

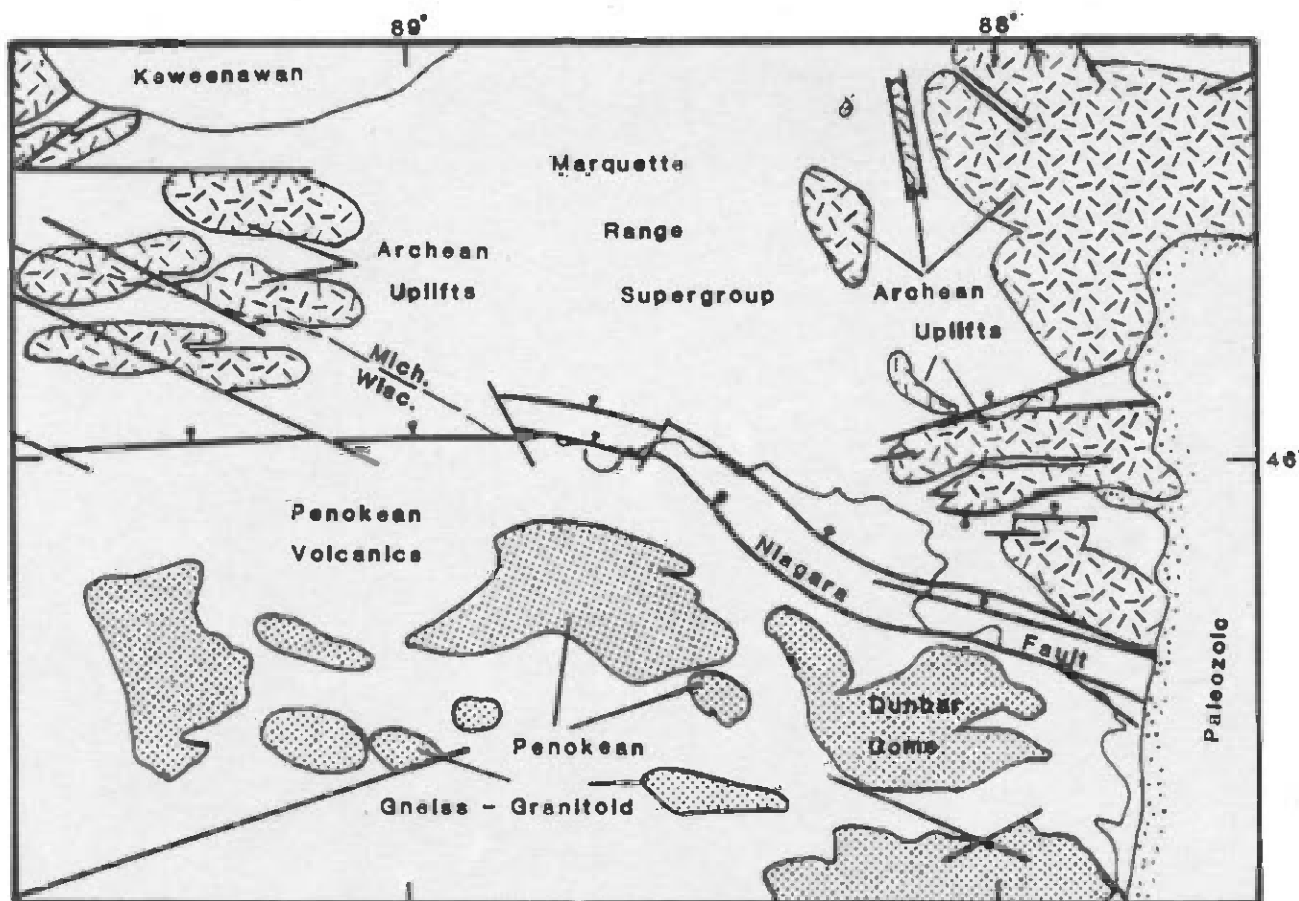
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FIELD TRIP 1

GUIDE TO THE GEOLOGY OF THE EARLY PROTEROZOIC ROCKS IN NORTHEASTERN WISCONSIN



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Guide to the Geology of the Early Proterozoic Rocks
in Northeastern Wisconsin

Field trip leaders

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DUNBAR GNEISS-GRANITOID DOME

By

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Introduction

As a part of regional investigations of the geology of the Precambrian rocks in the eastern part of the Lake Superior region (Michigan and Wisconsin), northeastern Wisconsin was chosen as one of the key areas for study because of its apparently unique geology and relatively abundant outcrop. In particular, the Dunbar dome and adjacent areas were chosen for emphasis. This terrane contains varied gneisses, amphibolite, and abundant granitoid rocks, all of Early Proterozoic age, and contrasts markedly with the adjacent terrane in northern Michigan. The study area also is a part of the Early Proterozoic east-trending volcanic belt in northern Wisconsin that contains economically promising strata-bound massive sulfide deposits. In addition, northeastern Wisconsin provides the opportunity to further study the age, extent, and cause of Middle Proterozoic events that reset Rb-Sr whole-rock and mineral ages throughout most of the eastern part of the Lake Superior region, as first noted by Aldrich and others (1965).

This summary of the geology, geochronology, and geochemistry of the rocks within and adjacent to the Dunbar dome is derived from papers in preparation by us and previous publications on the regional geology of adjacent areas to the north (Bayley and others, 1966; Dutton, 1971). Earlier reports on the ages of rocks in the general area by Banks and Cain (1969), Banks and Rebello (1969), Van Schmus, Thurman, and Peterman (1975), and Van Schmus (1980) were extremely useful.

R. A. Jenkins, M. G. Mudrey, Jr., and W. C. Prinz introduced us to the geology of the area, and together with many others stimulated our interest in the geology and mineral potential.

Summary of Geology

The Dunbar dome is one of several domes in northern Wisconsin that have cores of gneiss, migmatite, and granitoid rocks and are mantled by metavolcanic and metasedimentary rocks. Both the basement (core) and the mantle (cover) are of Early Proterozoic age. The domes occur within an east-trending curvilinear, convex northward belt at least 60 km wide that lies adjacent to the boundary of this terrane (Wisconsin magmatic zone) with the Michigan terrane to the north. The Michigan terrane, as defined here, consists of epicratonic metasedimentary and metavolcanic rocks (Marquette Range Supergroup) that unconformably overlie Archean basement rocks (Sims, Card, and Lumbers, 1981). The proposed boundary (Larue, 1983) between the two terranes is the Niagara (or Florence-Niagara) fault zone.

The domes in northern Wisconsin provide windows that expose parts of an extensive deeper crustal succession that lies beneath the thick pile of metavolcanic rocks in northern Wisconsin. Apparently, an Archean basement is lacking. However, a Nd-Sm isotopic study of two samples of Dunbar Gneiss (Cain, 1964) yielded ages of 2,130 Ma and 2,280 Ma, which probably indicates a component of Archean material in the source or a small degree of contamination of the magma during its ascent through Archean crust. Lead-isotope data on massive sulfide deposits and associated rocks in the Early Proterozoic belt of metavolcanic rocks in northern Wisconsin support this conclusion (Afifi and others, in press).

The Dunbar dome is a complex antiformal structure consisting of a central core and three lateral protuberances from the core, named the Niagara, Pembine, and Bush Lake lobes, respectively (fig. 1). The dome occupies an area of about 470 km². The stratigraphic-tectonic evolution of the dome spanned the relatively short time of about 30 Ma, from about 1,865 Ma to 1,835 Ma ago, during the Early Proterozoic. The dome coincides with a deep gravity depression of about 20 milligals (Ervin and Hammer, 1974), which is the southeasternmost low of a family of lows that extend about 35 km to the northwest.

The central core of the Dunbar dome is composed of biotite gneisses, migmatite, granite gneiss, and amphibolite, assigned to the Dunbar Gneiss of Cain (1964), and three granitoid bodies, which he called the Marinette Quartz Diorite, a megacrystic phase of the Newingham Tonalite (included by Cain (1964) in the Dunbar Gneiss), and a large elliptical body of Hoskin Lake Granite. The Niagara and Bush Lake lobes are composed of two other bodies of granite, which differ somewhat from the Hoskin Lake Granite. The Pembine lobe consists mainly of the Newingham Tonalite (formerly called Newingham Granodiorite by Cain, 1964). The granitoid bodies intruded the Dunbar Gneiss and a narrow fringing zone of the mantling Quinnesec Formation (volcanic succession) and stratigraphically older metasedimentary rocks, and apparently were emplaced in the order, from oldest to youngest, Marinette Quartz Diorite, Newingham Tonalite, and Hoskin Lake Granite. Granite pegmatite and aplite are abundant throughout the dome, especially in the Dunbar Gneiss. K-metasomatism, which was approximately contemporaneous with emplacement of the Hoskin Lake Granite, appreciably modified rock compositions in the northern part of the central core subsequent to their crystallization. Potassium was introduced during or after a cataclastic (ductile) deformation that recrystallized plagioclase and other minerals, to yield core-mantle (or mortar) textures and shears. The granitoid bodies were emplaced at relatively shallow crustal depths.

The supracrustal (cover) rocks compose a steeply dipping succession that dominantly faces stratigraphically outward from the core. They consist mainly of metavolcanic rocks and layered, mafic sills, assigned to the Quinnesec Formation, and coeval subvolcanic rocks (Twelve Foot Falls Quartz Diorite of Cain, 1964). The cover rocks also include a more local, thinner older succession of metasedimentary rocks, principally impure quartzite, stromatolitic marble, calc-silicate rocks, and biotite schist (metatuff?). The volcanic rocks are interpreted as having been deposited in deep water, whereas the sedimentary rocks have shallow-water attributes.

Granitoid rocks in the dome have general geochemical calc-alkaline characteristics, but the Marinette Quartz Diorite is slightly alkaline. The Dunbar Gneiss has relatively low Rb/Sr ratios (0.10-0.99) and steep rare earth element (REE) patterns ($[La/Yb]_n = 25-43$). They probably represent metamorphosed volcanic and related subvolcanic intrusive rocks. The Newingham Tonalite is compositionally homogeneous having high Sr (~690), low Rb-Sr (~0.066), and steep REE patterns ($[La/Yb]_n = 43$). It is compositionally similar to many Archean tonalites, and probably was derived by partial melting of a basaltic parent. The Hoskin Lake Granite and the closely associated granites of Spikehorn Creek and Bush Lake range in composition from granodiorite to granite, have relatively low Sr (58-300), high Th (23-40),

Rb/Sr >1, variable REE ($[La]_n = 57-163$), and negative Eu anomalies. The Marinette Quartz Diorite and Hoskin Lake Granite show overlapping major and trace element compositions, which apparently reflect partial K-metasomatism of the quartz diorite.

U-Pb zircon ages of rocks in the dome are clustered in the range 1,865 Ma to 1,835 Ma. The oldest rocks, the Dunbar Gneiss and the Quinnesec volcanics, are about 1,865 Ma old, whereas the Marinette Quartz Diorite and the Newingham Tonalite are inferred to be about 1,860 Ma. The youngest rock unit, the granite body of Spikehorn Creek in the Niagara lobe, has an age of $1,835 \pm 6$ Ma. Rb-Sr whole-rock and mineral ages are consistently reset and are 100 Ma or more younger than the zircon upper intercept ages, as discussed on following pages.

The Dunbar dome is interpreted as a large-scale fold-interference structure resulting from cross folding modified by diapirism and emplacement of the granitoid intrusive rocks. Many of the criteria indicative of diapirism, as listed by Brun and others (1981), are observed in the dome: (1) cleavage parallel to dome boundaries, (2) steeply plunging lineation in dome boundaries, and (3) higher strain intensities located on dome boundaries.

The Dunbar dome is surrounded by an asymmetrical annular zone of metamorphism in the cover rocks. An amphibolite-facies zone ranging from less than 0.5 km wide to at least 8 km wide lies adjacent to the core, and gives way outward to greenschist-facies rocks. The amphibolite zone is widest on the northern margin where it transects the Niagara fault zone (Dutton, 1971). Within the core, the Dunbar Gneiss has amphibolite-facies mineral assemblages, as does the northern part of the Marinette Quartz Diorite. The Dunbar Gneiss was metamorphosed during dynamothermal metamorphism accompanying D_1 ; whereas the annular metamorphic pattern, superposed on previously metamorphosed greenschist-facies supracrustal rocks during a late stage evolution of the dome, was dominantly the result of thermal metamorphism. Granite-tonalite dikes were emplaced into rocks in the amphibolite-facies zone during the younger thermal metamorphism.

The rocks in the Dunbar dome and surrounding environs compose part of a magmatic terrane, termed the Wisconsin magmatic zone, that differs in stratigraphy, structure, mineral deposits, and igneous rock chemistry from the epicratonic Michigan terrane to the north. Accordingly, we conclude that the Wisconsin magmatic zone evolved separately from the Early Proterozoic terrane to the north, and is an exotic terrane that was attached to the North American continent during the Early Proterozoic. Apparently the boundary between the two Proterozoic terranes is the Niagara fault, as suggested by Larue (1983). The doming was probably in response to collision of the two crustal blocks, which triggered the Penokean orogeny.

Rock Units

The Dunbar dome is composed of compositionally varied gneisses, assigned to the Dunbar Gneiss, and 5 younger intrusive units, which were emplaced, from oldest to youngest, in the order Marinette Quartz Diorite, Newingham Tonalite, Hoskin Lake Granite, granite of Bush Lake, and granite of Spikehorn Creek (fig. 1). The Marinette Quartz Diorite and the Hoskin Lake Granite were named

EXPLANATION (Figure 1)

MIDDLE PROTEROZOIC

Yd Diabase

EARLY PROTEROZOIC

Xsg Granite of Spikehorn Creek

Xbg Granite of Bush Lake

Xhg Hoskin Lake Granite

Xnt Newingham Tonalite

Xmqd Marinette Quartz Diorite

Xqd Twelve Foot Falls Quartz Diorite of Cain (1963)

Xmg Metagabbro sills

Xq Quinnesec Formation

Xms Metasedimentary rocks

Xdg Dunbar Gneiss of Cain (1964); includes abundant pegmatite and aplite and, in northeast part of central core, foliated intrusive megacrystic granodiorite

— Approximate contact

—  Fault, bar and ball on downthrown side

— Fault, relative movement not known

Facing direction of pillow lava

— — Metamorphic isofacies-gs, greenschist facies; am, amphibolite facies. After Bayley and others, 1966.

— — Metamorphic isograd-bi, biotite; gar, garnet. After Dutton, 1971.

Note: Rocks listed in inferred order, from youngest to oldest.

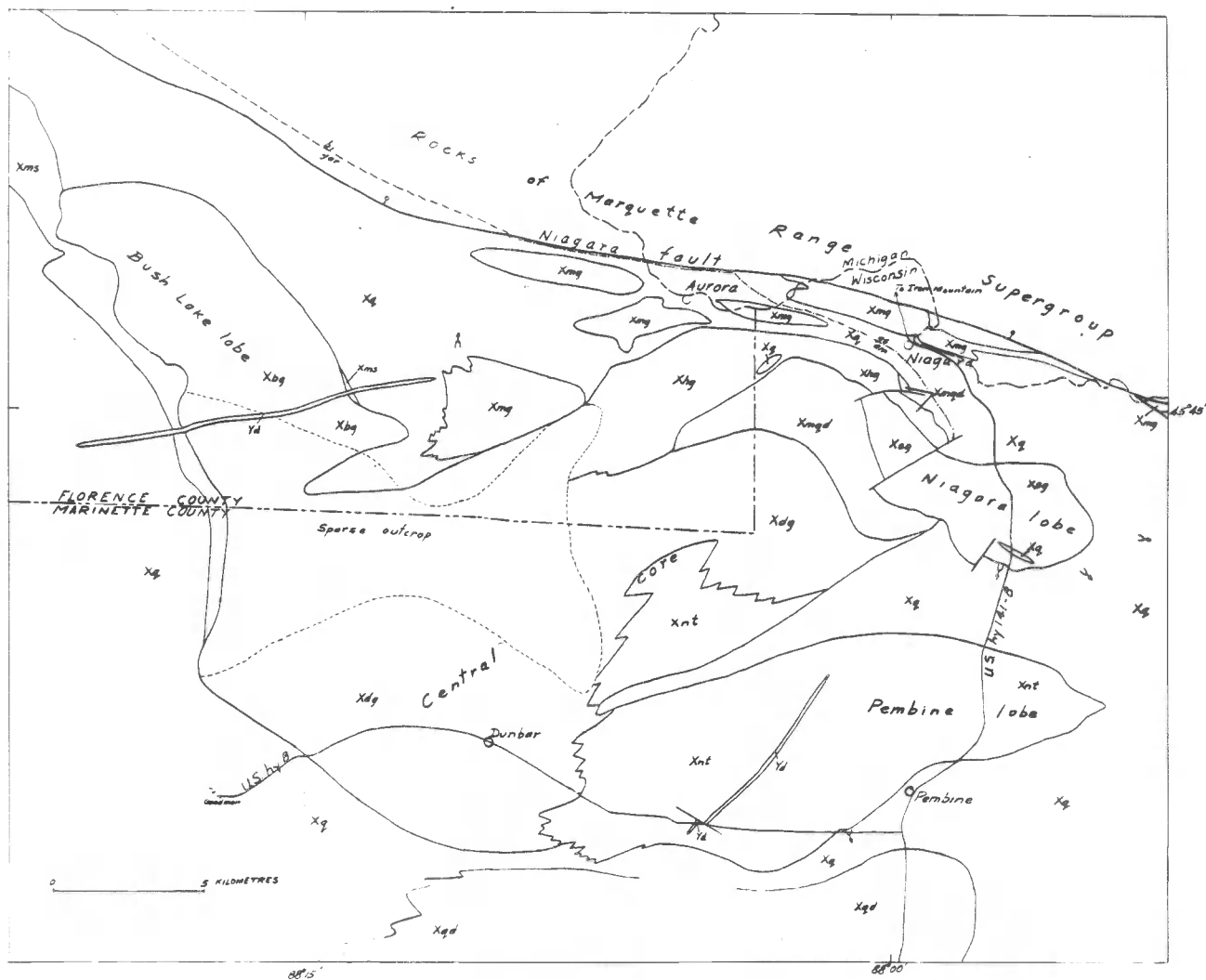


Figure 1.--Geologic map of Dunbar Gneiss-granitoid dome. In part modified from Dutton and Linebaugh, 1967.

by Prinz (1965); the Dunbar Gneiss and the Newingham Tonalite, formerly called the Newingham Granodiorite, were named by Cain (1964). The granites of Bush Lake and Spikehorn Creek are new, informal names for granite bodies previously called Hoskin Lake Granite (Bayley and others, 1966; Dutton, 1971).

The Dunbar Gneiss, as used herein, differs from the earlier usage by Cain in excluding a moderately large body of Newingham Tonalite that intrudes the Dunbar in the northeast part of the central core (fig. 1). The Dunbar Gneiss consists of partly migmatized biotite gneisses, lesser amphibolite, and granite gneiss of dominantly tonalite composition. Some of the granite gneiss contains conspicuous feldspar megacrysts. Granite pegmatite and aplite form abundant subconcordant sheets and steeply dipping dikes in the gneiss and amphibolite. The Dunbar Gneiss has been metamorphosed to amphibolite facies.

The Marinette Quartz Diorite is composed of intermediate and mafic rocks that seem to form a layered intrusive succession. The northern part of the body, adjacent to the Hoskin Lake Granite, has amphibolite-facies mineral assemblages.

The Newingham Tonalite is a remarkably uniform gray, medium-grained, foliated rock that is cut by dikes of similarly foliated, slightly porphyritic tonalite. It composes the Pembine lobe of the Dunbar dome and part of the central core. It intrudes the Dunbar Gneiss and the volcanic rocks of the Quinnesec Formation. The foliation in the Newingham Tonalite is a cataclastic (ductile) foliation that is oriented northeastward.

The Hoskin Lake Granite is a complex, crescent-shaped unit along the northern margin of the dome. The type Hoskin Lake Granite (Prinz, 1965; Bayley and others, 1966) is a distinctive rock characterized by oriented 1-5 cm tabular crystals of K-feldspar. Much of this facies also has K-feldspar porphyroblasts that lie athwart the foliation in the rock. As noted by Cain (1964), the southern margin of the granite is gradational into biotite gneisses of the Dunbar Gneiss and the Marinette Quartz Diorite, and evidence for an origin of the border phase of the granite by K-metasomatism is compelling.

The granite of Spikehorn Creek, which composes the Niagara lobe, is a massive, medium- to fine-grained rock that contains sparse, small K-feldspar phenocrysts. A similar, although somewhat coarser grained rock in the Bush Lake lobe (granite of Bush Lake) is assumed to be approximately equivalent in age to the granite of Spikehorn Creek. Formerly, both were called Hoskin Lake Granite (Bayley and others, 1966; Dutton, 1971).

Structure

The Dunbar dome is an irregular asymmetrical structure that interrupts and distorts the regional northwest-trending structural pattern in northeastern Wisconsin. It is characterized by a consistent parallelism of structures in the cover (supracrustal) rocks and in the margins of the core and by strongly foliated and lineated rocks, indicative of high strain, along the core-cover boundary. It has an estimated structural relief greater than 2 km. The outline of the dome is interpreted as resulting from polydeformation accompanied by diapirism and emplacement of granitoid rocks.

Small-Scale Structures

From examination of small-scale structures in the field, a sequence of four successive deformational events has been delineated in rocks within the core and the immediately adjacent cover rocks. The principal structures developed during the successive deformations are listed in table 1. Trajectories of the planar structures and lineations are plotted in figure 2.

Core Zone

D₁ structures--The oldest recognized structure is a pervasive foliation (S₁) that is subparallel to compositional layering (S₀) in the Dunbar Gneiss. It is defined mainly by a preferred orientation of biotite and hornblende. A lineation related to S₁ has not been recognized. Migmatization of the Dunbar occurred during or prior to S₁. Possibly, S₁ formed as an axial plane structure to early, rootless isoclinal folds.

D₂ structures--Folds (F₂) are conspicuous in the Dunbar Gneiss. A major antiform oriented N. 60° W. and plunging 35°-45° SE. has been delineated in the southwestern part of the Dunbar dome, and second order folds are common on the limbs. The folds are upright, slightly asymmetrical, open to closed structures. Except locally, the folds do not transpose the older foliation (S₁) and layering (S₀). An axial plane foliation (S₂) is best developed in the relatively massive tonalitic Dunbar Gneiss, where it is defined mainly by oriented tabular feldspars and biotite. A lineation (L₂) that is parallel to fold axes (F₂) is best developed in mica- and hornblende-rich gneisses and schists and is expressed by elongate minerals and mineral aggregates. D₂ preceded emplacement of the granitoid rocks in the Dunbar dome.

