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LOWER PROTEROZOIC VOLCANIC ROCKS AND THEIR SETTING IN THE SOUTHERN LAKE SUPERIOR DISTRICT

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Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district

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ABSTRACT

Studies of lower Proterozoic volcanic rocks in Wisconsin and northern Michigan reveal the existence of two different Penokean-age (about 1,900 to 1,800 m.y. old) geologic terranes. The terranes are in contact along the east-west trending Niagara fault and are confined between Archean craton to the north and progressively younger Proterozoic magmatic provinces to the south. The northern terrane shows some similarity to Andean-type continental margins. The geologic history of the area includes evidence of rifting, continental arc volcanism, and later orogenesis (collision?). Rocks in this environment were sutured to a southern terrane, the Penokean volcanic belt, which developed from an island arc and basin-type environment, probably flanking the continental margin.

The northern Penokean terrane contains thick units of sedimentary rocks, both platformal sequences and turbidites. Volcanic units are less abundant than sedimentary rocks and are typified by basalt flows and by lesser amounts of basaltic and rhyolitic volcaniclastic rocks. Penokean andesites are almost entirely absent from the northern terrane. Penokean calc-alkalic plutonic rocks are rare, whereas gabbroic sills and mafic layered complexes are common. The volcanic rocks display bimodal, tholeiitic trends with high iron enrichment. During what is considered to be the peak of the Penokean orogeny, the northern terrane rocks were affected by multiple deformations and metamorphic episodes. Tectonic styles in this region result from Archean basement uplifts and gneiss domes that exerted vertical stresses. Gneiss domes are outlined in the surrounding rocks by nodal patterns of metamorphic mineral zones.

Recent work and the integration of previous studies in the Penokean volcanic belt have shown the contrast between this region and the northern terrane. South of the Niagara fault, metavolcanic rocks are much more abundant than metasedimentary rocks. Sedimentary units appear to have been derived from varied, discontinuous sources and included conglomerates, graywackes, argillites, graphitic shales, tuffaceous sandstones, and dolomites. Penokean calc-alkalic volcanic suites and calc-alkalic plutons are uniquely abundant in the Penokean volcanic belt. However, minor quantities of tholeiitic volcanic and intrusive rocks occur within calc-alkalic suites in northeastern Wisconsin, just south of the Niagara fault. This area may have been the site of interarc magma genesis.

Tectonism in the Penokean volcanic belt can be distinguished by the lack of Archean basement, mantled gneiss domes, and metamorphic nodes. Greenschist-facies metamorphism was widespread throughout the belt. Higher-grade metamor-

phism was restricted to the vicinity of plutons and areas of locally intense deformation.

In spite of similarities, some features of modern plate-tectonic orogenies are not displayed by the Penokean. This leads to the conclusion that the Penokean may represent a transitional style of tectonism, not like Archean, nor exactly like modern plate-tectonic activity.

INTRODUCTION

Lower Proterozoic volcanic and associated rocks constitute a very large part of the exposed Precambrian bedrock in northern Wisconsin. These rocks can be viewed as making up a major tectonic belt, perhaps similar to granite-greenstone belts in Archean shields. Simplistic conclusions as to the character of this Penokean-age (approximately 1,860 to 1,800 m.y. old) belt are unrealistic, however, as large amounts of geologic data from many areas within the belt have never been collectively described and interpreted. This is due in part to the relative inaccessibility of much of the basic data in unpublished theses. We have integrated this information in order to compare Penokean rock chemistry and tectonic setting with more modern, Archean, and other Proterozoic volcanic suites. The result of our study is the derivation of a tectonic-petrologic framework for Penokean volcanism that best fits the available data.

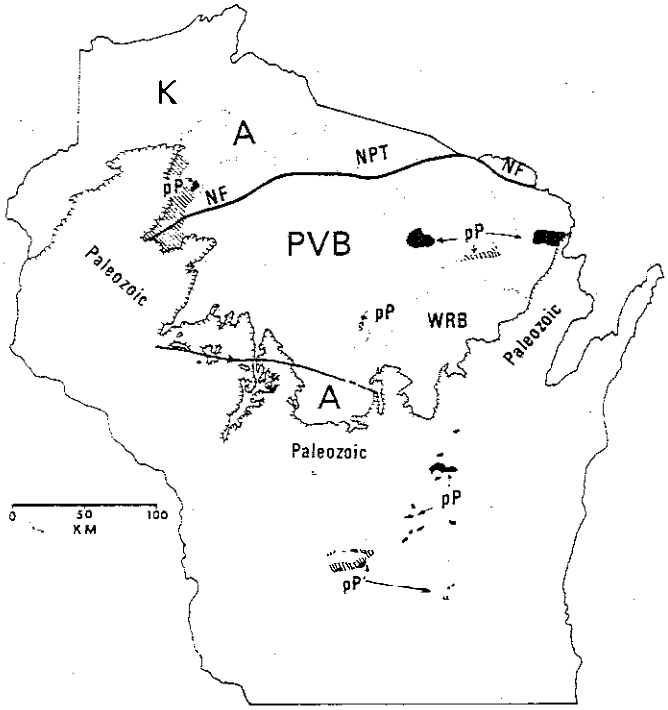


Figure 1. Major tectonic terranes in Wisconsin. Map modified from the page-size bedrock geology map of Wisconsin (Wisconsin Geological and Natural History Survey, 1981). K, Keweenawan terrane; A, Archean terranes; NPT, northern Penokean terrane; PVB, Penokean volcanic belt (southern terrane); NF, Niagara fault; WRB, Wolf River batholith; pP, post-Penokean; 1,760-m.y.-old magmatic rocks in black; quartzites cross-hatched.

The nature of tectonism during Proterozoic time places a major constraint on possible models for the origin of Penokean volcanic rocks. Some investigators have proposed that modern plate-tectonic processes have operated from Archean time (Burke and others, 1976; Condie, 1978). However, modern tectonic regimes often appear significantly different from those of the Archean, and any constant process of crustal evolution must have involved changes in structure and crustal composition. A thin, relatively mafic crust is often invoked for the Archean in contrast to thicker, more differentiated crust for the more recent Earth. Muehlburger (1980) noted that this thin crust and greater heat flow may have resulted in more rapid plate interactions in the early Precambrian than today. Without some unknown catastrophic change in dynamic processes, it follows that Proterozoic orogenies may in some ways be distinct from Archean tectonics and modern plate tectonics. The geology and chemical characteristics of lower Proterozoic volcanic rocks in Wisconsin may therefore provide a clearer understanding of the Penokean "Orogeny" (Goldich and others, 1961) and how it compares with modern and Archean tectonism.

PRECAMBRIAN GEOLOGIC SETTING

The Precambrian geology of northern Wisconsin and surrounding areas is characterized by several tectonic terranes, each consisting of a distinct group of rock units. These terranes are outlined on Figure 1.

Keweenawan-age (about 1,000 m.y. old) volcanic, sedimentary, and minor mafic intrusive rocks are the products of continental rifting in the extreme northwestern part of Wisconsin. A terrane including lower Proterozoic units and Archean-age granites, gneisses, and metavolcanic rocks (Greathead, 1975) lies southeast of the Keweenawan units. In the southern part of Michigan's Upper Peninsula and in northwestern Wisconsin, Archean gneisses and granites were reworked into domes during deformation (about 1,800 m.y. ago) with the overlying lower Proterozoic sedimentary and volcanic units (Sims, 1980). This terrane (referred to here as the northern Penokean terrane, NPT) is in fault-contact on the south with the dominantly volcanic and plutonic units of the Penokean volcanic belt (PVB).

Van Schmus (1976) recognized the distinctions between the two Penokean terranes and informally referred to the volcanic belt as a "volcano-plutonic belt." Larue and Sloss (1980) preferred the term "magmatic terrane" for the volcanic belt. All these designations emphasize that major 1,850-m.y.-old magmatic activity was widespread throughout the southern terrane in contrast with the predominantly sedimentary character of the northern Penokean terrane. In addition to the differences in rock types, the two terranes also contrast in age, the distribution of metamorphic facies, and structural style. The Niagara fault is the structure dividing the northern Penokean terrane from the Penokean volcanic belt. Deformational effects and metamorphism commonly intensify on either side toward the fault, but the most intense effects are not always restricted to the fault zone (Dutton, 1971).

Rocks of the Penokean volcanic belt are intruded on the southeast by alkalic granitic rocks of the Wolf River batholith (1,500 m.y. old). Along the southern margin of the volcanic belt, scattered exposures of Archean gneiss are restricted to south of a tectonic boundary (fault?) defined by changes in structural grain and geophysical anomalies (Fig. 1). The area south of this boundary is a structural domain unlike the rest of the Penokean volcanic belt and thus may constitute a third terrane involving Penokean magmatism and deformation (Maass and others, 1980). The southernmost exposures of Precambrian crystalline rock in Wisconsin are part of a 1,760-m.y.-old terrane of rhyolite, granite, and younger quartzose sedimentary units (Smith, 1978).

DISTRIBUTION AND CHARACTER OF PENOKEAN VOLCANIC ROCKS

Source of Information

Characteristics (excluding chemical compositions) of various Penokean volcanic suites are summarized below for the different areas of investigation where data are available (Fig. 2). These areas and the data sources utilized include:

Northern Penokean Terrane. The Marquette Range Supergroup (Weir, 1967; Dutton, 1971; Dann, 1978; Cudzilo, 1978).

Penokean Volcanic Belt. Northeast Wisconsin–Quinnesec area (Froelich, 1953; Thompson, 1955; Fulweiler, 1957; Prinz, 1959; Cain, 1962; Hall, 1971; Davis, 1977; Cummings, 1978; Cudzilo, 1978).

Rhinelander-Monico-Crandon area (Schriver, 1973; Venditti, 1973; Bowden, 1978; Schmidt and others, 1978; J. Hallberg, unpub. data).

Mountain area (Mancuso, 1960; Lahr, 1972; Motten, 1972; Cudzilo, 1978).

