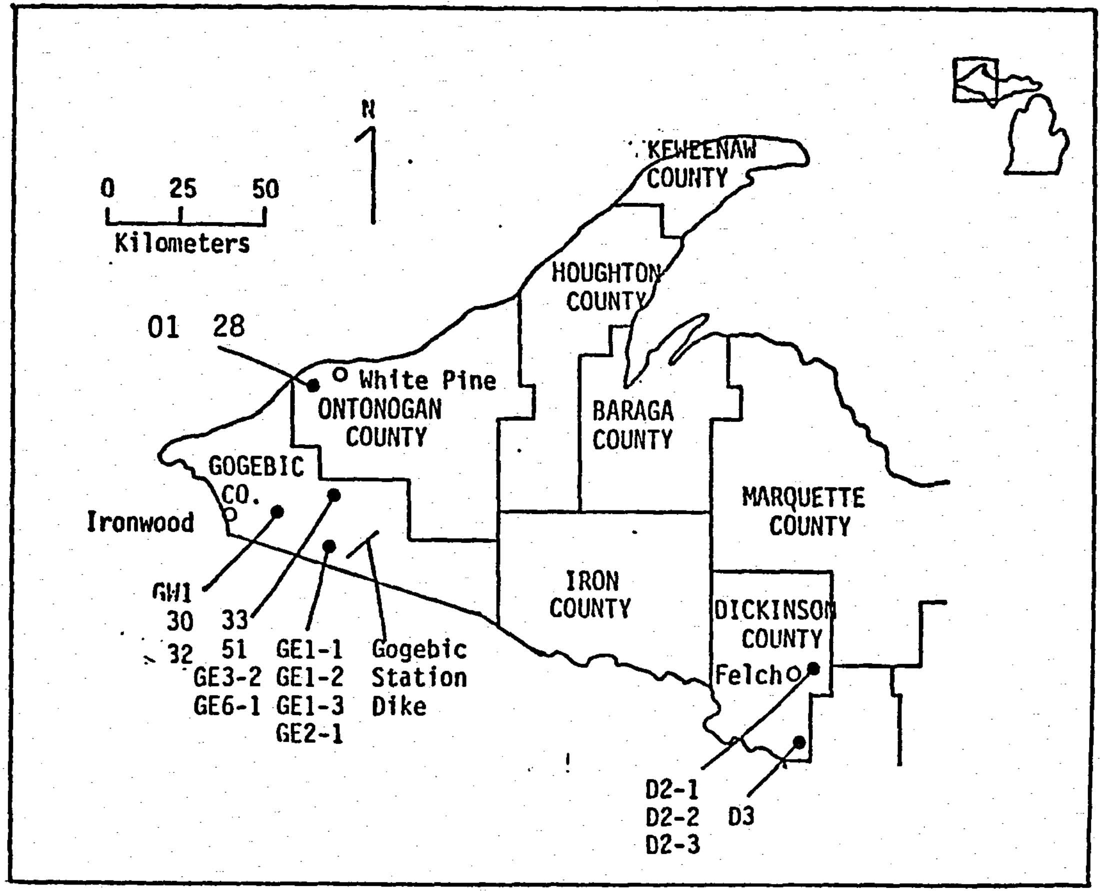


Figure 2. Sample site locations in Ontonagon, Gogebic, Iron and Dickinson Counties, Michigan. Numbers indicate locality designations. The Gogebic Station Dike has five sub-localities.

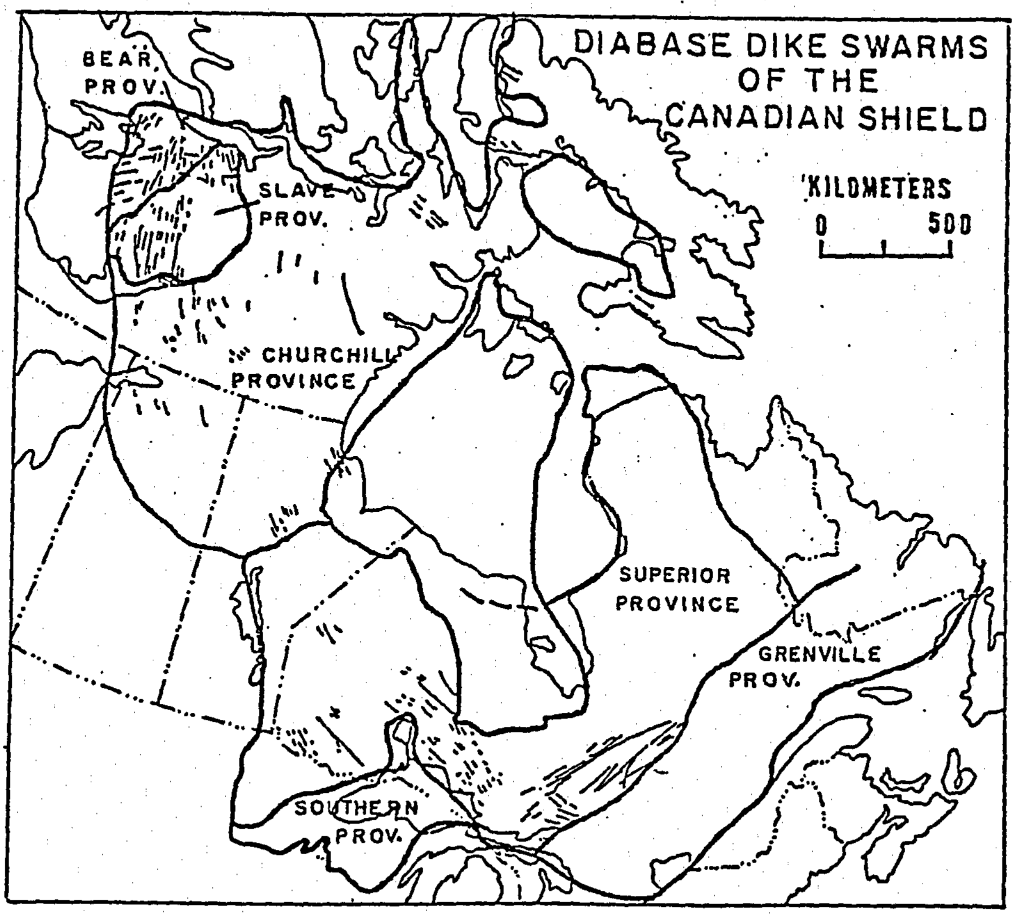


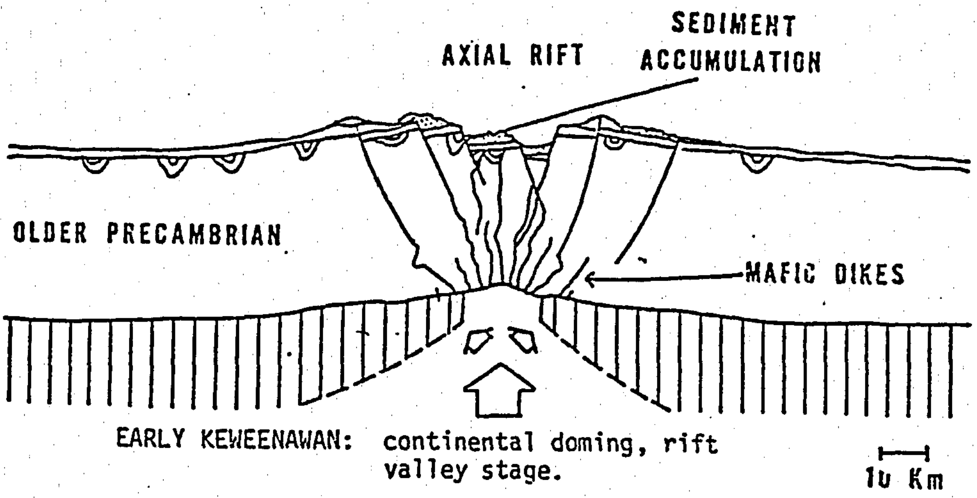
Figure 3. Tectonic provinces and Keweenawan dikes of the Canadian Shield (from Fahrig and Wanless, 1963).

1170 m.y. old. Additional evidence that these dikes are early Keweenawan in age comes from the negative magnetic polarity and specific paleopole correlations of some dikes (Bayley, 1959; Bayley and others, 1966; Dubois, 1962; Gair, 1968; Gair and others, 1956; James, 1968; James and others, 1961; Klasner and Cannon, 1978; Pesonen and others 1979; Puffett, 1974; and Shanabrook, 1978). Some dikes in the Porcupine Mountain State Park, however, intrude Middle Keweenawan volcanics and are younger than other dikes sampled in this study.

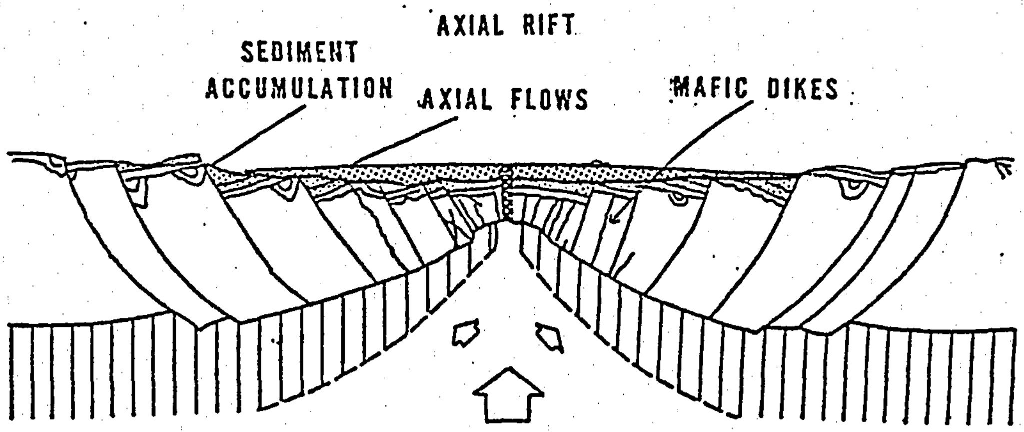
Most researchers in the region believe the Keweenawan volcanic activity represents a late Precambrian rifting episode (Figure 4). Before much separation of continental crust occurred, the dikes may have served as feeders for some of the early Keweenawan flows. Supporting field evidence consists of flow directions in the older flows which are random, indicating feeders were located over a wide area (Green, 1972), and dike swarms which occur on the periphery of the basin with strike parallel to the "rift trend" (defined here as the axis of the Lake Superior syncline).

The Penokean Orogeny is the most significant tectonic event which affected the host rocks prior to Keweenawan rifting This orogeny occurred about 1900 m.y. ago (Sims, 1976). Regional metamorphism altered pre-Keweenawan units (Figure 5), thus establishing a field criterion for identification of younger dikes located within lower and middle Precambrian terrain.

Keweenawan lava sequences north and west of the study area (Figure 1) rest unconformably on lower and middle Precambrian

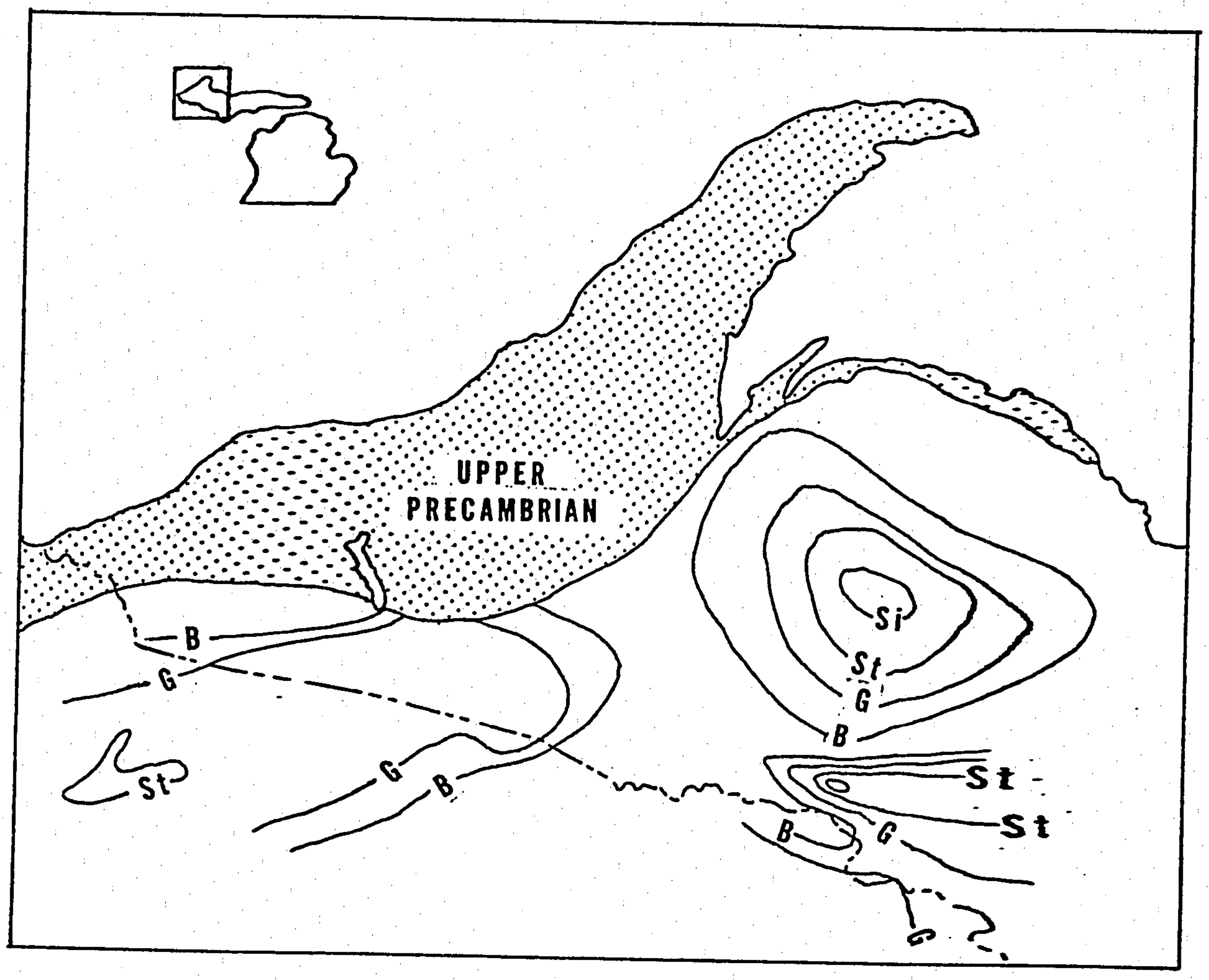


EARLY KEWEENAWAN: continental doming, rift valley stage.



MIDDLE KEWEENAWAN: early continental separation

Figure 4. Early stages of Keweenawan rift valley developement (from Fowler and Kuenzi, 1978).



METAMORPIC ISOGRADS

Si: Sillimanite
St: Staurolite
G: Garnet
B: Biotite

Figure 5. Zones of regional metamorphism in northern Michigan and Wisconsin (from James, 1955).

rocks. These extensive sequences of flood basalts (Baragar, 1977; Green, 1968, 1972, 1977, 1979; and White, 1960 and intrusive equivalents (the Duluth Gabbro for instance) are intertongued with and overlain by conglomerates and sandstones. Felsic units are of minor volume, mostly distributed in Minnesota and Michipicoten Island, and are rarely present in Michigan.

Keweenawan igneous units are correlated (Figure 6) by Green (1977), who also proposes four separate episodes of plateau volcanism during Keweenawan time. The Lower Keweenawan dikes of this study probably correlate with one of the early volcanic pulses as described by Green.

Results of the 1963 Lake Superior seismic experiment (Smith and others, 1966) indicate that the dikes may have been conduits for the Keweenawan lava flows. White (1966) proposes that a "wall of denser material representing one or more swarms" may account for high crustal velocites in the center of the Lake Superior basin as determined by Smith and others.

Previous Studies

Numerous workers have mapped and/or described dikes of Keweenawan age. In Marquette and Baraga Counties, many authors (Cannon, and others, 1980; Case and Gair, 1965; Clark and others, 1975; Gair, 1975; Gair and Thaden, 1968; Halls, 1975; Klasner and Cannon, 1978; Pesonen and others, 1979; Puffet, 1974; and Simmons, 1974) have noted the presence of mostly east-west trending Keweenawan dikes. Within the study area of this report, dikes of

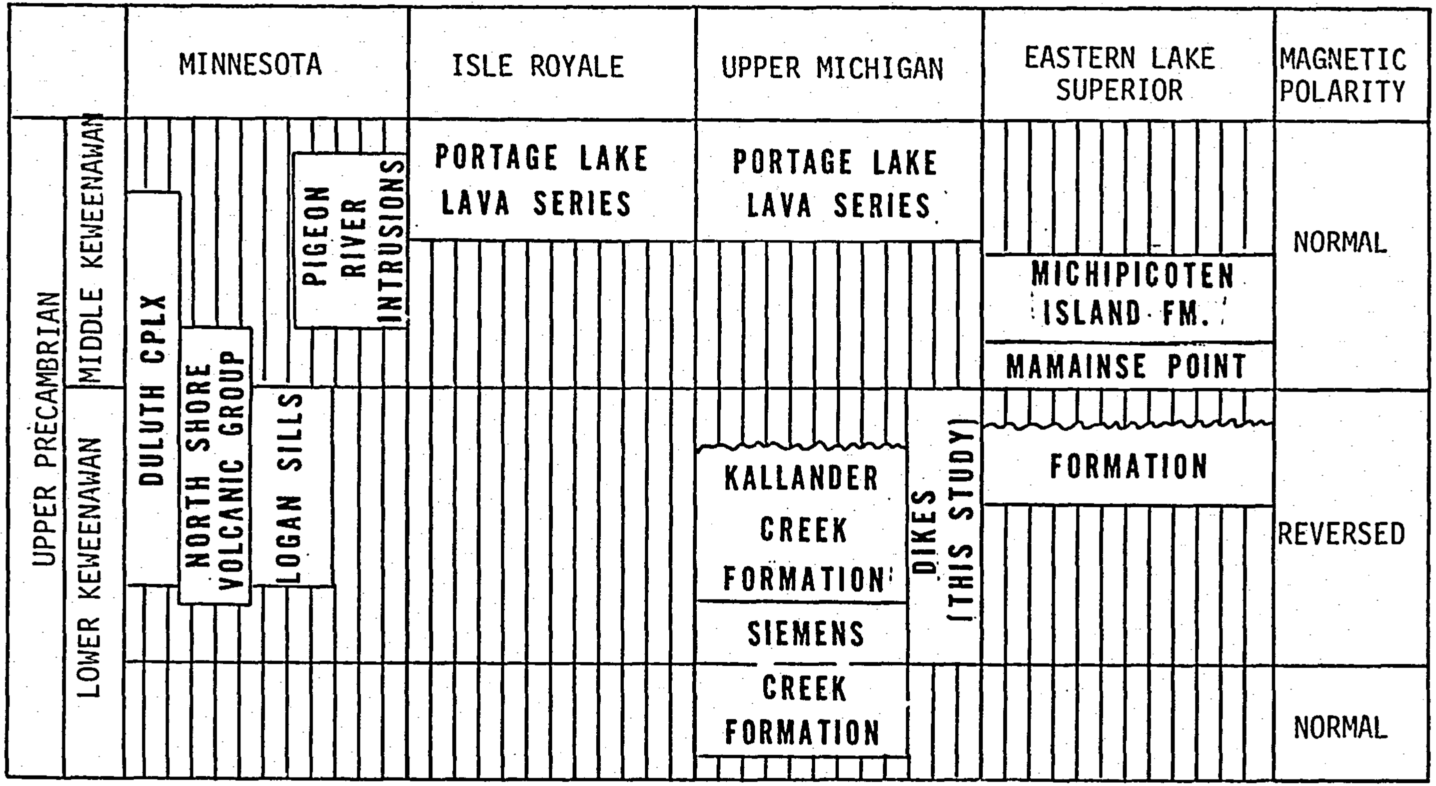


Figure 6. Stratigraphic correlation fo Keweenawan igneous units for the Lake Superior region (from Green, 1977).