D₃ structures--Structures related to D₃ are abundant in the northeastern part of the central core of the dome and in the Pembine lobe. The deformation consisted of two apparently distinct phases, designated D₃ and D₃', respectively (table 1), which probably resulted from the same stresses. During an early phase, the Marinette Quartz Diorite acquired a foliation and was folded into dominantly open folds that plunge gently southwest (fig. 2). Presumably at the same time, the Dunbar Gneiss in the north-central part of the core was refolded; the folds plunge gently northeastward and a mineral lineation given by aligned biotite aggregates and hornblende was developed parallel to fold axes. Subsequently, after emplacement of the Newingham Tonalite, continued stresses produced a nearly pervasive cataclastic (ductile) foliation (S₃') defined mainly by oriented biotite and quartz leaves in the intrusive rock. The foliation is dominantly oriented northeastward and dips moderately to steeply southeastward. In the contact zone between the Newingham Tonalite and the Dunbar Gneiss, the S₃' foliation crosscuts that (S₁) in the Dunbar Gneiss. An associated lineation generally is absent. Adjacent to the southeastern margin of the central core (loc. B, fig. 2), F₃' folds, which are mainly Z-type asymmetrical folds, are superposed on previously folded Marinette Quartz Diorite; hinge lines plunge moderately southwestward and axial surfaces dip southeastward, parallel to the associated S₃' foliation. These structures adjacent to the margin of the core are assigned to D₃, but in part could be D₄ structures.

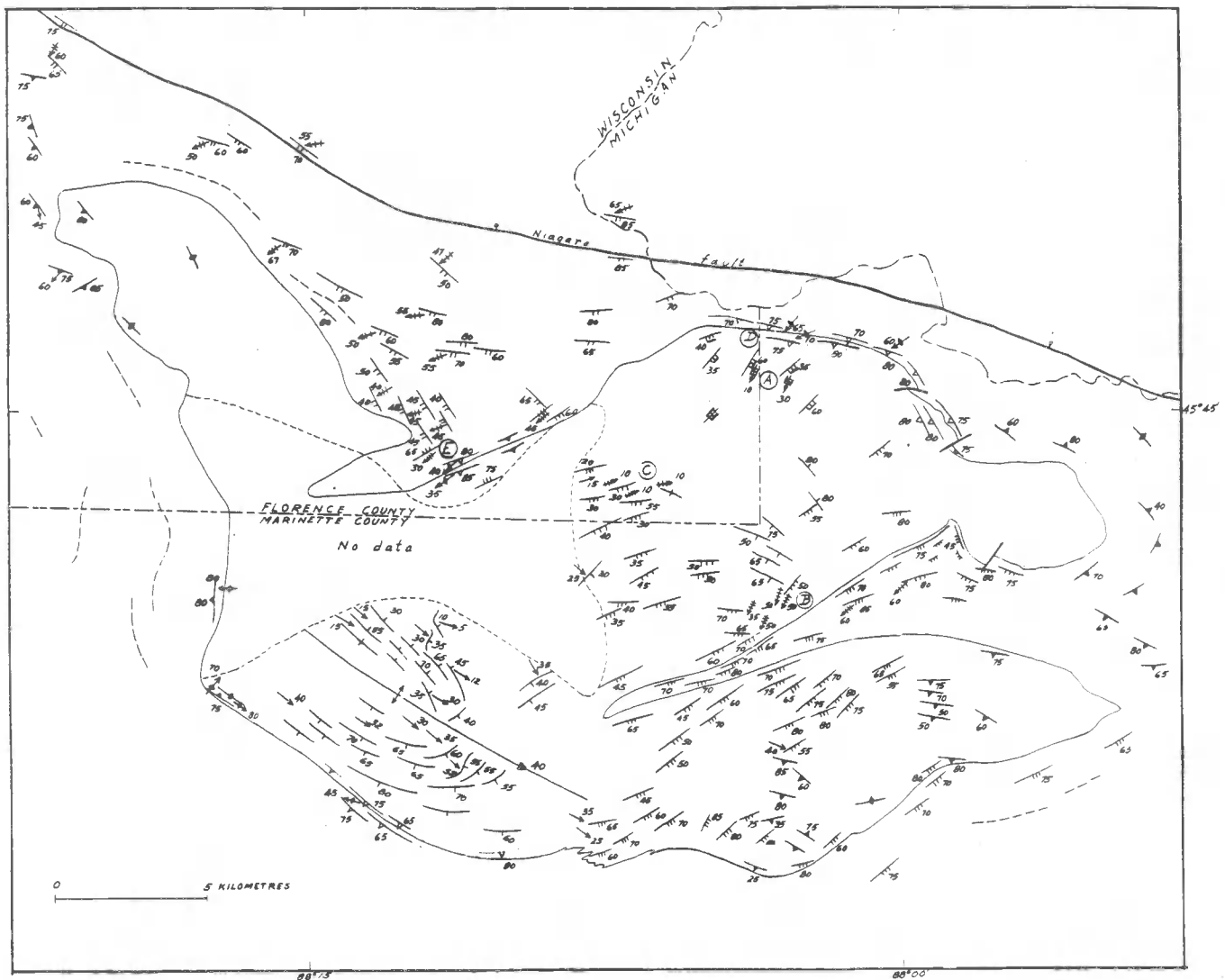


Figure 2.--Interpretive structure map, Dunbar dome

Planar and linear structures

- | | | | |
|--|--|--|--|
| | S ₁ , inclined vertical | | Fault, bar and ball on downthrown side |
| | L ₂ , showing plunge | | Fault, relative movement not known |
| | S ₂ ' | | Trend of magnetic anomaly |
| | L ₂ ' | | Locality referred to in text |
| | S ₃ | | |
| | L ₃ | | |
| | S ₃ ' | | |
| | L ₃ ' | | |
| | S ₄ | | |
| | L ₄ | | |
| | Foliation and lineation of uncertain designation | | |
| | Major F ₂ antiform | | |

Table 1.--Structural sequence, Dunbar dome

D ₁	Foliation parallel to layering in Dunbar Gneiss (S ₁).
D ₂	Northwest-oriented folds in Dunbar Gneiss and Quinnesec Formation (F ₂). Foliation parallel to axial planes of folds (S ₂). Local. Lineation parallel to fold axes (L ₂). Local.
D ₂ '	Stretching lineation (L ₂ ') parallel to local steeply plunging folds (F ₂) ₁ in cover-rocks, north side dome.
D ₃	Foliation parallel to layering in Marinette Quartz Diorite (S ₃). Lineation (L ₃) parallel to fold axes (F ₃).
D ₃ '	Cataclastic foliation parallel to axial planes of asymmetrical folds, northeast-trending (S ₃ '). Lineation (L ₃ ') parallel to fold axes (F ₃ ').
D ₄	Mylonitic foliation (S ₄) in core-cover boundary. Stretching lineation (L ₄).

D₄ structures--D₄ structures occur in the core-cover boundary. Inasmuch as they obliterate or strongly modify older structures in the core they are interpreted as being the youngest structures, although they could have overlapped D₃. The dominant structures are a mylonitic foliation and a stretching lineation defined by elongate clasts, rare folds, mullions, and slickenside striae. They are most intensely developed on the north margin of the core (D, fig. 2) where the foliation dips 70°-80° S., and the lineation uniformly plunges 60° SW. The zone of mylonitic foliation is as much as 500 m wide; the foliation decreases in intensity inward from the boundary, indicating that this deformation is strongly controlled by the core-cover boundary. A comparable steep mylonitic foliation exists along the northwest boundary of the central core, but the lineation is flatter. A steep foliation and mineral lineation also exists at the extreme southwest margin of the core of the dome.

It should be noted that the Pembine and Niagara lobes lack D₄ structures in their contact zones.

Mantle zone

The mantling metavolcanic and metasedimentary rocks were deformed together with the Dunbar Gneiss on northwest-trending fold axes during D₂, and subsequently were deformed in the core-cover boundary by D₃ and D₄. On a regional basis, folds and related mineral lineations in the supracrustal rocks plunge moderately to steeply either to the southeast or the northwest. On the southern margin of the Dunbar dome, inclusions of the Quinnesec Formation in the Newingham Tonalite (see figs. 1 and 2) are folded; the folds plunge moderately gently southeastward, subparallel to the major D₂ antiform axis in the Dunbar Gneiss, clearly indicating that folding in both rock types was coaxial.

The northwest-trending foliation and southwest-plunging mineral lineation in the Quinnesec Formation on the northeast side of the Bush Lake lobe are tentatively considered as late-stage D₂ structures, and are designated as S₂' and L₂', respectively (fig. 2). In this area, F₂ folds (as discussed above) seem to be absent, presumably because they have been obliterated by S₂' and L₂', both of which have fabrics indicative of high strain. As shown in figure 2 (loc. E), S₂' is reformed adjacent to the northwest boundary of the central core by D₃ structures. In this area, S-type, asymmetrical folds that plunge moderately southwestward and have a southeast-dipping axial plane foliation are developed adjacent to the boundary. They persist intermittently for a distance of 0.8 km away from the boundary.

The Quinnesec Formation on the north, overturned margin of the dome is intensely deformed and has a close-spaced foliation and a steeply plunging stretching lineation resulting from D₄. Pillows in the lavas are both flattened and stretched, and have length-width ratios of about 5:1. The stretching lineation is similar to that in the Quinnesec Formation on the northeast side of the Bush Lake lobe, but is more intense. As noted earlier, the Quinnesec also is intensely deformed on the northwest margin of the dome, but the lineation is flatter. In the same way, the Quinnesec is reformed adjacent to the southwest margin and has a moderately plunging lineation oriented westward. In the reentrant along the southeast margin of the central

core (fig. 2), the Quinnesec has a steep southeast-dipping foliation, and pillows are somewhat flattened; a mineral lineation plunges about 60° SW. As shown on figure 2, the structures are assigned to D_3 , but could in part have resulted from D_4 .

Large-Scale Structure

The Dunbar dome is interpreted as a large scale fold-interference structure resulting from superposition of F_2 and F_3 folds modified by diapirism and the emplacement of granitoid intrusive rocks.

The outline of the central core of the dome is mainly the result of superposed F_2 and F_3 folding. Its southern margin is the southwest limb of the major northwest-trending F_2 antiform cored by Dunbar Gneiss. Small-scale structures indicate that the antiform plunges moderately southeast (fig. 2), and in the crestal area both the Dunbar Gneiss and the overlying Quinnesec Formation are intruded by the large body of Newingham Tonalite (see fig. 1). Presumably, the antiform is doubly plunging, to account for the westward closure of the dome, but this cannot be confirmed because of the absence of exposures in the extreme western part of the dome. The steeply dipping cover rocks along the western margin and fabrics indicative of high strain indicate that diapirism was intense in this boundary zone. Diapirism also modified the southern margin of the central core, as indicated by an intense foliation and west plunging mineral lineation.

The northwest and southeast margins of the central core of the Dunbar dome are subparallel to small-scale D_3 structures, and are interpreted as the limbs of a major northeast-oriented antiform. The reentrant of Quinnesec Formation between the central core and the Pembine lobe, shown by the map pattern (fig. 2), is a major synform. The F_3 flattening folds in the Quinnesec Formation within the reentrant and on the northwest margin indicate that the core rocks behaved in a more viscous manner than the cover rocks, perhaps indicating inflation of the core during D_3 .

The northern, overturned margin of the central core, between the Hoskin Lake Granite and the Quinnesec Formation, was the site of intense D_4 deformation, which nearly completely obliterated older structures. We interpret these structures as resulting from inflation of the core, especially its northern part.

Evidence exists for at least one second-order diapir in the first order one, of the type described by Schwerdtner and others (1979). This is provided by the Niagara lobe, which is composed of nearly undeformed granite of Spikehorn Creek that transects at nearly right angles the outer (eastern) margin of the central core, composed here of Marinette Quartz Diorite. The granite in the Niagara lobe has a steep foliation near its walls, and the contact is in part at least tectonic. The volcanic rocks of the Quinnesec Formation are molded around the margin of the dome. We conclude that the lobe of granite flowed differentially upward and outward in a plastic state during a late stage of dome inflation, in a manner similar to that described by Brun and others (1981). As a consequence of the second-order diapir, a "cleavage triple point" was developed in the supracrustal volcanic rocks at the intersection of the Niagara lobe and the eastern margin of the main dome.

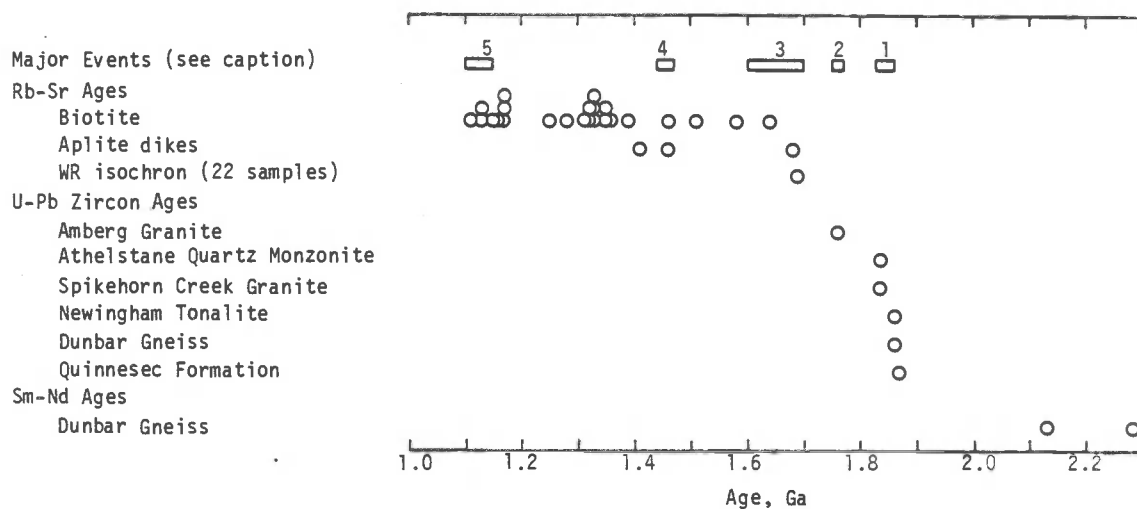


Figure 3.--Summary of selected isotopic ages for rocks of the Dunbar gneiss dome and environs. The events shown are: (1) the main interval of Penokean igneous activity, (2) the post-Penokean 1,760-Ma igneous event, (3) the 1,600 $\pm$ 50 Ma event that disturbed isotopic systems throughout much of the Precambrian of Wisconsin, (4) emplacement of the Wolf River batholith, and (5) Keweenawan igneous activity. Isotopic ages shown are from Aldrich and others (1965), Banks and Cain (1969), Banks and Rebello (1969), Van Schmus (1980), and USGS (unpublished Rb-Sr, U-Pb, and Sm-Nd ages).

Following this reasoning, the Bush Lake lobe is possibly also a second order diapir.

We interpret the D_1 structure in the Dunbar Gneiss as having formed earlier than, and at greater crustal depths, than the regional deformation (D_2) of the Dunbar Gneiss and the supracrustal rocks, for the deformation was accompanied by amphibolite-facies metamorphism and migmatization of the layered rocks; whereas D_2 took place under less intense metamorphic conditions, indicative of relatively shallow depths.

Analysis of the regional geology indicates that the Dunbar dome was developed during regional deformation related to the Penokean orogeny. The regional structural fabric and perhaps also the persistent southwest-plunging stretching lineation in the core-cover boundary of the dome, could have resulted from subhorizontal compression oriented north-northeastward. The northeast elongation of the central core and of the Pembine granitoid lobe appear to be related to more local forces, perhaps thermal perturbations within the core of the dome, for D_3 structures are virtually confined to the dome.

An origin of the dome through stacking of thrust sheets was considered, but rejected, because of the lack of stratigraphic evidence and other structures suggestive of thrusting.

Geochronology

The effects of repeated tectonic and thermal overprinting of rocks within and adjacent to the Dunbar dome are recorded in a spectrum of highly discordant isotopic ages (fig. 3). The principal units within the dome formed between $1,862 \pm 5$ Ma and $1,835 \pm 6$ Ma as shown by U-Pb zircon ages for the Dunbar Gneiss and granite of Spikehorn Creek, the oldest and youngest units, respectively. The supracrustal Quinnesec Formation has a U-Pb zircon age of $1,866 \pm 39$ Ma (Banks and Rebello, 1969), which is not resolvable from the ages of the core rocks. The Athelstane Quartz Monzonite of Van Schmus and others (1975), cropping out southeast of the Dunbar dome, was approximately coeval with some of the core rocks as shown by a U-Pb zircon age of $1,836 \pm 15$ Ma (Banks and Cain, 1969). The Amberg Quartz Monzonite of Van Schmus and others (1975) intrudes the Athelstane Quartz Monzonite and is equivalent in age to high-level granitoids and felsic volcanic rocks in central Wisconsin (Smith, 1983). Data for two fractions of zircon from a sample of the Amberg Quartz Monzonite (Van Schmus, 1980) define a chord with an upper intercept age of $1,756 \pm 19$ Ma.

Sm-Nd model ages of 2,130 and 2,280 Ma for two samples of Dunbar Gneiss (fig. 3) are substantially older than the crystallization ages defined by the zircon data. Other Early Proterozoic igneous rocks in northern Wisconsin have yielded similar "old" Sm-Nd ages (Nelson and DePaolo, 1982). The Sm-Nd ages, together with Pb-isotope data (Afifi and others, in press), strongly indicate a major involvement of Archean crustal material in the genesis of Early Proterozoic volcanic and plutonic rocks and syngenetic mineralization.

Post-doming events have severely perturbed Rb-Sr whole-rock and mineral ages. Twenty-two whole-rock samples (5 to 10 kg each), representing both massive and gneissic units within the Dunbar dome, define a Rb-Sr isochron of $1,688 \pm 28$ Ma, with an initial $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of 0.7038 ± 0.0013 (fig. 4). We attribute the disturbance of the Rb-Sr system at the whole-rock scale to open-system behavior related to cataclasis that variably affected all of the units in the dome. Recrystallization of biotite (and microcline where present) and sericitization and epidotization of plagioclase facilitated the mobility of Rb and Sr. Fluids undoubtedly played a major role in the migration of Rb and Sr as well as other elements. A relation between rock composition and degree of resetting is suggested by an isochron age of $1,733 \pm 43$ Ma obtained by regressing only those samples with $^{87}\text{Rb}/^{86}\text{Sr}$ ratios less than 3. This separation roughly divides the data according to rock type with the granites (sensu stricto) having $^{87}\text{Rb}/^{86}\text{Sr}$ ratios greater than 3 and the tonalites and granodiorites having ratios less than 3. This correlation between rock composition and degree of resetting of the Rb-Sr system is probably related to differences in physical properties of the rocks. The granites, being less biotitic and more quartz rich than the tonalites and granodiorites, probably deformed in a more brittle fashion, which led to a higher permeability and thus a greater opportunity for interaction with a fluid phase. Some of the units, although open systems on the sample-size scale (tens of centimeters), appear to have remained closed at larger scales. For example, average $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values calculated for the Dunbar Gneiss (11 samples) by weighting each sample by its Sr content, are used to calculate a model age of $1,875 \pm 70$ Ma, using an initial Sr ratio of 0.7017. Although the uncertainty is large, a model age is indistinguishable from the crystallization age given by the U-Pb zircon data.

Rb-Sr biotite ages of rocks within the Dunbar dome decrease from east to west (figs. 3 and 5). This variation is part of a regional pattern of Rb-Sr biotite ages that extends north to the Marquette trough (Peterman and Sims, 1984). Within this area, 54 biotite ages define a tripartite distribution with well defined modes at $1,580 \pm 70$ Ma, $1,320 \pm 50$ Ma, and $1,140 \pm 30$ Ma. The older group is a composite that contains the tightly clustered $1,630 \pm 30$ Ma ages for Archean rocks of the southern complex in northern Michigan (Van Schmus and Woolsey, 1975) and slightly younger ages from areas to the south (fig. 5). Van Schmus and Woolsey correlated the 1.63-Ga ages with a cryptic event that has affected Precambrian rocks over much of Wisconsin (fig. 3). A younger resetting event at $1,140 \pm 30$ Ma, recognized mainly in the western third of the Dunbar dome, occurred contemporaneously with Keweenaw (Middle Proterozoic) rifting and igneous activity. The coincidence of age discontinuities with northwest- and northeast-trending, vertically lineated shear zones (fig. 5) strongly suggests that differential uplift was a causative factor in producing the age pattern. Apparently, stresses attendant with rifting were transmitted over considerable distances and resulted in reactivation of existing faults and vertical adjustments of large magnitude.

The intermediate group of ages, $1,320 \pm 50$ Ma, does not correlate with any known events in the region (fig. 3). Aldrich and others (1965) suggested a thermal event at this time, but they did not elaborate on a cause. Possibly, the surface now characterized by the 1,320-Ma age group was uplifted and cooled during the Keweenaw from a depth at which the biotite systems were only partially reset.