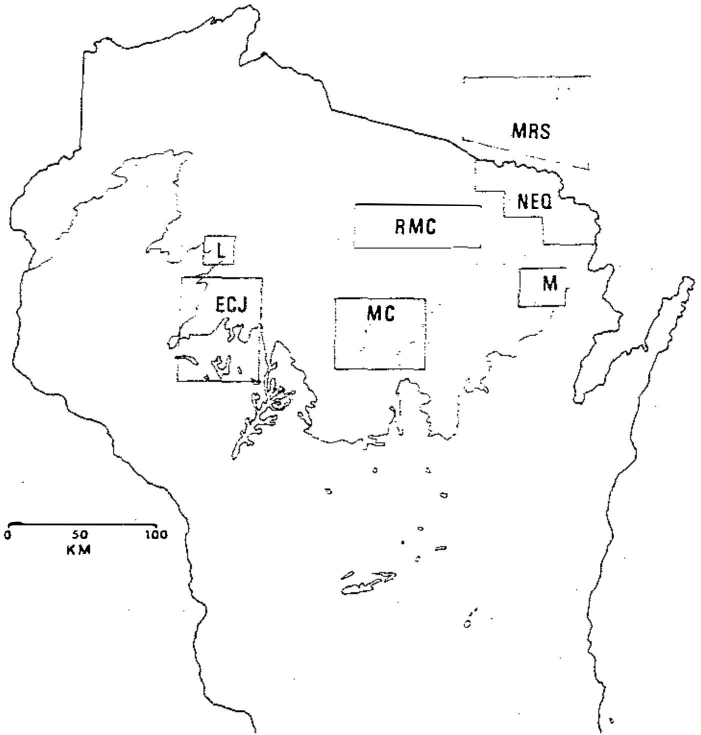


Figure 2. Locations of Penokean volcanic rocks mentioned in the text. MRS, Marquette Range Supergroup; NEQ, northeast Wisconsin–Quinnesec area; M, Mountain area; RMC, Rhinelander-Monico-Crandon area; MC, Marathon County; L, Ladysmith area; ECJ, Eau Claire-Chippewa-Jump Rivers area.

Marathon County (Voight, 1970; LaBerge and Myers, in prep.).

Ladysmith area (Edwards, 1920; May, 1977).

Eau Claire-Chippewa-Jump Rivers area (Myers and others, 1980).

In addition to these lower Proterozoic suites, geochemical data from Archean greenstones in northwestern Wisconsin (Greathead, 1975) were used for comparison with the younger rocks.

General stratigraphic relationships are known among the volcanic formations in the relatively well exposed Marquette Range Supergroup of the northern Penokean terrane (Table 1). Unfortunately, the typically limited bedrock exposure throughout the Penokean volcanic belt provides only a vague understanding of stratigraphy.

DESCRIPTION OF STUDY AREAS

Marquette Range Supergroup. Volcanic units exposed in the northern Penokean terrane include the Clarksburg, Hemlock, and Badwater Formations (Cudzilo, 1978; Dann, 1978) and the Emperor Complex (Dann, 1978). The Clarksburg and Hemlock Formations are approximate stratigraphic equivalents that underlie and are in part (Clarksburg Fm) interbedded with the Michigamme For-

TABLE 1. STRATIGRAPHIC POSITION OF PENOKEAN VOLCANIC UNITS

Northern Penokean Terrane					Penokean Volcanic Belt		
West (Gogebic Range)			East (Iron, Dickenson Counties)		East	Central	West
		(no equivalent)	Paint River Gp.		(no equivalent rocks)		
Marquette Range Supergroup	Baraga Gp.	Tyler Slate	Michigamme Formation	Badwater Greenstone	Quinnesec Formation (1850 m.y.)	Marathon County Volcanics (1850 m.y.)	Eau Claire River Volcanics (1850 m.y.)
				Michigamme Slate			
				Fence River Fm.			
				Hemlock/Clarksburg (1900 m.y.)			
			Goodrich Quartzite				
	Menominee Gp.	Ironwood Iron Fm. Emperor Volcanics	Vulcan Iron Fm.				
		Palms Quartzite	Felch Formation				
	Chocolay Gp.	Bad River Dolomite	Randville Dolomite		(no equivalent rocks)		
		Sunday Quartzite	Sturgeon Quartzite				
			Fern Creek Fm.				

Note: Volcanic Units underlined, modified from Sims, 1976.

mation (Bayley and others, 1966). The Badwater Formation is stratigraphically above the Michigamme Formation. All three volcanic units are members of the Baraga Group. The Emperor Complex is probably stratigraphically lower than or roughly equivalent to the Clarksburg and Hemlock Formations. This uncertainty in position is due to problems in regional stratigraphic correlation among depositional basins (Larue and Sloss, 1980). Emperor Complex volcanic units underlie and are interbedded with Ironwood Iron Formation which is below the Tyler Slate, an equivalent of the Michigamme Slate. The Emperor Complex includes both a series of tholeiitic sills intruding a basalt sequence and also a sequence of calc-alkalic volcanics (the Wolf Mountain Creek Formation). According to Dann (1978), the Wolf Mountain Creek Formation grades upward from a clastic sedimentary base through volcaniclastic sediments to interlayered massive and pillowed flows. Some hyaloclastites and flow breccias are also present in the upper units. Compositionally, the volcanic rocks range from basalt and andesite to dacite.

The Clarksburg, Hemlock, and Badwater Formations are comprised of similar volcanic units, though the Clarksburg contains no felsic members (Dann, 1978). It consists of mafic flows, tuffs, and coarse fragmental rocks that overlie iron formation. The Hemlock Formation consists of 600 m of basaltic flows, siliceous tuffs, and rhyolites. Badwater units are the youngest volcanic rocks, but also consist of pillowed mafic flows, mafic and felsic tuffs, and coarse fragmental rocks.

Metamorphism has destroyed most original textures in the Clarksburg, Hemlock, and Badwater Formations. Typical mineral assemblages include plagioclase, chlorite, epidote, calcite, hornblende, and in some places garnet, indicative of more intense metamorphism. However, the Emperor Complex, particularly the Wolf Mountain Creek Formation, displays many primary textural features and lower greenschist-facies metamorphic assemblages (Dann, 1978).

Northeast Wisconsin–Quinnesec Volcanics. The best exposures in the Penokean volcanic belt occur in eastern Florence and northern Marinette Counties (NEQ, Fig. 2). Most of the metavolcanic materials in this area have been grouped in the Quinnesec Formation. This formation consists mainly of basaltic flow rocks interlayered with andesites, rhyolites, pyroclastics, epiclastics, and minor iron formations in the southern part of the area (Cummings, 1978). To the north, near the Niagara fault, the Quinnesec contains massive and pillow basalts with interlayered rhyolite flows and tuffs. In this same area, there are many bodies of gabbro and ultramafic rocks (Hall, 1971). These units are more intensely deformed and metamorphosed than rocks of the Marquette Range Supergroup which occur north of the Niagara fault (Bayley and others, 1966; Dutton, 1971). Jenkins (1973) recognized four volcanic units, including the Quinnesec, separated by faults in the eastern part of the area. His other three units are the Beecher Formation, typically porphyritic flows with sodic-plagioclase phenocrysts; the Pemene Formation, consisting of spherulitic sodic-rhyolite and rhyodacite; and the McAlister Formation, which consists largely of mafic coarse-fragmental rocks. Sedimentary rocks are generally scarce but occur as thin interflow units throughout the area. Sedimentary rock types include iron formation, graphitic mudstone, impure marble, sandy dolomite, quartzite, and metagraywacke (Dutton, 1971; Davis, 1977; Cummings, 1978).

Much of the area of Quinnesec and related deposition was invaded by large volumes of plutonic rocks during the Penokean orogeny. As a result, many exposures of volcanic and sedimentary rocks show amphibolite-facies metamorphic effects (metamorphic hornblende, garnets, and so forth).

Rhinelander-Monico-Crandon Area. Outcrops in the Rhinelander-Monico-Crandon area (RMC, Fig. 2) are restricted to scattered exposures, many of which are dioritic to granitic intrusive rocks. Data on the volcanic rocks are limited to the vicinity of Monico and to exploration drill cores. Volcanic rocks in the Monico area (Schriver, 1973; Venditti, 1973) consist of a sequence of massive and pillowed mafic flows which are porphyritic to amygdaloidal. Phenocrysts were originally plagioclase and, more rarely, pyroxene. These flow units have been metamorphosed to assemblages of actinolite, chlorite, and epidote, and appear to overlie a succession of mixed felsic to intermediate tuffs, breccias, and mafic to intermediate flows. The breccias and tuffs have been tentatively correlated (M. Mudrey, personal commun.) with rocks exposed and drilled at the Pelican massive sulfide deposit, near Rhinelander and just west of Monico. In his study of the Pelican deposit, Bowden (1978) described foot-wall rocks as porphyritic and amygdaloidal mafic flows, flow breccias, tuffs, and epiclastic sediments. The breccias and tuffs are highly altered near the ore zone. Metamorphosed and hydrothermally altered mineral assemblages include the groundmass phases: iron-chlorite, epidote, zoisite-clinozoisite, actinolite, quartz, albite, calcite, and pyrite. Sausseritized plagioclase laths comprise most of the relict phenocrysts. In the hanging wall, units are distinguished by the presence of chert fragments and cherty tuffs as well as intermediate flows and crystal tuffs. Tuffaceous and massive intermediate volcanic rocks drilled during exploration of the Crandon massive sulfide deposit (Schmidt and others, 1978) are thought to be part of the same sequence exposed in the Monico area (M. Mudrey, personal commun.). Metamorphism in the Rhinelander-Monico-Crandon area is lower greenschist facies, but it is locally higher near contacts with plutonic rocks.

Mountain Area. The Waupee volcanic sequence or "formation" (Mancuso, 1960; Lahr, 1972) is exposed in the vicinity of Mountain, Oconto County, Wisconsin (M, Fig. 2). Most exposures show a trend near N. 55° E. with steep dips. Lahr (1972) divided the Waupee into three units. The basal unit consists of about 5,000 m of massive to porphyritic mafic flows. Typical mineral assemblages are dominated by hornblende and plagioclase. In some places, minor siliceous zones occur in tuffs and sediments interlayered with mafic flows. The middle member of the Waupee consists of quartzofeldspathic sediments with minor interlayered mafic flows. Lahr (1972) mentioned no thicknesses for the middle or upper units. The upper unit is made up of fine-grained and thinly laminated tuffs, with stratigraphic tops facing northwest. Locally, the Waupee rocks are intensely deformed and metamorphosed to middle amphibolite facies. These effects probably resulted from the close proximity to the Wolf River batholith, whose intrusion obscured much of the original nature of the Waupee volcanics.