Keweenawan age have also been reported in Iron County (Bayley, 1959; and Gair and others, 1956), Dickinson County (Bayley and others, 1966; James and others, 1961 and 1968) and Gogebic County (Fritts, 1969; Hubbard, 1971 and 1975; Prinz, 1969; Prinz and Hubbard, 1975; and Schmidt, 1976). Two exposures of "diorite" are located in the Porcupine Mountain State Park in Ontonogan County (Hubbard, 1975).

Keweenawan dikes outside of Michigan have been recognized in the Duluth area, Minnesota (Schwartz and others, 1940; Kilburg, 1972, in northern Cook County, Minnesota (Weiblen and other, 1972), Michipicoten Island, Ontario (Annells, 1974), Sault Ste. Marie and Mamainse Point area, Ontario (McConnell and Moore, 1926) as well as in other parts of Ontario.

General Approach to Problem

Samples of diabase were collected in a zone roughly perpendicular to the Lake Superior rift trend (Figure 1) to test whether dike petrology and/or geochemistry reflect the history of rifting during Keweenawan time. Assuming that the igneous and sedimentary history of rifting follows the model (Figure 4) proposed by Fowler and Kuenzi (1979), the dikes would evolve from oldest to youngest toward the active axis of lateral spreading (southeast to northwest in the study area).

Sample locations are shown in Figures 1 and 2. Units collected consist of 13 diabase dikes from the Wakefield-Marenisco-Lake Gogebic area, four diabase dikes from central and southern

Dickinson County and two "diorite" intrusives from the Porcupine Mountains State Park (Figure 7). Outcrops in these regions are severely limited and detail of geologic mapping is uneven.

The largest known dike in the study area (Figure 10) was sampled at five separate localities with the intent to determine if there were any systematic petrologic and/or geochemical trends along strike, and confirm whether the scattered outcrops of diabase do indeed represent a single large dike as mapped by Fritts (1969). It will hereafter be referred to as the Gogebic Station Dike, as two diagnostic outcrops are located near the ghost town of Gogebic Station.

A standard petrographic analysis was conducted for rocks from 23 outcrops. Detailed modal analyses was done on 20 selected thinsections representing 16 dikes. Six analyses were conducted on the Gogebic Station Dike (having five scattered outcroppings) to determine inter- and intra- outcrop variation in mineralogy. Several sites were not analyzed because of the fine-grained nature of the dikes.

Twenty-one samples (representing 13 dikes) were analyzed for all major elements except sodium by X-ray fluoresence. Sodium was determined by Flame Photometry on fifteen samples.

The geochemical data are used as a basis for statistical correlation. This approach provides a more objective comparison with basalts from different tectonic environments. Two basic formulas are used:

1. The sum for oxides of the quantity:

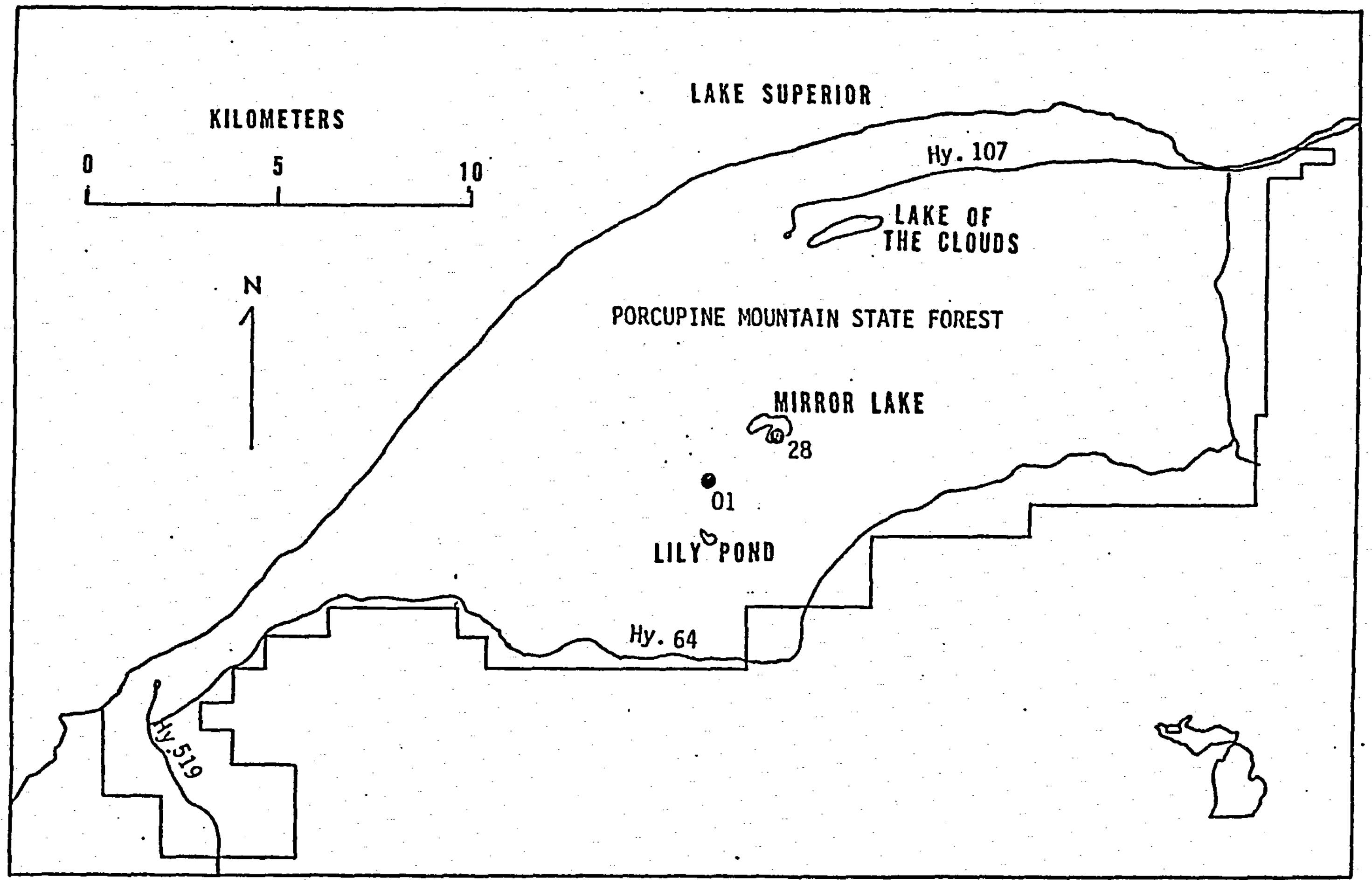


Figure 7. Location of sites 01 and 28 in the Porcupine Mountains State Park, Ontonagon, Michigan.

$$\frac{(X\%-KW\%)^2}{KW\%}$$

2. The sum for all oxides, of the quantity:

$$\frac{X\%-KW}{KW\%}$$

where X% is the concentration of an oxide of the basalt being correlated and KW% is the average oxide concentration of all Lower Keweenawan dikes. Oxides summed are SiO_2, Al_2O_3, TiO_2, FeO_t, MgO, CaO, Na_2O, and K_2O. Ranking based upon the results from each formula is done with the best relative correlation having the lowest sum. An overall ranking is produced by summing the ranking of both formulas. Appendix IV, Tables 8-11, list the rankings and data base.

FIELD RELATIONS AND PETROGRAPHY

Lower Keweenawan Dikes

The dikes divide into two major groupings. The first group consists of three dikes less than one meter in width. No complete modal analyses were done on this group, as the matrix is microcrystalline to cryptocrystalline (Figure 8a). Microphenocrysts of plagioclase and pyroxene in subequal concentration constitute about 12% of the rock. The matrix contains mineral grains which are less than 0.1 mm in diameter, while the pilotaxitic (Figure 8b) plagioclase laths (measured lengthwise) and pyroxene phenocrysts are 0.25 mm to 0.50 mm in diameter. The matrix consists of subophitic plagioclase and pyroxene with minor opaque minerals. The second group of dikes has widths from two to 20 meters (Table 1). The mean grain diameter at the center of the large dikes ranges from 0.5 mm to 1.0 mm (Figure 9a), grading outward to almost cryptocrystalline several centimeters from the dike walls. Country rocks exhibit little alteration by either smaller or larger dikes.

TABLE 1

ESTIMATED THICKNESS OF DIKES

	Thicknesses				
	Less than 1 M	1-4 M	5-15 M	Greater than 15 M	unknown
Localities	#30	GE6-1	#32	GE1-3	GE2-1
	#33	D3	#51	D2-1	GE3-2
	D2-2	GE6-2	GE1-1	Gog. St. Dike	GW1 Porc. Mtn. Dikes

Figure 8a. Dike #30 located south of Wakefield which dips steeply and is discordant.

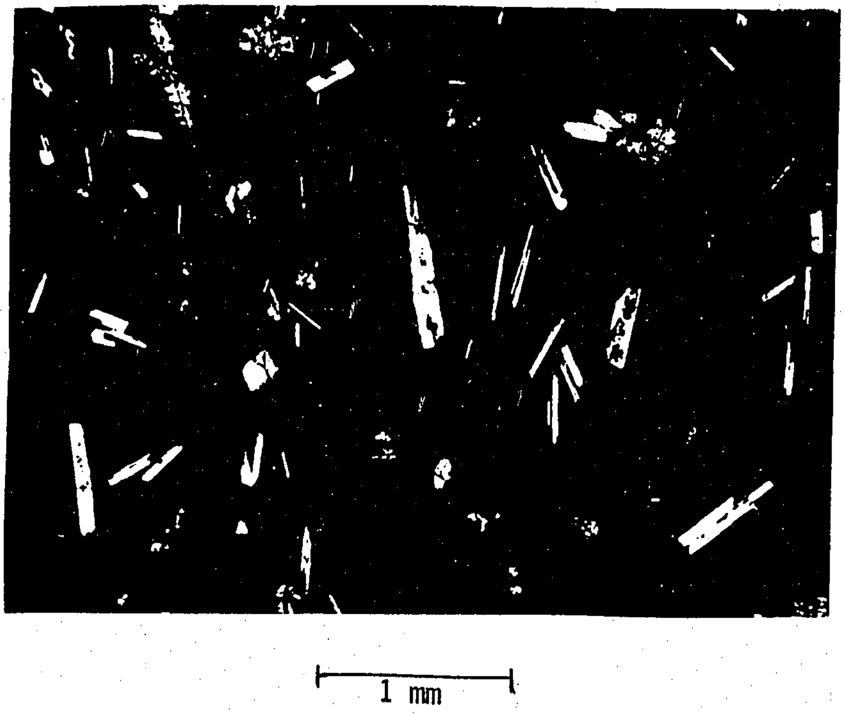


Figure 8b. Pilotaxitic texture of a fine grained, small dike.

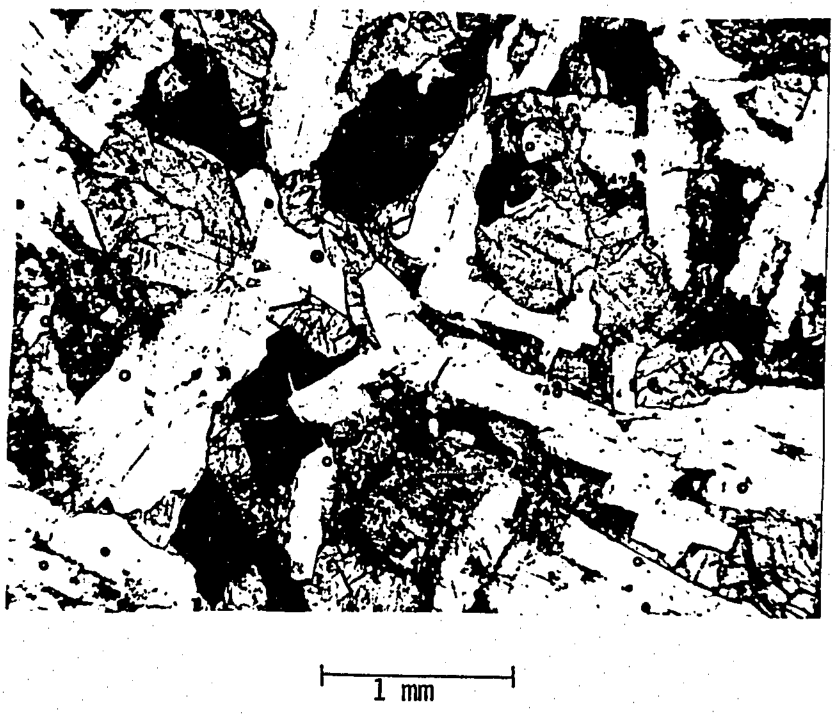


Figure 9a. Subophitic texture of a coarse grained large dike.

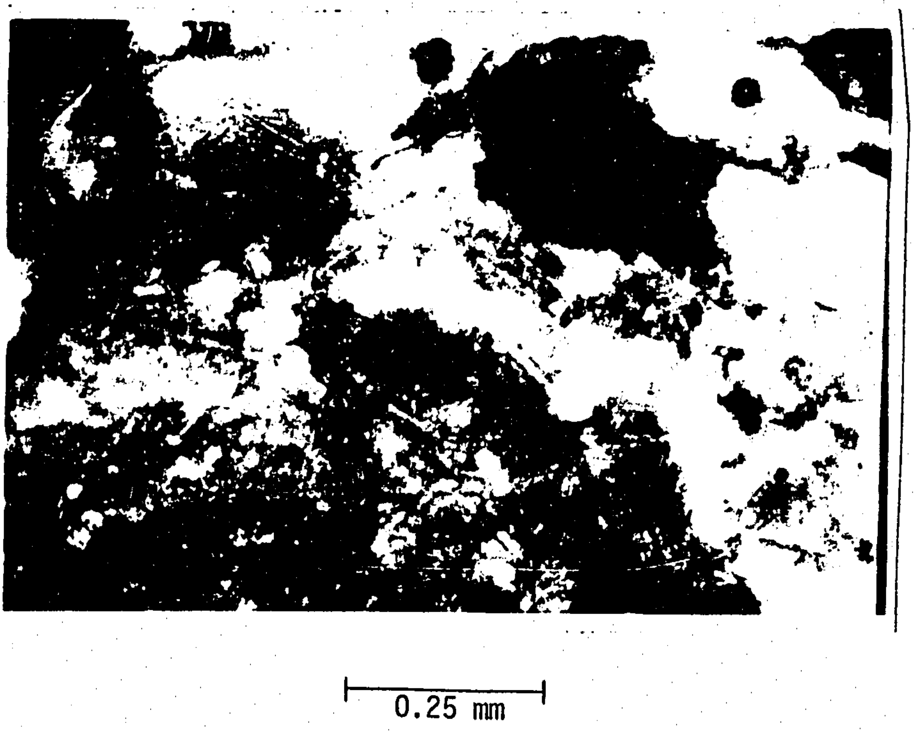


Figure 9b. Acicular apatite needles associated with matrix interstitial to the larger plagioclase and pyroxene crystals.

Aside from the main thrust of the study, one Lower Keweenawan dike, named the Gogebic Station Dike (Figure 10) was confirmed to be a single dike.

Major minerals of the coarser-grained (larger) dikes are plagioclase and pigeonitic pyroxene with subophitic texture (Figure 9a). Magnetite and ilmenite are minor, but ubiquitous constituents. Hematite is present locally. The magnetite and ilmenite are sometimes intergrown, with both primary and secondary varieties. Orthoclase and quartz occur locally as micropegmatitic intergrowths associated with needles of apatite (Figure 9b). Some of the large dikes exhibit extensive alteration. Plagioclase is sericitized and pyroxene has altered to magnetite and chlorite. The interstitial minerals are closely associated with various secondary minerals such as chlorite and biotite. Uniquitous, but minor, iron staining occurs. In one case there is extensive hematite replacement. Although no olivine is present, it is locally pseudomorphed by chlorite.

Structural relations are difficult to confidently determine because of poor exposure. It is possible that some of the intrusions may actually be sills or flow remnants. However, based upon interpretation of aeromagnetic surveys, most are known to be dikes.

Strikes for the Lower Keweenawan dikes of this study generally are northeasterly (Figure 11) in line with the rift trend. Secondary stresses, pre-existing fracture patterns, and other zones of weakness typical of a rifting environment determine specific dike orientations.