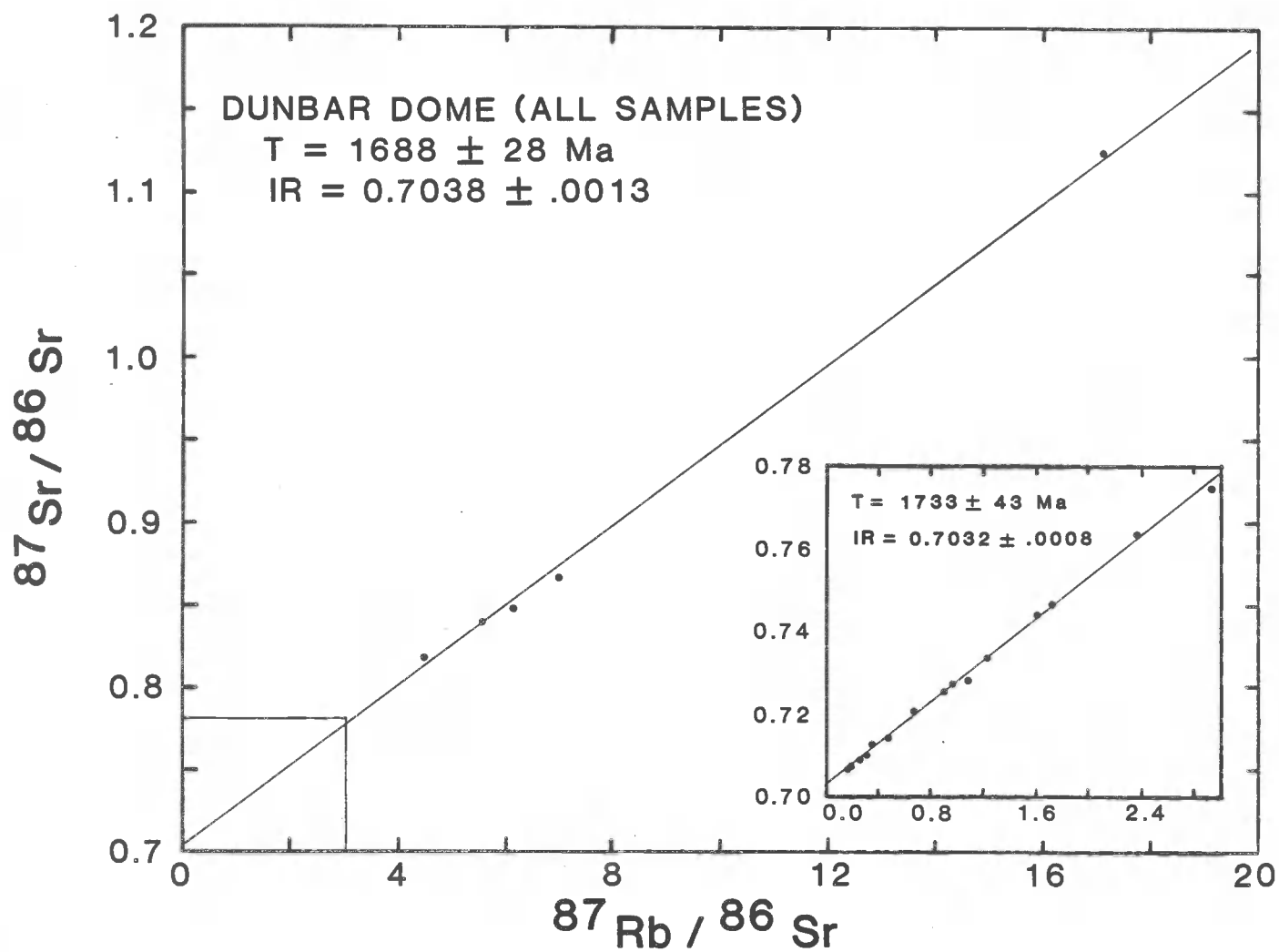


Figure 4.--Whole-rock Rb-Sr isochron for samples of all units within the Dunbar dome. The isochron of $1,688 \pm 28 \text{ Ma}$ is based on all of the samples (22). The inset shows samples with $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of less than 3 (mainly tonalites and granodiorites).

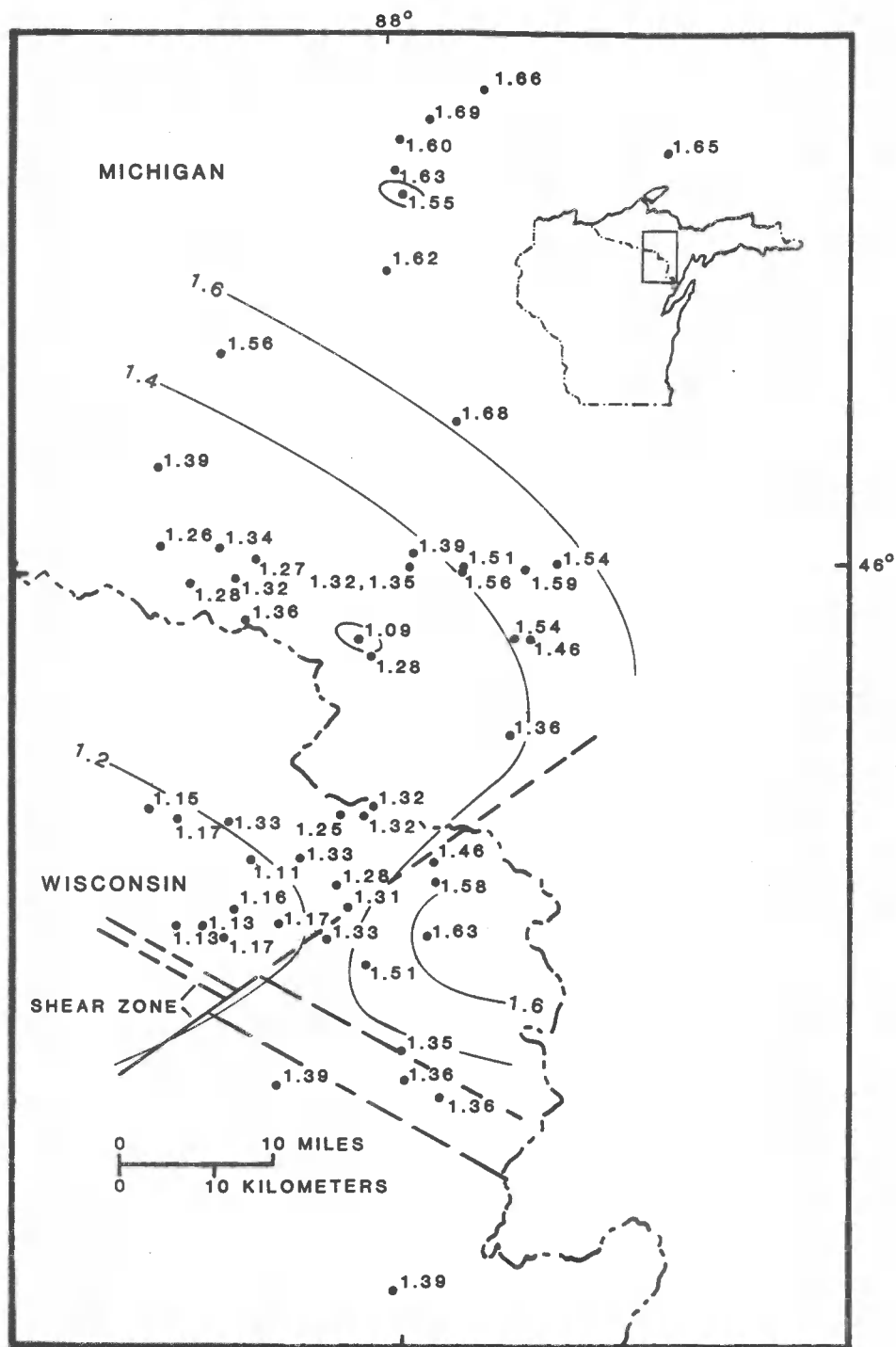


Figure 5.--Rb-Sr biotite ages in billions of years (Ga) for Archean and Early Proterozoic rocks in northeastern Wisconsin and adjacent northern Michigan. Data are from Van Schmus and Woolsey (1975) for the southern Complex, Aldrich and others (1965) for the Felch trough area, and Peterman and Sims (unpublished) for the Dunbar dome and vicinity.

Evolution of Dome

The stratigraphic-tectonic evolution of the Dunbar dome spanned a relatively short time of about 30 Ma, from about 1,865 to 1,835 Ma (table 2), during the Early Proterozoic.

The first recognized event was the formation of the volcanic and plutonic (tonalitic) protoliths of the Dunbar Gneiss, probably as part of a succession covering a large area in an oceanic regime. Following an early deformation (D_1) at moderate crustal depths and the rise of the Dunbar Gneiss to shallower crustal levels, quartz sand, dolomite, and volcanic tuff(?) were deposited unconformably on the Dunbar Gneiss in a shallow-water environment. Later, vast quantities of tholeiitic volcanic rocks (Quinnebec Formation) were deposited in deep water, probably in a back-arc basin (Schulz, 1984). Comagmatic, subvolcanic sills of mafic composition were intruded into the volcanic pile. Onset of regional compression produced a northwest-trending, generally steeply dipping, structural fabric (D_2) in the basement and supracrustal successions. After culmination of the regional deformation (D_2), the Marinette Quartz Diorite was emplaced in the northeast part of the Dunbar dome, apparently as a layered, crescent-shaped sheet essentially along the contact between the underlying Dunbar Gneiss and the overlying Quinnebec volcanics. Subsequently, the Newingham tonalite was intruded. The Newingham was emplaced at the base of the Quinnebec Formation, and it contains abundant xenoliths of both the Quinnebec Formation and the Dunbar Gneiss in the contact zone. The Marinette Quartz Diorite was emplaced before or during deformation D_3 , which produced dominantly northeast-trending structures in the rock and was accompanied by amphibolite-facies metamorphism in the hotter and deeper(?) northern part of the dome. During later stages of the deformation (D_3), the Newingham Tonalite was emplaced and then deformed. The major structure imposed on it was a cataclastic (ductile) foliation that dominantly trends northeastward and has a northwest vergence. A major northeast-trending antiform resulting from deformation D_3 produced the northeast-trending margins of the central core of the dome. Concomitantly with rise of the thermal isograds in the dome, the Hoskin Lake Granite was emplaced along the northern margin of the dome during late stages of D_3 , mainly as a magma but in part by K-metasomatic replacement of the Marinette Quartz Diorite and the Dunbar Gneiss. At this stage, K-bearing fluids permeated parts of the central core, selectively replacing parts of the Marinette Quartz Diorite and the Dunbar Gneiss, apparently by migration of the fluid along more permeable cataclastic zones. K-metasomatism continued in the northern, hotter part of the dome; and rise and inflation of the central core produced a northward vergence, and was accompanied by rotation of the country rocks in the margins of the dome into conformity with the core-cover boundary (D_4). Contemporaneously, the cover rocks adjacent to the central core were metamorphosed to amphibolite facies. The thermal metamorphic aureole was exceedingly wide on the northern and northwestern margins of the central core, where the amphibolite facies zone is at least 8 km wide, far in excess of that to be expected by conduction of heat from a magma such as the Hoskin Lake Granite. The thermal activity in the core led to the emplacement of abundant granitoid dikes in the inner (amphibolite grade) part of the metamorphic aureole. Continued rise of the geotherms in the northern segment of the dome led to development of a granitic magma (granite of Spikehorn Creek), which was emplaced by outward, diapiric

Table 2.--Stratigraphic-tectonic evolution of Dunbar dome

Age in Ma	Deformation	Event
1,835		Quartz-tourmaline veinlets and fluorite in brittle fractures
		Emplacement of granite of Spikehorn Creek and, possibly, granite of Bush Lake into Niagara and Bush Lake lobes, respectively, as diapirs; and intrusion of aplite and pegmatite into Dunbar Gneiss
	D ₄	Continued rise in isotherms centered on northern part of core accompanied by diapiric rise of dome, rotation of older structures into conformity with core-cover boundary, and metamorphism of adjacent cover rocks and northern part of core rocks
		Emplacement of Hoskin Lake Granite, in part by K-metasomatism of older rocks
~1,860	D ₃	Deformation on northeast axes (restricted areally), after emplacement of Marinette Quartz Diorite and Newingham Tonalite
	D ₂	Deformation of Dunbar Gneiss and supracrustal rocks on northwest axes, to produce regional structural fabric
		Deposition of a thick succession of tholeiitic volcanic rocks (Quinnesec Formation)
		Unconformity
		Deposition of shallow-water sediments
		Unconformity
	D ₁	Foliation parallel to layering in Dunbar Gneiss of Cain (1964); metamorphism of Dunbar to amphibolite facies, migmatization, and intrusion of granite pegmatite and aplite
~1,865		Formation of volcanic and plutonic (tonalitic) protolith of Dunbar Gneiss

flow into the Niagara lobe, a second-order dome. The granite of Bush Lake was intruded at about the same time. At a late stage of evolution of the Dunbar dome, quartz and tourmaline were mobilized into brittle fractures both within and outside the core, and fluorite was mobilized locally into fractures in the Hoskin Lake Granite.

Tectonic Environment

Recognition that the Dunbar Gneiss and, by implication, other bodies of crystalline rocks in northern Wisconsin are cores of domal structures exposing deeper crustal rocks has an important bearing on the Proterozoic stratigraphy and paleogeography of the region during Early Proterozoic time. Crystalline rocks of Early Proterozoic age, such as those exposed in the Dunbar dome, have not been delineated in northern Michigan despite extensive, detailed mapping, and it seems certain that they are absent or at least of minor significance. Also, in northern Wisconsin, volcanic rocks dominate the supracrustal sequence, whereas interbedded sedimentary and volcanic rocks characterize the Marquette Range Supergroup in Michigan. Chemically, the volcanic rocks in the two parts of the region differ substantially. Those in northern Michigan, as indicated by volcanic rocks in the Hemlock Formation, are largely bimodal with abundant tholeiitic basalt and minor high-K₂O rhyolite. The basalt shows strong iron enrichment and high TiO₂ and incompatible-element contents (Fox, 1983); they are compositionally similar to continental rift basalts, such as those of the Keweenaw in Minnesota. In contrast, the volcanic rocks of the Quinnesec Formation range from basalt through andesite to rhyolite, lack strong iron enrichment, and have back-arc basin compositional affinities (Schulz, 1984).

Other contrasts in the two areas are marked differences in the mineral deposits contained in the Early Proterozoic successions (Sims, 1976). Iron-formations and associated enriched iron deposits are the dominant ore deposits in the Marquette Range Supergroup of Michigan, whereas massive sulfide deposits are dominant in northern Wisconsin and iron-formations are thin and sparse.

A critical stratigraphic problem is the relationship of the shallow-water sedimentary rocks in the Dunbar dome to the shallow-water deposits at the base (Chocoma Group) of the Marquette Range Supergroup. We suggested earlier (Schulz and Sims, 1982) that the strata in both areas are possibly correlative; but the chemical differences in the overlying volcanic rocks and other differences, such as the volume of Early Proterozoic plutonism in the two terranes, now lead us to interpret the sedimentary rocks as being homotaxial rather than stratigraphically correlative.

Data presented here, together with regional geologic relationships (fig. 1; Morey and others, 1982), are consistent with an interpretation that the Wisconsin magmatic zone is an exotic terrane that evolved in an oceanic-arc setting and was attached to the North American continent during the Early Proterozoic. Apparently the boundary between the two Proterozoic terranes is the Niagara fault zone, as suggested by Larue (1983). Probably the doming, which exposes the gneiss and granitoid rocks in the cores, was in response to collision of the two crustal blocks, which triggered the Penokean orogeny. The westward extent of the Wisconsin magmatic zone remains equivocal, for if

indeed it does extend across the midcontinent rift system into Minnesota, only remnants of the vast accumulation of Early Proterozoic volcanic rocks apparently remain there.

The conclusions reached here support the earlier interpretation of Van Schmus (1976), based on broad geologic considerations, that the Early Proterozoic epicratonic successions in the Great Lakes area accumulated at a continental margin. A variant of this interpretation later was presented by Cambray (1978) and Larue (1983). The earlier interpretation of one of us (Sims, 1976; Sims and others, 1981) that the Early Proterozoic sequences in the Great Lakes area accumulated in an intracratonic setting no longer is tenable for the whole region.

On the basis of new chemical and structural data obtained in this and other parts of Wisconsin and northern Michigan, Schulz and others (1984) have proposed a tectonic model of early crustal rifting and spreading, subsequent subduction and formation of a complex volcanic arc, and collision of the arc, first with Archean crust on the south and then with the continental margin Proterozoic sequence and Archean crust of northern Michigan on the north (the Penokean orogeny).

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Geochemistry of the Dunbar gneiss-granitoid dome,
Northeastern Wisconsin

by

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Introduction

Samples from the major rock units that make up the Dunbar gneiss-granitoid dome have been analyzed for major and trace elements (including rare-earth elements - REE) to determine their compositional characteristics and aid in deciphering their petrogenesis. Representative analyses are presented in tables 1 and 2 and shown graphically in figures 1 through 9.

Dunbar Gneiss

Samples of Dunbar Gneiss range from tonalite to granite, are calc-alkaline (figs. 1 and 2), and define general trends of decreasing Al_2O_3 , FeO_T , MgO , CaO , TiO_2 , Na_2O , and Sr contents and increasing K_2O and Rb contents with increasing SiO_2 content. Except for mafic amphibolite units found interlayered with the Dunbar Gneiss, samples in which SiO_2 is less than 60 weight percent appear to be absent. The rocks have Rb/Sr ratios ranging from about 0.15 to 1.0 (fig. 4) and K/Rb ratios ranging from about 260 to 160; increasing Rb/Sr ratios correlate positively with SiO_2 content.

The chondrite-normalized REE data for Dunbar Gneiss samples are shown in figure 5. All samples show steep patterns with relatively enriched light-REE (chondrite-normalized $\text{La}=[\text{La}]_N=71-360$) and depleted heavy-REE ($[\text{La}/\text{Yb}]_N=45-18$; except one example at 217). The sample with the steepest slope and most depleted heavy-REE is from a leucocratic layer within more biotitic tonalite gneiss. The two samples having the lowest total REE abundances have the highest SiO_2 content (i.e., 75 and 74 weight percent). Except for these two samples, the rocks show small negative Eu anomalies.

Table 1.-- Representative analyses of samples from the Dunbar Gneiss and
Newingham tonalite.

	1	2	3	4	5	6
SiO ₂	61.7	63.6	75.0	49.8	66.6	68.0
Al ₂ O ₃	17.5	16.3	13.5	15.7	18.0	15.7
Fe ₂ O ₃	1.02	0.88	0.08	1.50	1.1	0.51
FeO	4.41	4.07	1.22	6.70	2.4	2.64
MgO	1.64	1.64	0.22	8.50	1.6	1.38
CaO	3.20	3.87	1.25	11.6	4.5	3.53
Na ₂ O	4.22	4.21	3.17	2.24	4.1	3.88
K ₂ O	3.16	2.42	4.51	1.06	1.7	2.15
TiO ₂	0.82	0.82	0.14	0.35	0.37	0.37
P ₂ O ₅	0.18	0.26	<0.05	<0.05	0.18	0.13
MnO	0.09	0.09	<0.02	0.19	0.03	0.04
H ₂ O ⁺	0.85	0.37	0.24	1.68	0.82	-
H ₂ O ⁻	0.02	0.05	0.10	<0.01	0.10	LOI=0.51
CO ₂	0.03	0.03	0.03	<0.01	0.05	-
*Rb	-	118	229	-	-	67
Sr	-	443	232	-	-	656
Y	-	-	7.8	-	-	-
Zr	-	282	68	-	-	126
Nb	-	-	14.5	-	-	-
+U	3.6	3.1	2.2	-	0.96	1.8
Th	10.0	10.3	12.2	0.46	2.6	6.0
Ta	3.78	3.95	2.58	0.14	0.44	1.75
Hf	6.75	7.6	2.39	0.74	2.0	3.4
Cr	7.8	25	17	323	14	42
Co	10.2	9.9	1.34	39.5	8.77	6.97
Sc	5.13	8.0	1.05	45.8	6.74	4.5
Zn	74	-	26	117	-	-
Rb	137	117	250	42	40	69
Ba	883	810	1620	80	570	961
Cs	5.65	4.9	10.9	4.22	0.81	6.1
La	35.1	63.2	26.1	3.8	12.5	27.9
Ce	61.8	119	42.1	6.0	22.8	52.0
Nd	27	34	15.9	-	7.2	17
Sm	5.1	7.13	2.47	1.14	1.27	2.67
Eu	1.17	1.76	0.67	0.45	0.44	0.77
Gd	4.4	-	1.4	-	-	-
Tb	0.66	0.94	-	0.38	0.11	0.26
Yb	1.16	1.55	0.52	2.07	0.18	0.42
Lu	0.20	0.21	0.06	0.33	0.03	0.06

Major and minor elements by rapid rock methods or XRF

*By XRF analysis

+By instrumental neutron activation analysis.

LOI = Loss on ignition

1-3 - Dunbar Gneiss

4 - Amphibolite within Dunbar Gneiss

5-6 - Newingham tonalite

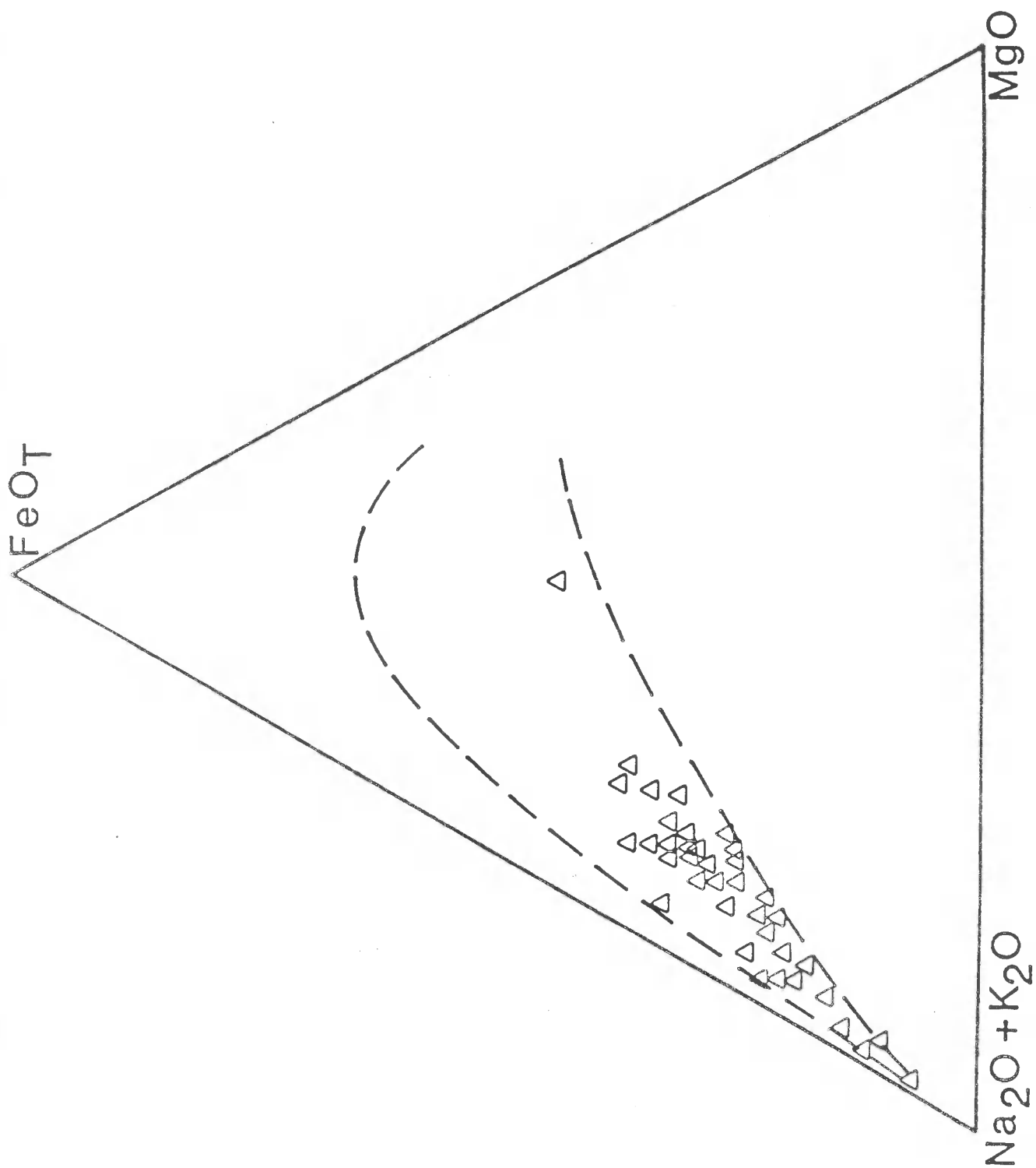


Figure 1.-- FeO_T - MgO - $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram for rocks of the Dunbar dome. Dashed lines show field for igneous rocks from convergent plate margins (from Brown, 1982).