Marathon County. Relatively good exposures of Penokean volcanic rocks are found in Marathon County (MC, Fig. 2) (Voight, 1970; LaBerge and Myers, in prep.) Voight (1970) described the volcanic sequence of northwestern Marathon County as interlayered massive basalts and andesites, with no evidence of pyroclastic material. The basalts exhibit ophitic and amygdaloidal textures and are composed of epidote, chlorite, magnetite, and minor actinolite. According to Voight (1970), "andesites" commonly display trachytic textures with subhedral microlites of plagioclase and anhedral albite in a groundmass of epidote, chlorite, and opaques. Porphyritic andesites contain twinned and zoned sodic-plagioclase phenocrysts in a groundmass of subhedral albite, epidote, sericite, and opaques. In other parts of Marathon County, particularly central and eastern, rhyolites and felsic tuffs are exposed along with graywackes and minor iron formation (LaBerge and Myers, in prep.). Rhyolites are massive, often porphyritic, and occasionally display original flow banding. Coarse fragmental units and crystal and lapilli tuffs are also present in some areas.

Ladysmith Area. Much of the stratigraphic information from the western part of the volcanic belt comes from drill core data of the Ladysmith massive sulfide deposit (L, Fig. 2). The deposit is within a sequence of steeply dipping schistose volcanic and sedimentary rocks, truncated by granite intrusions (May, 1977). Rock types identified, mostly from drill core, include dacitic to rhyolitic crystal tuffs, massive dacitic to andesitic flows (now metamorphosed to actinolite schists), and rhyolitic tuffs, represented by quartz-sericite (±andalusite) schists.

Eau Claire-Chippewa-Jump Rivers Area. The southwesternmost exposures of the Penokean volcanic belt occur in the Eau Claire, Chippewa, and Jump River Valleys (ECJ, Fig. 2). Much of the geology in this region is summarized in Myers and others (1980). Rocks in the area include basaltic, andesitic, and rhyolitic flows, tuffs, and coarse fragmental rocks interstratified with siliceous volcanogenic sediments, slates, quartzites, and conglomerates. Myers and others (1980) have suggested that the volcanic rocks of the Eau Claire area are younger than and overlie amphibolite units. Volcanic rocks of the Jump River valley are described by Cummings (Myers and others, 1980) as basaltic and andesitic flows that are interbedded with andesitic to rhyolitic fragmental rocks. The rhyolitic flows and coarse fragmental materials lead Cummings to propose the existence of a felsic eruptive center in the Jump River area. Although no thicknesses were given, the extent of these rocks exposed suggests that they are at least several hundreds of metres thick (Myers and others, 1980).

AGE DATA

The few radiometric ages available for Penokean volcanic rocks in northern Wisconsin and the Upper Peninsula of Michigan thus far indicate that volcanism was probably earlier in the Marquette Range Supergroup (NPT) than in the Penokean volcanic belt (Van Schmus and Bickford, 1981). Felsic units in the Hemlock Formation are about 1,900 m.y. old (U-Pb, Van Schmus, 1976). U-Pb zircon ages of volcanic suites from three different areas within the Penokean volcanic belt are all about 1,850 m.y. (Van Schmus, 1980). This is roughly the age of rhyolites from the Quinnesec Formation (Banks and Rebello, 1969), from Marathon County, and from Eau Claire County (Fig. 2). The zircon ages correlate well with Pb-Pb model ages of near 1830 m.y. for volcanogenic sulfide deposits located in the central and western parts of the Penokean volcanic belt (Stacey and others, 1977). Anorogenic rhyolites south of the main volcanic belt are near 1,760 m.y. old and represent a change in tectonic environment after the Penokean orogeny (Van Schmus and Bickford, 1981).

INTERPRETATION OF GEOCHEMICAL DATA

Because the many sources used in this data compilation probably vary in quality, chemical analyses were chosen according to certain criteria. For example, odd analyses, such as rocks described as basalt but containing 25% Al_2O_3 or 30% SiO_2 were rejected. This type of situation may arise from misidentification or major analytical errors. In addition, samples with element abundances totaling less than 95% or more than 102% were not incorporated in the compilation. Averaged compositions of mafic, intermediate, and felsic volcanic rocks from both Penokean terranes are shown in Table 2.

Several variation diagrams were tested for data interpretation, but only a few were selected to best display the relationships among different volcanic suites. Unfortunately, trace elements were not analyzed in most studies

TABLE 2. AVERAGE COMPOSITION OF VOLCANIC ROCKS FROM BOTH PENOKEAN TERRANES

Northern Penokean Terrane

	Rhyolite (68-72% SiO_2)	SD	Andesite (57-62% SiO_2)	SD	Basalt (47-51% SiO_2)	SD
SiO_2	69.19	1.89	59.20	2.78	48.80	1.35
Al_2O_3	12.24	0.84	14.13	1.11	14.56	1.48
Fe_2O_3*	5.43	0.90	9.93	0.76	14.23	1.93
TiO_2	0.39	0.12	1.13	0.01	1.54	0.49
MgO	1.25	0.95	4.58	0.50	5.78	2.00
CaO	0.72	0.92	4.53	0.96	8.19	3.20
Na_2O	2.26	1.78	5.54	0.90	2.73	0.75
K_2O	4.66	2.64	1.35	1.06	0.72	0.44
N	3		3		21	

Penokean Volcanic Belt

	Rhyolite (68-72% SiO_2)	SD	Andesite (57-62% SiO_2)	SD	Basalt (47-51% SiO_2)	SD
SiO_2	69.86	1.70	59.24	1.76	49.15	1.17
Al_2O_3	14.03	1.74	15.16	2.02	15.35	2.14
Fe_2O_3*	3.95	2.32	8.71	2.16	12.65	1.91
TiO_2	0.33	0.30	0.59	0.34	0.71	0.32
MgO	0.90	1.12	4.08	1.68	5.30	1.54
CaO	1.95	1.65	4.39	1.56	10.41	2.25
Na_2O	4.07	1.36	3.92	1.43	2.36	2.04
K_2O	2.50	1.76	1.39	0.96	0.62	0.51
N	8		16		27	

Note: Elements are in weight percent.
N is the number of samples.
* Total iron computed as Fe_2O_3.
SD is standard deviation.

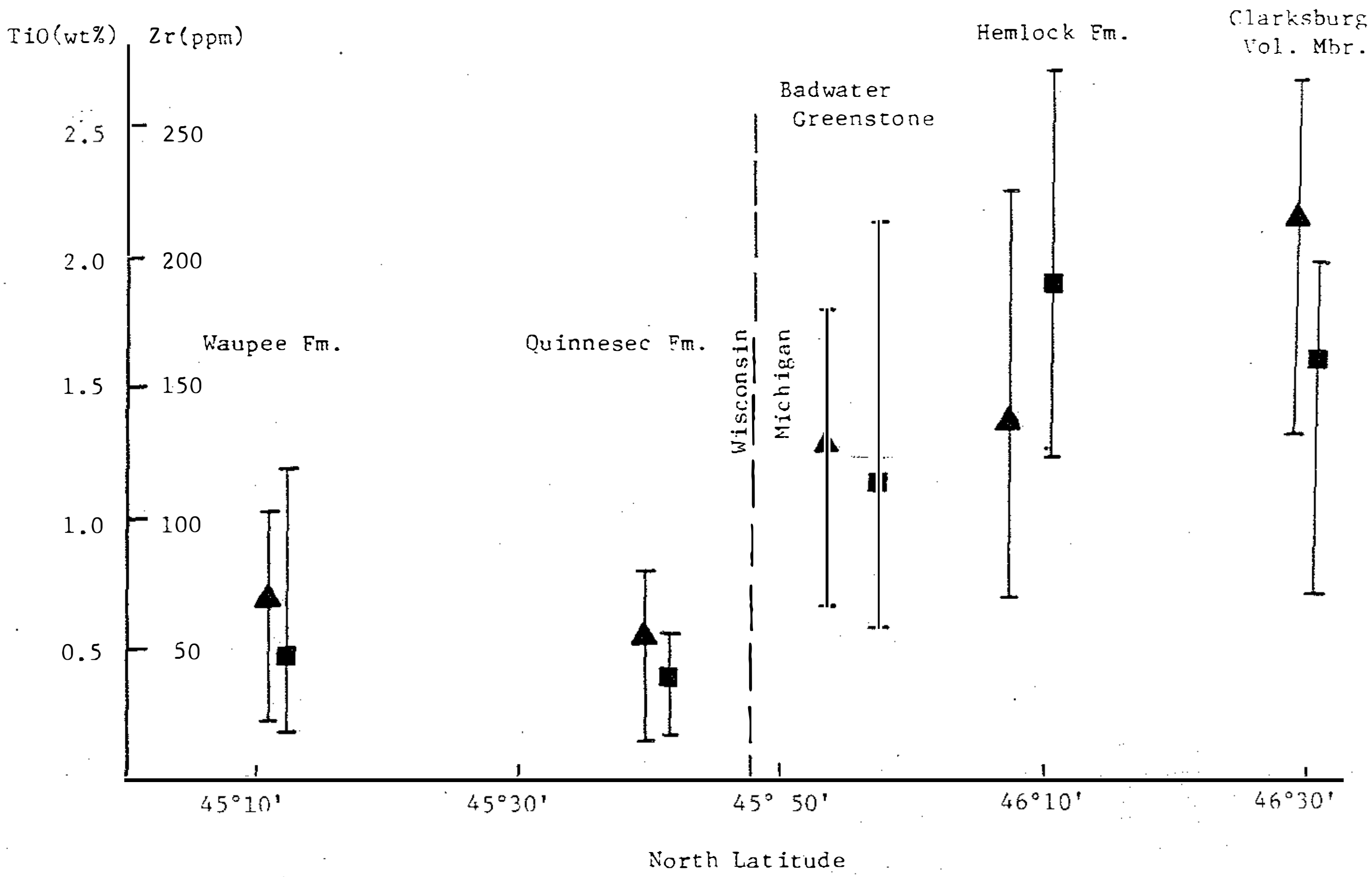


Figure 3. Plot of TiO_2 and Zr versus latitude from Cudzilo (1978). Solid triangles represent TiO_2 in weight percent. Solid squares represent Zr in parts per million. Vertical bars represent range of values for each unit.

and their usefulness as indicators of tectonic environments are thus limited. It was also not practical to interpret most plots of the more mobile elements (such as Al_2O_3, CaO, and the alkalis) which tend to be more affected by the influences of hydrous alteration. The plots eventually utilized for data comparison include: SiO_2 histogram, SiO_2 versus $\log_{10}K_2O/MgO$, Ni versus MgO, total Fe versus MgO, Zr-Ti-Sr, and Ti versus Zr. Although it could be argued that alteration or other processes complicate geochemical interpretation, the present study was specifically intended to emphasize major similarities and differences among volcanic rock suites. In fact, a twofold empirical test validated the use of the data plots. On each diagram there is a good grouping of samples from the same area (and not always from the same study), and more important, there is general agreement among conclusions from the different plots.