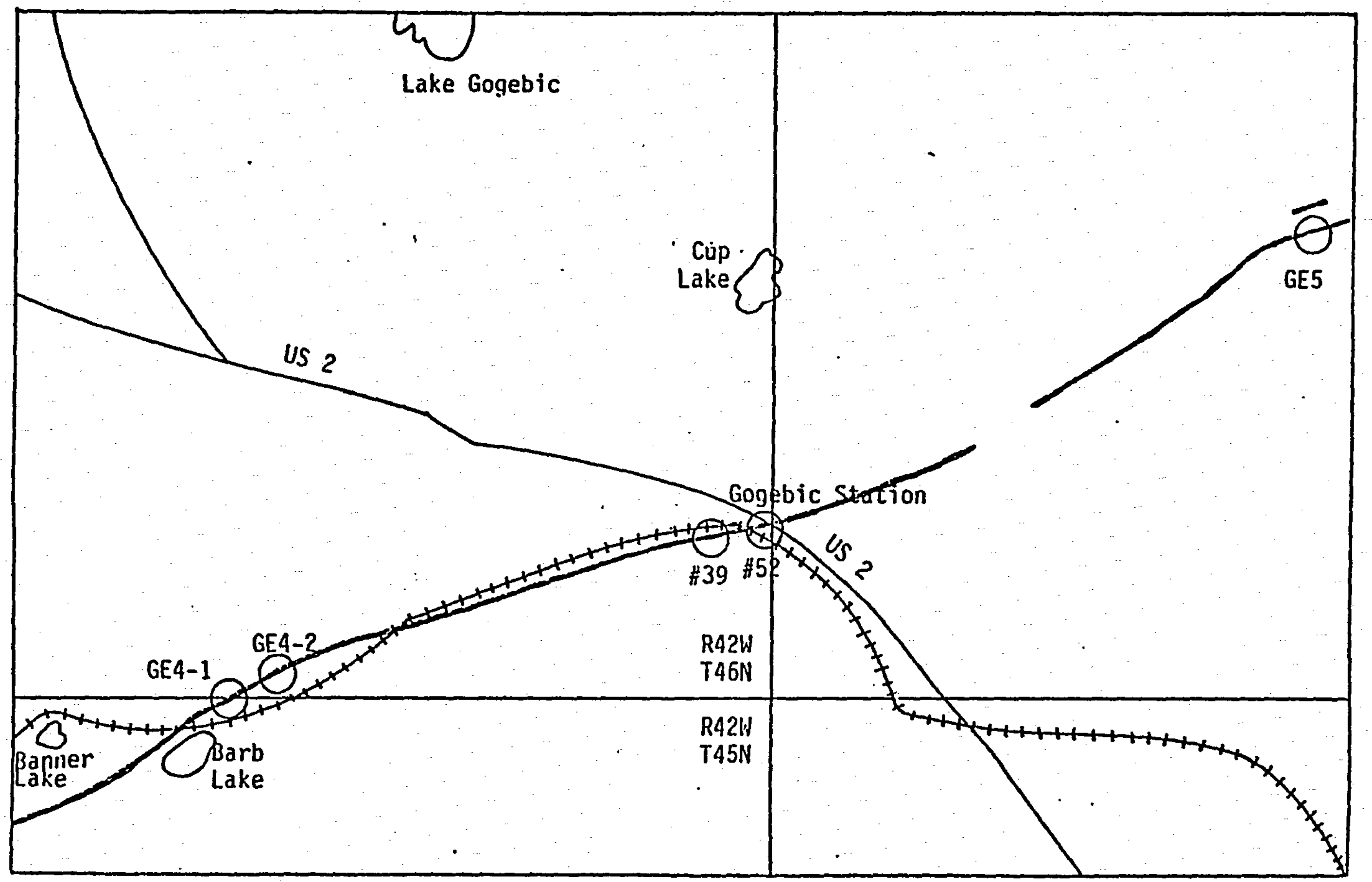


Figure 10. The Gogebic Station dike (sample locations GE4-1, GE4-2, #39, and GE5) is the largest dike of this study. Figure is from Fritts (1969). The dike is about 22 kilometers in length and width is about 50 M.

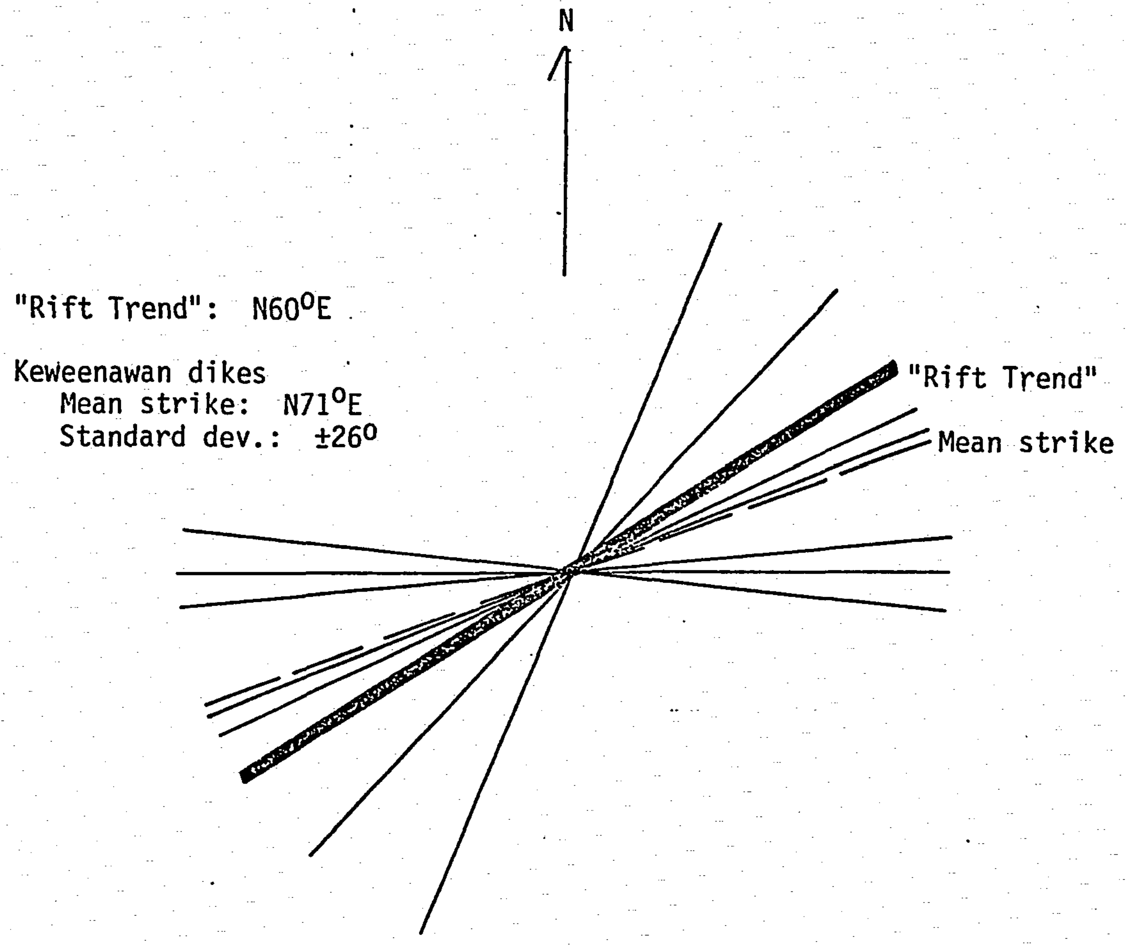


Figure 11. Strikes of Lower Keweenawan dikes.

Contacts dip more steeply than 60°, most being vertical or nearly vertical (Figure 12). Jointing is often perpendicular to dike walls, while bifurcation and pinching out is visible in only one exposure (Figures 13a and 13b). Columnar structure is not visible at any location, in contrast to Keweenawan dikes intruding Minnesota's North Shore Group (Figure 14).

Although there are no obvious regional mineralogical or textural trends amongst these dikes (Appendix I, Table 2), similarities with Lower Keweenawan flows in the area are apparent (Table 3). Based solely upon petrologic data, stratigraphic equivalence is neither proven nor disproven.

Mineral paragenesis has been deduced and is summarized in Figure 15. Subophitic plagioclase and pyroxene crystallized early with plagioclase continuing to form throughout most of the cooling history. Interstitial minerals crystallized later. Pyroxene which formed earlier is sometimes recrystallized to magnetite-ilmenite and chlorite. Some sericitization of plagioclase also occurred. These alterations were probably induced by the late release of water to the system. Reactions that account for most of the alteration can be summarized as follows:

$$\text{pyroxene} + H_2O \text{---------} \text{ chlorite} + \text{uralite}$$

$$\text{plagioclase} + H_2O \text{ ---------} \text{ sericite}$$

No evidence of metamorphism was observed. Alteration visible is most likely due to deuteric effects.

Figure 12. Dike #30, about twenty centimeters in width, exhibiting the fine grained nature of the smaller dikes.

Figure 13a. Dike D2-2 showing bifurcation, east of Felch in central Dickinson County, Michigan. Dike contacts can be seen above the notebook and also above the hammer.

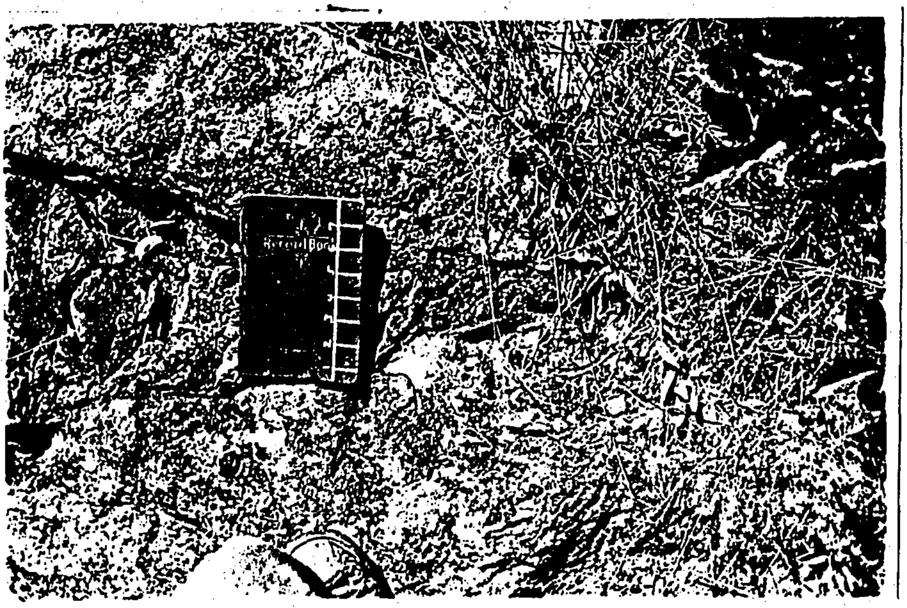


Figure 13b. Dike D2-2 where it pinches out.

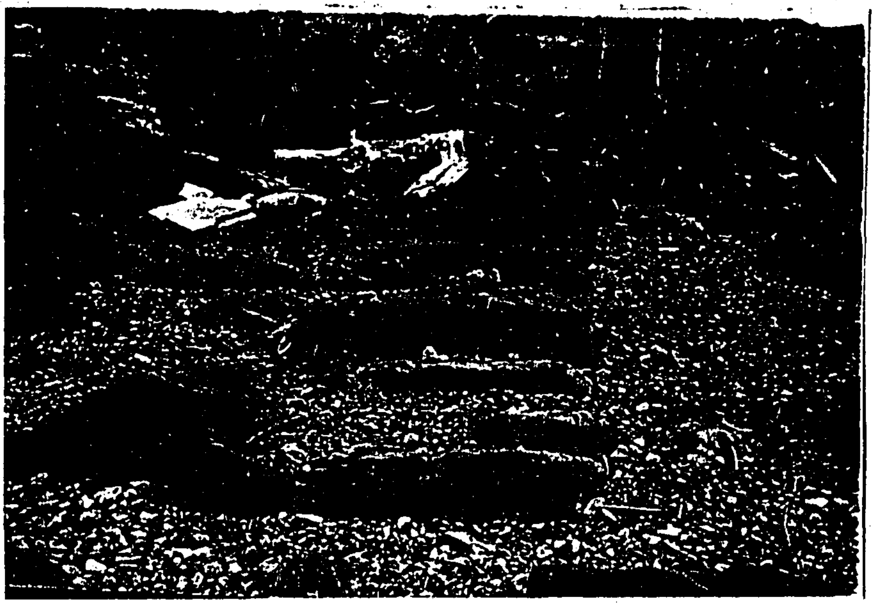


Figure 14. Columnar structure of a dike near Duluth, Minnesota which intrudes basalt flows of the North Shore Volcanic Group.

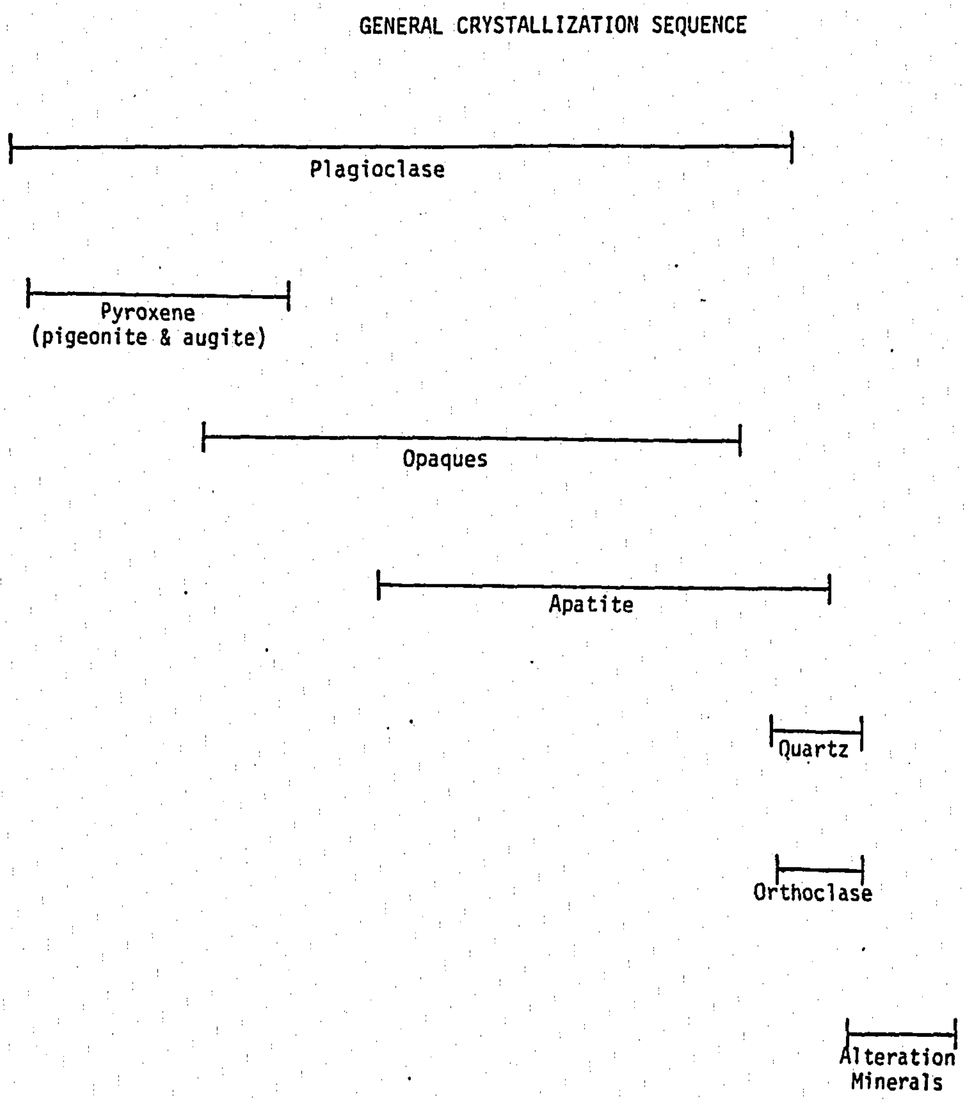


Figure 15. Crystallization sequence based upon petrographic evidence.

Porcupine Mountain Dikes

The Porcupine Mountain dikes (locations 01 and #28 in Figures 2 and 7) intrude Middle Keweenawan units. No contacts are exposed at either location so the relations to the enclosing rocks are unknown. It is known that the intrusive bodies are surrounded by the Unnamed Formation which generally is andesite with some felsite members (Hubbard, 1975).

In thin section these dikes are extensively altered. Plagioclase is sericitized and pyroxene has been altered to chlorite and other undetermined minerals. Opaque minerals are hematite, pyrite and magnetite. The dike at location #28 on Mirror Lake is much finer-grained (0.7 mm average grain size) than the coarse-grained outcrop at location 01. Location 01 shows some variability in grain size, but ranges between 1.5 mm to 2.5 mm with plagioclase laths occasionally as large as one to two cm in diameter.

GEOCHEMISTRY

Oxide concentrations for selected dikes from the study area are reported in Appendix III, Table 6. As compared to average tholeiitic basalt (Hyndman, 1972, Tables 1 and 2), Lower Keweenawan diabases are low in Al_2O_3 and high in TiO_2, K_2O and P_2O_5. FeO_t is moderately higher than the average basalt. A detailed chemical correlation with specific basalts from 63 localities throughout the world is discussed later in the text.

The Lower Keweenawan diabases can be classified as follows: 1) tholeiitic, with one being alkalic, according to the Irvine and Baragar (1971) classification (see Figures 16 and 17); 2) quartz tholeiitic, with three being alkali or high alumina types, according to the Yoder and Tilley (1962 classification). The younger Porcupine Mountain diorites are more alkalic and MgO-rich than the diabases (Figures 17 and 18). Their somewhat lower concentrations of TiO_2 and FeO_t and higher concentrations of MgO and K_2O render them olivine-normative (Appendix III, Table 7), as opposed to the quartz-normative Lower Keweenawan dikes.