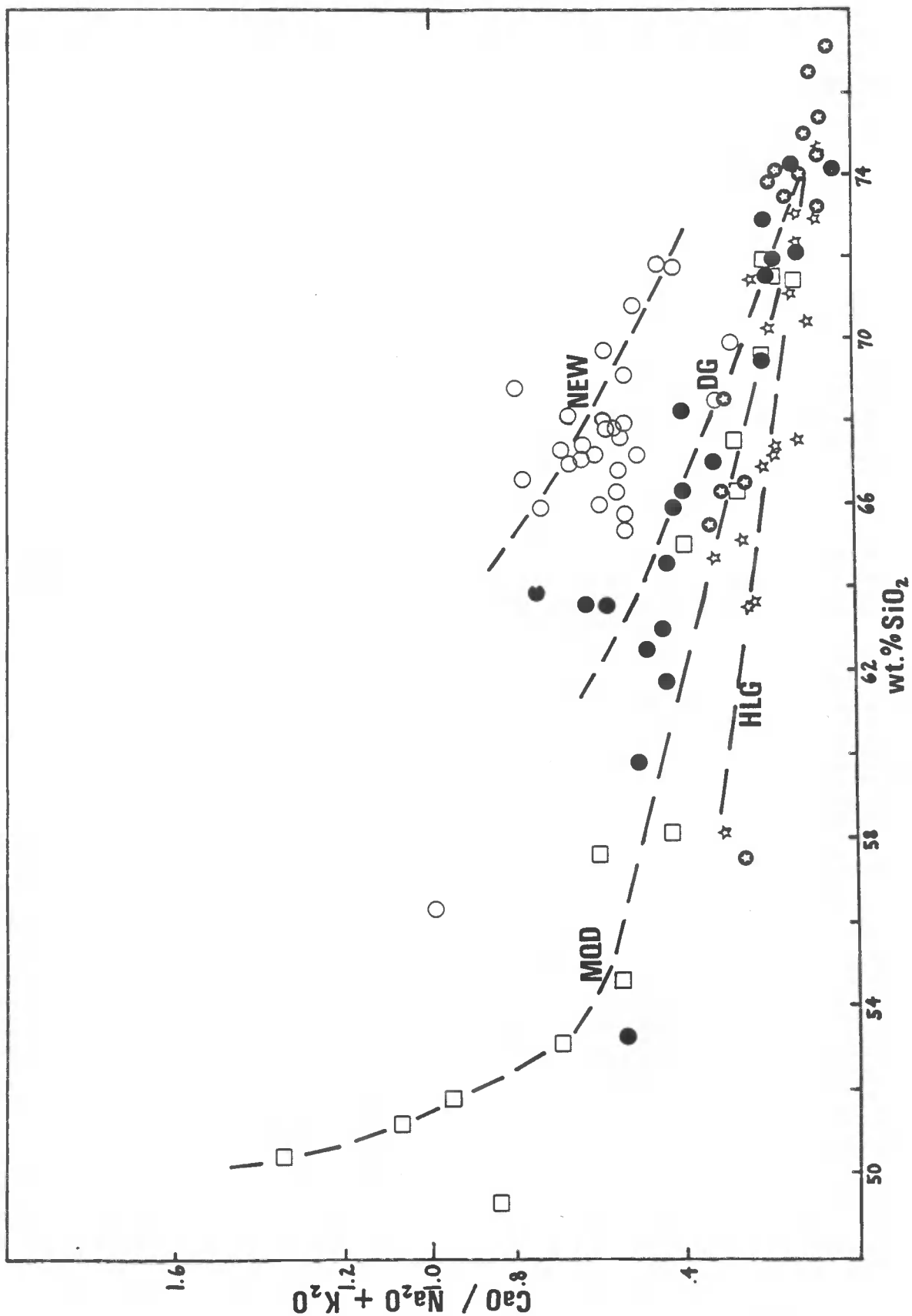


Figure 2.--Modified Peacock diagram for rocks of the Dunbar dome. New = Newingham tonalite, DG = Dunbar gneiss, MQD = Marinette Quartz Diorite, HLG = Hoskin Lake Granite (may include MQD), (data plotted includes that of Cudzilo, 1978). Circle with star = Athelstane Quartz Monzonite.

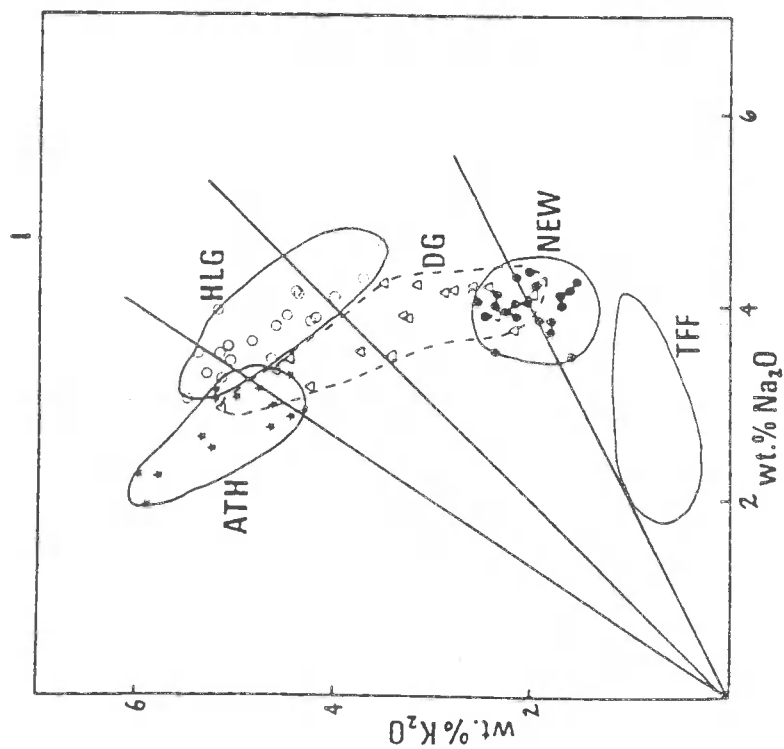


Figure 3.--K₂O-Na₂O diagram for rocks of Dunbar dome.
ATH = Athelstane Quartz Monzonite; TFF = Twelve Foot
Falls quartz diorite. Other labels as in figure 2.

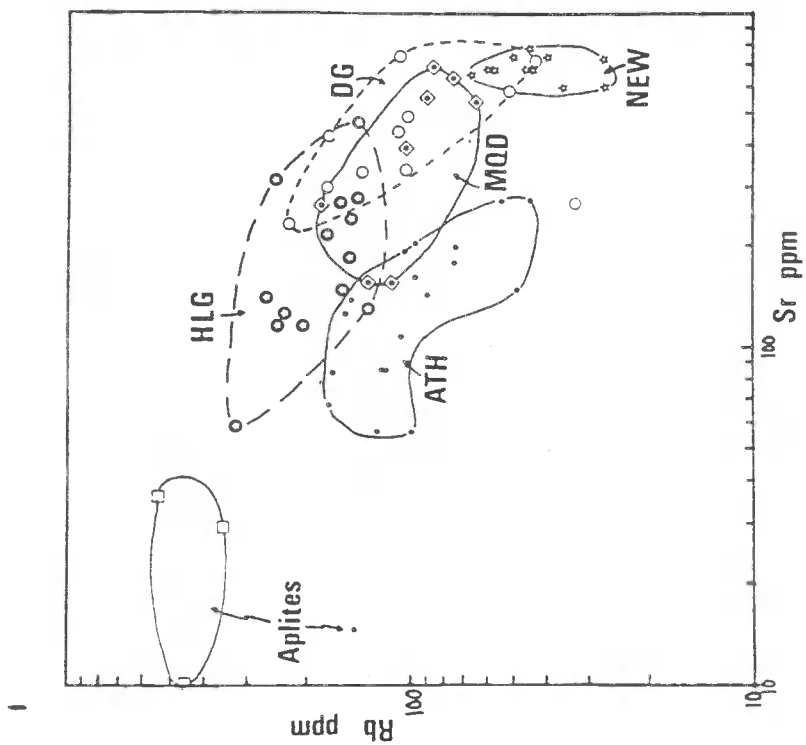


Figure 4.--Rb-Sr variation in rocks of Dunbar dome
and Athelstane Quartz Monzonite.

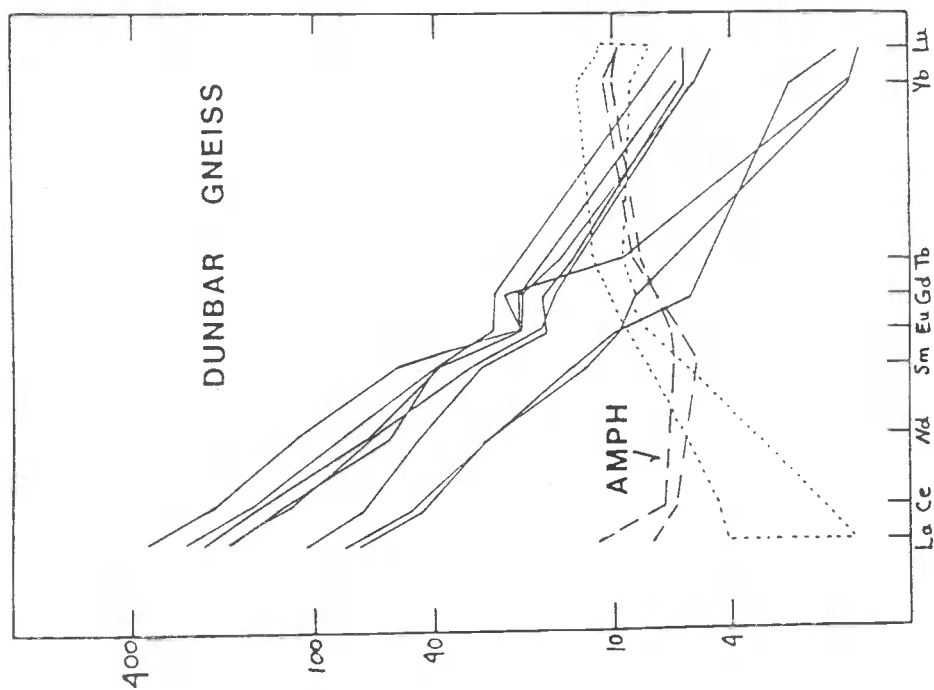


Figure 5.--Chondrite normalized REE for samples of Dunbar Gneiss (solid lines) and amphibolite enclaves in gneiss (Amph). Dotted field for basalts of the Quinnesec Formation.

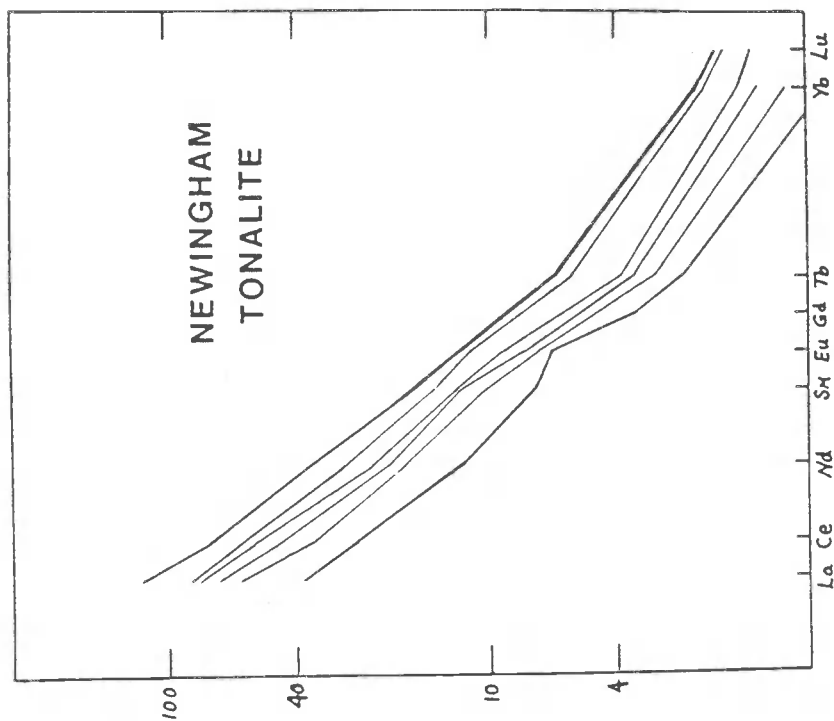


Figure 6.--Chondrite normalized REE for samples of Newingham tonalite.

The amphibolites within the Dunbar Gneiss are basaltic in composition (Table 1) and are generally similar to the basalts of the Quinnesec Formation (Schulz, this volume) except for having higher K_2O and relatively enriched La and Ce contents. The rare-earth elements Sm through Lu show a steep positive slope in the amphibolites (fig. 5) whereas the slope of La to Ce is distinctly negative. The steep positive slope of the heavy REE is similar to that observed for Quinnesec basalts which are strongly depleted in light REE (fig. 5), suggesting that the amphibolites were originally also depleted in light REE. The present enrichment of light REE (i.e., La and Ce) in the amphibolites, as well as K_2O , may have resulted from interaction with their surrounding light-REE-enriched felsic gneisses during amphibolite facies metamorphism.

On the bases of the field and geochemical data, the protolith for the Dunbar Gneiss is interpreted to have been a sequence of interlayered intermediate to felsic volcanic and related intrusive rocks. The overall compositional similarity with intermediate to felsic rocks of recent magmatic arcs formed at convergent-plate margins (Brown, 1982; fig. 1) suggests that the Dunbar Gneiss protolith may have formed in a similar tectonic setting. The steep REE patterns suggest that the parent magmas were probably derived from mafic to intermediate, garnet-bearing sources (Hanson, 1981), perhaps at lower crustal levels. The trace-element characteristics of the Dunbar Gneiss samples are distinct from those of the structurally younger intermediate to felsic volcanic rocks of northeastern Wisconsin (Schulz, this volume); this difference supports the structural interpretation that the Dunbar Gneiss represents the product of an older cycle of magmatic activity.

Newingham Tonalite

The intrusive Newingham tonalite is remarkably homogeneous in composition and shows only a small range in SiO_2 content (fig. 2). The tonalite is higher in Al_2O_3 , MgO , CaO , and Sr and is lower in FeO_T , TiO_2 , K_2O , and Rb than the Dunbar Gneiss (Table 1 and figs. 3 and 4). It is also characterized by lower Rb/Sr ratios ($<.10$) (fig. 4) and higher K/Rb ratios (>260). The samples show steep REE patterns (fig. 6) ($[\text{La}/\text{Yb}]_N=48-40$) somewhat similar to those of the Dunbar gneisses but with mostly lower total REE abundances and show either no or slightly positive Eu anomalies. A strong correlation exists between increasing Rb/Sr ratio, increasing total REE abundance, and decreasing magnitude of the Eu anomaly. This correlation reflects the role of plagioclase fractionation in the magmas parental to these rocks.

The Newingham tonalite is calcic (fig. 2) and is compositionally similar to Archean tonalites such as those of the Vermilion district of Minnesota (Arth and Hanson, 1975) and elsewhere (O'Nions and Pankhurst, 1978). Their low Rb/Sr ratios, high Sr contents, and strong heavy-REE depletions have been considered indicative of melts derived by partial melting of eclogite or garnet amphibolite (Arth and Hanson, 1972). However, the relatively high light-REE contents of the Newingham tonalite samples would preclude a typical tholeiitic basalt (which has depleted or flat light REE) as a parent (Hanson, 1981). A lithologically heterogeneous lower crust, probably more mafic than the source for the protoliths of the Dunbar gneisses (i.e., lower feldspar content at high grades of metamorphism), may have been the source of the parent magma of the Newingham tonalite.

Marinette Quartz Diorite

The Marinette Quartz Diorite (MQD) is distinct from the other units of the Dunbar dome in having alkalic to alkali-calcic affinities (fig. 2). These affinities are reflected in the high total alkali, TiO_2 , P_2O_5 , and REE contents of the more mafic samples (Table 2). The Marinette Quartz Diorite has a complex northern border zone where it is intruded by and is in contact with the Hoskin Lake Granite. Throughout a broad zone, the MQD is variably metasomatized and partially assimilated by the Hoskin Lake Granite, resulting in intermediate to felsic compositions that overlap with those of the granite. Away from this broad contact zone, the MQD appears to be relatively mafic and more uniform in composition although more data are needed to fully establish its original compositional range.

The chondrite-normalized REE patterns for samples of MQD are shown in figure 7. Most of the samples have similar steep REE patterns in which $[\text{La}]_N$ ranges from 170 to 340 and $[\text{Yb}]_N$ ranges from 6.5 to 12. Samples mostly show a small negative or no Eu anomaly; the one sample having a large positive Eu anomaly contains abundant megacrysts of plagioclase. Two samples from within the contact zone of the MQD with the Hoskin Lake Granite have lower REE abundances than the other samples (fig. 7) and patterns similar to those of the Hoskin Lake Granite (compare figs. 7 and 8).

The alkaline affinity and trace-element characteristics of the MQD suggest that the parent magma was alkaline, perhaps an alkali basalt. The relatively early occurrence of alkaline magmatism in a dominantly calc-alkaline magmatic terrane appears to be somewhat anomalous but may have an analogue in the early alkalic plutons present within the calc-alkaline plutonic belt of California (Miller, 1977).

Table 2.-- Representative analyses of samples from the Marinette Quartz Diorite, Hoskin Lake Granite, granites of the Bush Lake and Niagara lobes, and associated late aplites.

	1	2	3	4	5	6	7
SiO ₂	51.8	65.0	69.1	73.0	72.7	74.6	74.2
Al ₂ O ₃	16.8	15.9	15.0	13.7	13.6	13.7	14.5
Fe ₂ O ₃	1.97	0.64	0.56	0.31	0.27	0.23	0
FeO	7.77	3.01	2.67	1.78	2.07	0.96	0.65
MgO	3.50	1.56	0.91	0.41	0.40	0.15	0.12
CaO	6.18	3.20	1.91	1.06	1.19	0.65	0.43
Na ₂ O	3.88	4.30	3.45	3.51	2.74	3.43	5.21
K ₂ O	2.62	3.69	4.69	4.63	5.48	5.06	3.90
TiO ₂	2.42	0.79	0.51	0.18	0.27	0.03	<0.02
P ₂ O ₅	0.64	0.18	0.11	<0.05	0.09	<0.05	<0.05
MnO	0.15	0.07	0.05	0.05	0.04	0.03	<0.02
H ₂ O ⁺	1.23	0.44	0.63	-	0.39	-	-
H ₂ O ⁻	0.07	0.02	0.13	LOI=0.44	0.12	LOI=0.28	LOI=0.17
CO ₂	<0.01	0.04	0.08	-	0.02	-	-
*Rb	-	-	153	244	270	329	454
Sr	-	-	279	117	143	58	9.75
Y	-	-	15	-	31	-	98
Zr	-	-	163	137	154	57	35
Nb	-	-	39	-	32	-	60
+U	3.1	2.8	4.5	11	11	15	7.6
Th	19.4	23	33.7	25.4	46	24.0	6.6
Ta	3.85	3.50	4.61	5.50	3.90	5.78	23.2
Hf	5.87	4.63	5.91	4.9	5.0	2.80	2.90
Cr	6.4	17	22	23	18	22	28
Co	28.5	9.67	5.75	2.41	2.54	0.74	0.60
Sc	13.1	6.35	3.31	1.70	4.85	3.20	18.1
Zn	94	58	44	-	47	-	-
Rb	84	128	159	244	283	321	459
Ba	701	1050	705	466	787	184	65
Cs	4.36	3.42	4.21	7.1	5.73	12.8	1.5
La	57.2	54.3	56.3	32.0	69	19.6	5
Ce	118	83.1	85.6	59.0	121	42	11
Nd	60	28	28	18	48	16	-
Sm	10.2	4.21	4.43	3.22	8.45	4.05	3.9
Eu	2.50	1.12	0.89	0.54	0.88	0.29	0.03
Gd	8.6	3.3	3.3	-	9.0	-	-
Tb	1.01	0.34	0.39	0.52	0.85	0.99	1.44
Yb	2.20	1.08	1.38	1.14	2.6	3.51	11.1
Lu	0.325	0.15	0.19	0.19	0.43	0.54	1.56

Major and minor elements by rapid rock methods or XRF

*By XRF analysis

+By instrumental neutron activation analysis.