Chemical differences between the two Penokean terranes are apparent on all the variation diagrams. Cudzilo (1978) illustrated this contrast with his Figure 10 (Fig. 3 this paper, by permission) of relative TiO_2 and Zr abundances. The contrast between volcanism in the two terranes is also the most striking feature of SiO_2 histograms (Fig. 4). In the northern terrane, all Penokean volcanic units except the calc-alkalic portion of the Emperor Complex (Wolf Mountain Creek volcanics) are bimodal volcanic suites, devoid of andesites. Basaltic rocks (53% to 56% SiO_2 as an upper limit) predominate, but samples from all but the Clarksburg Formation include rhyodacite to rhyolite. Definite bimodality does not occur for any of the analyzed suites south of the Niagara fault. Unfortunately, the impression of bimodality can be given in some areas if sampling biases are not taken into consideration. An example of this relates to the Penokean volcanogenic sulfide deposits (May, 1977), where many samples were analyzed from near ore zones, in which case analyses of samples were biased toward the felsic side. Metamorphosed intermediate to felsic tuffs are host rocks in the Ladysmith (May, 1977), Crandon (Schmidt and others, 1978), and Pelican (Bowden, 1978) massive sulfide deposits. Although Van Schmus and Bickford (1981) have stated to the contrary, andesites are well represented in all areas of the Penokean volcanic belt and include rocks of widely variable metamorphic facies and deformational fabric. These intermediate volcanic rocks are defined by their SiO_2 contents (Fig. 4) as well as their overall chemical and physical character described in various

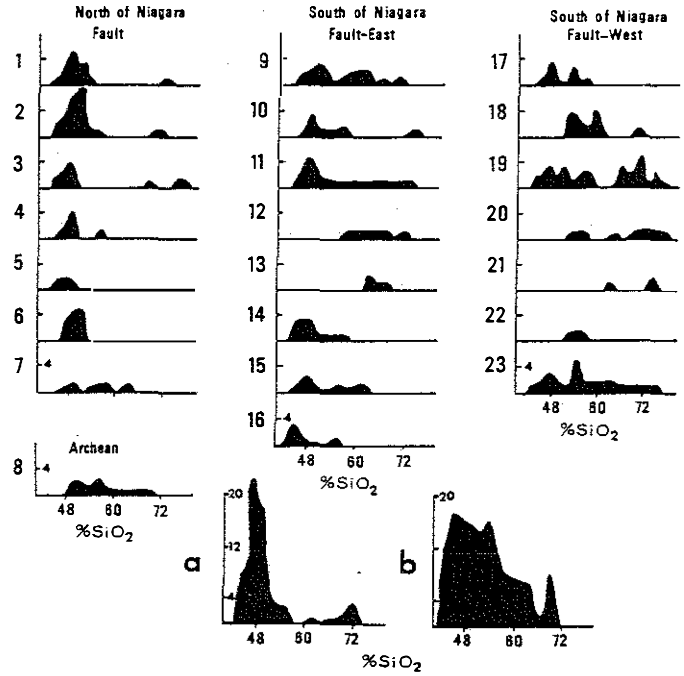


Figure 4. SiO_2 histograms for various Penokean, Wisconsin Archean, and composite volcanic suites. SiO_2 in weight percent. 1, Hemlock Formation (Cudzilo, 1978); 2, Hemlock Formation (Dann, 1978); 3, Badwater Formation (Cudzilo, 1978); 4, Badwater Formation (Dann, 1978); 5, Clarksburg Formation (Cudzilo, 1978); 6, Emperor Complex, tholeiitic (Dann, 1978); 7, Emperor Complex, calc-alkalic (Dann, 1978); 8, northwestern Wisconsin Archean volcanics (Greathead, 1975); 9, northeast Wisconsin–Quinnesec area (Davis, 1977); 10, northeast Wisconsin–Quinnesec area (Hall, 1971); 11, Quinnesec Formation (Cudzilo, 1978); 12, Beecher Formation (Cudzilo, 1978); 13, Pemene Formation (Cudzilo, 1978); 14, Mountain area, Waupee volcanics (Lahr, 1972); 15, Mountain area, Waupee volcanics (Cudzilo, 1978); 16, northeast Wisconsin–Quinnesec area (Cummings, 1978); 17, Monico area (Schriver, 1973); 18, Monico area (Venditti, 1973); 19, Rhinelander area, Pelican massive sulfide deposit (Bowden, 1978); 20, Marathon County (LaBerge and Myers, in prep.); 21, Ladysmith area, Ladysmith massive sulfide deposit (May, 1977); 22, Ladysmith area (Edwards, 1920); 23, Eau Claire-Chippewa-Jump Rivers area (Myers and others, 1980); a, composite of all samples north of the Niagara fault; b, composite of all samples south of the Niagara fault.

studies. The only Archean metavolcanic rocks studied in Wisconsin are north of the Penokean volcanic belt (Greathead, 1975). These Archean samples cover all silica ranges but are concentrated toward the basalt end.

In more modern environments, silica bimodality is usually equated with tensional tectonics (rifting) in continental or oceanic settings (Condie, 1976b). Silica distributions that include andesites usually imply arc volcanism, either continental or island. Modern analogues suggest that most magmas in the northern Penokean terrane originated in tensional environments, whereas those in the Penokean volcanic belt were orogenic products.

Regardless of some problems that might be caused by K_2O mobility, SiO_2 plotted against K_2O/MgO (Fig. 5) reveals some general relationships. Samples from modern calc-alkalic volcanic suites (continental and island arc) cluster close to or above a reference trend line defined by several volcanoes from the northwestern Philippine arc (DeBoer and others, 1980). Mafic suites, such as ocean-floor tholeiites, plot near the origin (Fig. 5a), whereas more differentiated suites trend toward higher K_2O values, but at slope angles consistent with their relative increase in K_2O. Anorogenic suites, such as continental flood-volcanics (Leeman and Vitaliano, 1976; Wright and others, 1973), and Keweenawan rift-volcanics (Green, 1972) show relative K_2O enrichment trends below the calc-alkalic line. Archean suites from various regions, including Wisconsin, typically follow trends of lower K_2O/MgO increase, above the calc-alkalic line. These trends reflect high MgO rather than low K_2O content.

With reference to K_2O content, none of the Penokean volcanic suites from Wisconsin and northern Michigan can really be considered as alkaline in any classification scheme. The northern Penokean terrane suites all conform to anorogenic, continental-tholeiite trends, although some of the felsic rocks from this region are more magnesian than those of modern analogues (Fig. 5a, 5b). This may be due to the specific nature of bimodal volcanism during the Penokean orogeny. The calc-alkalic Wolf Mountain Creek suite (Dann, 1978) forms a small field distinct from the rest, suggesting a magma genesis unique in this terrane.

South of the Niagara fault (Fig. 5c, 5d), differentiation trends are more complex. As Cudzilo (1978) observed, the Waupee volcanics are more alkaline than all other units examined in his study. At low SiO_2, the Waupee rocks parallel anorogenic suites. Samples from May (1977), Bowden (1978), and Cummings (1978) show the effects of alteration (magnesium metasomatism) during mineralization. All other suites from the central and western part of the volcanic belt including Monico (Schriver, 1973; Venditti, 1973), Marathon County (LaBerge and Myers, in prep.), and the Chippewa River valley (Myers and others, 1980) conform to calc-alkalic patterns and trends.

Further geochemical observations can be summarized as follows:

1. Volcanic rocks in the northern Penokean terrane plot in fields representing anorogenic tholeiites, usually similar to continental suites (Figs. 6, 7, 8). High iron enrichment is evident in Figure 6. Many of these samples overlap high-iron Archean greenstones but do not show an equivalent enrichment in MgO, characteristic of komatiites. In addition, Archean volcanic rocks are typified by higher Ni/MgO ratios (Fig. 7) than all but those Penokean suites containing sulfide mineralization. The Penokean volcanic rocks from both the northern and volcanic belt terranes are not appreciably different than some suites from

modern tectonic environments. However, with the prominent exception of SiO_2 contents, most chemical data suggest that volcanism in the Penokean volcanic belt, like that in the northern Penokean terrane, was somewhat distinct from volcanism during the Archean. Even for samples with equal SiO_2 contents, Penokean calc-alkalic suites contain generally lower amounts of total Fe, MgO, TiO_2 and Ni than Archean suites (Table 2; Condie, 1976a; Gunn, 1976).

2. A calc-alkalic character is evident for samples from throughout the Penokean volcanic belt shown on Figures 6, 7, and 8. The only major deviation from orogenic arc-type chemistry is exhibited by the Quinnesec and associated Beecher and Pemene Formations (Hall, 1971; Cudzilo, 1978). These samples are chemically similar to rocks from the Flin Flon and Hastings Proterozoic regions of Canada (Moore, 1977) which contain both calc-alkalic and tholeiitic units (Fig. 6). Quinnesec volcanism was conspicuously more complex than the rest of the Penokean volcanic belt. There is, in addition, the impression of possible iron enrichment in the northeast relative to the rest of the belt (Fig. 6). This phenomenon probably indicates a fundamental change in the character of arc volcanism from southwest to northeast.

STRUCTURE OF THE VOLCANIC BELT

The structural complexities encountered in the northern Penokean terrane are discussed in Cannon (1973) and Klasner (1978), specifically for northern Michigan. The structural geology of the Penokean volcanic belt has never been studied in any detail. However, in spite of limited exposure, enough data, including much from the authors' own study, are now available to draw some general conclusions regarding the structural history of this area.