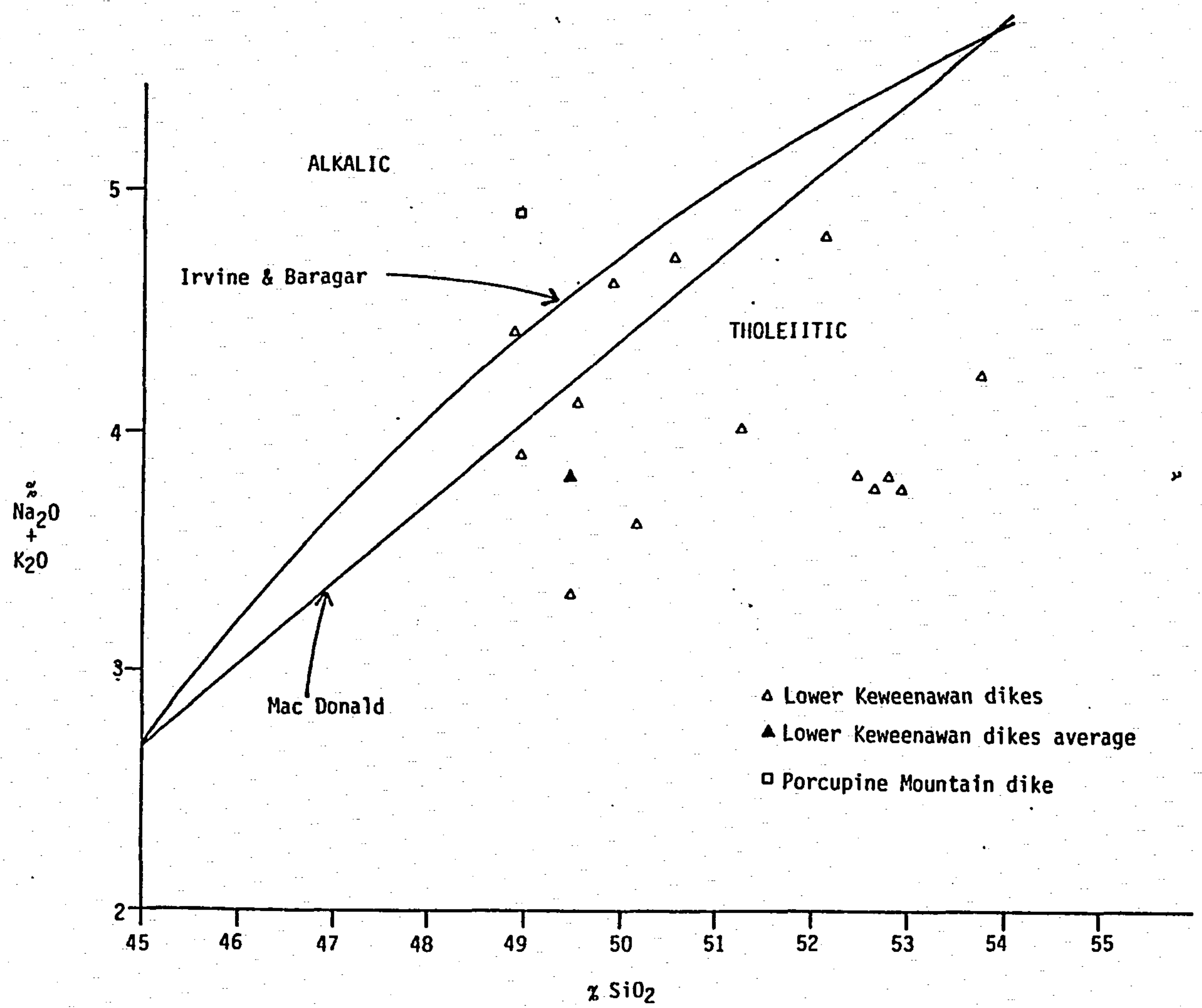


Figure 16. Plot of total alkalies vs. silica for classification of basalts (Irvine and Baragar, 1970). Composition of Lower Keweenawan dikes and the Porcupine Mountain dikes are shown.

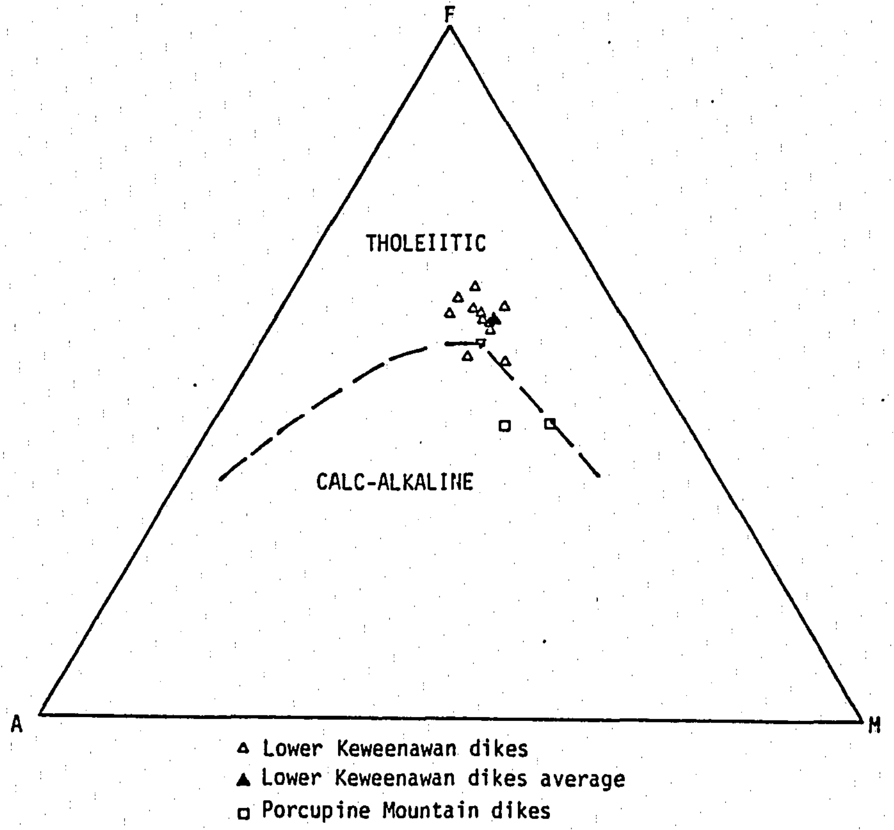


Figure 17. A-F-M Diagram (A=Al_2O_3, F=total iron, M=MgO); classification of basalts from Irvine and Baragar (1979). Compositions of Lower Keweenawan dikes and the Porcupine Mountain dikes are shown.

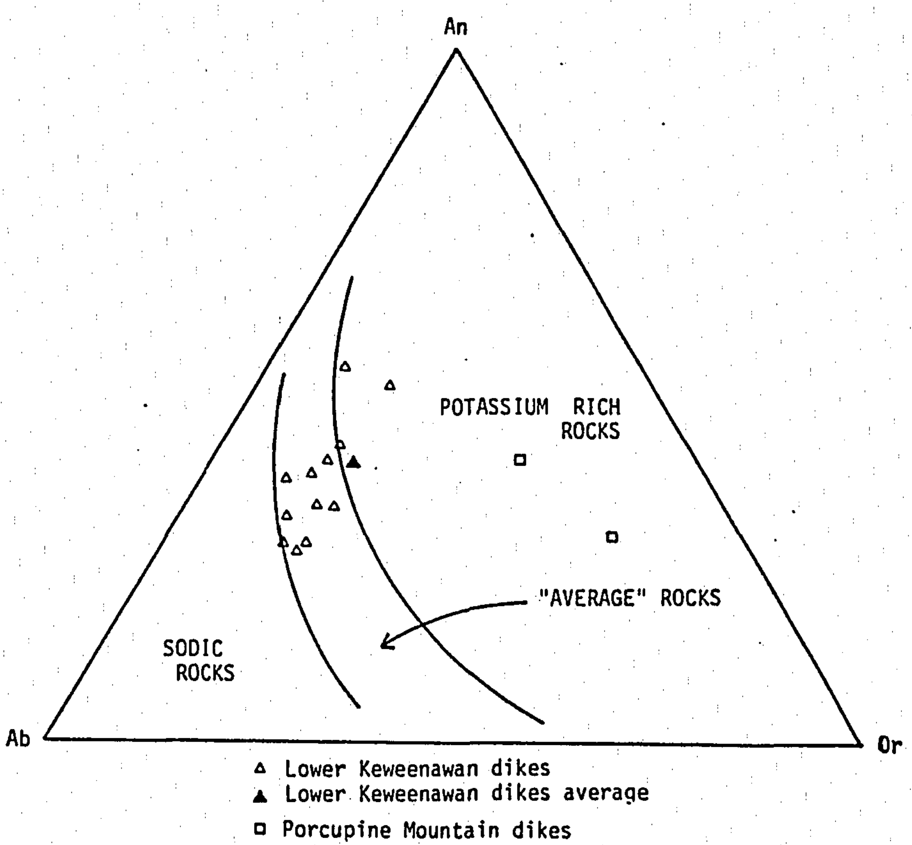


Figure 18. Basalt classification based on normative minerals Albite-Anorthite-Orthoclase (Irvine and Baragar, 1970). Compositions of Lower Keweenawan dikes and the Porcupine Mountain dikes are plotted.

DISCUSSION AND INTERPRETATION OF THE GEOCHEMISTRY

Introduction

Based upon structure, mineralogy, texture and chemistry, the dikes of this study fall into two major groups: Lower Keweenawan and the (younger) Porcupine Mountain dikes.

The Lower Keweenawan dikes are given more detailed treatment because they represent the first indications of Keweenawan rifting. This analysis should, therefore, yield information and insights regarding the geochemical nature of early Keweenawan rifting including possibly the evolution into full-scale rifting, as evidenced by extrusion of voluminous flood basalts.

The Porcupine Mountain dikes may represent a mafic exception to the felsic volcanism which characterized the last stages of this rift episode.

Lower Keweenawan Dikes

Parental magma

Lower Keweenawan dikes display a tholeiitic differentiation trend. This statement is based on data distribution on a Cpx/Ol/Ne/Q tetrahedron. Figure 19 represents the projection from the clinopyroxene peak onto the basal triangle Ol'/Ne'/Q'. The dikes fall well outside of the critical plane of undersaturation as define by Yoder and Tilley (1962).

Two models are considered here regarding magma genesis.

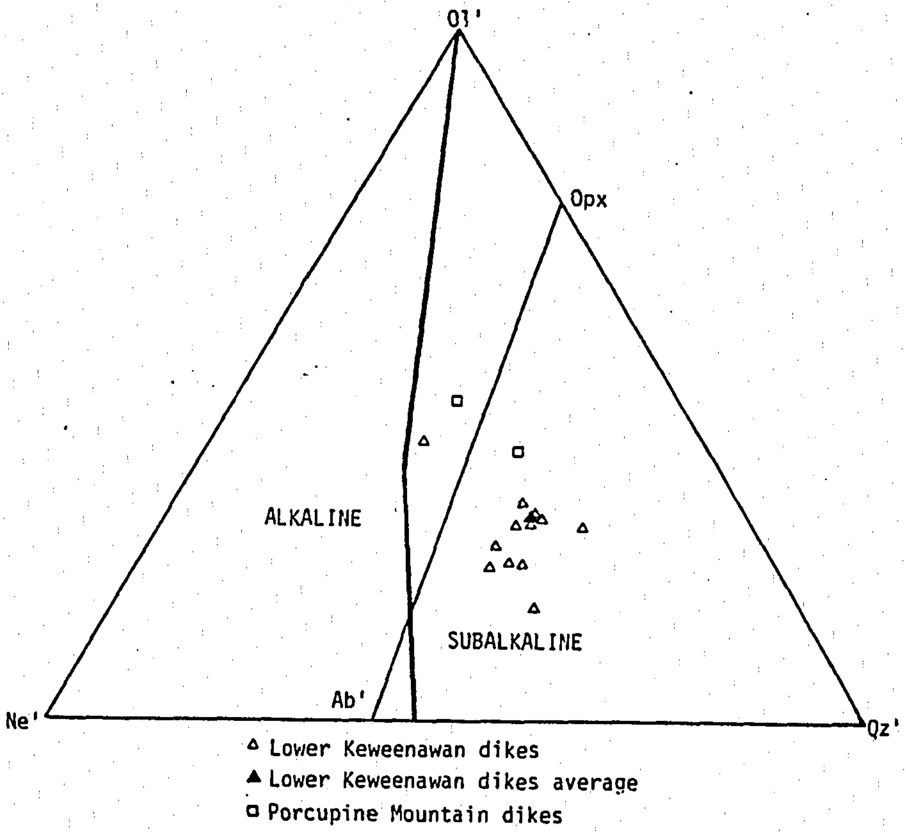


Figure 19. Representation of the Clinopyroxene-Olivine-Nepheline-Quartz normative minerals tetrahedron (Irvine and Baragar, 1970). The Ol'-Ne'-Qz' triangle represents the projection from the Clinopyroxene peak onto the basal triangle. Normative mineral compositions of the Lower Keweenawan dikes and the Porcupine Mountain dikes are shown.

These were chosen because they seem to provide the most satisfactory explanation of the dikes and extrusive flows that relate to the rifting event that generated these dikes.

The petrogenetic scheme of Green and Ringwood (1967), and Green (1969) as depicted in Figure 20 relates crystal fractionation amongst basaltic magmas at moderate to high pressures and assumes a "closed" system. Another model offered by Ringwood (1975) using different parameters is also considered. The model (Figure 21) assumes a much lower percentage of partial melting of pyrolite (about 1%). Initial magma generation is at greater depths than the Green and Ringwood (1967) model and also assumes 0.1% H_2O content.

Applying the Green and Ringwood (1967) and Green (1969) model indicates two possible parental magmas for the basaltic rocks of this study (Figure 20): 1) olivine tholeiite resulting from 25-30% partial melting of pyrolite at a depth of 35-70 km; 2) high alumina olivine tholeiite from 20-25% partial melting of pyrolite at a depth of 30 km.

Fractional crystallization at low pressures (5 kb) and shallow depths (0-15 km) from any of these possible parents could produce the quartz tholeiite basalt composition of the Lower Keweenawan dikes. If the Green and Ringwood model is used, an olivine tholeiite parental magma is required if one wishes to assume the same magma source for the Portage Lake Lava Series, the Middle Keweenawan extrusives located north of this study area. This would account for the high alumina concentration

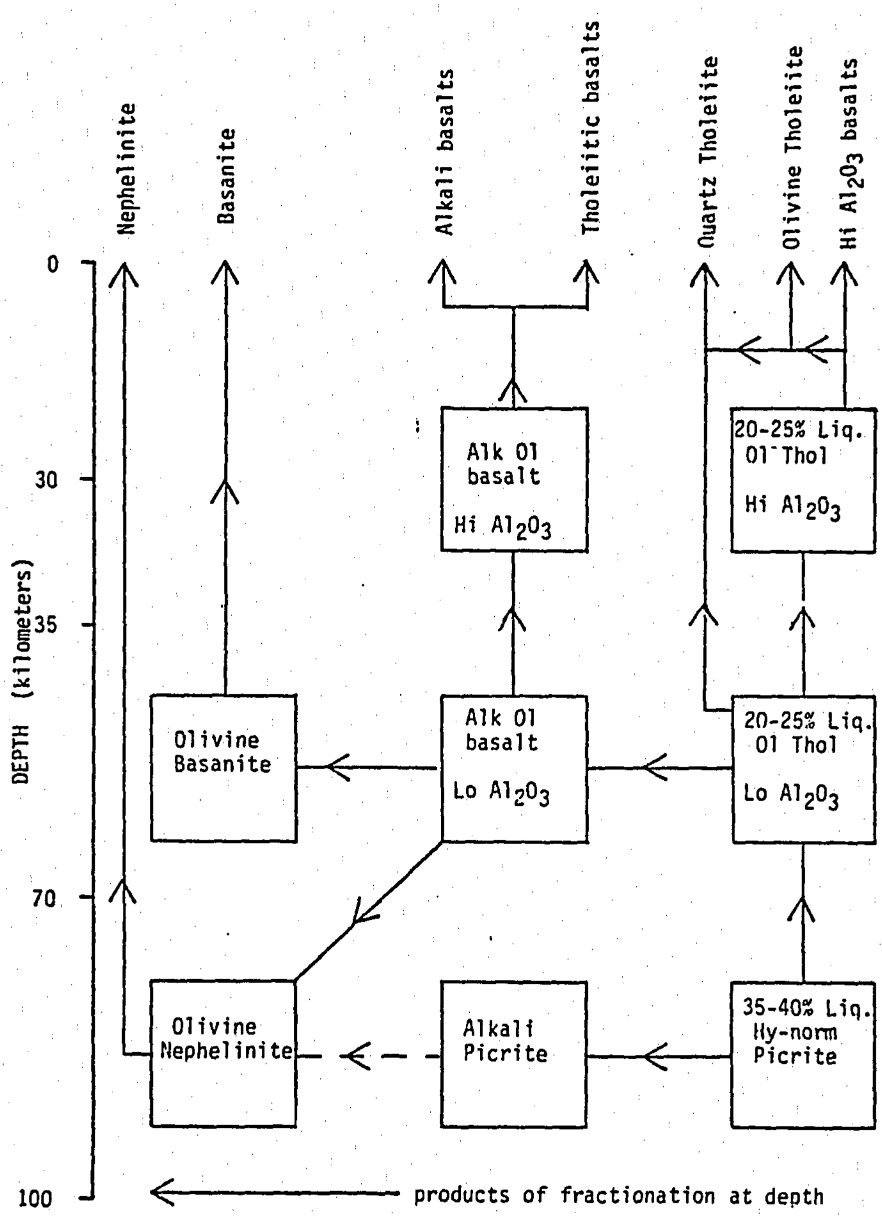
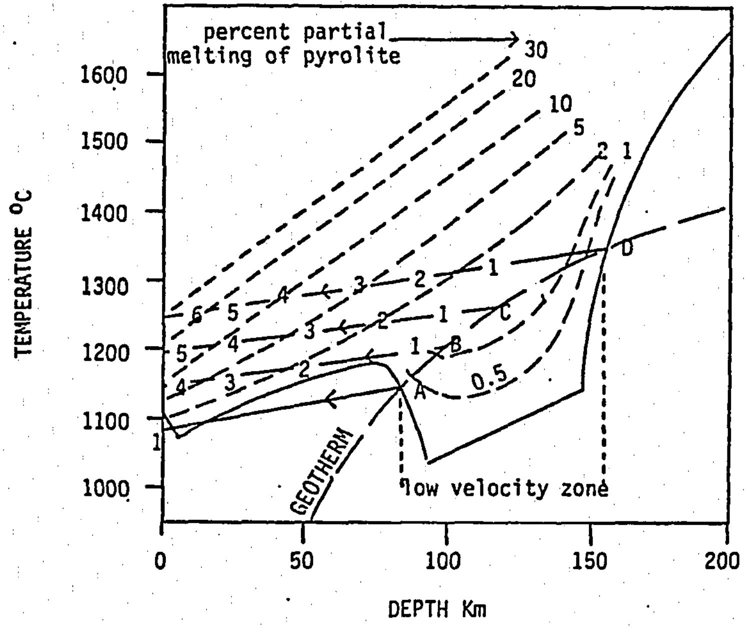


Figure 20. Crystal fractionation relationships among various basaltic magmas (from Green & Ringwood, 1967 and Green, 1969).

of the Portage Lake Lava Series.