LOI = Loss on ignition

1-2 - Marinette Quartz Diorite

3-4 - Hoskin Lake Granite (4 from Niagara lobe)

5-6 - Granite of the Bush Lake lobe

7 - Aplite dike cutting Dunbar Gneiss

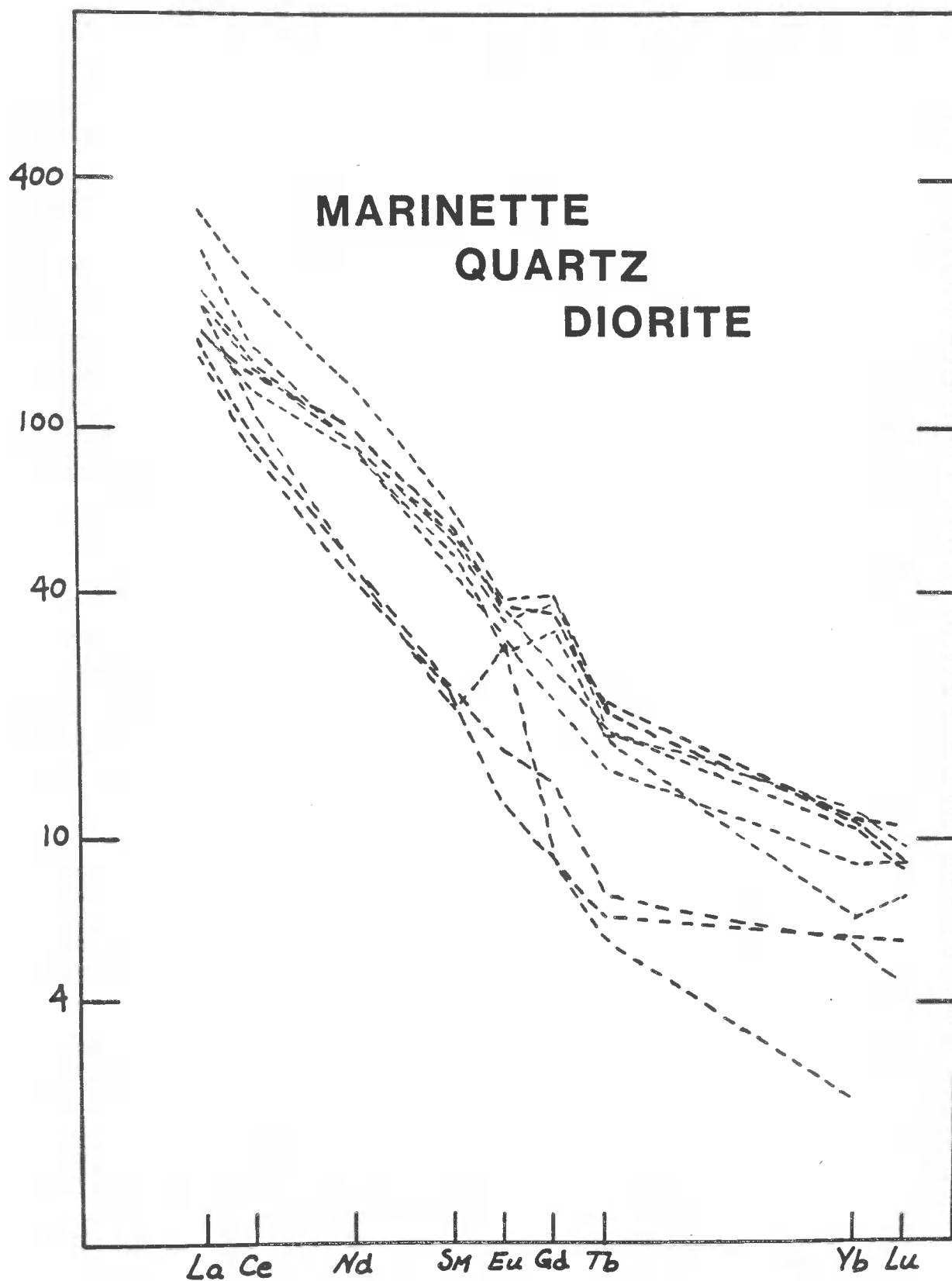


Figure 7.--Chondrite normalized REE for samples of
Marinette Quartz Diorite.

Hoskin Lake Granite and Granites of the Bush Lake and Niagara Lobes

The granites of the Niagara and Bush Lake lobes and the Hoskin Lake Granite share overall chemical similarities although systematic differences are recognized (Table 2). Relative to the more felsic segments of the Dunbar Gneiss, these granites have slightly higher K_2O , TiO_2 and Rb contents and lower Al_2O_3 , MgO, CaO, and Na_2O contents. The granite of the Niagara lobe and the Hoskin Lake body are compositionally similar except that the Hoskin Lake Granite has a slightly higher K_2O content. Rb/Sr ratios range from about 0.55 to 2.0 (fig. 4) and show a positive correlation with increasing SiO_2 content; K/Rb ratios range from about 250 to 155 and show a negative correlation with increasing SiO_2 content. The samples show light-REE enrichment, small to moderate negative Eu anomalies, and decreasing light-REE abundance with increasing SiO_2 ; they also show only slightly fractionated heavy-REE (fig. 8).

The granite of the Bush Lake lobe is compositionally distinct from that of the other two bodies in being slightly higher in average SiO_2 and K_2O contents and in having higher K_2O/Na_2O , U/Th and Rb/Sr ratios. The REE patterns are also distinctive (fig. 8) and have large negative Eu anomalies, relatively flat heavy-REE slope, and significant depletion in the light-REE with increasing SiO_2 content.

Intruding the western part of the Dunbar dome are numerous garnet-bearing aplite and pegmatite bodies. The aplites are strongly depleted, relative to the granites, in FeO_T , MgO, CaO, TiO_2 , P_2O_5 , MnO, Sr, Zr, Ba, Eu, and light-REE but are enriched in Y, Ta, Nb, Rb, and the heavy-REE (Table 2 and figs. 4 and 8). They also show very low Zr/Hf (<17) and Nb/Ta (<4.7) ratios.

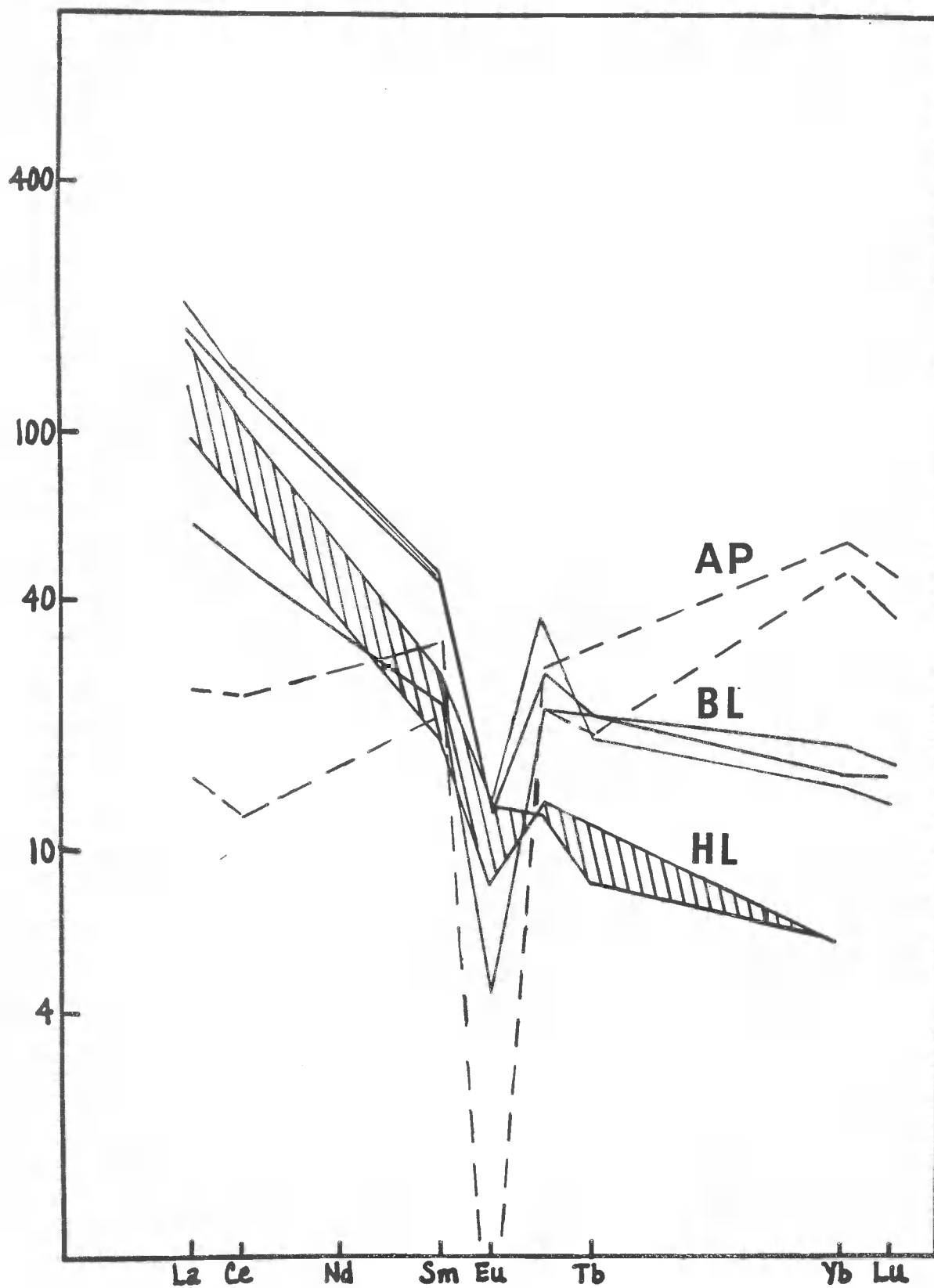


Figure 8.--Chondrite normalized REE for samples of Hoskin Lake Granite (HL), Bush Lake granite (BL) and aprites cutting Dunbar Gneiss (AP).

The compositional characteristics of these aplites are not compatible with their derivation by partial melting of the Dunbar Gneiss. Rather, they are interpreted as the late-stage differentiates of the granite of the Bush Lake lobe. Shown in figure 9 are the relative enrichments and depletions in the average composition of the aplites relative to the least fractionated granite of the Bush Lake lobe (i.e., lowest SiO_2 and highest Sr contents). The enrichment and depletion patterns are similar to those documented by Hildreth (1979) for the compositionally zoned silicic Bishop tuff except for Al, Mn, Sm, Hf and Th. Hildreth (1979; 1981) discussed in some detail the problems related to explaining such elemental fractionations by any model of crystal settling or rock assimilation, and he proposed a model of liquid-state convection-driven thermogravitational diffusion to account for the relative geochemical enrichments and depletions. However, Mittlefehldt and Miller (1983) have recently suggested that fractionation of REE-rich accessory phases (in particular, monazite) in conjunction with feldspar and ferromagnesian phases can also produce similar geochemical patterns in felsic magmas. Present data for the granite of the Bush Lake lobe and aplite association do not allow critical testing of the alternative hypotheses. It may be significant, however, that Th and the light REE are depleted in the aplites relative to the granite of the Bush Lake lobe (fig. 9), perhaps reflecting the fractionation of monazite (Mittlefehldt and Miller, 1983).

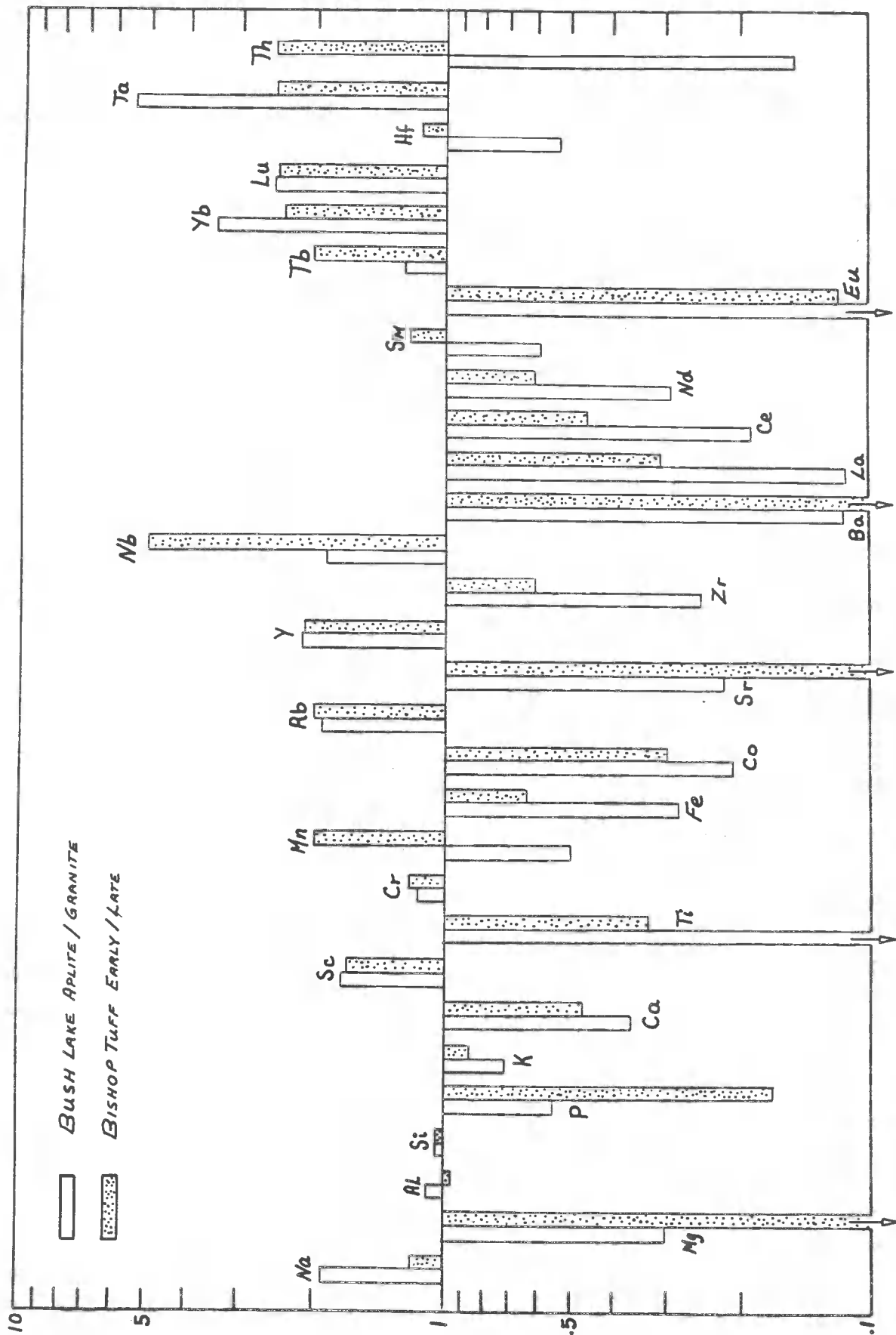


Figure 9.--Enrichment factors in average aplite relative to Bush Lake granite compared to those of the Bishop tuff (Hildreth, 1979). See text for discussion.

Conclusions

The meta-igneous rocks of the Dunbar gneiss-granitoid dome show a progression with time to more silicic and higher K_2O compositions. This progression reflects, at least in part, a progressive change in the nature of the sources providing the more evolved magmas. The overall calc-alkaline nature of these rocks and their changes in chemistry with time are similar to those observed in recent magmatic arcs formed at convergent-plate margins (Brown, 1982). The compositions of these gneissic and granitoid rocks, particularly when taken in conjunction with the geological and geochemical evidence from the surrounding volcanic rocks (Schulz, this volume), strongly suggest that plate-tectonic and magmatic processes largely similar to those recognized to be active today were already operative in the Early Proterozoic.

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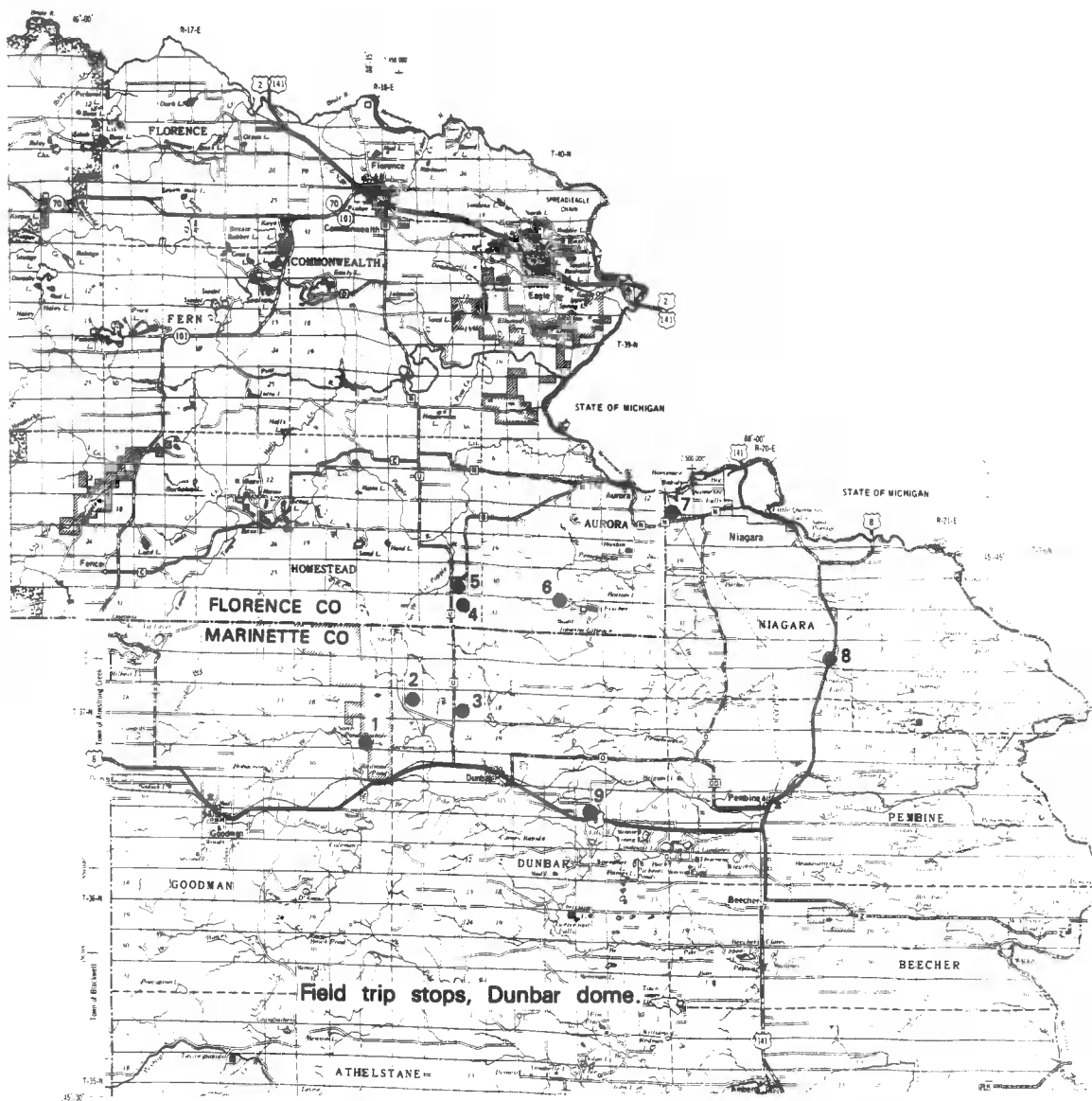
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FIELD TRIP LOG AND DESCRIPTIONS DUNBAR GNEISS - GRANITOID DOME

By

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FIELD EXCURSION

Road Log

Log begins and ends at Dunbar, Wisconsin - at junction of First Street and U.S. highway 8. Descriptions of field stops are given separately on following pages.

Mileage

- 0.0 Dunbar. Drive west on U.S. highway 8.
- 1.6 Junction of Marinette County highway U and U.S. highway 8. Continue westward.
- 4.5 Turn right (north) on secondary road to Coleman Lake Club. Permission should be obtained from Manager of the Coleman Lake Club of Goodman, Wisconsin.
- 6.2 Clearing at house and barn. Walk eastward about 800 feet to outcrops of Dunbar Gneiss (Stop 1). Return to vehicles and proceed south back to U.S. highway 8.
- 7.9 Junction with U.S. highway 8. Turn left (east).
- 10.8 Junction of U.S. highway 8 with Marinette County highway U. Turn left (north) on Co. U.
- 12.0 Turn left (west) on Spur Lake road (secondary road).
- 13.9 Outcrops on east side road (Stop 2) of Dunbar Gneiss. Return to County highway U.
- 15.8 Junction, Spur Lake road and Co. U.
- 16.2 Outcrops on east side road (Stop 3). Walk eastward from blasted road cut (Dunbar Gneiss).
- 20.5 Junction Co. U and Co. B. Turn right (east) on Co. B and proceed due E (including dirt road) for 0.5 mi.
- 21.0 Turn right (south) on secondary road and proceed for 0.5 mi. Cars will park here. Walk south on unimproved road to Stop 4.
- 21.7 (Stop 4). Outcrop on knob is a highly deformed facies of Dunbar Gneiss.
- 22.4 Return to vehicles, and proceed north to Co. hy B. Junction of east-west secondary road. Turn left and proceed onto Co. B.
- 22.8 Farmhouse just east of junction of Co. B and Co. U. Obtain permission from owner. Walk south to outcrop (Quinnesec volcanics) behind barn. (Stop 5). Return to vehicles. Proceed east on Co. B.

Mileage

- 28.2 Junction of Co. B with north-south asphalt road. Turn right (south).
- 31.6 Curve in road to left (east). Continue eastward.
- 31.9 Outcrop south side of asphalt road on small knob. (Stop 6A). A companion outcrop (Stop 6B) to be observed is on north side of road, about 0.1 mile west of Stop 6. Return to east-west asphalt road and proceed east.
- 36.2 Junction asphalt road with County highway N. Turn right (east) on Co. N.
- 37.9 Railway crossing. Park and walk north along railway. (Stop 7) includes 3 separate outcrops, A, B, and C. Return to cars, and proceed east on Co. N into the town of Niagara.
- 39.9 Junction Co. N and U.S. highway 141. Turn right on U.S. 141 and proceed through Niagara.
- 43.1 Junction of U.S. highway 8 with U.S. 141. Proceed south on hy 141-8.
- 46.3 (Stop 8). Outcrop east side of highway exposing the contact zone between granite of Spikehorn Creek and Quinnesec volcanics. Return to cars and proceed south on U.S. 141-8 through Pembine.
- 52.4 Junction U.S. hy. 8 and U.S. 141-8. Turn right (west) on hy. 8.
- 58.0 (Stop 9). Outcrops on north side highway 8. Return to cars and proceed west to Dunbar.
- 61.2 Dunbar, Wisconsin. End of log.