Although the typical style of deformation is not greatly different in the volcanic belt, the effects of large gneiss-dome development are only observed in the northern Penokean terrane, that is, north of the Niagara fault and its continuation to the west (Fig. 9). South of the fault, the most pervasive structural element is a penetrative foliation

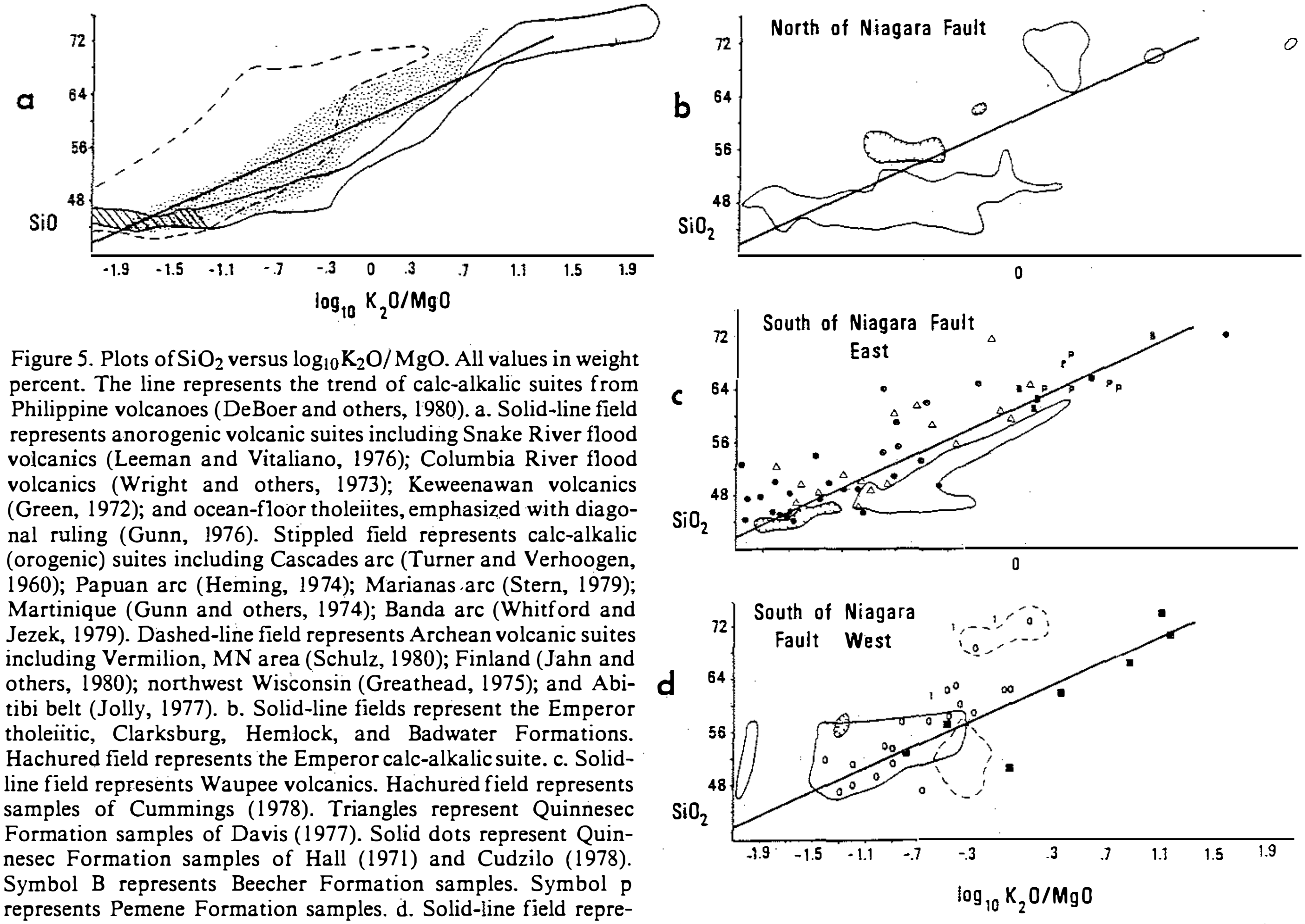


Figure 5. Plots of SiO_2 versus $\log_{10}K_2O/MgO$. All values in weight percent. The line represents the trend of calc-alkalic suites from Philippine volcanoes (DeBoer and others, 1980). a. Solid-line field represents anorogenic volcanic suites including Snake River flood volcanics (Leeman and Vitaliano, 1976); Columbia River flood volcanics (Wright and others, 1973); Keweenawan volcanics (Green, 1972); and ocean-floor tholeiites, emphasized with diagonal ruling (Gunn, 1976). Stippled field represents calc-alkalic (orogenic) suites including Cascades arc (Turner and Verhoogen, 1960); Papuan arc (Heming, 1974); Marianas arc (Stern, 1979); Martinique (Gunn and others, 1974); Banda arc (Whitford and Jezek, 1979). Dashed-line field represents Archean volcanic suites including Vermilion, MN area (Schulz, 1980); Finland (Jahn and others, 1980); northwest Wisconsin (Greathead, 1975); and Abitibi belt (Jolly, 1977). b. Solid-line fields represent the Emperor tholeiitic, Clarksburg, Hemlock, and Badwater Formations. Hachured field represents the Emperor calc-alkalic suite. c. Solid-line field represents Waupee volcanics. Hachured field represents samples of Cummings (1978). Triangles represent Quinnesec Formation samples of Davis (1977). Solid dots represent Quinnesec Formation samples of Hall (1971) and Cudzilo (1978). Symbol B represents Beecher Formation samples. Symbol p represents Pemene Formation samples. d. Solid-line field represents Monico area samples. Hachured-line field represents Ladysmith area samples (Edwards, 1920). Dashed-line field represents Rhinelander area samples (Bowden, 1978). Solid squares represent Marathon County Samples. Symbol 0 represents Eau Claire-Chippewa-Jump River area samples. Symbol 1 represents Ladysmith area samples (May, 1977).

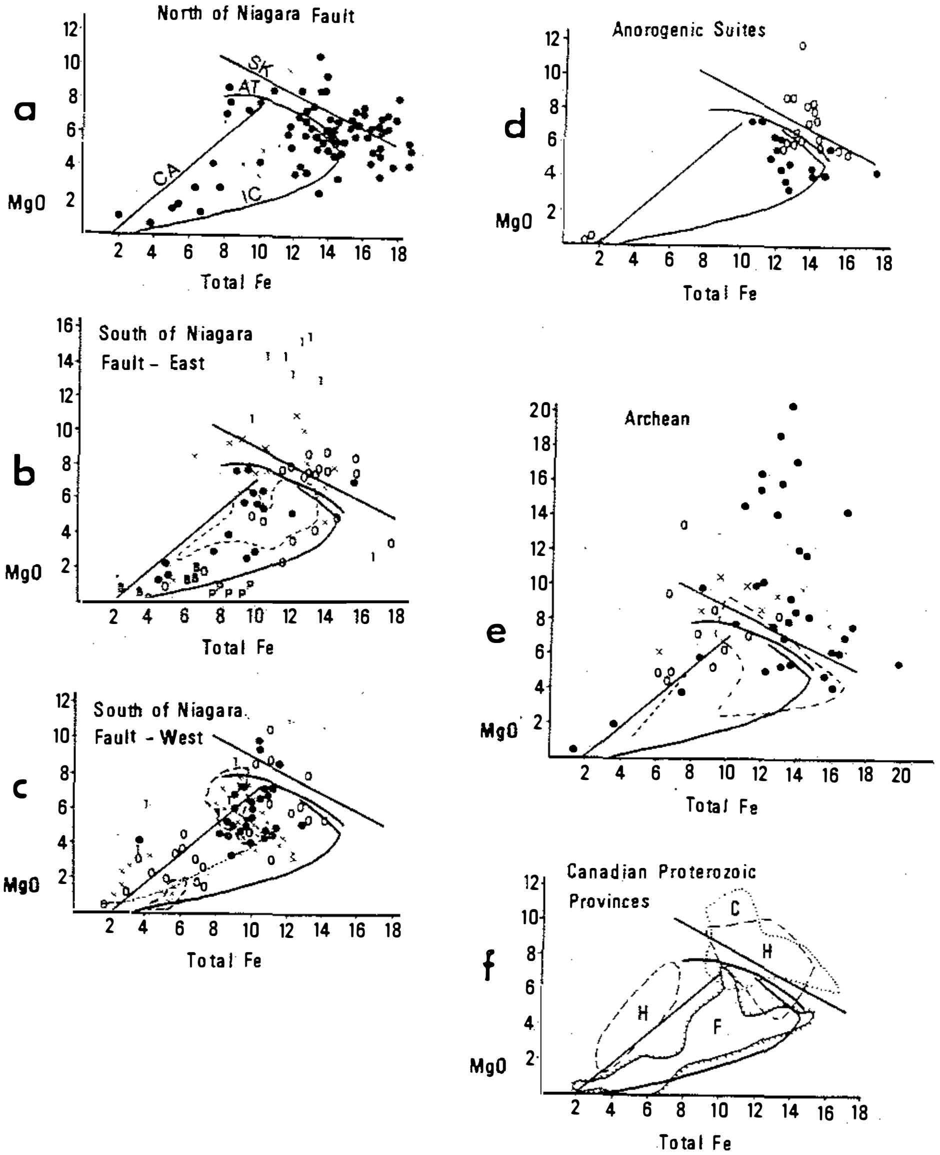
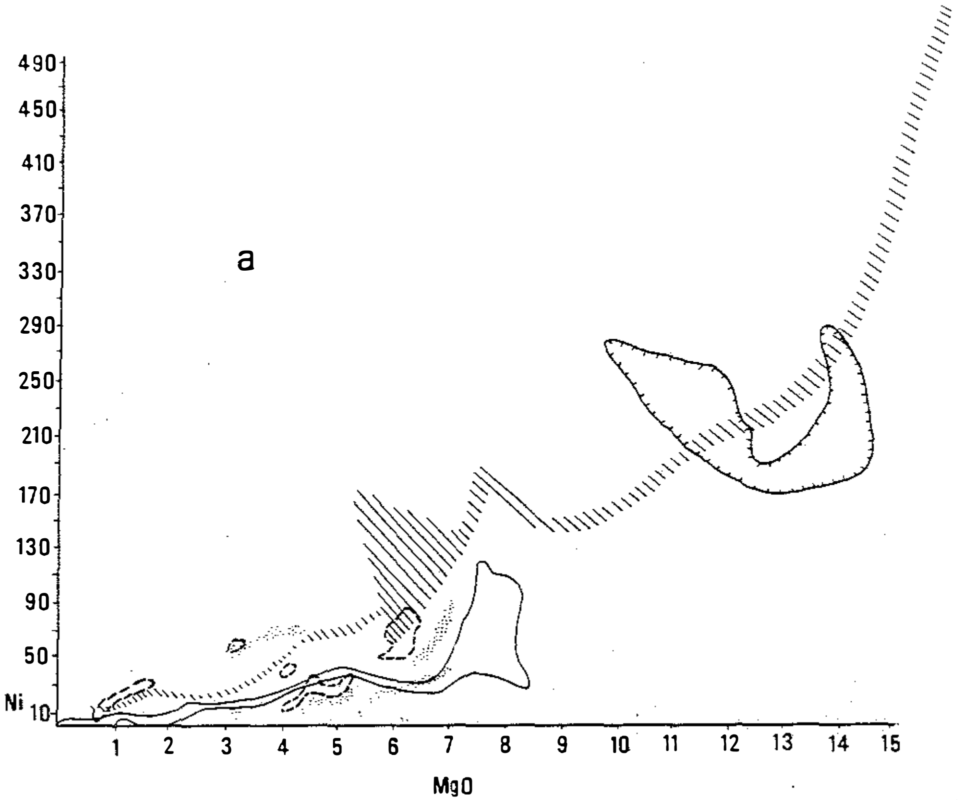