In applying Ringwood's (1975) model to Keweenawan volcanism, consideration must first be given to the elevated geotherm in a rifting event. The thermal gradient and therefore the intitial melt conditions would be located to the left of the average geotherm on Figure 21. This could result in an olivine basanite magma during early rifting (2% partial melting), originating at 50-90 km depth. With a rising thermal gradient, later in the rifting, greater partial melting (about 5%) at shallower depths (25-75 km) could generate high alumina alkali basalt or alkali olivine basalt. The magma during early rifting would have more time to fractionate since it would not have easy access to the surface. Later in the rift sequence, with parental magma being located closer to the surface and having more direct conduits to the surface, the magmas thus extruded would have less opportunity to fractionate. This interpretation is supported by quartz tholeiites being common in early Keweenwan time with the mildly alkalic and high alumina lavas being extruded later.

The relatively high concentration of K_2O and P_2O_5 of the Lower Keweenawan dikes may be caused by a process similar to that presented by Rose (1979) to account for the geochemical trends of the Middle Kewenawan Portage Lake Lava Series. He describes three cycles where K_2O and P_2O_5 concentration is high early in the flow sequence and gradually decreases later (upward). Local high-level magma chambers could produce lower concentrations of these elements later in an extrusive sequence when convective homogeni-



A1	High-temperature peridotite
B1	Olivine nephelinite
B2	Olivine basanite
B3	High-Al alkali basalt
B4	Quartz tholeiite
C1	Olivine nephelinite
C2	Olivine basanite
C3	Alkali olivine basalt
C4	High-Al basalt
C5	Quartz tholeiite
D1	Olivine nephelinite
D2	Olivine basanite
D3	Alkali olivine basalt
D4	Olivine basalt
D5	High-alumina olivine thol.
D6	Olivine tholeiite

Figure 21. Ringwood's (1975) model of basaltic magma generation and possible magma types derived.

zation was less effective. This could occur after a large extrusive event, such as the extrusion of the Greenstone Flow. Presuming the dikes analyzed for this study are part of an early extrusive sequence, K_2O and P_2O_5 enrichment can be expected.

Variation Trends and Correlations

Numerous comparative diagrams have been constructed to determine if these dikes display any systematic trends or groupings that relate to geography, structure, country rocks or oxide concentrations. Specifically, diagrams constructed are oxide/distance to rift axis, oxide/Solidification Index, oxide/Differentiation Index, oxide/country rock lithology,and oxide/structural features. None of these diagrams yield consistent results.

Therefore, a different approach was attempted, to achieve a better understanding of the dike's environment of crystallization. A statistical correlation of the Lower Keweenawan basalts was made with other basalts from a wide variety of geologic settings to consider possible analogies regarding their magmatic environment and history of crystallization. Basalts from throughout the world, as well as other Keweenawan rocks, are considered; average composition of the Lower Keweenawan dikes is the basis for comparison.

Basalts from outside of the Lake Superior region which provide the best correlation are typical plateau basalts and volcanics associated with tensional tectonics of both continental and ocean association (Appendix IV, Table 8). The non-porphyritic flows of Mull (of the Scottish Tertiary province) have the most correlative bulk chemistry of any of the volcanics considered in the statistical analysis. These flows are of uncertain correlation to other volcanics in that region, but are considered to be typical plateau basalts.

Other regions outside of North America that show a good fit to the data are the basalts of the South African Karoo region, and the Deccan plateau flood basalts of the Bombay, India area. These are ranked 3rd and 4th, respectively (Appendix IV, Table 8), and show similar depletion of Al_2O_3 and MgO, and enrichment of FeO_t and TiO_2. In both cases the flows lower in the sequences correspond more closely to dikes of this study than do later flows. This supports the assumption that the dikes are representative of early volcanics in the region.

Correlation with other plateau basalts located throughout North America is best to volcanics that are approximately contemporaneous to the late Precambrian Keweenawan event. Both Tobacco Root Mountain dikes in central North America (1120 m.y.B.P.) and the Copper River flood basalts in northwest Canada (1100-1120 m.y. B.P.) are very similar to the Lower Keweenawan dikes (about 1160 m.y. B.P.). They are ranked 2nd and 5th respectively (Appendix IV, Table 8). Both basalts exhibit similar trends of enrichment of FEO_t, K_2O, and TiO_2 with depletion of MgO, CaO, and Al_2O_3. It is uncertain whether this similarity is due to an overrepresentation of the late Precambrian in North America or if the good correlation reflects processes unique to the igneous activity during this period.

Columbia River flows also correlate well, although flows later in the sequence (Late Yakima time) exhibit the greatest similarity. This is contradictory to the better correlation with the earlier sequences of other regions, as discussed earlier.

Many of the Icelandic basalts also show good correlation to these Keweenawan dikes, supporting Baragar's (1977) contention that the Keweenawan generally is analogous to the Icelandic setting.

Green (1977) makes a similar comparison based on: 1) similar areal extent and thickness of individual flows; 2) similar dikes associated with the extrusive flows (the lesser number of dikes in the Lake Superior region is attributed to their exposure only on the periphery of the main rift zone whereas in Iceland the main rifting center is exposed), and; 3) similar physical and compositional character of the volcanics.

Appendix IV (Table 8) emphasizes the good correlation of the Icelandic basalts, at least so far as the dikes of this study are concerned. The dominant basalt type of the region, the tholeiites, show the best correlation. Unfortunately, geochemical data of the numerous dikes exposed in Iceland and the relationship of their chemistry to the lavas has not yet been determined.

The differences between Iceland volcanics and those of Keweenawan age can be accounted for by consideration of differences in the thermotectonic regimes. One of the major distinctions between Iceland and the Keweenawan setting is a thinner crust underlying the Icelandic volcanics. Green (1977) ascribes this to the slower and more sporadic nature of Keweenawan igneous activity. Also, the interlayered and intertongued sandstones and coarse conglomerates associated with Keweenawan lava sequences are conspicuously lacking in Iceland. Highland margins provided a source for these continental sediments, as described and explained by Fowler and Kuenzi (1979).

North American volcanics with a somewhat poorer correlation are approximately contemporaneous basalts of Seal Lake and Gardar of Greenland. Baragar (1977) has suggested that these may have a common tectonic origin (he also includes the Keweenawan rocks). He believes that they all result from a single Precambrian episode. He further proposes, based upon geochemical analogies, that these plateau basalts may be continental analogs to a plume-generated ocean island system. Although the statistical comparison with these basalts does not add support to this suggestion, a more detailed treatment is presented in the discussion of tectonic environment.

Baragar's analogy is consistent with the Keweenawan/Iceland comparison, as Iceland volcanics are purported to represent a plume-generated oceanic island (Baragar, 1977; Morgan, 1972; and Wilson, 1973), centered upon a rifting zone. This idea has geophysical, structural and geochemical data to support it. The chemistry of the dikes studied herein is consistent with this interpretation. Enrichment of FeO_t, TiO_2, and K_2O and depletion of Al_2O_3 and MgO, typical of this type of tectonic environment (Baragar, 1977) is present.

A careful comparison of the Lower Keweenawan dikes of this study with other Keweenawan volcanics shows the latter to have higher concentrations of Al_2O_3, lower FeO_t, and a greater range of CaO. The alkalies and other elemental abundances show a similar range of concentrations. In plotting alkalies against SiO_2, the average dike composition falls well within the Keweenawan field (Figure 22). On the AFM ternary diagram (Figure 23), the average composition of the dikes is fairly close to the line of separation but is nevertheless within the Keweenawan field. Also, if all individual Keweenawan analyses were plotted, rather than averages, the fields of the Lower Keweenawan dikes and other Keweenawan basalts would show a large overlap. The statistical correlation of the other Keweenawan basaltic volcanics produces four, and possibly five, groupings (Appendix III, Table 11). The first numerical set has the best correlation of the dikes. These are Lower Keweenawan volcanics, although the average used for Mamainse Point basalts also include some Middle Keweenawan basalts. If the individual analyses are compared, it appears that the Logan intrusions of Minnesota have a similar range of composition.

Although dikes of this study are far removed geographically from the Logan intrusives, the similarity in chemistry (Appendix III, Table 12) is striking. The elemental abundances, standard deviations and oxide concentration ranges compare favorably. Paleopole positions for the Logan intrusions indicate that they correlate with the early Keweenawan age of the Baraga and Marquette County dikes (Pesonen and Halls, 1979). Some of the dikes within the study area

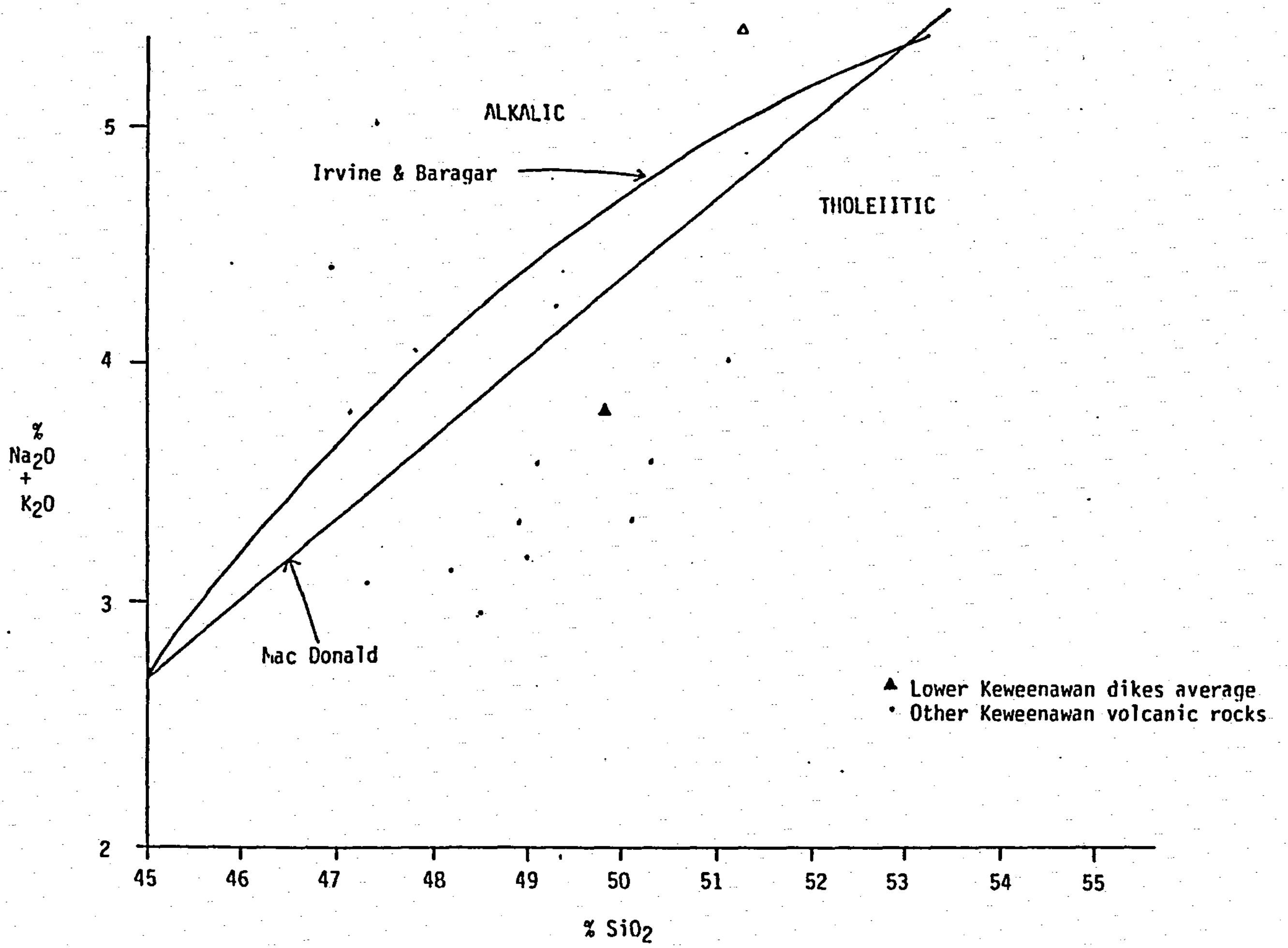


Figure 22. Diagram showing total alkalies vs. silica for Lower Keweenawan dikes and Keweenawan volcanic rocks (Irvine and Baragar, 1970). See text for explanation.

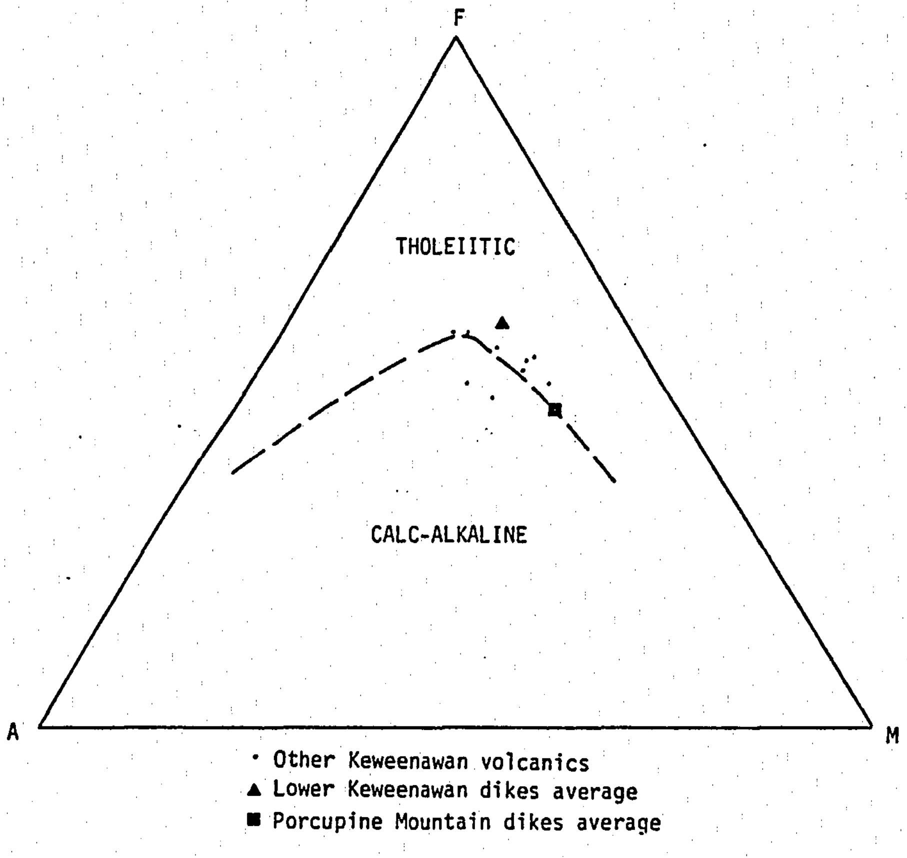


Figure 23. A-F-M diagram showing the average composition of the Lower Keweenawan dikes and other Keweenawan rocks.

have paleopoles similar to those in the Marquette and Baraga County areas. The paleopoles of the lowermost part of the North Shore lavas and the lower sequence of the Mamainse Point lavas also show a Lower Keweenawan direction. Although the Mamainse Point dikes analysed by Massey (1978) have a poor correlation, they do show a very similar position on an AFM diagram (Figure 24). Unfortunately, this author does not have access to these complete analyses which would allow a more thorough comparison.

When this study was first conceived, it was anticipated that the Powdermill Group (the Siemens Creek and Kallander Creek Formations) would be likely candidates for a close chemistry correlation to Lower Keweenawan dikes. This was expected because of the geographic proximity, similar age, and basaltic nature of these flows. Although these volcanics compare fairly well, it is suprising that other Keweenawan volcanics much further removed geographically compare more favorably.

The Portage Lake Lava Series, Michipicoten Island basalts, and the North Shore Volcanics produce the least favorable comparison of the Keweenawan basaltic volcanics considered in the statistical correlation. This is not suprising as these flows are probably much younger than the dikes.