Description of Field Stops

- Stop 1. SW1/4 SW1/4 sec. 21, T.37N., R.18E., Goodman 7-1/2 minute quadrangle. Outcrops in partly grassy and wooded area, 1,000 feet east of Coleman Lake Club road.

Large outcrops of Dunbar Gneiss--interlayered biotite gneisses with a few thin, intercalated layers of amphibolite, cut by abundant white pegmatite and pink aplite. Layers generally 1-24 inches thick. All rocks deformed by northwest-trending folds having steeply dipping limbs and axial planes striking N.45-50°W.; folds plunge ~40°SE. The foliation (S_1) is subparallel to layering (S_0). Some pegmatite shows incipient boudinage. On the northwest part of outcrop, foliation planes oriented N.80W., 45°S. have a crenulation and mineral lineation plunging 45° S.25°W. that is younger than F_1 . Probably it is related to strain near core-cover boundary.

The northwest-trending folds and accompanying southeast-plunging lineation is virtually identical to the structure elsewhere in the Dunbar Gneiss in the central core of the dome. This gneiss has a U-Pb discordia age of $1,862 \pm 5$ Ma. The Rb-Sr system in this rock has been reset, and a Rb-Sr biotite age on one sample is 1,125 Ma.

Suggested additional stop; it will not be visited on this field excursion. SE1/4 SE1/4 sec. 19, T.37N., R.18E., Goodman quadrangle. Rock knob adjacent to cleared area, southeast of dirt road. Moderately homogeneous hornblende-biotite gneiss. Rock has a strong foliation and lineation, indicative of high strain. Foliation, N.50°W., 90°; lineation (mineral alinement), 80° S.50°E. Gneiss is cut by 2-3-inch biotite granite dikes and by pink pegmatite and aplite.

The steeply plunging lineation is characteristic of structures of rocks in and near the core-cover boundary, where ductility contrasts during diapirism were large. One sample gave a Rb-Sr biotite age of 1.13 Ga.

- Stop 2. Center sec. 15, T.37N., R.18E., Dunbar 7-1/2 minute quadrangle. Excellent, partly lichen-free outcrops of migmatitic Dunbar Gneiss. Consists mainly of compositionally layered rocks, biotite gneiss and lesser amphibolite, intruded by megacrystic biotite granite gneiss, granite pegmatite, and aplite. All rocks are deformed. Foliation: N.50-55°W., 90°. Foliation, expressed by biotite and hornblende alinement, is generally parallel to compositional layering but locally transects intrusive contacts of megacrystic granite gneiss at 10°-15° angles.

The protolith of the layered gneiss here and at Stop 1 is considered to be calc-alkaline volcanic rocks.

Stop 3. SW1/4 SW1/4 sec. 13, T.37N., R.18E., Dunbar 7-1/2 minute quadrangle. Blasted outcrop of Dunbar Gneiss on east side Co. U and outcrops on ridge extending to east.

The outcrop in road cut is site of USGS sample W143 and, apparently, of dated sample 5 of Banks and Cain (1969). Sample W143 gave a U-Pb zircon concordia upper intercept age of $1,862 \pm 5$ Ma and a lower intercept age of 471 ± 23 Ma. Aplite from this outcrop has a Rb-Sr model age of 1.4 Ga.

The outcrops east of the road cuts are composed mainly of a megacrystic granite gneiss that contains rafts of layered amphibolite. Lineation in the amphibolite plunges 20° - 25° N. 85° - 90° E. Locally, the amphibolite is refolded by folds having N. 50° W. steep axial surfaces. The granite gneiss has a pervasive N. 70° W. foliation.

The granite gneiss (Dunbar Gneiss) has the composition of tonalite, and is interpreted as a plutonic protolith.

Stop 4. SE1/4 NW1/4 sec. 36, T.38N., R.18E., Dunbar 7-1/2 minute quadrangle. Rock knob near south end of north-south dirt road that connects with Florence County highway B.

Biotite augen gneiss which is interpreted as an intensely deformed variety of Dunbar Gneiss. Foliation, N. 75° E., 85° S.; lineation, 30° S. 45° W. The high strain apparent in the rock is the result of strong ductile deformation in the vicinity of the core-cover boundary; the outcrop is less than 1,000 ft from the boundary.

Stop 5. NW1/4 SW1/4 sec. 25, T.38N., R.18E., Dunbar 7-1/2 minute quadrangle. Outcrop south of farmhouse at junction of Florence County highways U and B. Ask permission of owner. Outcrop of metavolcanics and coarser grained metagabbro (amphibolite grade) of Quinnesec Formation. Two periods of folds are visible in the rocks. An older, dominant foliation (S_2), N. 20° - 40° W., 45° SW. and accompanying lineation (L_2), 45° S. 65° W., is deformed by small-scale asymmetrical folds (F_4) (S-type) that plunge 50° S. 80° W. The folds have an axial plane foliation (S_4), N. 55° E. $\sim 90^{\circ}$. The younger deformation (D_4) exhibits transitional brittle-ductile behavior. The outcrop is about 0.6 mi northwest of the core-cover boundary.

The younger folds and foliation are interpreted as the result of flattening strain caused mainly by outward inflation (to the northwest) of the central core of the dome against the metavolcanics. Similar asymmetrical folds (S-type) can be seen in outcrops of the same rocks on the west side of highway U in SE1/4 SE1/4 sec. 26, T.38N., R.18E.

Stop 6. SE1/4 SE1/4 sec. 28, T.38N., R.19E. Outcrops in rock knobs on both sides of asphalt road along bottom of section 28. Outcrops on south side of road (A) shows partial replacement of Dunbar Gneiss by K-feldspar, to yield Hoskin Lake-type granite; outcrop on north side of road is typical of much of the Hoskin Lake Granite (B).

Stop 7. Outcrops along Chicago, Milwaukee, St. Paul and Pacific Railway north of Florence County hy. N, Iron Mountain 7-1/2 minute quadrangle. Secs. 7 and 18, T.38N., R.20E. Involves about a 2 mi walk along railway.

A. Outcrop of Hoskin Lake Granite, 0.2 mi north of County highway N. The granite is coarse grained and has abundant large tabular K-feldspar grains that give a foliation, N.85°W. ~65°S. It contains inclusions of volcanic rocks from the Quinnesec. Numerous fractures transect the granite.

B. Outcrop in blasted cut, 0.2 mi north of station A. SW1/4 sec. 7, T.38N., R.20E. A 45-ft-wide wedge of intensely foliated amphibolite (Quinnesec Formation) occurs in the Hoskin Lake Granite. It strikes N.70°W. and dips 75°S. The adjacent granite is intensely fractured (brittle-ductile deformation). The wedge is interpreted as a tectonic block, faulted into the granite. Tourmaline veins are present in the southern part of the cut.

C. Outcrop of Quinnesec volcanics, east side of railway tracks. SW1/4 sec. 7, T.38N., R.20E. The metavolcanics (amphibolite grade) have a strong, close-spaced foliation (S_4) (N.80°W., 65°S.) and a steep stretching lineation (L_4) (62° S.15°W.) expressed by mineral alinement, rodding, boudins, crinkles, and flattened and stretched pillows. Deformed pillows can be seen on crest of knob, near south end of outcrop. Tight folds (F_4) that plunge parallel to the linear fabric and have N.80°W., 65°S. axial surfaces can be observed at places.

The high strain exhibited here is indicative of the intense deformation on the overturned, north margin of the central core of the Dunbar dome, and is controlled by the core-cover boundary. Qualitative estimates of stretched pillows indicate a maximum length to width ratio of about 5:1. Deformation is indicative of transitional brittle-ductile behavior.

Suggested additional stop; it will not be visited on this trip. Outcrop of metamorphosed Marinette Quartz Diorite, 0.2 mi south of County highway N on railway. The quartz diorite is a layered gneiss (amphibolite facies) that locally is cut by small dikes of Hoskin Lake Granite and leucogranite. The layering dips moderately to gently and is folded into round-crested open upright folds that plunge 30° S.15W. A conspicuous mineral lineation is subparallel to fold hinges.

Stop 8. SW1/4 sec. 1, T.37N., R.20E., Pembine NW 7-1/2 minute quadrangle, east side U.S. highway 8-141; blasted cut.

Outcrop is the southern margin of the granite of Spikehorn Creek in the Niagara lobe against Quinnesec Formation. Contact of main body of granite is a steep fault whose surface is coated by chlorite. The granite is reddened by alteration of feldspar, and itself is faulted. It contains small inclusions of amphibolite. Dikes of granite of Spikehorn Creek and leucogranite intrude the Quinnesec on the south side of the faulted contact.

Suggested additional stop: Outcrop 0.5 miles north of Stop 8; it will not be visited on this trip.

This outcrop shows the contact of the granite of Spikehorn Creek with an inclusion of volcanics from the Quinnesec. The granite, on north side of contact, is reddened, and in the contact zone contains veins of gray and smoky quartz, tourmaline, and pyrite. In the contact zone, the rocks have a cataclastic (mainly ductile) foliation and a steep lineation (plunges 75°SE.). A gray porphyry cuts the metavolcanic rocks in the southern part of the outcrop; both rock types are cut by dikes of red leucogranite.

This lobe (Niagara lobe) of granite is interpreted as a diapir that bulged outward from the central core during a late stage in the evolution of the Dunbar dome, as evidenced by the uniformity of the granite, its lack of a penetrative foliation, and a foliation in the surrounding metavolcanics that conforms closely to the core-cover boundary. The granite is the youngest dated rock in the dome; it has a U-Pb zircon discordia age of 1,836±6 Ma.

Stop 9. (Time permitting) SW1/4 SE1/4 sec. 34, T.37N., R.19E., Dunbar NE 7-1/2 minute quadrangle. Smooth outcrops in cleared area, 150 ft north of U.S. highway 8, adjacent to trail. Contact zone of Newingham Tonalite. This outcrop of Newingham Tonalite contains inclusions of amphibolite and biotite gneiss (Dunbar Gneiss). On east side of draw, the tonalite is reddened by surface alteration. In draw, contact can be seen between Dunbar Gneiss and the tonalite; it strikes N.55°E. and dips steeply. Foliation in the gneiss is N.50°-55°E., 70°SE; foliation (S₃) in tonalite is N.80°E., 65°SE. The foliation in the tonalite is younger than that in the gneiss; it crosscuts the contact but is only weakly developed in the gneiss.

This structural relationship can be seen at many places in the contact zone between the Dunbar Gneiss and the Newingham Tonalite.

Suggested additional stop; it will not be visited on this trip. SE1/4 NW1/4 sec. 21, T.36N., R.19E., Twelvefoot Falls 7-1/2 minute quadrangle. Twelvefoot Falls on North Branch Pike River, in Twelvefoot Falls County Park. Note: this stop is about 3.5 mi south of U.S. highway 8, and can be reached via the Lily Lake Road.

Spectacular outcrops along the river expose the Twelvefoot Falls Quartz Diorite of Cain (1964). The outcrops are on the southern margin of a wide shear zone that strikes $\sim N.70^{\circ}W.$ and dips $75^{\circ}-85^{\circ}N.$, and is more than a mile wide; lineations are nearly vertical. The same strongly foliated rocks at Eighteenfoot Falls on the northern line of section 21 also are sheared in the same fashion.

At Twelvefoot Falls, relatively unsheared but highly altered quartz diorite occurs on the south side of the falls. Elsewhere, however, the quartz diorite has a strong, close-spaced foliation expressed by shears and aligned muscovite and chlorite, which was formed by transitional brittle ductile deformation. At the falls, an 18-inch-wide dacite dike is parallel to a fault that strikes $N.70^{\circ}W.$ and dips ca. $80^{\circ}N.$

Thin sections of rocks in the broad, northwest-trending shear zone (Twelvefoot Falls shear zone) show abundant shears, generally filled with chlorite or muscovite, and extreme alteration of hornblende and plagioclase. Garnet is a local metamorphic mineral. Microcline is present at places in fractures in the rocks.

Volcanic Rocks of Northeastern Wisconsin

by

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INTRODUCTION

Volcanic rocks of northeastern Wisconsin were examined as a part of the regional investigations of the geology of the Precambrian rocks in Wisconsin and Upper Michigan. The Pembine 15" quadrangle was chosen for particular emphasis because it contains relatively abundant outcrops of volcanic rocks and adjoins areas previously mapped or currently under investigation. The rocks in this area are the easternmost exposures of the east-trending volcanic-plutonic belt in northern Wisconsin that contains at least four stratabound, base-metal, massive sulfide deposits.

The volcanic rocks of northeastern Wisconsin occur south of the Menominee and Iron River-Crystal Falls iron-bearing districts and are separated from rocks of the Marquette Range Supergroup by the Niagara fault zone (see Bayley and others, 1966; Dutton, 1971). The volcanic rocks were originally designated the "Quinnesec schist" by Van Hise and Bayley (1900) after outcrops of greenstone schists and associated mafic intrusive rocks found at Quinnesec Falls on the Menominee River in southern Dickinson County, Michigan. The name was subsequently changed to Quinnesec Greenstone by Leith and others (1935) and to Quinnesec Formation by James (1958). James applied the term Quinnesec Formation to the belt of greenstone, amphibolite, and schist in the southern part of Dickinson County, Michigan, and the adjacent parts of Wisconsin.

Although the name Quinnesec Formation is presently accepted and widely used to designate the volcanic and associated rocks in northeastern Wisconsin, Jenkins (1973) noted that at least four lithologically distinct volcanic units could be defined in the central part of the Pembine quadrangle. Jenkins considered three of these units sufficiently different from the lithologies of the type area of the Quinnesec Formation (Prinz, 1959; Bayley and others, 1966) to warrant their separate designation. He proposed the informal names McAllister formation, Beecher formation, and Pemene formation for these units. Recently, DePangher (1982) proposed that the Quinnesec Formation be designated the Quinnesec Group consisting of five lithostratigraphic units having formational status.

For the purposes of this report, the informal nomenclature proposed by Jenkins (1973) for the volcanic rocks of the area is used (see fig. 1). I recognize that formal revision of the present stratigraphic nomenclature of the volcanic rocks of the area is warranted. However, such revision should not be undertaken until after present mapping and regional compilation efforts are completed.

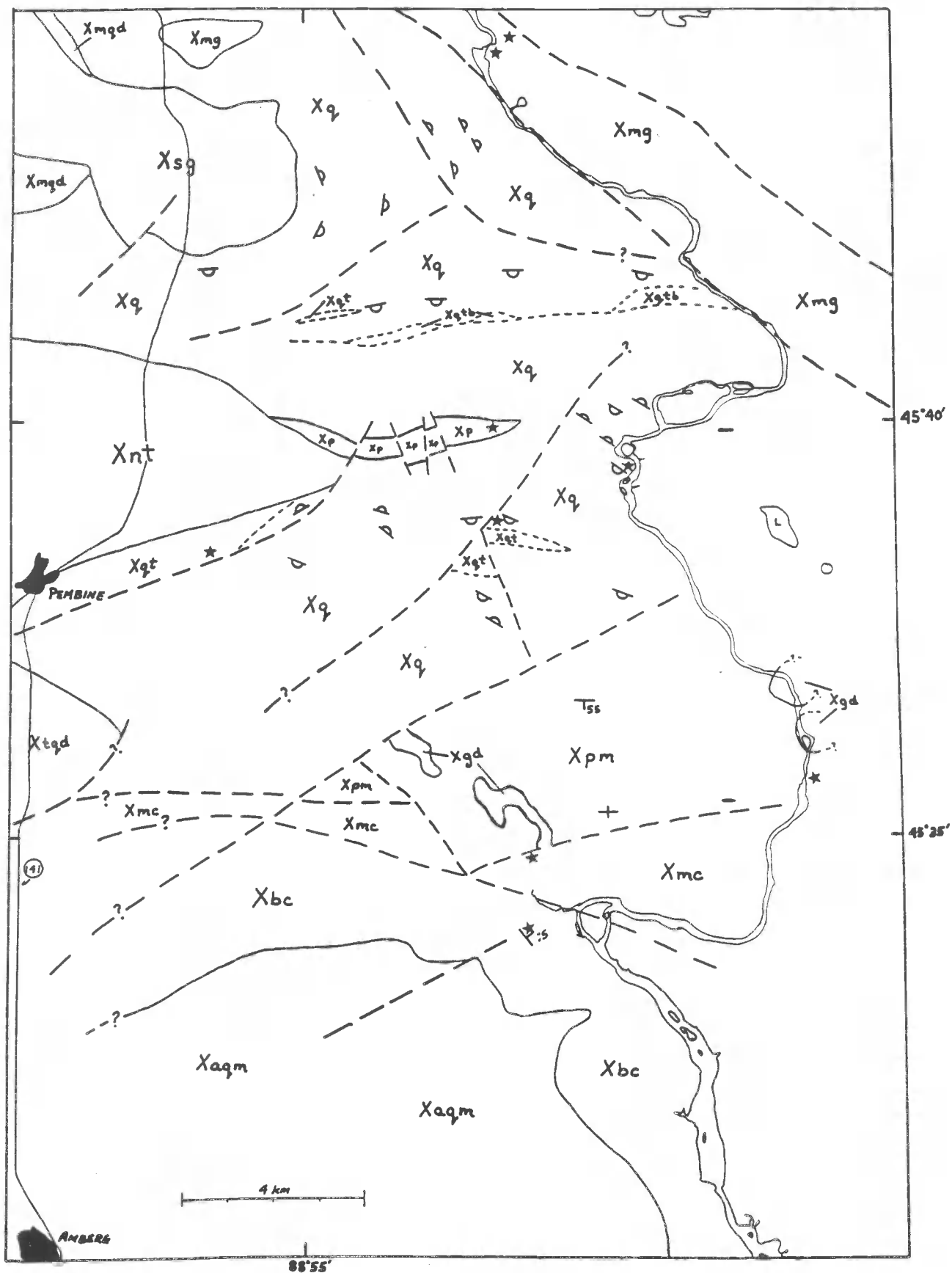
This summary of the geology and geochemistry of the volcanic rocks of northeastern Wisconsin is based largely on my work on the rocks in the Pembine 15" quadrangle (relatively detailed mapping in the north and reconnaissance mapping in the south) and the thesis studies of Hall (1971), Jenkins (1973), Cudzilo (1978), and DePangher (1982). Inasmuch as the mapping and regional compilation of the geology of the area are still incomplete, this summary represents only an interim report. The volcanic rocks north and northwest of the Pembine quadrangle were

EXPLANATION (Figure 1)

Early Proterozoic

Xaqm	Athelstane Quartz Monzonite
Xsg	Spikehorn Creek granite
Xnt	Newingham tonalite
Xmqd	Marinette Quartz Diorite
Xgd	Granodiorite (includes diorite to granite)
Xtqd	Twelve Foot Falls Quartz Diorite
Xpm	Pemene formation of Jenkins (1973): dominantly micro-spherulitic rhyolite.
Xmc	McAllister formation of Jenkins (1973): basaltic and andesitic breccias.
Xbc	Beecher formation of Jenkins (1973): andesites, dacites, and felsic volcaniclastic rocks.
Xq	Quinnesec Formation: dominantly basalt and diabase with some andesite, metagabbro sills (Xmg), peridotite (Xp), tuff (Xqt), and breccia (Xqtb).

— — —	Approximate contact
— — —	Fault
U	Facing direction of pillow lava
T ₅₅	Strike and dip of bedding
★	Field trip stop locations



described by Bayley and others (1966) and Dutton (1971), respectively, who also summarized earlier work in the region. Greenberg and Brown (1983) recently reviewed the major-element geochemistry of the volcanic rocks of northeastern Wisconsin.

GENERAL GEOLOGY

Volcanic and associated rocks are relatively well exposed in an arcuate belt east and north of the Dunbar gneiss-granitoid dome in Marinette and Florence Counties of northeastern Wisconsin. Volcanic rocks and associated sedimentary rocks are also exposed in scattered outcrops in a belt south of the dome (Cummings, 1978), but their stratigraphic relationships to the volcanic rocks to the east cannot be directly established because of intervening glacial cover. To the north and northeast, the volcanic sequence is truncated by the Niagara fault (Bayley and others, 1966 and Dutton, 1971), which marks a major discontinuity in the rocks of the region. North of this fault, rocks of the Michigamme Formation and other units of the Marquette Range Supergroup occur along with basement uplifts of Archean gneissic rocks. To the south, the supracrustal rocks of northeastern Wisconsin are bounded by the Athelstane Quartz Monzonite (Medaris and others, 1973); to the west of the Dunbar dome, outcrop is lost under glacial drift.

The supracrustal sequence includes units of basalt, andesite, dacite and rhyolite flows and volcanoclastic material, and locally, sedimentary rocks including graywacke, black graphitic slates, and iron-formation. Pyritic to pyrrhotitic massive sulfide bodies are also present locally (Hollister and Cummings, 1982; LaBerge, 1983). Gabbro sills are common, particularly in the northern part of the sequence (Bayley and others, 1966). Serpentinite bodies, commonly with some associated gabbros are also present locally (see fig. 1). The units of the Dunbar gneiss-granitoid dome intrude the volcanic rocks west of the Pembine quadrangle, and the Athelstane Quartz Monzonite intrudes them to the south. Small intrusive bodies ranging from hornblendite and gabbro to granite and including lamprophyre dikes and plugs are widespread, particularly in the southeastern part of the volcanic sequence in the Pembine quadrangle. The Twelve Foot Falls Quartz Diorite (Wadsworth, 1962) intrudes volcanic rocks in the area south of the Dunbar dome (see fig. 1 of Sims and others, in this field guide).

The supracrustal rocks and associated subvolcanic intrusive rocks are variably replaced by greenschist facies mineral assemblages throughout the eastern outcrop area but contain assemblages as high grade as amphibolite facies adjacent to the Dunbar gneiss-granitoid dome and further to the west. The rocks were regionally folded on northwest-trending axes and are now at or near vertical in attitude throughout much of the area, but they commonly lack a penetrative cleavage in the east. As a result, primary textures and structures are generally well preserved. Units generally face outwards from the margins of the Dunbar dome and Athelstane intrusion.

The volcanic and associated rocks are broken into several blocks or segments by high-angle faults. High-angle faults also appear to bound the major lithologic units in the Pembine quadrangle (Jenkins, 1973; see fig. 1). Because of uncertainties in the amount of displacement on these faults and the complexity of folding, detailed correlations between blocks have not been possible.