Figure 6. Plots of total iron versus MgO. All values in weight percent. Trends (from Moore, 1977) on all diagrams include SK, Skaergaard; AT, abyssal tholeiites; CA, cascades; and IC, Iceland. a. Solid dots represent the Emperor tholeiitic, Clarksburg, Hemlock, and Badwater volcanic Formations. Symbol x represents Emperor calc-alkalic suites. b. Dashed-line field represents Waupee samples. Solid dots represent Quinnesec Formation samples of Davis (1977). Symbol x represents Quinnesec Formation samples of Hall (1971). Symbol 0 represents Quinnesec Formation samples of Cudzilo (1978). Symbol B represents Beecher Formation samples. Symbol p represents Pemene Formation samples. Symbol l represents samples of Cummings (1978). c. Dotted-line represents trend of Papuan arc volcanics (Heming, 1974). Dashed-line field represents Marathon County samples. Solid dots represent Monico area samples. Symbol x represents samples of Rhinelander area samples (Bowden, 1978). Symbol 0 represents Eau Claire-Chippewa-Jump River area samples (Myers and others, 1980). Symbol l represents Ladysmith area samples (Edwards, 1920; May, 1977). d. Solid dots represent Columbia River flood-volcanics (Wright and others, 1973). Symbol 0 represents Snake River flood-volcanics (Leeman and Vitaliano, 1976). e. Dashed-line represents "primitive" calc-alkalic trend (Jolly, 1977). Dashed-line field represents Abitibi tholeiitic samples (Jolly, 1977). Solid dots represent Finnish greenstone belt samples (Jahn and others, 1980). Symbol x represents Vermilion greenstone belt samples (Schulz, 1980). Symbol 0 represents northwest Wisconsin samples (Greathead, 1975). f. All fields are of Canadian lower Proterozoic volcanic suites (Moore, 1977). H, dashed-line field represents Hastings area volcanics. C, dotted-line field represents Circum-Ungava belt volcanics. F, hachured-line field represents Flin Flon area volcanics.



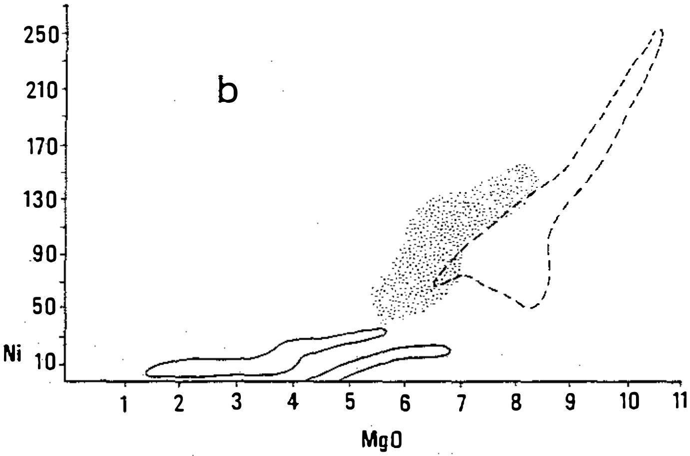


Figure 7. Plot of Ni versus MgO. Ni values in parts per million. MgO in weight percent. a. Solid-line field represents Quinnesec, Beecher, and Pemene Formations (Cudzilo, 1978). Dashed-line fields represent Clarksburg, Hemlock, and Badwater samples (Cudzilo, 1978). Stippled fields represent Waupee samples (Lahr, 1972; Cudzilo, 1978). Hachured-line field represents samples from Cummings (1978). Diagonally ruled field represents Archean suites (Condie, 1976a; Jahn and others, 1980; Schulz, 1980). b. Solid-line fields represent island arc suites (Heming, 1974; Gunn and others, 1974; Stern, 1979). Dashed-line field represents ocean-floor and mid-ocean ridge suites (Bougault and Hekinian, 1974). Stippled field represents continental flood volcanics (Leeman and Vitaliano, 1976).

associated with isoclinal folding during the Penokean orogeny. The folding is responsible for the steep to overturned dips of most bedded rocks in the belt. The axial trend of Penokean folding is east to northeast in the extreme western part of the belt, gently arching through the Marathon County–Rhinelander region, and east to southeast in Florence and Marinette Counties (Fig. 9). Major northeast- to east-trending faults are subparallel with the primary foliation and fragment the belt into many subregions or structural blocks. Fault displacement directions or magnitudes cannot be determined from the available data. Secondary features, such as crenulations, cross-cutting open folds, and folded lineations are common, particularly in areas of 1,850-m.y.-old plutonic activity. The secondary fold axial planes typically trend northwest to northeast.

Excellent examples of Penokean structures can be observed in northeastern Wisconsin. Here, anticlines and synclines several kilometres across have been mapped in both Penokean terranes. In the Marquette Range Supergroup (Bayley and others, 1966; Dutton, 1971), these large folds have been refolded and then faulted in a series of steps, exposing lower crustal levels to the south, up to the Niagara fault and the Quinnesec Formation. The Quinnesec Formation also contains large isoclinal folds, some of which are doubly plunging (Jenkins, 1973; Cummings, 1978). Cross-folds, well-developed lineations, flattened clasts, ductile shear zones, and other intense deformational features in the Quinnesec appear to be related to Penokean plutons rather than to any earlier complexity.

Due to the lack of continuous exposure, the regional

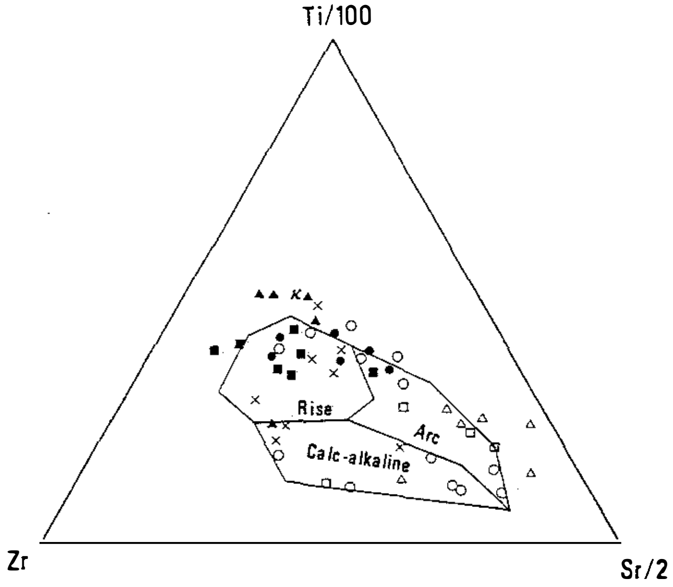


Figure 8. Ternary plot of Zr-Ti-Sr. Solid squares represent Hemlock Formation samples (Cudzilo, 1978). Solid dots represent Badwater Formation samples (Cudzilo, 1978). Solid triangles represent Clarksburg Formation samples (Cudzilo, 1978). Circles represent Quinnesec Formation samples (Cudzilo, 1978). Open triangles represent Waupee volcanics (Cudzilo, 1978). Open squares represent Monico area samples (J. Hallberg, unpub. data). Symbol *K* represents Keweenawan basalt average (Green, 1972). Symbol x represents Archean samples (Condie, 1976a; Cudzilo, 1978).

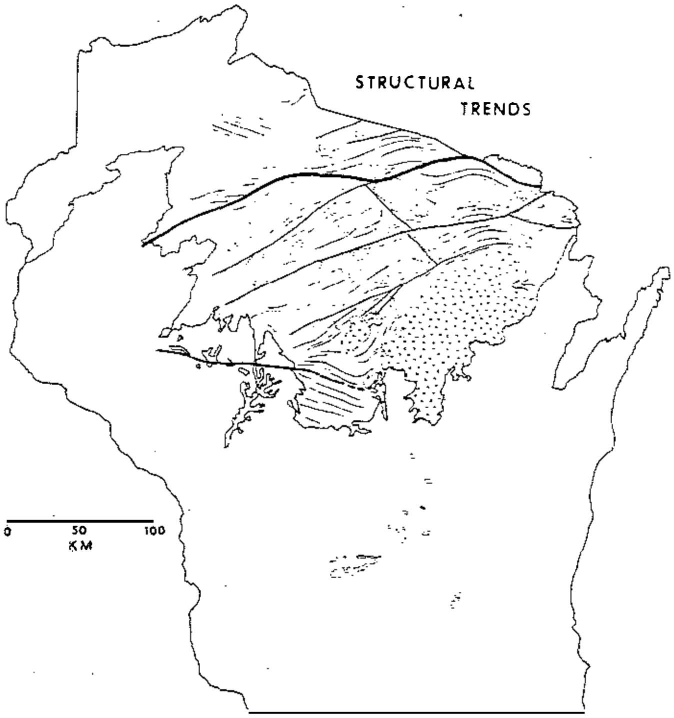


Figure 9. Structural trends in the Penokean terranes of northern Wisconsin. Heavy lines indicate major Penokean tectonic boundaries. Lighter lines indicate trends of faults and foliation. Penokean intrusive rocks are shown in pattern. Structural data and lithologic boundaries from Greenberg and Brown (1980) and Wisconsin Geological and Natural History Survey (1981).

structure of most of the western portion of the volcanic belt is poorly understood. Volcanogenic rocks in the Monico area have been refoliated near major east-west faults. Some of these rocks also show strong flattening and lineation near discrete plutons (Venditti, 1973). Bowden (1978) proposed the existence of a major antiform in the Pelican ore body, but similar features are not exposed in the Rhinelander area. In Marathon County, a pattern of broad folds with well-developed foliation has been observed by LaBerge and Myers (in prep.). Locally complex deformation in Marathon County is similar to that in areas to the northeast. There is also the possibility of some post-Penokean structures introduced in association with intrusion of the Wolf River batholith (Brown and Greenberg, 1981).