The diagrams and statistical correlations do not allow for any definitive statements regarding possible parental magmas of the dikes relative to other Keweenawan extrusive rocks, nor can a definitive assessment be made as to whether these dikes may have been feeders

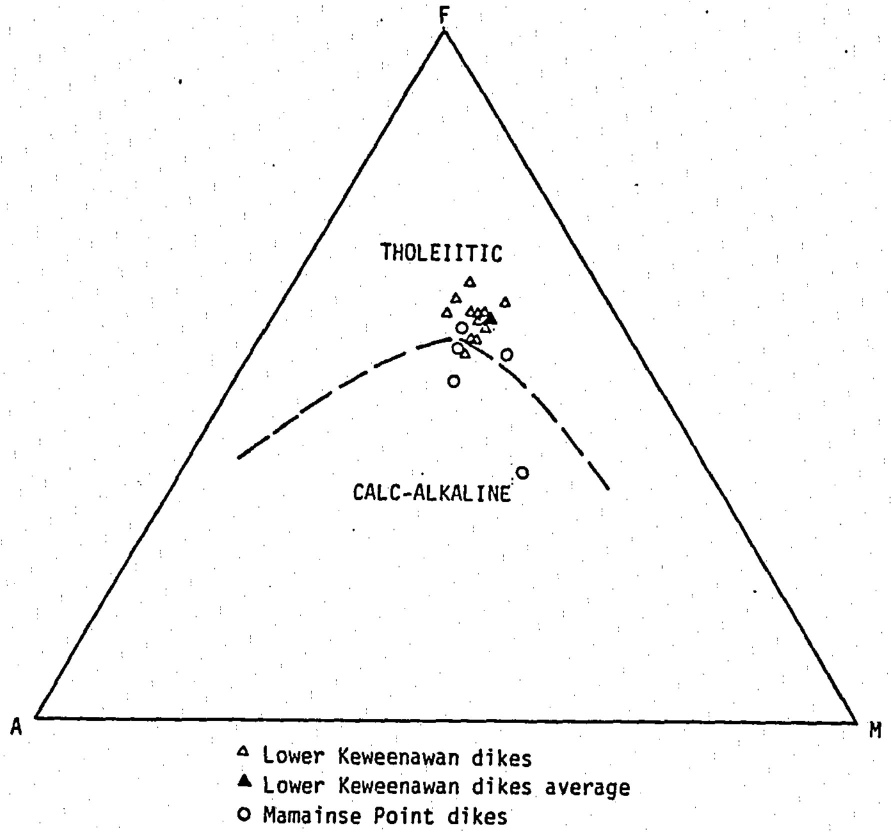


Figure 24. A-F-M diagram showing the average composition of the Lower Keweenawan dikes and the Mamainse Point dikes from Massey (1979).

for specific flows or flow sequences in the region. The most similar contemporaneous Keweenawan volcanics are located a great distance from these dikes. Therefore, the igneous units in the region are not likely to have had the same parental magma, but the magmas for the volcanics in early Keweenawan time (and perhaps later) were probably the result of similar processes of initial magma formation, fractional crystallization enroute to the surface, and magma separation prior to extrusion. The changing nature of conditions of magma formation in a rift sequence accounts for the different geochemistry of flow sequences in the region.

Tectonic environment

As stated earlier in this text, the Keweenawan magmatism represents best the continental analog of an oceanic plume-generated system centered upon a rift zone such as Iceland. Pearce (1977) plots $MgO/FeO_t/Al_2O_3$ (Figure 25) and establishes fields distinguishing ocean island, orogenic, continental, and spreading center island tectonic environments. If the Icelandic analogy holds true Keweenawan basalts should plot within the spreading center island field (Figure 25). This does not prove to be the case. However, the analyses published for post-glacial Iceland basalts (Appendix III, Table 13) also do not plot in the spreading center island field. Their data do have good overlap with the Keweenawan field, falling intermediate between the Lower Keweenawan dikes and other Keweenawan basaltic volcanics. For reasons unknown, Pearce's data do not seem applicable to either the Icelandic volcanics or the dikes of this study. Keweenawan vol-

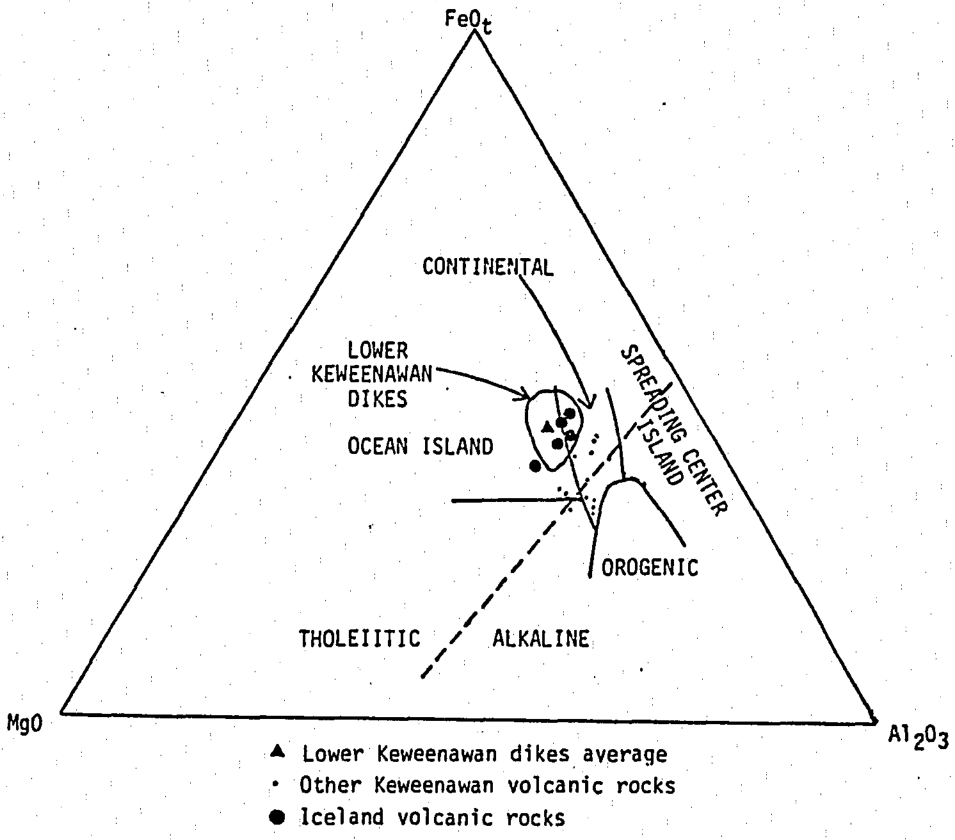


Figure 25. MgO-FeO$_t$-Al$_2$O$_3$ diagram designed to discriminate basalts from different tectonic environments (Pearce, 1977). Averages of Lower Keweenawan dikes and other Keweenawan volcanics are shown.

canics do fall within the tholeiitic field of Pearce, confirming the already established tholeiitic nature of these dikes.

Pearce (1975) proposes use of $K_2O/TiO_2P_2O_5$ ternary diagram as a method for discriminating oceanic from non-oceanic basalts. When other Keweenawan basaltic provinces are plotted (Figure 26), they fall substantially within the oceanic field. The dikes of this study, however, plot well within the continental field. This is expected as the dikes would have been intruded during the initial stages of a rift episode, at first having a continental character, then later developing an oceanic character. The location of the dikes on the margin of the rifting center and within pre-Keweenawan terraine would support this contention. Another explanation, as discussed earlier, may simply relate to the history of differentiation of the parental magama and have nothing to do with the tectonic environment.

Muller's (1980) diagram of $FeO_t/MgO/$ vs. TiO_2, however does provide support for the ridge island analogy. Both the dikes and other Keweenawan volcanics fall within the ridge island field (Figure 27), although the dikes do overlap somewhat into the ocean island field.

Porcupine Mountain Dikes

As discussed previously, the chemical composition of the Porcupine Mountain dikes is distinct from that of the Lower Keweenawan dikes. This distinctiveness is illustrated in Figures 16, 17, 18, 19 and 23.

An interpretation concerning parental magma or tectonic environment is difficult because of the inadequate number of samples and the

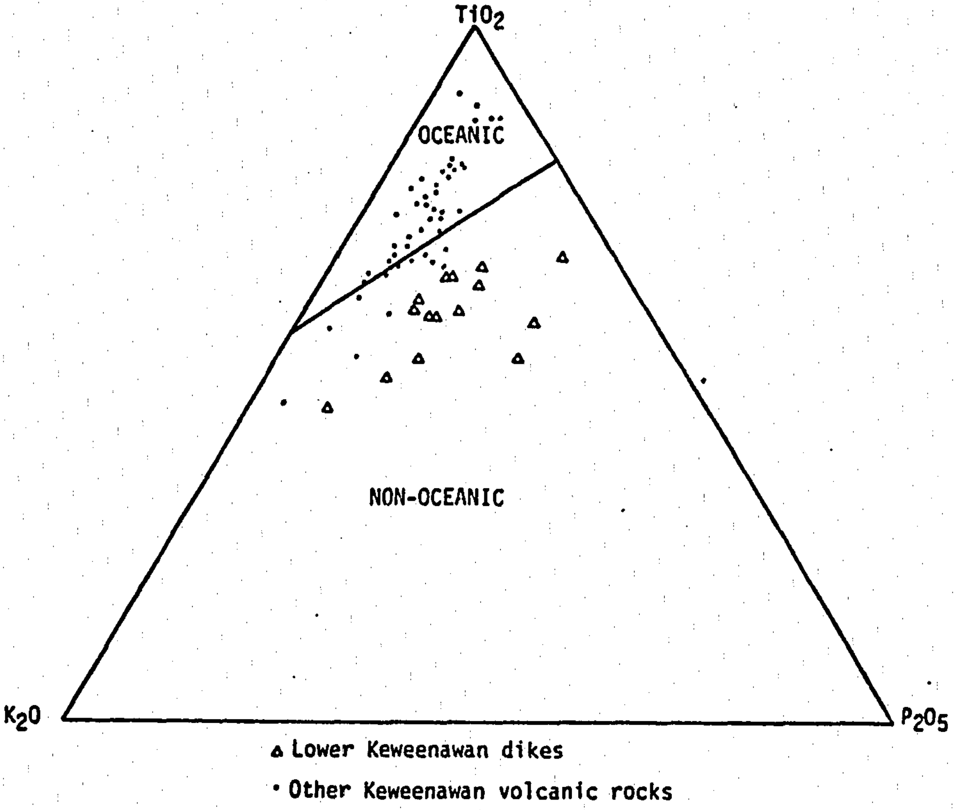


Figure 26. K_2O-TiO_2-P_2O_5 diagram designed to discriminate between ocean and non-oceanic basalts (Pearce, 1974). The Lower Keweenawan dikes and other Keweenawan volcanics are shown.

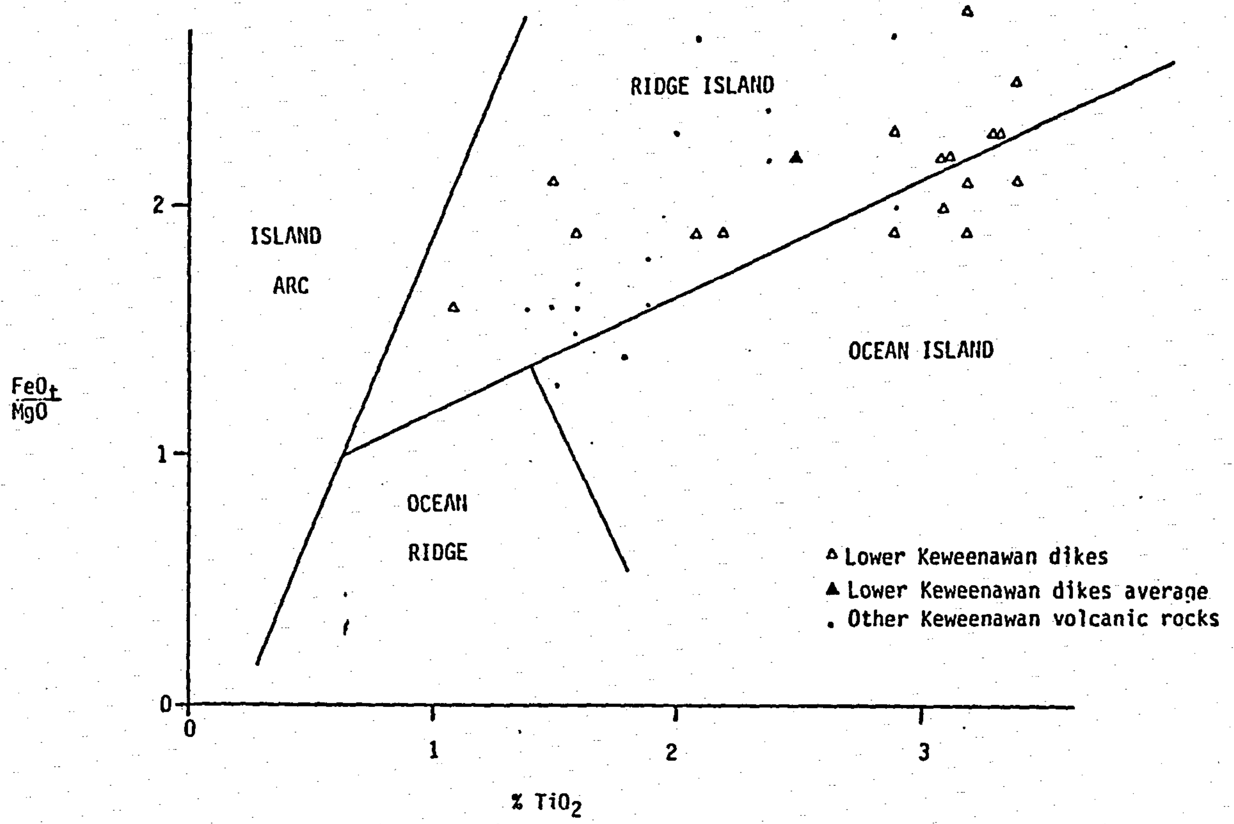


Figure 27. FeO_t/MgO vs. TiO_2 diagram enabling discrimination of basalts from different tectonic environments (Muller, 1980). Lower Keweenawan dikes and averages of other Keweenawan volcanics are shown.

apparent subaerial weathering that these intrusives have undergone. However, it does appear that these dikes have followed a tholeiitic differentiation trend, as these volcanics fall well outside the field of undersaturation (Figure 18 of Ringwood, 1975). The chemistry of these does not appear to relate to the basaltic phase of Keweenawan volcanism. They appear to have intruded later in Keweenawan time.

CONCLUSIONS AND SUMMARY

Based upon structural, petrologic, and geochemical evidence, the dikes of this study show two major groupings: 1) the Porcupine Mountain dikes, located in Ontonagon County, which are probably post Middle Kewenawan in age, and; 2) the Lower Keweenawan dikes located in Dickinson, Iron and Gogebic Counties.

Lower Keweenawan Dikes

There two major rock types: fine-grained smaller dikes, and the coarse-grained central portions of larger dikes. Major minerals are plagioclase and pigeonitic pyroxene with varying amounts of intersertal quartz, postasium feldspar, apatite, and secondary minerals (mostly chlorite). Opaque minerals are present in minor quantity. The fine-grained dikes are microporphyritic. The phenocrysts consist of sub-equal amounts of plagioclase and pyroxene. The dikes dip steeply, and the mean strike is northeasterly, although some of the dikes also trend east-west.

The chemistry of the Lower Keweenawan dikes, as compared with other basalts, is characterized by low Al_2O_3, high TiO_2, K_2O, P_2O_5, and moderate FeO_t enrichment. Most of the dikes are classified as quartz tholeiite. A more detailed consideration of the Gogebic Station Dike confirms it to be a single large dike.

Several parental magmas are possible. Simple melting of anhydrous pyrolite at depths of 35-70 km could yield magma with olivine tholeiite or high alumina olivine tholeiite composition, respectively; olivine tholeiite magma is more probable since it would fit with compositions within the Portage Lake Lava Series. Additional possibilities arise if we assume 0.1% H_2O, and a smaller amount of partial melting, as well as an elevated geothermal gradient (during a rift event): 1) 50-90 km depth and 2% partial melting would produce olivine basanite magma; 2) 25-75 km depth and 5% partial melting could produce a high alumina alkali basalt or alkali olivine basalt magma. Any of these parental magmas could ultimately produce a quartz tholeiite composition, depending upon the amount of fractionation. A tholeiitic differentiation trend is likely with fractional crystallization at shallow depth. Enrichment of K_2O and P_2O_5 may be controlled by cycles of intrusion relating to convective homogenization of high level magma chambers during crystallization. No specific chemical trends amongst the dikes exist, nor does the geochemistry seem to relate in any systematic fashion to geographic distribution, structure, or type of country rocks.

A statistical correlation was made with other basaltic rocks throughout the world, including other Keweenawan rocks. These dikes compare best with plateau-type flood basalts and basalts associated with tensional tectonics, both continental and oceanic. Additionally, an analogy with an Icelandic-type tectonic setting is suggested. This is consistent with the proposal that Keweenawan volcanic rocks represent the continental analog of a thermal plume centered upon a rifting zone such as Iceland.

Correlation with other Keweenawan igneous rocks shows that Lower Keweenawan dikes correlate best with earliest Keweenawan volcanic rocks, particularly hypabyssal units in Minnesota (the Logan intrusions).

Although no definite statement can be made regarding the possibility that these dikes were feeders for specific lava sequences in the area, it can be stated that similar processes controlled the crystallization of all Early Keweenawan igneous units, and possibly later Keweenawan volcanic rocks as well.

Porcupine Mountain Dikes

Structural relations imply that these dikes were emplaced during a post-Middle Keweenawan magmatic episode. The chemistry is distinct from the Lower Keweenawan dikes (alkali basalts rather than quartz tholeiites); they are also more altered. No definite conclusion can be made regarding either parental magma(s) or correlation with other volcanic rocks in the region.

APPENDIX I

Petrographic Techniques and Data

Modal analyses were conducted in standard fashion. A minimum of 500 grain counts were made. Detailed modal percents and other pertinent data for the Keweenawan dikes are listed in Table 2, and for the Porcupine Mountain dikes in Table 3. Regional averages for the Lower Keweenawan dikes are reported in Table 4.