As mentioned in the "Introduction", four major volcanic units have been recognized in the Pembine quadrangle (Jenkins, 1973); the Quinnesec Formation, the McAllister formation, the Beecher formation, and the Pemene formation. These formations, in the order listed, represent progressively more silicic rock units. Jenkins suggested that the order of naming above represented the order of decreasing age. This conclusion was based largely on an analogy with other volcanic terranes, which commonly show a progression to more silicic rock compositions with time. Insofar as this analogy is valid and applicable to the volcanic sequence in the Pembine quadrangle, the stratigraphic sequence proposed by Jenkins (1973) may be valid. However, significant lateral variations in the nature of volcanic rocks can also occur and could be difficult to decipher after deformation. Present geologic data support the interpretation that the Quinnesec Formation (as used by Jenkins) is the oldest volcanic unit. The relative ages of the other units, however, remain uncertain. The regional structure indicates that the McAllister formation may be younger than the Beecher formation but older than the Pemene formation. Further work is required to resolve the stratigraphy of these units.

Until recently, the age of the volcanic rocks in northeastern Wisconsin was a point of controversy. Van Hise and Bayley (1900) and Bayley (1904) originally interpreted the "Quinnebec schists" as early Precambrian principally because of the striking similarity of these rocks to Archean greenstones elsewhere in the Lake Superior region. Van Hise and Leith (1911) subsequently assigned the Quinnebec Formation to a post-Michigamme age (i.e. middle Precambrian) on the base of the interpretation of Hotchkiss that the Michigamme Formation graded upwards into volcanic rocks in Florence County, Wisconsin. Dutton later reinterpreted the relationship in this area and placed a fault between the volcanic rocks to the south and Michigamme Formation to the north. Bayley and others (1966) and Dutton (1971), while acknowledging that decisive field evidence to establish the age of the Quinnebec Formation was lacking, favored an early Precambrian age.

Banks and Rebello (1969) reported a U-Pb zircon age of $1,866 \pm 39$ Ma for a rhyolite sample from an area west of the Pembine quadrangle and south of the Dunbar dome. This age, which is not resolvable from the ages of the rocks of the Dunbar dome (see Sims and others, this field guide), is now generally taken as that of the volcanic sequence throughout northeastern Wisconsin although this rhyolite locality is isolated from the main areas of outcrop. Recently, Warren Beck of the University of Minnesota has obtained a similar age for the basaltic rocks of the Quinnebec Formation by the Sm-Nd technique (Beck, personal communication, 1984). Thus, the age of the volcanic rocks of northeastern Wisconsin now seems to be established as Early Proterozoic and not Archean as once thought. Their age is similar to that obtained for the massive sulfide

deposits near Crandon, Monico, and Ladysmith to the west (Sims, 1976) and to ages of other volcanic and plutonic rocks of the northern Wisconsin magmatic terrane (Van Schmus, 1980). It is still uncertain, however, whether the Early Proterozoic magmatic rocks of northern Wisconsin are significantly younger than the rocks of the Marquette Range Supergroup in Upper Michigan.

STRATIGRAPHY

The four lithostratigraphic units that compose the volcanic rock sequence in the Pembine quadrangle are described below. Although the rocks are metamorphosed at least to the greenschist facies, the prefix "meta" is generally omitted throughout this report for simplicity.

Quinnesec Formation

The Quinnesec Formation, as used in this report, is the dominant volcanic unit in the Pembine quadrangle extending from the northern border to at least the middle of the quadrangle (fig. 1). Its stratigraphic thickness is not known because of the complexities of folding and faulting but is probably on the order of several thousand meters.

The Quinnesec Formation consists predominantly of pillowed to massive tholeiitic basalt, diabase, and lesser pillowed and fragmental andesite. Andesite increases in abundance southward in the unit and is generally plagioclase and clinopyroxene phyric and amygdaloidal. Basalt is generally pillowed, and pillow shape and size vary between areas. Locally, basaltic pillow breccia and highly variolitic pillow lava is encountered, particularly near the center of the quadrangle. In the north-central

part of the map area, several distinctive tuff and breccia units are present (fig. 1). Fragments are very fine grained, light green, and commonly amygdaloidal and appear to be more siliceous than their matrix. Felsic tuffs and breccias are also present particularly in the southern part of the unit. (Felsic fragmental units were also reported by Bayley and others (1966) and Dutton (1971) to exist north and northwest of the Pembine area.

Fine to medium-grained diabase is common throughout the unit and is particularly abundant in the northern part. A distinctive quartz bearing diabase extends over a wide area in the north-central part south of the tuff and breccia units (fig. 1). Dikes of diabase are locally identified and may represent feeders to overlying flows.

Sedimentary rocks are rare within the Quinnesec Formation. Where present, they consist mostly of chert, graywacke, slate, and iron-formation. Iron-formation, occurring as thin units interlayered with clastic sedimentary rocks or tuffs, consists of interlayered chert and siderite (Cummings, 1978).

The Quinnesec Formation is intruded in the western part of the map area by the Marinette Quartz Diorite, the Newingham tonalite, and the Spikehorn Creek granite (fig. 1). To the south, it is in fault contact with the Pemene formation.

McAllister Formation

The McAllister formation extends in an east-west belt in the south-central part of the map area (fig. 1) and ranges in thickness from about 300 meters in the west to 3,000 meters in the east (Jenkins, 1973). The unit is steeply dipping; limited evidence indicates that it is probably northward facing. It consists of basaltic to andesitic breccia and locally massive flows. Fragments in the breccia are distinctive in containing large pyroxene crystals generally replaced by amphibole. Amygdules are also common in some fragments. An increase in fragment size to the east indicates that the source area for this dominantly volcaniclastic unit may be east of the present Menominee River.

Beecher Formation

The Beecher formation extends in a north-facing, east to southeast-striking belt in the southern part of the map area and is in contact to the south with the intrusive Athelstane Quartz Monzonite (fig. 1). The unit is at least 3,000 meters thick (Jenkins, 1973). The lower part consists dominantly of plagioclase and clinopyroxene phyric andesite and dacite lavas and pyroclastics. Upwards in the unit, bedded tuffs and acidic fragmentals predominate. Black slates are also locally present in the upper part of the unit.

The lower part of the Beecher formation, where intruded by the Athelstane Quartz Monzonite, has a well-developed foliation and steeply plunging lineation. Dikes of Athelstane Quartz Monzonite are present only for a short distance from the intrusive contact.

Pemene Formation

The Pemene formation occurs over a broad oval area in the south-central part of the map area (fig. 1) and is well outlined by the local topography. It is at least 2,000 meters thick and consists predominantly of microspherulitic, plagioclase-phyric rhyolite and rhyodacite lavas and breccias. The flows are interlayered with a few thin, graded sedimentary units, suggesting that the rhyolite flows were possibly extruded subaqueously. Individual flows were estimated by Jenkins (1973) to range from about 150 to 400 meters in thickness.

The Pemene formation shows little evidence of a penetrative structural fabric. The flows show a southward dip in the north and are near vertical in the south. Jenkins (1973) interpreted the structure of the formation as an east-trending, asymmetric, doubly plunging syncline.

INTRUSIVE ROCKS

A variety of intrusive rocks is found within the supracrustal sequence of the Pembine quadrangle. These range from clearly synvolcanic bodies like the diabases to post-tectonic lamprophyric dikes and plugs. The intrusive rocks associated with the Dunbar gneiss-granitoid dome are discussed by Sims and others (this field guide) and are not further considered herein.

Gabbro Bodies

Numerous large gabbro bodies are present within the Quinnesec Formation, particularly north and northwest of the Pembine quadrangle (Bayley and others, 1966). These bodies are more or less conformable to the mafic lavas and probably represent synvolcanic sills.

Two such bodies are present in the Pembine quadrangle (fig. 1). The smaller body in the northwest part of the area consists of medium to coarse-grained gabbro and diorite and locally contains abundant hornblendite to gabbro xenoliths. Intrusive breccia is locally developed where diorite dikes intruded the gabbro (e.g. road cut, Highway 8, NE1/4SE1/4, sec. 24, T.38N., R.20E.).

A larger gabbroic body, named the Sturgeon Falls sill by Prinz (1959), occurs along the east side of the Menominee River in Michigan and trends southeast for a distance of at least 12 km. Both the upper and lower portions of this sill are fault bounded, the northern fault being an extension of the Niagara fault.

The Sturgeon Falls sill is unique in having serpentinite and pyroxenite along the north side. The pyroxenite generally occurs between the gabbro and serpentinite but also forms narrow bands within the gabbro. Gabbro and anorthositic gabbro compose the bulk of the sill. Anorthosite is locally well developed within the gabbroic part of the sill whereas magnetite-rich gabbro composes the southwestern part. The overall stratigraphy of the sill, with ultramafic rocks along the northern side and magnetite gabbro along the southern side suggests that the sill faces southwest. The consistency of the stratigraphy further suggests that the body may represent a differentiated sill similar in many respects to the

Kiernan sills within the Hemlock Formation in Michigan (Bayley, 1959). However, the Sturgeon Falls sill is compositionally distinct from the Kiernan sills (see discussion below). On the basis of overall similarity in metamorphism, structure, and composition between the Sturgeon Falls sill and the Quinnesec Formation basalts, the sill is interpreted as synvolcanic in age, although Bayley and others (1966) considered the gabbroic sills as "post-Animikie" in age.

Peridotite Bodies

Several small peridotite bodies, now altered to serpentinite, occur in the south-central part of the map area, but the largest and best exposed body occurs in the north-central portion within the Quinnesec Formation basalt (fig. 1). This peridotite body trends east and outcrops discontinuously for a distance of about 4.5 km. The peridotite shows few primary textures, contains serpentinite and large magnetite crystals, and is locally cut by veins of carbonate and cross-fiber asbestos. Mineralogically banded and massive gabbro, locally cut by mafic to ultramafic(?) dikes, occurs south of the peridotite and locally appears to also crosscut it. At the western end, the peridotite is cut by pyroxenite dikes composed of coarse (1-5 cm) amphibole pseudomorphs after pyroxene.

Foliation and banding in the associated gabbro are more or less at right angles to the lithologic contacts. Also, dikes found cutting the gabbro and serpentinite do not appear outside the body. These features suggest that this serpentinite-gabbro body may be fault bounded and tectonically emplaced.

Biotite-Pyroxene Diorites

Several bodies of biotite-clinopyroxene-bearing diorite to quartz diorite intrude the Pemene and McAllister formations (fig. 1). Rocks range from fine to medium grained and contain variable amounts of amphibole, clinopyroxene, plagioclase, biotite and quartz. Opaque minerals and apatite are also present as minor phases. Most of the amphibole appears to be pseudomorphous after pyroxene.

Miscellaneous Bodies

Several small bodies of dacite porphyry and blue quartz-eye porphyry occur within the volcanic units in the southern half of the Pembine quadrangle. These probably represent subvolcanic intrusions related to the felsic volcanic rocks of the Beecher and Pemene formations.

Several lamprophyre dikes and plugs have been identified within the map area. These are generally small bodies and are difficult to distinguish from mafic volcanic rocks in the lichen-covered outcrops of the area. The lamprophyres consist of prismatic hornblende and biotite crystals in a feldspar matrix.

Athelstane Quartz Monzonite

The Athelstane Quartz Monzonite intrudes the Beecher formation in the southern part of the Pembine quadrangle (fig. 1) and extends for an unknown distance to the south and west. It consists dominantly of medium to coarse grained quartz monzonite and locally contains numerous metavolcanic inclusions. The Athelstane Quartz Monzonite is dated at $1,836 \pm 15$ Ma (Banks and Cain, 1969). The Amberg Granite, which intrudes the Athelstane Quartz Monzonite in the southern part of the map area, is $1,756 \pm 19$ Ma (Van Schmus, 1980).

GEOCHEMISTRY

Representative analyses of volcanic rocks from units within the Pembine quadrangle are presented in Table 1. Their compositional variations are shown in figures 2-8. Greenberg and Brown (1983) recently reviewed the major-element chemistry of volcanic rocks from northeastern Wisconsin and concluded that they are dominantly calc-alkaline and exhibit characteristics of rocks found in modern volcanic arcs. The data of this study confirm these conclusions and provide further information on the nature and evolution of the volcanic sequence.

The overall calc-alkaline character of the northeastern Wisconsin volcanic rocks is shown by the AFM (fig. 2) and Jensen cation (fig. 3) diagrams. However, many of the basalts, diabases, and gabbros of the Quinnesec Formation are tholeiitic. Figures 2 and 3 also illustrate the marked compositional differences between the volcanic rocks of northeastern Wisconsin and those of the Marquette Range Supergroup in Upper Michigan, which are bimodal, show strong iron enrichment trends, and are enriched in TiO_2 relative to those in northern Wisconsin.

Chondrite-normalized rare-earth-element (REE) patterns for Quinnesec basalts and diabases are shown in figures 4 and 5. Most of the samples are characterized by marked light-REE depletions ($[\text{La}/\text{Yb}]_N = .10-.54$) even more extreme than is typical of ocean-floor basalts (fig. 4). REE abundances show a wide range ($[\text{Yb}]_N = 7-25$) that only poorly correlates with MgO content. The relative depletion of light-REE generally increases as REE abundance decreases, suggesting that these basalts may represent melts derived by progressive partial melting of the same mantle source.

Table 1.-- Representative analyses of volcanic rocks from the Pembine
Quadrangle, northeastern Wisconsin.

	1	2	3	4	5	6	7	8
SiO ₂	49.7	47.8	53.4	48.4	56.2	60.9	70.2	74.6
Al ₂ O ₃	16.3	15.9	15.5	15.5	16.5	12.8	13.4	13.5
Fe ₂ O ₃	1.9	3.2	2.1	2.5	2.4	1.4	0.97	0.84
FeO	6.7	8.0	7.7	9.5	7.6	6.0	4.2	2.1
MgO	8.1	8.8	4.1	7.7	3.8	7.0	0.78	1.3
CaO	12.8	11.5	5.8	9.8	8.0	5.5	1.3	0.19
Na ₂ O	2.0	0.81	4.7	2.1	3.4	2.8	4.7	5.9
K ₂ O	0.27	0.10	0.27	0.18	0.34	2.2	2.2	1.7
TiO ₂	0.53	0.43	1.1	1.2	0.92	0.37	0.43	0.29
P ₂ O ₅	0.09	0.07	0.19	0.15	0.16	0.20	0.12	0.09
MnO	0.18	0.17	0.14	0.18	0.18	0.20	0.13	0.03
H ₂ O ⁺	1.4	3.2	3.4	3.1	1.7	1.1	0.96	0.65
H ₂ O ⁻	0.17	0.08	0.09	0.21	0.07	0.17	0.10	0.11
CO ₂	0.21	0.96	3.0	0.06	0.24	0.03	1.6	0.01
Rb	8	<5	<5	<5	8	51	53	45
Sr	89	87	151	135	307	392	184	69
Ba	54	16	47	104	104	1130	1005	631
Zr	43	31	80	80	61	99	166	173
Y	23	22	35	25	17	21	43	40
Nb	<5	<5	<5	8	<5	6	14	14
Cr	400	105	14	223	11	469	2	2
Co	41	53	37	46	36	26	1.7	0.7
Sc	56	59	43	46	40	29	12.9	12.0
Ta	0.065	--	0.093	0.30	0.13	0.27	0.74	0.79
Hf	1.02	0.60	2.20	1.99	1.40	2.37	4.48	5.12
Th	0.14	--	0.22	0.25	0.53	3.72	6.51	7.65
U	0.28	0.27	--	--	0.21	1.43	2.20	2.29
La	1.37	0.49	2.12	3.27	4.82	16.4	27.5	29.4
Ce	3.90	1.88	6.79	9.6	12.1	33.3	58.6	67.9
Sm	1.36	1.02	2.81	2.58	2.15	3.43	7.28	7.80
Eu	0.62	0.53	1.00	0.91	0.73	0.83	1.63	1.47
Tb	0.54	0.50	1.04	0.65	0.49	0.54	1.20	1.16
Yb	2.58	2.34	3.80	2.65	1.80	1.90	4.97	5.53
Cu	0.37	0.38	0.58	0.36	0.27	0.28	0.78	0.81

1-2 Quinnebec diabbases
3-4 Quinnebec basalts
5 Quinnebec andesite
6 Beecher andesite
7-8 Pemene rhyolites

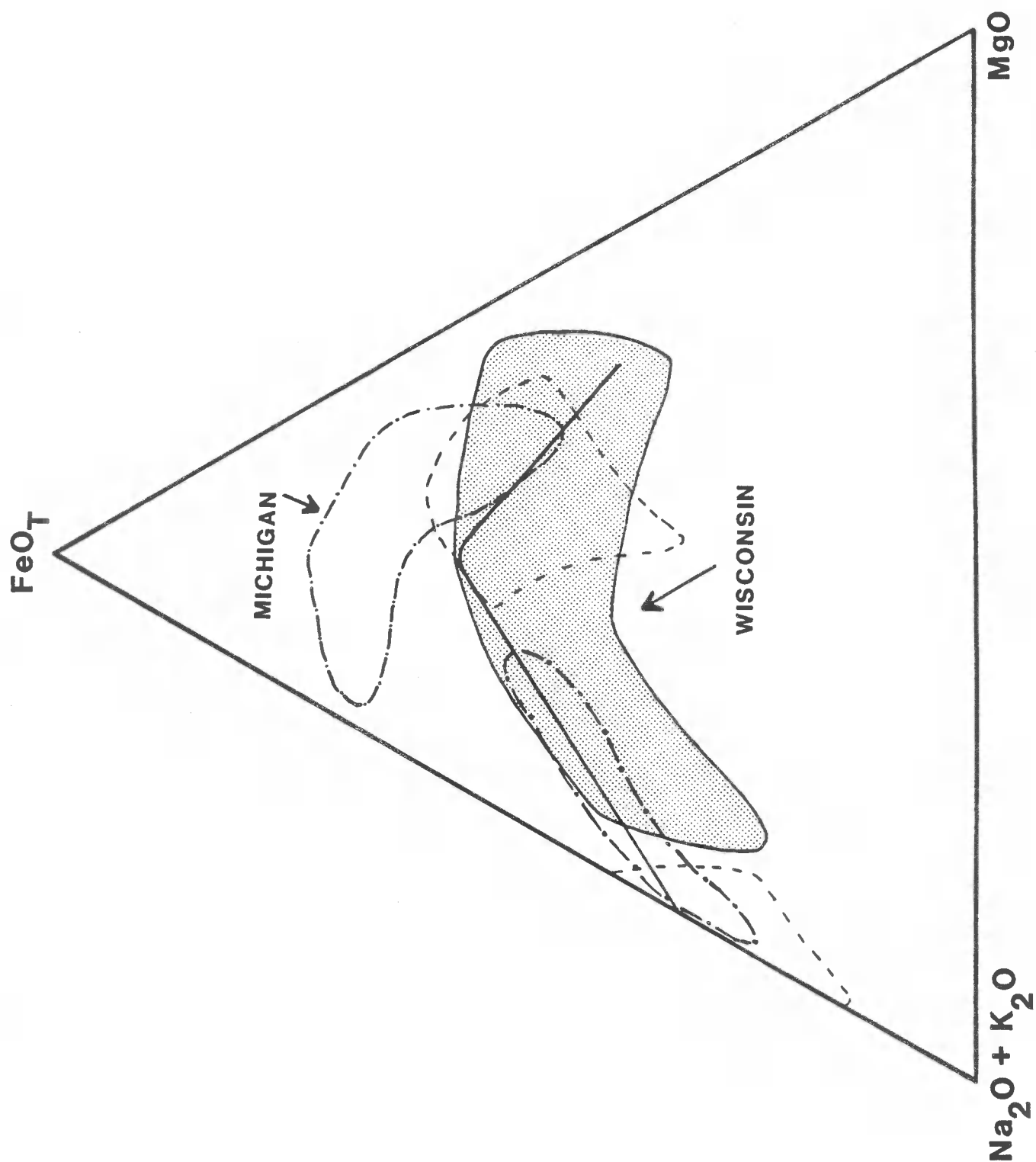


Figure 2.-- FeO_T - MgO - $\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram for volcanic rocks of northeastern Wisconsin (stipled field) compared to volcanic rocks of upper Michigan (dot-dash fields) and Monico area of Wisconsin (dashed fields).

The strong light-REE depletion indicates that this source had undergone prior partial melting. This conclusion has recently been confirmed by the Nd isotopic work of Warren Beck (Beck, personal communication, 1984). These strongly light-REE depleted basalts are similar to those of the lower units of the Troodos Complex (Kay and Senechal, 1976). A smaller group of basalts from the Quinnesec Formation are only moderately depleted in light-REE (fig. 5). These are very similar in many respects to modern ocean floor basalts (figs. 5-8). The two gabbro samples from the Sturgeon Falls sill have light-REE depletion patterns similar to those of the basalts (fig. 4).

The chondrite-normalized REE patterns for one Quinnesec Formation andesite, two Beecher formation andesites, and three Pemene formation rhyolites are shown in figure 6. The samples show progressive enrichment in light-REE, and, with increasing total REE abundances, show larger negative Eu anomalies. These REE patterns are typical of calc-alkaline volcanic rocks of modern arc systems (e.g., North Island, New Zealand, Reid, 1983).

The general island-arc compositional affinities of the northeastern Wisconsin volcanic rocks are further illustrated in figures 7 and 8 in terms of Y-Cr variations and Hf/Th-Ta/Th ratio variations, respectively. Like the volcanic rocks in modern arcs, the rocks of northeastern Wisconsin show marked depletions in high-valence cations like Zr, Hf, Ta, Y, and Ti. The basalt samples from the Quinnesec Formation that plot in the fields of mid-ocean ridge basalts in figures 7 and 8 represent the group of basalts in which light-REE are only moderately depleted (fig. 5).