The structural geology of the Penokean volcanic belt can best be summarized as simple folding parallel to the belt axis, followed by faulting and plutonism in a continuous deformation sequence. Increased strain during the Penokean orogeny tightened folds into isoclines and imposed strong axial planar foliations. Local complexity can most often be attributed to stress regimes near plutons and faults in a relationship similar to that observed between plutonism and metamorphism (Fig. 10).

REGIONAL METAMORPHISM WITHIN THE PENOKIAN VOLCANIC BELT

Dutton and Bradley (1970) and Morey (1978) have provided summaries of Precambrian metamorphic patterns in Wisconsin. This work has been updated through recent bedrock mapping (Greenberg and Brown, 1980), which has enabled an improved understanding of the relationship of metamorphism to rock types and structure.

The metamorphism of Penokean rocks can be summarized in terms of contrasting patterns north and south of the Niagara fault. Well-documented metamorphic patterns and mineral assemblages in the northern Penokean terrane are defined by bullseye-type nodes (James, 1955; Cannon, 1973). The nodes have been attributed to basement uplifts and are outlined by annular successions of diagnostic mineral assemblages. The resulting metamorphic zones are well developed in pelitic metasedimentary rocks. However, the relative scarcity of outcrops in general and metapelites in particular south of the Niagara fault have made the definition of metamorphic zones much more difficult in the Penokean volcanic belt. In mafic rocks, such as metabasalts and metaandesites, amphibolite-facies conditions are often

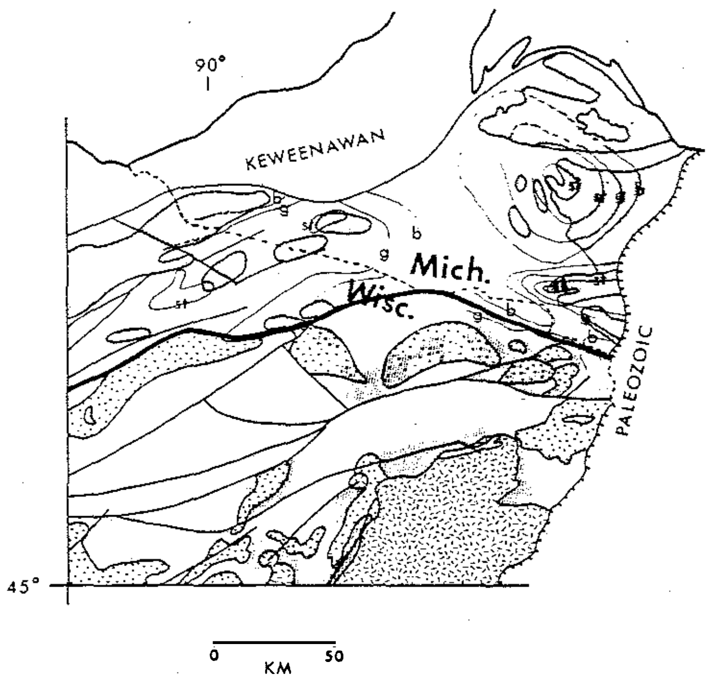


Figure 10. Map of portions of northern Wisconsin and northern Michigan showing nodal metamorphic patterns in the northern Penokean terrane and more localized metamorphism in the Penokean volcanic belt. Major faults are shown in Wisconsin. Archean gneisses and granites are shown by shading. Penokean gneisses and granites are shown by a dotted pattern. The Wolf River batholith granites and syenite are shown by a random dash pattern. Metamorphic isograds are outlined in the northern Penokean terrane. Mineral zones appear as follows: si-sillimanite; st-staurolite; g-garnet; b-biotite. A lined pattern represents areas in the Penokean volcanic belt with amphibolite facies metamorphic assemblages. Modified from James (1955), Dutton and Bradley (1970), Sims (1976), and Greenberg and Brown (1980).

indicated by metamorphic hornblende instead of actinolite, which is stable in most greenschist assemblages. Garnet and biotite were also commonly noted in mafic metatuffs of amphibolite facies. Many metarhyolites exist in areas affected by middle amphibolite-facies metamorphism, but these rocks only show subtle changes, such as recrystallization and chemical-structural transformation of micas, feldspars, and so forth.

It is commonly recognized (Morey, 1978) that the Penokean volcanic belt is predominantly greenschist facies. Rocks of higher metamorphic grade appear to be localized near plutons and in limited areas of intense deformation, such as between plutons or along major structural boundaries (Fig. 10). There is little reason to suspect that this metamorphic intensity correlates with any particular age distinction among Penokean volcanic units. There is also no indication in the Penokean volcanic belt of nodal metamorphic patterns even proximal to Archean gneisses along the southern margin of the volcanic belt (Fig. 1). This contrasts with the nature of Archean basement involvement in the northern Penokean terrane.

Higher grades of metamorphism are developed in deformed granitic rocks of Penokean and Archean age, both within and peripheral to the volcanic belt, respectively. Within the belt, amphibolite-facies metavolcanic and metasedimentary units occur in areas of great structural complexity, such as along the Chippewa River Valley (Myers and others, 1980), in the Mountain area (Lahr, 1972), or in the Rib River area in western Marathon County (LaBerge and Myers, in prep.). Some of these rocks are migmatitic and can be explained by the invasion of magmas or the exposure of deeper levels of erosion, or both.

Within a few kilometres of the northern and eastern periphery of the Wolf River batholith (Fig. 1), staurolite and garnet-bearing assemblages have been attributed to intrusion-related post-Penokean deformation (Brown and Greenberg, 1981; Fig. 10). Some metamorphism related to the intrusion of the Wolf River batholith was characterized by static porphyroblast growth, but in many areas there was also the attendant development of deformational fabrics.

No broad, regional metamorphic patterns are known or would be necessarily expected to accompany the anorogenic 1,760-m.y.-old magmatic event in Wisconsin. There is, however, isotopic and possibly mineralogic evidence for a dynamo-thermal "event" in Wisconsin 1,600 ± m.y. ago (Van Schmus, 1980; Sims and Peterman, 1980; Brandon and others, 1980; Brown and Greenberg, 1981; Geiger and others, 1982). Although direct evidence of 1,600-m.y.-old magmatism is not known in Wisconsin, Brown and Greenberg (1981) have suggested that much localized metamorphism and various complex structural features in central Wisconsin may be related to anorogenic uplift and pluton intrusion at this time. Just how much of the metamorphism and deformation in Wisconsin is actually post-Penokean is difficult to assess at present.

TECTONIC GENESIS OF THE PENOKEAN OROGENY IN WISCONSIN

Because the Penokean volcanic belt of northern Wisconsin is between an Archean craton to the north and some Archean rocks exposed to the south (Fig. 1), different concepts of its evolution must account for the preceding Archean tectonism. These concepts are discussed below and by Larue and Sloss (1980).

The most commonly accepted view of Archean shield development in the southern Lake Superior region is summarized in Sims (1976) and further developed in Sims (1980). In this model, two crustal blocks, a granite-greenstone terrane and an older, northern, gneiss terrane, were welded together in the Archean to form the "basement" for all younger rocks in the region. No other published interpretations have challenged the concept of

Archean tectonics presented in this model. Sims (1976, 1980) also invoked a crustal foundering mechanism to explain the deposition of lower Proterozoic sedimentary and volcanic material in an intracratonal basin upon the Archean crust. The foundering process implies subsidence but not the actual development of rifting. Penokean deformation, metamorphism, and intrusion were attributed to reactivation of the suture between the two Archean terranes.

Although Archean-age rocks are known from only the extreme northwest and southern fringe of the exposed Precambrian in Wisconsin (Fig. 1), it has been suggested that highly deformed and metamorphosed amphibolites within the Penokean volcanic belt are probably Archean (Sims and Peterman, 1980; LaBerge and Myers, in prep.). Sims (1980, p. 115) has also asserted that all gneisses in the region are likely Archean because the Penokean orogeny "was not a gneiss-forming event." If true, this supposition would place specific constraints on tectonic interpretations of the Proterozoic. However, age data (Van Schmus, unpub. data) have shown that at least all the analyzed gneisses from within the Penokean volcanic belt are Penokean, and these obviously indicate "gneiss-forming" conditions after Archean time. As in Wisconsin, investigators once assumed that the lower Proterozoic Flin Flon belt of Manitoba was composed of Archean rocks. In spite of apparent similarities with Archean terranes, dated rock units in the Flin Flon and Penokean volcanic belts are younger.