TABLE 2

MODAL PERCENT OF THE LOWER KEWEENAWAN DIKES

Location # Mineral	32	GW1	30	51	GE1-1	GE2-1	GE1-3	GE2-1
Plagioclase	52	43	--	39	45	34	43	18
Anorthite (Plagioclase)	59	47	--	57	46	53	54	?
Pyroxene	26	30	--	17	31	29	26	25
Magnetite-Ilmenite	11	13	--	19	13	15	12	--
Hematite	--	--	--	--	--	--	--	51
Chlorite	5	9	--	25	9	7	19	5
Sericite	3	3	--	1	3	trace	trace	trace
Interstitial (Apa., Qz., & Or.)	4	2	--	1	3	12	trace	1
Cryptocrystalline groundmass	--	--	85	--	--	--	--	--
Plagioclase phenocrysts	--	--	7	--	--	--	--	--
Pyroxene phen.	--	--	8	--	--	--	--	--
Basalt variety	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite

TABLE 2 (continued)

MODAL PERCENTS OF THE LOWER KEWEENAWAN DIKES

Location # / Mineral	GE3-2	GE6-1	GE6-2	GE5*	52*	39-1*	39-2*	GE4-1*
Plagioclase	45	46	43	40	43	33	33	40
Anorthite (Plagioclase)	60	50	55	56	56	52	52	53
Pyroxene	21	37	31	26	28	33	32	37
Magnetite-Ilmenite	12	8	16	10	15	13	18	10
Hematite	--	--	--	--	--	--	--	--
Chlorite	20	6	8	23	15	21	16	13
Sericite	trace	1	trace	trace	trace	trace	trace	trace
Interstitial (Apa., Qz., & Or.)	1	1	3	trace	trace	trace	trace	trace
Cryptocrystalline groundmass	--	--	--	--	--	--	--	--
Plagioclase phenocrysts	--	--	--	--	--	--	--	--
Pyroxene phen.	--	--	--	--	--	--	--	--
Basalt variety	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite

* Gogebic Station Dike

TABLE 2 (continued)

MODAL PERCENTS OF THE LOWER KEWEENAWAN DIKES

Location # Mineral	GE4-2*	D2-3	Low. Kew. Mean	Std. Dev.	Gog. St. Dike	W. of Lk. Gog.	Marenisco area
Plagioclase	36	38	40	7	38	41	43
Anorthite (Plagioclase)	53	54	not calculated		54	not calculated	
Pyroxene	23	22	28	6	29	29	21
Magnetite-Ilmenite	15	18	18	3	9	13	16
Hematite	--	--	not calculated		--	--	--
Chlorite	24	16	14	7	14	12	18
Sericite	trace	trace	trace	not calc.	trace	trace	trace
Interstitial (Apa., Qz., & Or.)	trace	3	3	3	trace	trace	trace
Cryptocrystalline groundmass	--	--	not calculated		--	--	--
Plagioclase phenocrysts	--	--	not calculated		--	--	--
Pyroxene phen.	--	--	not calculated		--	--	--
Basalt variety	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite	--	Quartz Tholeiite	Quartz Tholeiite	Quartz Tholeiite

TABLE 3

PETROLOGY OF LOWER KEWEENAWAN LAVA FLOWS AND DIKES

Unit Mineral	Diabase Dikes	Siemens Creek	Kallander Creek
Plagioclase	40-50%	50%	50%
Pyroxene	10-30%	10-20%	15%
Opaques	16%	7-20%	20%
Chlorite	5-25%	3-10%	15-20%
Apatite	trace	trace	-----
Quartz	trace	trace	-----
Epidote	-----	4-10%	-----
Basalt variety	Quartz Tholeiite	Quartz Tholeiite	Tholeiite

TABLE 4

MODAL PERCENTS OF THE PORCUPINE MOUNTAIN DIKES

Location Mineral	28	01	Mean	Standard Deviation
Plagioclase	53	38	45	11
Pyroxene	10	31	20	15
Magnetite-Ilmenite-Pyrite	2	trace	not calculated	
Hematite	trace	15	not calculated	
Chlorite and other alteration minerals	34	10	22	17
Sericite	trace	4	not calculated	
Interstitial	--	4	not calculated	
Basalt variety	Tholeiite	Tholeiite	Theoliite	

APPENDIX II

Chemical Procedures and Machine Settings

X-Ray Fluoresence

The X-Ray fluoresence analysis was performed on a Phillips-Norelco Vacuum Spectrograph. Conditions of operation are listed in Table 5. Pressed cylindrical discs, consisting of powdered rock rimmed with boric acid, were prepared on a Beckman press at 20,000 psi. Contamination was minimized by powdering rock fragments on a SPEX/Mixer with a tungsten vessel and grinding ball.

Ideal operating conditions for each element (Table 5) were run without changing settings. Drift corrections were made when the deviation from the initial count exceeded 0.7%. Linear drift was assumed. Standard linear calibration curves were constructed using United States Geological Survey crushed rock standards G-2, GSP-1, AGV-1, PCC-1, DTS-1, BCR-1, which are granite, granodiorite, andesite, peridotite, dunite, and basalt, respectively. Dunite and peridotite, were not used in calibration curves for the iron and manganese determinations because of high count rates relative to the other standards. Apparently the high concentrations of magnesium in the dunite and peridotite present matrix interference (enhancement) for iron and manganese.

Flame Photometry

Sodium in fifteen samples was analyzed by Flame Emission on a Beckman Atomic Absorption-Spectrophotometer System. A linear calibration curve was constructed from United States Geological Survey rock standards G-2, AGV-1, PCC-1, and BCR-1.

Dissolution Procedure

For accurate analysis by the Flame Emmission method it was first necessary to completely dissolve the sample for dilution in a water solution. The method used here has been slightly modified from a procedure described by Hutchinson (1974) using a Parr teflon bomb. Fifty milligrams of powdered rock sample were transferred to the teflon vessel; 0.5 ml of aqua regia were added to the sample to insure thorough wetting. Three ml of 48% of HF acid were carefully poured to the teflon vessel. The teflon cap was replaced, the cup put in the metal jacket and top secured. The bomb with the acid/rock solution was then heated to 110^{0}C for 30-40 minutes and allowed to cool.

The solution in the teflon vessel was transferred into a 50 ml polystyrene spex bottle, rinsing the teflon cup thoroughly with distilled water to assure complete transfer. Total volume did not exceed 10 ml. Powdered boric acid (2.2 gm) was added to the acid/rock solution and stirred until the boric acid was completely dissolved. Five to ten ml were added, which should result in a clear homogeneous solution. The acid/rock solution was then diluted to volume (100 ml) and stored in a polyethelene container.

Error

The mean total oxide percent was 99.8%, with a standard deviation of 2.77%. Errors may result from the following: 1) volatiles were not analyzed; 2) reporting of iron as total iron, and 3) matrix interference.

TABLE 5

X-RAY FLUORESENCE CONDITIONS OF OPERATION

Element	Tube	Counter Voltage (kV)	Base	Window	2θ Peak	Collimator	Crystal	Vacuum or Air
Si	Cr	1.61	3.0	7.0	107.7	coarse	EDDT	vacuum
Ti	W	1.47	1.5	3.0	86.0	fine	LiF	air
Al	Cr	1.41	0.0	2.5	103.0	coarse	ADP	vacuum
Fe	Cr	1.41	4.0	4.5	57.2	fine	LiF	air
Mn	W	1.47	2.5	3.0	62.8	fine	LiF	air
Mg	Cr	1.60	0.5	3.0	43.1	coarse	KAP	vacuum
Ca	Cr	1.41	1.0	4.0	113.0	fine	LiF	air
K	Cr	1.41	1.5	6.0	118.0	coarse	LiF	air
P	Cr	1.60	1.5	6.0	89.0	coarse	EDDT	vacuum

In all cases operation conditions were: Line K_α, and counting time of 100 seconds. Background was negligable.

APPENDIX III

Geochemical Data

TABLE 6

GEOCHEMICAL DATA FOR THE LOWER KEWEENAWAN DIKES

Location #	GW1-1	GW1-2	30	33	GE1-3	GE2-1	GE3-2	GE6-1
Oxide or Mineral								
Oxides								
SiO_2	52.2	50.7	49.5	44.4	53.8	46.8	48.7	51.3
TiO_2	3.2	3.2	3.1	3.1	1.5	1.6	2.9	2.9
Al_2O_3	12.4	13.7	11.3	11.9	11.1	14.9	12.4	13.4
FeO_t	13.6	13.6	15.7	13.3	14.3	14.3	13.4	13.7
MnO	0.18	0.17	0.21	0.18	0.20	0.17	0.22	0.18
MgO	4.8	6.5	7.2	6.5	6.7	7.5	7.0	5.9
CaO	8.4	8.8	10.6	9.3	7.6	11.7	10.3	9.8
Na_2O	3.3	3.2	2.3	2.2	3.1	¢	¢	2.7
K_2O	1.5	1.5	1.0	3.1	1.1	0.4	1.1	1.3
P_2O_5	0.72	1.00	0.78	0.69	0.46	0.81	0.92	0.85
total	100.3	102.5	101.7	94.7	99.9	¢	¢	102.0
Normative minerals								
Orthoclase	8.9	8.9	6.1	18.4	6.7	¢	¢	7.8
Anorthite	14.7	18.4	17.5	13.6	13.1	¢	¢	24.5
Albite	27.8	27.3	19.4	10.5	26.2	¢	¢	15.2
Quartz	5.5	1.3	1.4	0.0	4.3	¢	¢	8.4
Diopside	18.2	15.2	24.9	22.4	15.9	¢	¢	15.2
Hypersthene	10.7	15.7	18.8	0.0	24.9	¢	¢	16.2
Olivine	0.0	0.0	0.0	10.8	0.0	¢	¢	0.0
Magnetite	6.7	6.9	6.7	6.7	4.4	¢	¢	6.5
Ilmenite	6.1	6.2	5.9	9.0	2.9	¢	¢	5.5
Apatite	1.7	2.4	1.7	1.7	2.0	¢	¢	2.0
Nepheline	0.0	0.0	0.0	2.6	0.0	¢	¢	0.0
Anorthite/Plag.	34.6	40.3	47.4	56.4	33.3	¢	¢	61.7

¢: not calculated

TABLE 6 (continued)

GEOCHEMICAL DATA FOR THE LOWER KEWEENAWAN DIKES

Location # / Oxide or Mineral	52*	39*	GE4-1*	GE4-2*	D2-1	D2-2	D3-1
Oxides							
SiO_2	48.9	49.6	49.0	48.3	49.9	50.2	49.0
TiO_2	3.4	3.1	3.2	3.3	3.2	2.1	2.2
Al_2O_3	12.9	13.6	14.0	12.8	11.7	12.9	13.4
FeO_t	15.2	14.6	14.4	13.9	15.4	14.9	14.4
MnO	0.19	0.17	0.19	0.20	0.16	0.20	0.20
MgO	6.0	6.5	6.7	6.7	5.3	5.2	7.3
CaO	9.7	11.0	11.0	9.1	7.5	9.9	10.7
Na_2O	3.3	3.2	2.1	¢	3.2	2.4	¢
K_2O	1.1	0.9	0.8	1.5	1.4	1.2	1.3
P_2O_5	0.85	0.97	0.91	0.90	0.72	0.76	0.73
total	101.5	103.6	102.3	¢	99.5	99.8	¢
Normative minerals							
Orthoclase	6.7	5.6	4.5	¢	8.3	7.2	¢
Anorthite	17.2	19.8	26.2	¢	13.4	20.9	¢
Albite	27.8	27.3	17.8	¢	27.3	20.5	¢
Quartz	0.0	0.0	3.5	¢	3.1	2.9	¢
Diopside	20.6	23.1	18.3	¢	15.8	19.7	¢
Hypersthene	14.6	9.2	16.8	¢	16.2	17.7	¢
Olivine	1.9	3.5	0.0	¢	0.0	0.0	¢
Magnetite	7.2	6.7	6.7	¢	6.7	5.3	¢
Ilmenite	6.5	5.9	6.1	¢	6.1	3.9	¢
Apatite	2.0	2.4	2.0	¢	1.7	1.7	¢
Nepheline	0.0	0.0	0.0	¢	0.0	0.0	¢
Anorthite/Plag.	38.2	42.0	59.7	¢	32.9	50.5	¢

¢: not calculated *: Gogebic Station Dike

TABLE 6 (continued)

GEOCHEMICAL DATA FOR THE LOWER KEWEENAWAN DIKES

Location # Oxide or Mineral	Gog. St. Mean	Gog. St. Std. Dev.	Gog. St. Range	D3-2	Lower Kew. Mean	Lower Kew. Std. Dev.	Lower Kew. Ranage
Oxides							
SiO_2	49.0	0.5	48.3-49.6	52.5	49.8	4.5	44.8-53.8
TiO_2	3.3	0.1	3.1- 3.4	1.1	2.5	0.15	1.1- 3.4
Al_2O_3	13.3	0.6	12.8-14.0	12.7	12.0	2.3	11.1-14.9
FeO_t	14.5	0.5	13.9-15.2	11.5	14.0	1.4	11.5-15.7
MnO	0.19	0.01	0.17-0.20	0.16	0.19	0.02	0.17-0.20
MgO	6.3	0.4	6.0- 6.7	7.0	6.4	2.7	4.8- 7.3
CaO	10.2	1.0	9.1-11.0	11.9	9.2	1.0	7.5-11.9
Na_2O	2.9	0.7	2.1- 3.3	2.4	2.4	0.8	2.1- 3.3
K_2O	1.1	0.3	0.8- 1.5	1.4	1.4	0.3	0.4- 1.5
P_2O_5	0.90	0.06	0.82-0.97	0.73	0.77	0.07	0.46-1.00
total	102.5	1.1	101.5-103.6	101.4	99.3	2.8	94.7-103.6
Normative minerals							
Orthoclase	6.7	1.1	4.5- 6.7	8.3	8.3	3.5	4.5-18.4
Anorthite	19.8	4.6	17.2-26.2	19.8	19.5	4.1	13.4-26.2
Albite	24.6	5.6	17.8-27.8	20.5	20.5	5.8	10.5-27.8
Quartz	1.5	2.0	0.0- 3.5	0.8	2.6	2.6	0.0- 8.4
Diopside	20.6	2.4	18.3-23.1	28.8	17.5	4.2	15.2-28.2
Hypersthene	13.5	3.9	9.2-16.8	16.2	18.7	6.1	9.2-24.9
Olivine	1.8	1.8	0.0- 3.5	0.0	1.3	3.2	0.0-10.8
Magnetite	6.9	0.3	6.7- 7.2	3.7	5.8	1.1	3.7- 7.2
Ilmenite	6.2	0.3	5.9- 6.5	2.1	4.7	1.8	2.9- 9.0
Apatite	2.0	0.2	2.0- 2.4	1.7	1.7	0.3	1.7- 2.4
Nepheline	0.0	0.0	0.0- 0.0	0.0	0.2	0.7	0.0- 2.6
Anorthite/Plag.	46.6	11.4	38.2-59.7	49.1	48.8	10.0	32.9-61.7

TABLE 7

GEOCHEMICAL DATA FOR THE PORCUPINE MOUNTAIN DIKES

Location # Oxide or Mineral	28-2	28-3	01-Wa	01-Wb	Mean
Oxides					
SiO_2	45.2	40.1	49.0	50.0	46.1
TiO_2	1.3	1.5	1.3	1.6	1.4
Al_2O_3	13.6	14.1	13.2	9.0	12.5
FeO_t	11.2	11.1	9.6	12.6	11.1
MnO	0.16	0.14	0.19	0.17	0.17
MgO	10.6	8.5	8.1	4.2	7.9
CaO	8.6	9.3	10.7	10.3	9.8
Na_2O	2.3	----	3.5	----	2.9
K_2O	1.9	1.1	1.4	1.3	1.5
P_2O_5	0.59	0.72	0.75	0.67	0.68
total	99.5	----	97.7	----	96.6
Normative minerals					
Orthoclase	11.1	----	8.3	----	not calculated
Anorthite	21.1	----	16.1	----	
Albite	19.4	----	29.4	----	
Quartz	0.0	----	0.0	----	
Diopside	13.9	----	26.0	----	
Hypersthene	0.0	----	0.0	----	
Olivine	22.2	----	11.6	----	
Magnetite	4.2	----	4.2	----	
Ilmenite	2.4	----	2.4	----	
Apatite	1.3	----	1.7	----	
Nepheline	0.9	----	2.3	----	
Anorthite/Plag.	52.1	----	35.4	----	

APPENDIX IV

Statistical Techniques and Data

The basalts are ranked according to best relative correlation as determined by the statistical technique described on pages 11 and 13. The best correlation is listed first and the poorest last.

TABLE 8

CORRELATION OF LOWER KEWEENAWAN DIKES WITH BASALTS OF OTHER REGIONS EXCLUSIVE OF KEWEENAWAN VOLCANICS

Comparison Basalt	(no. in Table 12)	$\sum \frac{(\%X-\%KW)^2}{\%KW}$	$\sum \frac{\lvert\%X-\%KW\rvert}{\%KW}$
Non-prophyritic central basalts of Mull	1	0.56	0.76
Coppermine River	2	0.40	0.83
South African Karoo basalts	3	0.69	0.81
Indian Deccan basalts-northern Province	4	0.86	0.47
Tobacco Root Mountain dikes-Group B	7	0.89	0.74
Iceland quartz tholeiite	8	0.75	0.93
Iceland saturated tholeiite	10	0.93	1.07
Lake Yakima Columbia River basalt	11	1.09	1.00
Thingmuli volcano, Iceland basalt	12	0.94	1.27
East Greenland Tertiary dikes (THOL 2)	13	1.13	1.31
Northeast Newfoundland, alkali basal dikes	14	1.93	1.11
Peripheral district basalts, New Zealand	16	1.64	1.18
Iceland saturated tholeiite	17	1.41	1.37
East Greenland Tertiary dikes (THOL 1)	18	1.62	1.31
Yakima type of Columbia River basalt	20	2.14	1.23
Iceland alkali-olivine basalt	21	2.08	1.41
Iceland transitional alkali basalt	22	1.57	1.62
Hawaiin tholeiites	23	2.10	1.61
Hawaiin tholeiites and olivine tholeiites	24	2.26	1.59
Azores plagioclase and olivine basalts	25	2.34	1.50
Pictore Gorge River basalt	26	2.10	1.65
Plateau basalts of Mull	27	2.18	1.65
Tobacco Root Mountain dikes-group C	30	2.98	1.62
Chill zone of the Palisades sill	31	2.53	1.75
Iceland alkali olivine basalts	32	2.61	1.75
Average continental basalt	33	3.14	1.69
Japan basalts, Izu peninsula	34	2.29	1.91
Hawaiin alkali-olivine basalt	36	3.11	1.78
Iceland olivine tholeiite	37	2.75	1.98
Gulf of Aden & Red Sea tholeiitic basalts	38	2.93	1.94
Tobacco Root Mountain dikes-Group A	42	2.98	2.15
Chill zone of the Dillsburg sill	43	3.18	2.08
Japanese alkali-olivine basalts	44	3.82	1.82
Nicaraguan basalts	47	4.57	1.83
Pacific tholeiites	48	3.23	2/21
Seal Lake basalt flow	49	3.43	2.08
Cascade Range & Oregon plateau basalts	51	4.43	1.98
Northern Marianas Island tholeiites	52	4.42	2.20
Tasmanian undifferentiated basalts	54	5.85	2.49
Pacific & Atlantic tholeiites	55	6.16	2.61
Japanese tholeiites	56	5.08	2.95
Chill zone of the Skaergaard intrusion	57	6.53	2.52
Chill zone of the Stillwater complex	58	6.32	2.91
Northeast Ireland olivine basalts	59	7.67	2.89
Chill zone of Bushveld lopolith	60	8.29	3.23
North Carolina dolerite dikes	61	8.32	3.25
Anarctic Ferrar dolerite	62	8.46	3.47
Indian Ocean gabbros	63	14.20	3.60

TABLE 9

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	1	2	3	4	5^{o}	6^{o}	7	8
SiO_2	50.90	50.84	51.71	50.35	46.85	49.11	50.3	50.26
TiO_2	2.10	2.27	3.01	2.51	2.38	2.31	2.58	2.47
Al_2O_3	13.07	13.63	12.50	13.55	13.72	14.84	12.1	13.52
FeO_t	13.1	12.91	12.0	14.0	13.59	12.91	15.2	15.12
MgO	4.96	6.88	7.15	5.27	6.84	6.40	4.38	5.58
CaO	9.47	7.90	8.42	10.42	8.69	9.54	8.36	9.18
Na_2O	2.79	2.98	2.45	2.57	3.26	2.67	2.51	2.48
K_2O	1.31	1.54	1.68	0.64	1.13	0.92	1.23	0.56
No. of analyses	8	163	29	15	4	30	5	12

^{o}: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	9^{o}	10	11	12	13	14	15^{o}	16
SiO_2	48.9	49.2	50.5	49.15	48.25	46.36	52.83	47.26
TiO_2	2.8	2.6	3.2	2.87	2.92	2.21	2.37	2.48
Al_2O_3	14.4	14.0	13.6	13.23	13.13	16.17	14.29	14.91
FeO_t	12.4	13.91	14.3	13.9	12.80	12.06	12.32	11.84
MgO	6.2	6.1	4.4	5.5	5.69	6.11	5.07	8.05
CaO	9.1	10.1	8.4	9.79	10.67	7.93	7.51	9.98
Na_2O	2.6	2.6	2.9	2.87	2.59	3.07	3.24	3.13
K_2O	0.76	0.5	1.4	0.49	0.52	1.45	1.19	1.20
No. of analyses	8	56	4	10	3	15	5	5

^{o}: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	17	18	19[o]	20	21	22	23	24
SiO_2	49.51	49.4	50.3	54.5	46.88	47.00	51.08	49.36
TiO_2	2.39	3.25	1.9	2.6	2.41	3.71	2.80	2.50
Al_2O_3	13.97	13.7	14.8	14.1	15.53	13.84	13.27	13.94
FeO_t	13.28	13.0	10.9	11.7	11.47	15.12	11.0	11.2
MgO	5.97	6.7	5.9	4.1	6.1	5.96	8.05	8.44
CaO	10.79	11.5	8.7	8.0	10.4	9.74	10.60	10.30
Na_2O	2.71	2.4	2.6	3.0	2.6	2.98	2.18	2.13
K_2O	0.29	0.46	1.0	1.5	0.5	0.65	0.43	0.38
No. of analyses	11	4	3	8	56	9	32	181

[o]: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	25	26	27	28^o	29^o	30	31	32
SiO_2	46.61	50.2	46.05	51.0	51.26	52.5	52.33	46.83
TiO_2	2.94	1.6	3.10	2.1	2.87	0.94	1.35	2.38
Al_2O_3	15.47	15.9	15.24	14.8	13.98	15.4	14.91	16.12
FeO_t	11.1	15.1	13.7	11.8	12.47	10.0	10.0	11.71
MgO	7.32	6.6	8.23	4.4	4.63	6.32	7.39	7.47
CaO	11.32	10.5	8.74	6.1	6.99	9.43	10.12	10.26
Na_2O	2.89	2.7	2.62	3.2	3.26	1.93	2.08	3.27
K_2O	1.06	0.5	0.46	1.4	2.15	1.40	0.83	0.60
No. of analyses	8	16	3	7	5	6	1	8

^{o}: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	33	34	35^o	36	37	38	39^o	40^o
SiO_2	51.95	52.3	50.07	46.87	48.01	49.28	50.12	47.34
TiO_2	1.21	1.1	1.77	2.72	1.87	1.58	1.52	1.68
Al_2O_3	16.44	14.5	16.27	13.98	14.09	15.34	16.86	16.16
FeO_t	10.41	13.6	9,59	11.9	12.45	11.37	10.64	10.92
MgO	5.95	5.1	7.00	9.82	8.29	6.63	6.64	6.94
CaO	9.88	10.0	9.3	10.47	11.77	11.42	9.99	6.91
Na_2O	2.52	2.1	2.40	2.84	2.17	2.54	2.77	3.75
K_2O	0.87	0.4	0.52	0.68	0.29	0.25	0.57	1.34
No. of analyses	946	11	3	7	12	15	?	1

^{o}: Keweenawan volca

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	41^{o}	42	43	44	45^{o}	46^{o}	47	48
SiO_2	47.39	48.6	52.24	48.11	47.1	49.00	49.95	49.91
TiO_2	1.53	1.22	1.07	1.72	1.62	1.58	1.42	1.69
Al_2O_3	16.82	13.7	15.06	15.55	15.3	17.39	17.65	14.61
FeO_t	10.7	11.7	10.4	9.9	7.8	11.02	9.7	11.3
MgO	6.65	7.42	7.38	9.31	4.15	6.88	6.05	8.49
CaO	9.87	11.9	10.57	10.43	10.6	10.21	11.43	11.42
Na_2O	2.63	2.06	2.00	2.85	2.2	2.7	2.38	1.90
K_2O	0.48	0.33	0.64	1.13	1.6	0.50	0.87	0.34
No. of analyses	?	9	3	7	2	?	9	7

^{o}: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	49	50[o]	51	52	53[o]	54	55	56
SiO_2	47.68	48.22	49.47	51.17	48.53	53.36	49.94	49.78
TiO_2	1.98	1.50	1.53	0.94	1.38	0.59	1.51	0.68
Al_2O_3	17.15	17.07	17.85	17.24	17.83	16.45	17.25	15.69
FeO_t	12.84	11.21	9.7	10.6	10.98	8.8	8.7	11.6
MgO	7.04	8.36	6.96	5.13	6.85	6.72	7.28	7.79
CaO	7.93	9.68	9.97	10.78	6.91	11.49	11.86	11.93
Na_2O	3.77	2.55	2.90	2.60	2.55	1.60	2.76	1.21
K_2O	0.59	0.57	0.72	0.72	0.41	0.91	0.16	0.29
No. of analyses	?	6	21	7	4	6	10	3

[o]: Keweenawan volcanic rocks

TABLE 9 (continued)

CHEMICAL ANALYSES OF BASIC VOLCANIC ROCKS

Overall rank Oxide	57	58	59	60	61	62	63
SiO_2	48.17	50.9	46.98	51.64	48.6	51.19	49.8
TiO_2	1.41	0.45	1.20	0.34	0.57	0.45	0.40
Al_2O_3	18.97	17.7	15.16	18.74	16.9	15.75	16.64
FeO_t	9.8	10.2	11.38	9.3	9.66	8.9	5.02
MgO	7.86	7.7	11.87	6.87	10.59	10.77	9.90
CaO	10.51	10.5	10.33	10.99	10.42	11.04	14.23
Na_2O	2.45	1.88	2.13	1.59	2.03	1.44	2.39
K_2O	0.19	0.24	0.23	0.14	0.20	0.38	0.42
No. of analyses	2	1	6	1	4	1	4

o: Keweenawan volcanic rocks

TABLE 10

REFERENCES FOR TABLE 9

1. Non-porphyritic central basalts of Mull; (Bailey, and others, 1924, Table II, No. 1-8, p. 17).

2. Coppermine River basalt; (Baragar, 1969, Table V, p. 33).

3. Southern African Karoo basalts-northern Province; (Cox, and others, 1967, No. A, B, C, D, D_2, D_3, Table 3, p. 1462).

4. Indian Deccan basalts; (Suskeswala, and others, 1958, Table 3, p. 1487).

5. Alkali basalts-North Shore Volcanics, Elys Peak; (Kilburg, 1972, Table 3, p. 25).

6. Mamainse Point basalts; (Annells, 1973, Table 1, No. 1, p. 20).

7. Tobacco Root Mountains, Montana; (Wooden, and others, 1978, Table 1, Group B-Primary, p. 471).

8. Iceland Quartz Tholeiite, Askja Myvátn area; (Jakobsson, 1972, Table 1, No. 3, p. 367).

9. Logan Intrusions, Minnesota; (Weiblen, and others, 1972, Table V-35, p. 396).

10. Iceland saturated tholeiite, post-glacial zones; (Jakobsson, 1972, Table 1, No. 7, p. 367).

11. Late Yakima type of Columbia River basalt; (Waters, 1962, Table 2, p. 162).

12. Thingmuli volcano, Iceland basalts; (Carmichal, 1964, Table 7, No. 1-10, p. 109).

13. Tertiary Dike swarms, Kangerdlugssuaq area, East Greenland; (Nielson, 1978, Table 2, No. 2-4, p. 69).

14. Alkalic basalt, dikes northeast Newfoundland; (Joyasinghe, 1978, Table 1, p. 850).

15. South Shore basalt, Michipicoten Island; (Annells, 1974, Table VI, No. 5).

16. Basalts of peripheral district of South Island, New Zealand; (Benson, 1941, Table 1; No. E, p. 541).

TABLE 10

REFERENCES FOR TABLE 9

17. Saturated tholeiite, Veidivoten region; (Jakobsson, 1972, Table 1, No. 2, p. 367).

18. Tertiary dike swarms, Kangerdlugssuaq area, East Greenland; (Nielson, 1978, Table 1, No. 1, 2, 6, 7, p. 68).

19. Siemens Creek Formation, Michigan; (Hubbard, 1975, Table 2, p. 536).

20. Yakima type of Columbia River basalt; (Waters, 1962, Table 2, p. 162).

21. Iceland Snaefellsnes region, alkali-olivine basalt; (Jakobsson, 1972, Table 1, No. 6, p. 367).

22. Iceland transitional alkali basalt, Torfajokull region; (Jakobsson, 1972, Table 1, No. 4, p. 367).

23. Hawaiian tholeiites; (Kuno, and others, 1957, Table No. 1, p. 213).

24. Hawaiian tholeiites and olivine tholeiites; (MacDonald, and others, 1964, Table 9, No. 8).

25. Azores plagioclase basalts and olivine basalts; (Esewein, 1929, No. 7-10 and 13-16).

26. Picture Gorge River basalt; (Waters, 1962, Table p. 162).

27. Plateau basalts of Mull; (Bailey, and others, 1924, Table 1, No. 1-3, p. 15).

28. Kallander Creek Formation, Michigan: (Hubbard, 1975, Table 2, p. 536).

29. Kallander Creek Formation, Wisconsin, Mellon-Upson area, alkali-olivine basalts; (Cooper, p. 1973, p. 50).

30. Tobacco Root Mountains, Montana; (Wooden, 1978, Table 1, Group C, p. 471).

31. Chill zone of Palisades sill; (Walker, 1940, Table 3).

32. Iceland alkali-olivine basalt, Westman Islands; (Jakobsson, 1972, Table 1, No. 5, P. 367).

TABLE 10

REFERENCES FOR TABLE 9

33. Average continental tholeiite; (Manson, 1968).

34. Izu peninsula, Japan; (Kuno 1950, Table 5, No. 6, p. 1009).

35. Isle Royale, Michigan; (Huber, 1973, Table 1, IR-23, IR-74, IR-40, p. 11)

36. Hawaiian alkai-olivine basalts; (Kuno, and others, 1957, Table 10, No. 2, p. 213).

37. Iceland olivine tholeiite, Reykjanes region; (Jackobsson, 1972, Table 1, No. 1, p. 367).

38. Gulf of Aden and the Red Sea tholeiitic association; (Gass, 1970, Table 2, p. 376).

39. Kearsarge Flow basalt, Portage Lake Volcanics, Keweenaw, Michigan; (Broderick, 1935, p. 513).

40. Portage Lake Volcanics-"typical glomeroporphyrite basalt," Keweenaw Point, Michigan; (Broderick, 1935, No. 3103, p. 536).

41. Greenstone Flow, Portage Lake Volcanics, Keweenaw Point, Michigan; (Broderick, 1935, p. 513).

42. Tobacco Root Mountains, Montana; (Wooden, 1978, Table 1, Group A-Primary, p. 471).

43. Chill zone of Dillsburg sill; (Hotz, 1953, Table 4, No. 14, 21, 284, p. 690).

44. Japanese alkali-olivine basalts; (Kuno, and others, 1957, Table 10, No. 2, p. 213).

45. Mamainse Point dikes; (Annells, 1973, Table II-1, p. 42).

46. Greenstone Flow, Portage Lake Volcanics, Keweenaw Point, Michigan; (Broderick, 1935, p. 513).

47. Nicaraguan basalts; (Williams, 1952, Table 2, No. 2, p. 41).

48. Pacific tholeiites; (Kuno, 1966, p. 202).

49. Seal Lake basalt flow, Proterozoic, Labrador, Canada; (Annells, 1974).

TABLE 10

REFERENCES FOR TABLE 9

50. Mamainse Point Formation, Quebec Mine basalt member; (Annells, 1974, Table VI, No. 1, p. 136).

51. High-alumina basalts of Cascade Range and Oregon plateaus; (Waters, 1962, Table 5, p. 165).

52. Northern Marianas Island tholeiites; (Schmidt, 1957, Table 6, No. 11, p. 157).

53. North Shore Volcanics, olivine-tholeiite; (Green, 1972, p. 314).

54. Tasmanian undifferentiated diabases; (Edwards, 1942, Table 3, No. 1, p. 465).

55. Pacific and Atlantic tholeiites (dredged); (Engel and others, 1965, Table 3, No. 1, p. 273).

56. Japanese tholeiites; (Kuno, 1960, Table 6, p. 141).

57. Chill zone of Skaergaard intrusion; (Wager and Deer, 1939, No. XIIIa, p. 147).

58. Chill zone of Stillwater Complex; (Hess, 1960, Table 36, No. 1, p. 105).

59. Northeast Ireland, Tertiary olivine basalt; (Patterson, 1952, p. 286).

60. Chill zone of Bushveld lopolith; (Hall, 1932, Table XXX, No. 1, p. 310).

61. Triassic dolerite magmas; (Ragland, 1968, p. 68).

62. Anarctic Ferrar dolerite; (Gunn, 1966, Table 2, p. 968).

63. Indian Ocean gabbros; (Vinogradov, 1972, Table 6, p. 130).

TABLE 11

CORRELATION OF LOWER KEWEENAWAN DIKES WITH OTHER KEWEENAWAN VOLCANIC ROCKS

Comparison Keweenawan basalt	(no. in Table 12)	$\sum\frac{(\%X-\%KW)^2}{\%KW}$	$\sum\frac{\lvert\%X-\%KW\rvert}{\%KW}$
North Shore Volcanics-Elys Peak	5	0.71	0.90
Mamainse Point basalts, Ontario	6	0.71	0.84
Logan intrusions, Minnesota	9	0.81	0.84
South Shore basalt, Michipicoten Island	15	1.53	1.26
Siemens Creek Formation, Michigan	19	1.42	1.15
Kallander Creek Formation, Michigan	28	2.76	1.47
Kallander Creek Formation, Wisconsin	29	2.15	1.80
Isle Royale, Michigan	35	3.28	1.64
Portage Lake Volcanics, Kearsearge Flow	39	3.26	1.85
Portage Lake Volcanics, "typical"	40	3.45	1.82
Portage Lake Volcanics, Greenstone Flow	41	3.35	1.87
Mamainse Point dikes, Ontario	45	4.83	1.79
Portage Lake Volcanics, Greenstone Flow	46	3.57	1.93
Michipicoten Island, Maimainse Point Fm.	50	3.72	2.00
North Shore Volcanics	53	4.70	2.31

TABLE 12

CHEMICAL ANALYSES FOR THE LOGAN INTRUSIONS, MINNESOTA

Analyses #	1	2	3	4	5	6	7
Oxide							
SiO_2	46.60	47.20	50.04	47.50	59.00	46.60	49.88
TiO_2	4.90	2.79	3.76	3.74	3.40	1.13	1.19
Al_2O_3	14.10	14.23	11.70	12.94	13.10	16.80	18.55
FeO_t	13.27	15.85	15.32	15.03	15.35	12.76	10.40
MnO	0.21		0.15	0.22	0.22	0.20	0.09
MgO	5.80	7.21	4.20	5.62	5.60	9.60	5.77
CaO	12.10	8.32	7.16	8.38	7.45	10.30	9.7
Na_2O	2.27	2.57	3.47	2.39	2.52	1.82	2.59
K_2O	0.32	0.75	1.03	1.07	1.16	0.29	0.68

From: Green, 1972.

TABLE 12 (continued)

CHEMICAL ANALYSES FOR THE LOGAN INTRUSIONS, MINNESOTA

Oxide	Mean	Std. Dev.	Range
SiO_2	48.9	1.6	46.6-51.2
TiO_2	2.8	1.2	1.1-4.9
Al_2O_3	14.4	2.2	11.7-18.5
FeO_t	12.4	3.2	10.2-15.8
MnO	0.18	0.05	0.09-0.22
MgO	6.2	1.6	4.2- 9.6
CaO	9.1	1.6	7.2-12.1
Na_2O	2.6	0.5	1.8- 3.5
K_2O	0.76	0.33	0.3- 1.2

From: Green, 1972.

TABLE 13

CHEMICAL ANALYSES FOR ICELAND POST-GLACIAL BASALTS

Rock type Oxide	ol- thol.	sat. thol	qz- thol.	transit. alk.- thol.	alk. ol- thol.	alk.- ol. thol.	sat. thol.
SiO_2	48.01	49.51	50.26	47.00	46.83	46.88	49.2
TiO_2	1.87	2.39	2.47	3.71	2.38	2.41	2.6
Al_2O_3	14.09	13.97	13.52	13.84	16.12	15.53	14.0
FeO_t	12.45	13.28	15.0	15.12	11.71	11.47	13.91
MnO	0.21	0.21	0.24	0.21	0.19	0.22	0.2
MgO	8.29	5.97	5.58	5.96	7.47	7.51	6.1
CaO	11.77	10.96	9.18	9.74	10.26	11.07	10.4
Na_2O	2.17	2.71	2.48	2.98	3.27	2.90	2.6
K_2O	0.29	0.42	0.56	0.65	0.60	0.71	0.5

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