Another view of the Penokean is based predominantly on radiometric age data and rock distribution (Van Schmus, 1976). In this model, the Penokean is considered as an analogue of Phanerozoic compressive orogenies, with tectonism concentrated along a south-facing margin of the Superior shield. The Archean gneisses south of the Penokean volcanic belt lack the evidence to be considered as inliers of a basement continuous with the Archean craton to the north. More plausible explanations for these exposures are that they may represent rifted continental (cratonic) fragments, or "a microcontinent that was accreted onto the Superior craton during the Penokean Orogeny and formed part of the crust upon which an arc was developed" (Van Schmus and Bickford, 1981, p. 284). A modification of the plate-tectonic idea includes Cambray (1978), which emphasized rifting prior to collisional orogeny along the craton margin. Larue and Sloss (1980) later refined the rifting-sediment interpretations of Cambray (1978). In each case, the concept of collisional orogeny requires a tectonic suture (the Niagara fault) where the Penokean material was welded to the craton. The Niagara fault is also the boundary between the continental margin (northern Penokean terrane) and volcanic arc (Penokean volcanic belt) regimes in the plate-tectonic reconstruction. At present, the fault can be geophysically delineated as the surface separating two crustal blocks of contrasting density (Davis, 1977) and magnetic signature (Zietz and others, 1977).

A most significant contribution to the understanding of the Penokean has been made by Van Schmus and Bickford (1981). They examined these particular rocks along with all other Proterozoic belts in the U.S. midcontinent. The authors discussed several versions of a model to explain the succession of younger magmatic provinces (belts) away from the Archean craton in the north (Fig. 5 in Van Schmus and Bickford, 1981). Their tentative conclusion was that this succession resulted from the progressive accretion and subsequent cratonization of new crust, beginning with the Penokean terranes.

The Penokean material accreted to the Archean craton is similar in many ways to more modern orogenic suites. However, some factors complicate the direct adaptation of a modern plate-tectonic continental margin or island arc model to the Penokean orogeny. As Van Schmus and Bickford (1981) mentioned and in contrast to the interpretation of Upadhyay and Ard (1980), there are no good candidates for ophiolite suites in either Penokean terrane. Known mafic-ultramafic rock complexes in the region are poorly preserved and appear more similar to Archean complexes than modern ophiolites. Penokean metamorphism is also more typical of that in Archean granite-greenstone terranes, where the geometry of metamorphic zones is intimately associated with plutons and local sites of intense deformation (Jolly, 1978). Structural development as a result of the Penokean orogeny is sympathetic with metamorphism, which means that major Penokean structures do not include the horizontal components commonly associated with thrusting and multiphase folding in Phanerozoic orogenies. Vertical tectonic styles are dominant both in Wisconsin (Greenberg and Brown, 1980; Brown and Greenberg, 1981) and in the Upper Peninsula of Michigan (Cannon, 1973; Klasner, 1978). Even along the possible tectonic suture, represented by the Niagara fault (Fig. 1), there is little indication of thrusting (Dutton, 1971: Greenberg and Brown, 1980).

There are problems in directly attributing the Penokean orogeny to simple plate-tectonic processes. However, both Archean and rifting origins for the Penokean volcanic belt are unlikely, and some types of collisional orogeny may be the closest analogue. The structural and metamorphic similarities with tectonism in Archean greenstone belts could indicate that the Penokean event was somewhat transitional in tectonic character between Archean and plate-tectonic orogenies.

Late or post-Penokean age (1,760 m.y. ago; Smith, 1978) volcanism is evident south of the exposed volcanic belt in Wisconsin. The 1,760-m.y.-old volcanic rocks are all rhyolitic and are associated with potassic granites of the same age. The granite-rhyolite suite has been considered as late Penokean, but it is more likely post-Penokean in that the rocks indicate a change to anorogenic tectonism (Anderson and others, 1980). Anorogenic magmatism continued throughout the midcontinent during most of Precambrian time.

SUMMARY AND CONCLUSIONS

Previously uncompiled data from Wisconsin and northern Michigan reveal various aspects of lower Proterozoic volcanism and related tectonism which are considered unique in the midcontinent (Van Schmus and Bickford, 1981). Penokean-age (about 1,900 to 1,850 m.y. ago) volcanic rocks in the Lake Superior region occur in two fundamentally different terranes. Age data suggest that volcanic rocks in the northern Penokean terrane are about 50 m.y. older than those in the Penokean volcanic belt (Van Schmus and Bickford, 1981). The two-terrane tectonic framework is similar to that discussed by Sims (1976; 1980) for the Archean in the same region. The Penokean terranes are separated by the northeast-southwest-trending Niagara fault, which is clearly defined in northeast Wisconsin but can only be traced west by its geophysical signature beneath glacial overburden to the west. The two terranes on either side of the fault represent two distinct tectonic environments whose major contrasts are listed in Table 3.

Penokean sedimentation in the northern terrane indicated increasing tectonic instability and crustal subsidence (Cambray, 1978; Larue and Sloss, 1980). Larue and Sloss (1980) mentioned that the change from platformal clastic and carbonate sediments to turbidites and volcanic materials signaled continental rifting. Prolonged rift development led eventually to a continental margin environment. Volcanic activity in the northern Penokean terrane was dominated by flood basalts and bimodal basalt-rhyolite suites. Chemically, these rocks are equivalent to modern continental-rift suites and some from ocean floor and ridge environments. The calc-alkalic suite from the Emperor Complex (Dann, 1978) may have developed from an Andean-type continental arc on the rifted margin. Descriptions of Penokean-age rocks from Minnesota (Morey, 1972) and the Southern Province of Ontario (Card and others, 1972) make it clear that these areas are continuations of the northern Penokean terrane.

We have shown that volcanic and associated sedimentary rocks in the southern terrane (Penokean volcanic belt) exhibit volcanic arc-derived characteristics. Limited stratigraphic information indicates that depositional sequences in some areas began with basalt-rich lower units, with apparent gradations upward through andesites to more felsic volcanic materials and related clastic sediments. Centers of exhalative activity associated with felsic volcanism are suggested by minor iron formations and massive sulfide mineralization (May, 1977; Cummings, 1978; Bowden, 1978; Schmidt and others, 1978). Sporadic occurrences of metasedimentary rock types such as graphitic slate, calc-silicate marble, volcanic conglomerate, and slumped turbidites interbedded with flows and tuffs suggest widely variable depositional environments. Observed depositional features such as pillow lavas and sedimentary structures strongly favor subaqueous over subareal environments within the volcanic belt.

TABLE 3. SPECIFIC CONTRASTS BETWEEN THE TWO PENOKEAN TERRANES

Northern Penokean Terrane	Penokean Volcanic Belt
1) Contains rocks including gneisses dated older than 1860 m.y. (Archean)	1) Contains no rocks dated older than about 1860 m.y.
2) Contains abundant thick sedimentary units and subordinate amounts of tholeiitic volcanic rocks	2) Contains abundant calc-alkalic volcanic rocks and subordinate amounts of diverse sediment types
3) Volcanic rocks dated at 1900 m.y.	3) Volcanic rocks dated at 1850 m.y.
4) Contains major iron formations	4) Contains no major iron formations
5) Contains very few Penokean plutonic rocks	5) Contains large volumes of Penokean plutonic rocks
6) Metamorphism defined by nodal patterns	6) No evidence of nodal metamorphic patterns
7) Contains mantled gneiss domes cored by Archean rocks	7) Contains no mantled gneiss domes

The chemistry of volcanic suites south of the Niagara fault are dominantly calc-alkalic. The greater abundance of iron and tholeiitic characteristics noted in Waupee and Quinnesec suites is a reflection of the complex volcanism taking place south of a continental margin. Samples of Waupee volcanic units cannot be classified as alkaline, but they are significantly more alkaline and iron-rich than other suites to the west. Quinnesec Formation samples range into ocean-floor tholeiitic fields on chemical variation diagrams. Pemene Formation samples, also from northeastern Wisconsin, follow an Icelandic trend on the total Fe/MgO diagram (Fig. 6).

Several gabbroic intrusions occurring near the Niagara fault in the northeast Quinnesec area (Prinz, 1959; Dutton, 1971; Greenberg and Brown, 1980) may suggest the possibility of tensional tectonics on a local scale, or they could have intruded along the boundary between Penokean terranes. However, even the more tholeiitic suites south of the fault need not be equated with those in the northern terrane. The large proportion of fragmental volcanic rocks (Garcia, 1978), abundances of andesites (Fig. 4), and common occurrence of chemically intermediate plutons (diorite, tonalite, granodiorite) are orogenic characteristics unique to the southern terrane. These details and the paucity of confirmed Archean basement in the volcanic belt tend to argue against the Penokean basin concept of Sims (1976, 1980).

The Penokean volcanic belt does have a possible analogue in the island arc environments of the modern western Pacific Ocean. Among these arcs, sedimentation is con-

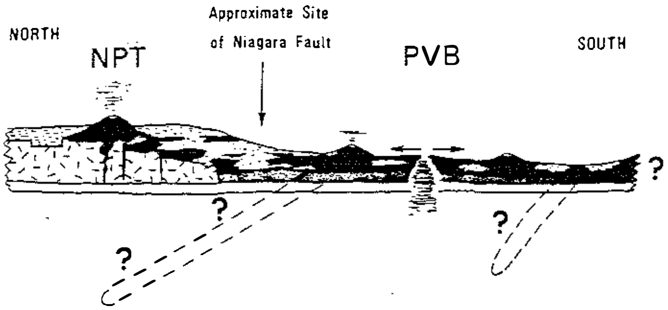


Figure 11. Cross-section of possible plate-tectonic environments for the NPT (northern Penokean terrane) and the PVB (Penokean volcanic belt). Horizontal arrows represent possible interarc spreading. Large dashes and question marks suggest possible subduction. Black areas represent volcanogenic materials of the Andean-type in the NPT and of island arcs in the PVB. Sedimentary materials are represented by a small, dashed pattern. Random dashes represent Archean continental crust. Oceanic crust and the lower crust are represented by a shaded pattern and no pattern, respectively.

trolled by complex, isolated sources including volcanic centers and small interarc basins. Limited interarc spreading and small ocean environments might explain the presence of localized tholeiitic magma generation in the northeastern part of Wisconsin.

It is our conclusion that the best explanation for the origin of Penokean volcanism consists of a rifted continental margin and continental arc that existed north of the proposed suture and a complex island arc situated to the south (Fig. 11). This concept is compatible with previous reconstructions (Van Schmus, 1976; Cambray, 1978; Larue and Sloss, 1980). Existing data limit any more detailed comparisons with modern plate-tectonic environments. We also acknowledge that metamorphic and structural features illustrating the culmination of the Penokean orogeny may not have simple modern analogues. In this one respect the Penokean terranes resemble Archean greenstone belts. However, Penokean volcanic rocks are chemically distinct from Archean magmas and may be products of a primitive style of plate tectonics.

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