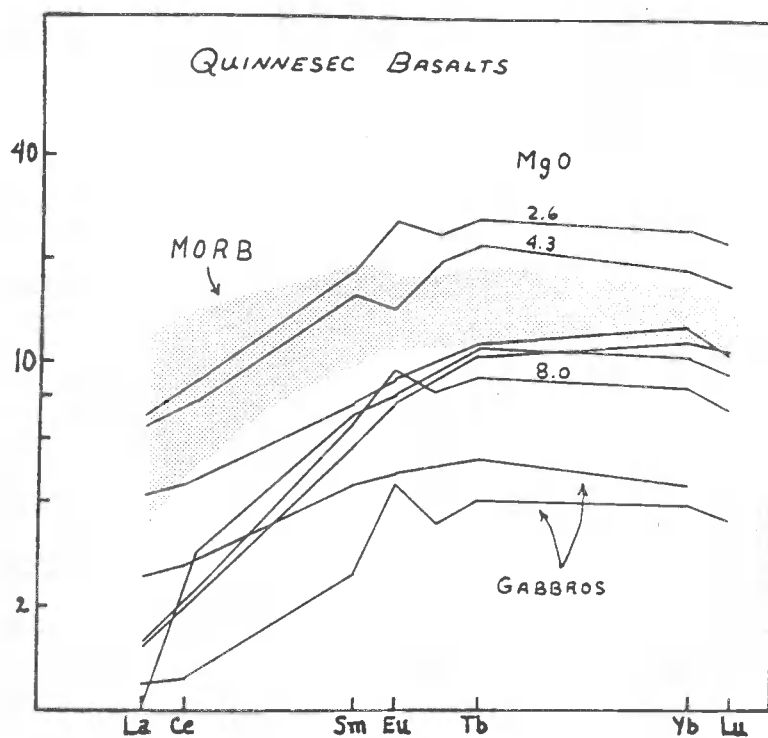


Figure 4.--Chondrite normalized REE for some Quinnesec Formation basalts and gabbros of the Sturgeon Falls sill. MORB = field for mid-ocean ridge basalts.

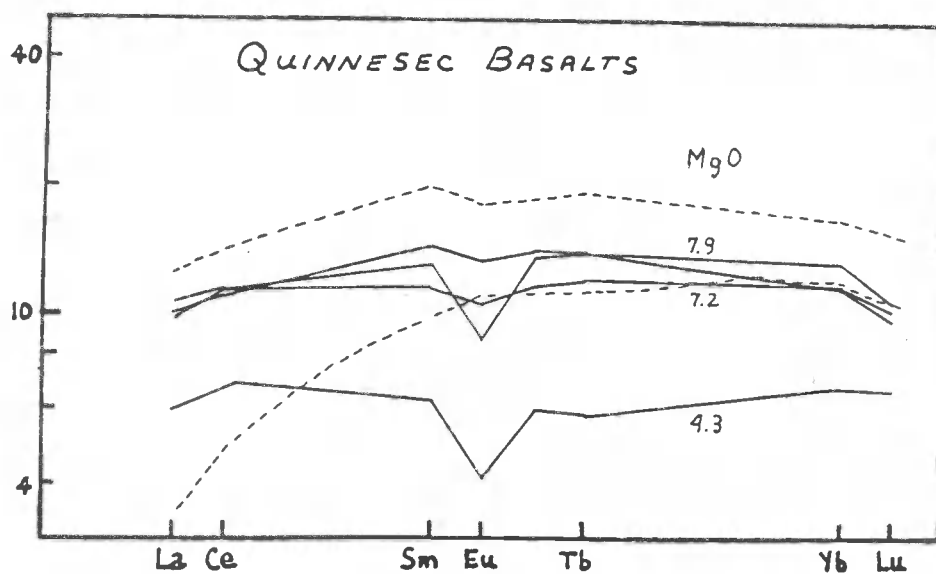


Figure 5.--Chondrite normalized REE for some Quinnesec Formation basalts. Average MORB shown by dashed field.

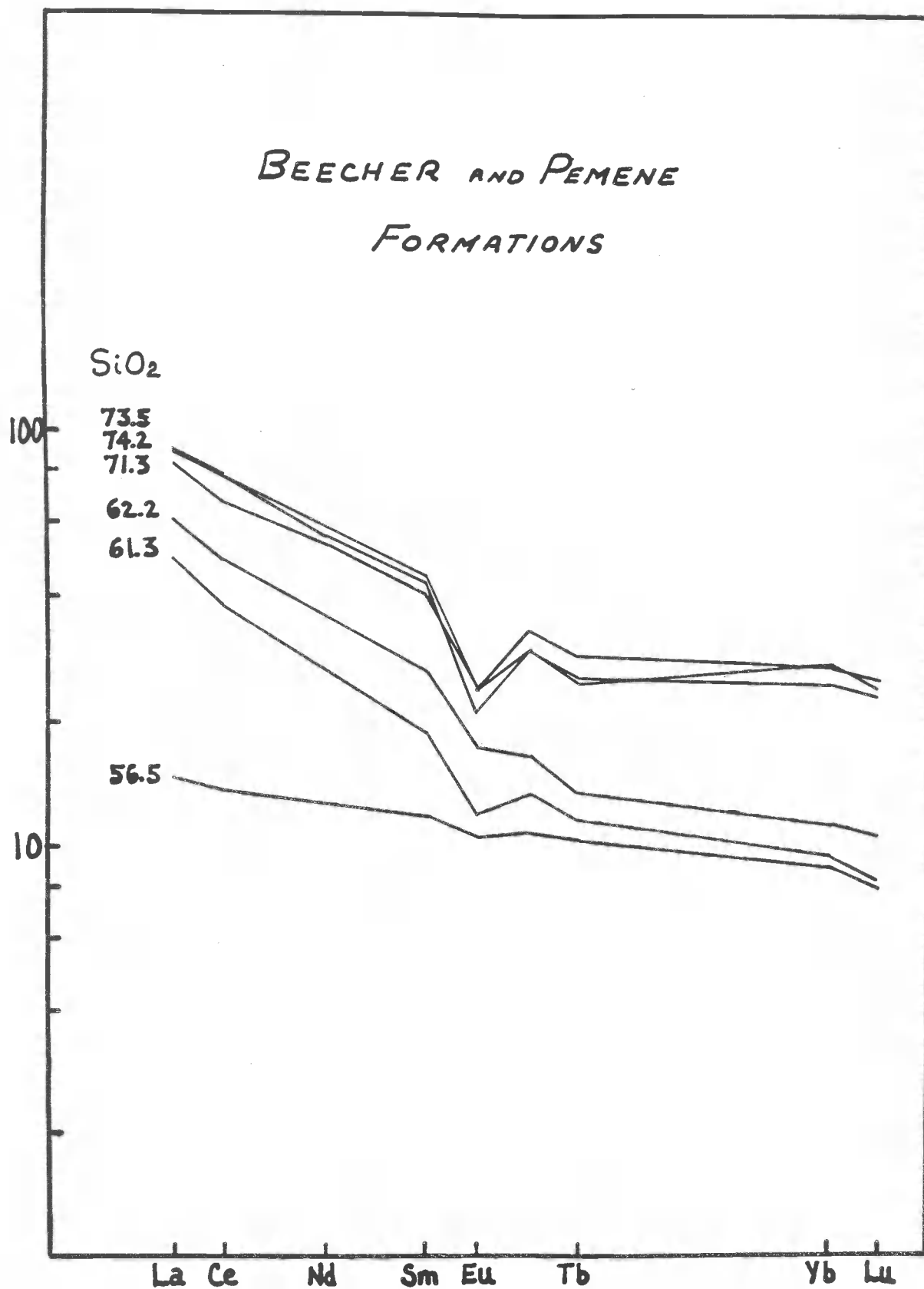


Figure 6.--Chondrite normalized REE for one Quinnesec Formation andesite (56.5, SiO₂), two Beecher formation andesites (61-62, SiO₂) and three Pemene formation rhyolites (71-73.5, SiO₂).

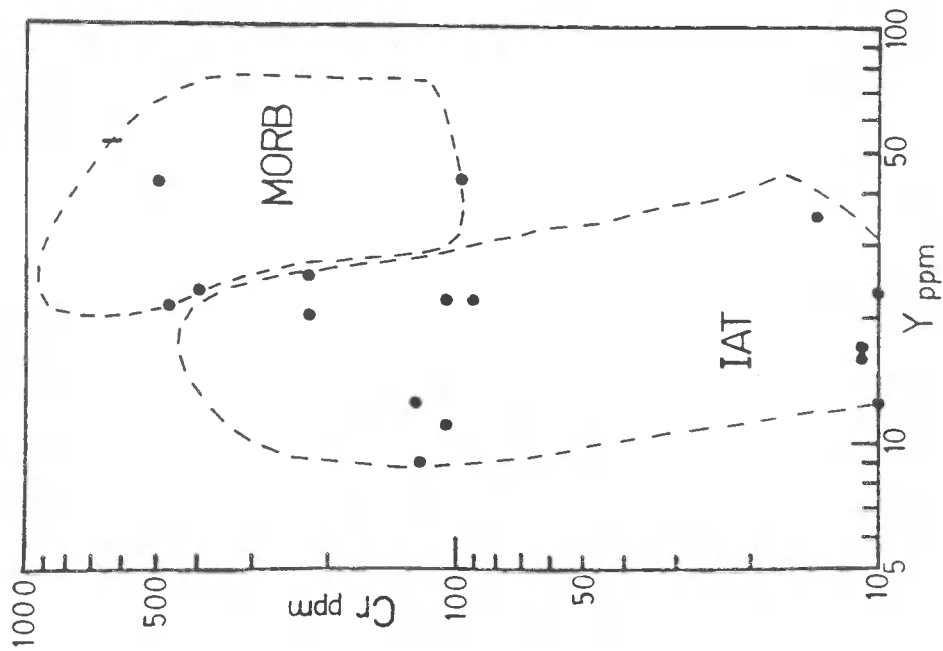


Figure 7.--Cr-Y variation for northeastern Wisconsin volcanic rocks. IAT=Island arc tholeiite field; MORB=Mid-ocean ridge basalt field. (After Pearce, 1982).

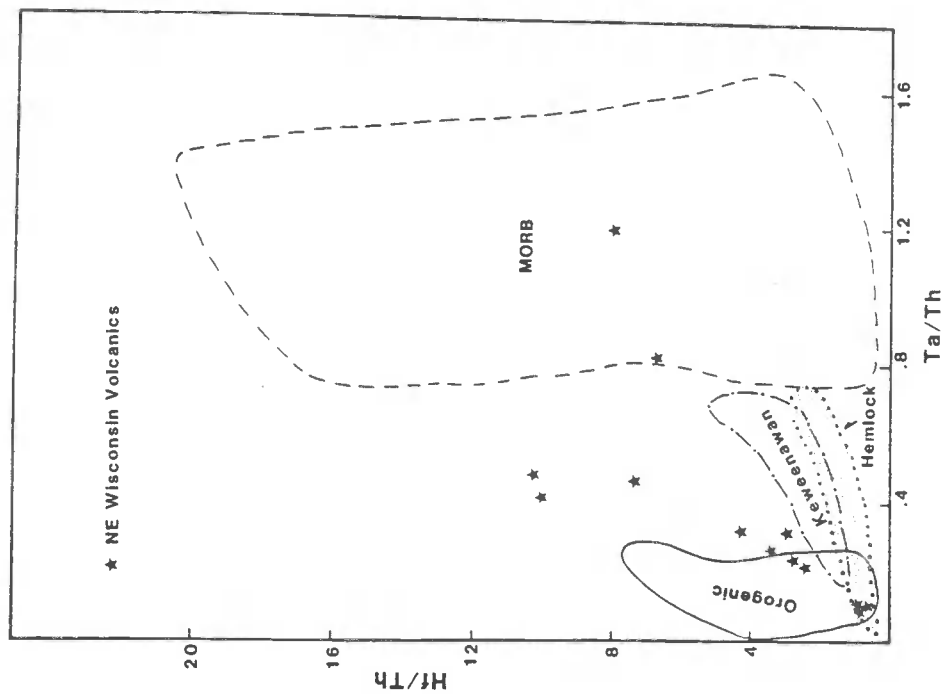


Figure 8.--Hf/Th vs Ta/Th variation in volcanic rocks of northeastern Wisconsin (stars) (after Noiret and others, 1981). Note similarity between Hemlock and Keweenaw volcanic rocks. Hemlock data from Fox (1983).

TECTONIC IMPLICATIONS

Both the nature and geochemistry of the volcanic rocks of northeastern Wisconsin suggest that the rocks formed in a magmatic arc similar in many respects to modern oceanic island-arcs (e.g., like those of the western Pacific, Hamilton, 1979). The presence of tectonically emplaced ultramafic rocks (ophiolite fragments(?)) with basalts of mid-ocean-ridge chemical affinities further indicates such an environment of formation. The general absence in Upper Michigan of magmatic rocks having similar affinities suggests that the associated subduction was to the south. The eventual collision of the magmatic arc formed as a result of the southward subduction probably resulted in the deformation event recognized as the Penokean Orogeny (Schulz and others, 1984). Thus, the Niagara fault zone, as proposed by Larue (1983), probably represents the zone of suturing between the magmatic arc terrane (northern Wisconsin volcanic-plutonic belt) and the Archean crust and miogeosynclinal cover sediments (passive margin sequence; Marquette Range Supergroup) to the north.

One feature typical of many subduction-zone assemblages but notably missing from northern Wisconsin is a melange sequence representing rocks of a possible fore-arc basin and accretionary wedge. Recent Deep Sea Drilling Project drilling in the western Pacific, however, has shown that arc systems situated over steeply dipping Benioff zones commonly lack both fore-arc basins and abundant trench sediments (Uyeda, 1983). This finding suggests that the northern Wisconsin magmatic system may have formed over a steeply dipping subduction zone, thus precluding accumulation of a thick sedimentary wedge.

The overall nature and geochemistry of the rocks of the northern Wisconsin volcanic-plutonic belt strongly suggest that tectonic processes during the Early Proterozoic generally were similar to plate-tectonic processes operating today. Although many aspects of the geology, tectonics, and paleogeography remain to be established for the Early Proterozoic rocks of the Lake Superior region, they now seem to represent another example of the Wilson cycle (i.e. opening and closing of an ocean basin) in the geologic record.

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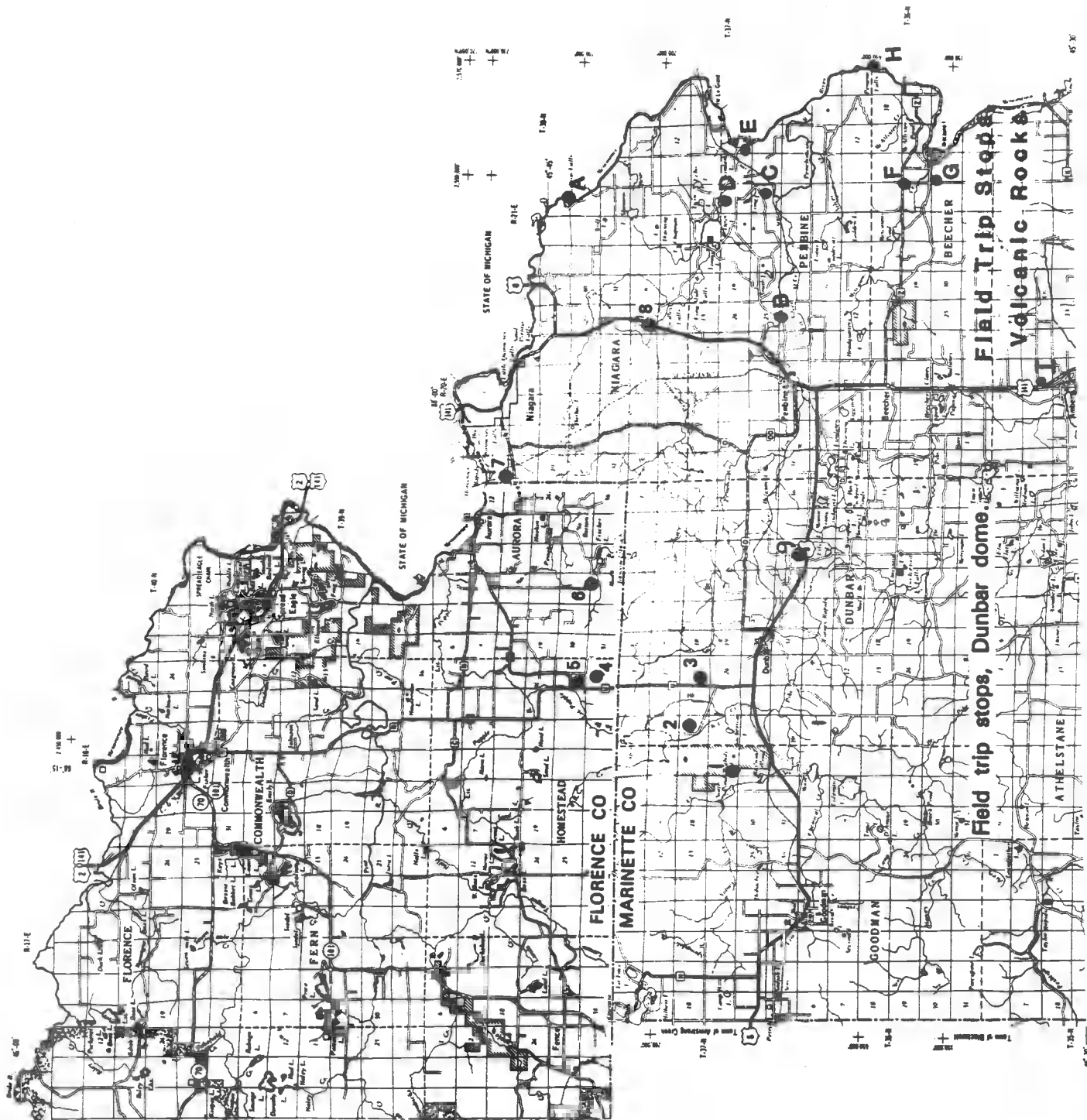
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Field Trip Log and Descriptions of Stops to accompany

Volcanic Rocks of Northeastern Wisconsin

by

Klaus J. Schulz



Field Excursion

Road Log

Log begins at the Pembine Post Office, Wisconsin, on U.S. Highway 141-8 and ends with Stop H at Pemene Falls. Descriptions of stops are given separately on the following pages.

Mileage

- 0.0 Pembine Post Office, Wisconsin, on U.S. Highway 141-8. Proceed north.
- 8.7 Junction with U.S. Highway 8. Turn right (east) and proceed to Norway, Michigan.
- 13.15 Junction with U.S. Highway 2. Turn right and proceed to Vulcan, Michigan.
- 14.8 Turn right on Main Street in Vulcan. Pass Vulcan Middle School on right.
- 15.5 Follow right fork in road onto River Road.
- 17.5 Bridge across Menominee River.
- 17.95 Turn right onto secondary road going to Sturgeon Falls Dam.
- 18.1 Outcrop on west (right) side of road. STOP A1. Serpentinite of the Sturgeon Falls sill. Return to vehicles and proceed south.
- 18.5 Take left fork in road down to Sturgeon Falls Dam.
- 18.6 Outcrop to north (right). STOP A2. Gabbro of the Sturgeon Falls sill. Return to vehicles and proceed back through Vulcan and Norway to U.S. Highway 141-8 toward Pembine. Go south (left) on U.S. Highway 141-8 to intersection with Kremlin Road (just north of Pembine).
- 36.3 Junction with Kremlin Road. Turn left (east).

Mileage

- 38.0 Railroad tracks (Soo line) and bridge across the South Branch Pemebonwon River. Park vehicles on right shoulder of road and walk along trail going east along the south side of the river. STOP B. Tuff unit of the Quinnesec Formation. Return to vehicles and proceed east on Kremlin Road.
- 40.35 Junction with dirt road going south. Turn right.
- 40.75 Junction with east-west dirt road. Turn left.
- 43.35 Outcrop south side of road. STOP C. Pillow basalt of the Quinnesec Formation. Return to vehicles, turn around and proceed back to Kremlin Road. (Note - We backtrack because beavers have flooded the dirt road further to the east).
- 46.35 Junction with Kremlin Road. Turn right and proceed east for about 2.3 miles.
- 48.65 Turn left (north) onto dirt road and proceed 0.35 miles.
- 49.0 Outcrops on both sides of road. STOP D. Foliated gabbros and massive diabases associated with large serpentinite body of the Quinnesec Formation. Return to vehicles, turn around, and return to Kremlin Road.
- 49.35 Turn left (east) onto Kremlin Road.
- 50.9 Junction with road to Pemebonwon Dam and Quiver Falls. Turn right (south) and proceed 0.15 miles to railroad tracks.
- 51.05 Cross railroad tracks (Soo line) and take sharp left onto dirt road.
- 51.8 Quiver Falls. STOP E. Pillowed and variolitic basalts of the Quinnesec Formation. Return to vehicles, turn around, and return to U.S. Highway 141-8 via Kremlin Road.

Mileage

- 60.25 Junction of Kremlin Road with U.S. Highway 141-8. Turn left (south) and proceed 3.75 miles to County Z.
- 64.0 Junction with County Z. Turn left (east).
- 70.85 Junction with Marek Road. Turn right (south), proceed 0.15 miles, and park.
- 71.00 Outcrop on east (left) side of road. STOP F. Volcanic breccia of the McAllister formation. Return to vehicles and continue south 1 mile.
- 72.0 Outcrop on east (left) side of road. STOP G. Felsic volcaniclastic rocks of the Beecher formation. Return to vehicles, turn around, and go back to County Z.
- 73.3 Turn right (east) onto County Z and continue east across the Menominee River.
- 77.45 Turn left (north) onto dirt road and proceed north about 1.05 miles to dirt road going down (west) to river.
- 78.5 Turn left onto dirt road toward river.
- 78.65 Pemene Falls. STOP H. Rhyolites of the Pemene formation. Return to vehicles and return via County Z to U.S. Highway 141.

END TRIP

NOTE: If time permits, we will make an additional stop. At intersection of County Z and Highway 141, turn left (south) and proceed about 4 miles to intersection of Highway 141 and Black Sam Road. Outcrop is in field, southeast of intersection.

Description of Field Stops

STOP A1. NW1/4SW1/4 sec. 26, T.39N., R.29W., Faithorn 7 1/2-minute quadrangle. Outcrop extends along low hill to the northwest.

The knob next to the road and several outcrops to the northwest consist of serpentinite. The serpentinite is fine grained, is green to black, and is cut by thin seams of carbonate and asbestos. Many fracture surfaces have a silky luster and are reddish brown. The rock consists mostly of colorless antigorite, carbonate minerals, and magnetite. Rare chromite grains are also present.

To the northwest along this outcrop, the serpentinite is interlayered with, and/or is cut by, fine grained diabase and porphyritic (plagioclase) diabase. Serpentinite is found at several localities along the north side of the Sturgeon Falls sill and appears to lie near the base of body. Locally, pyroxenite is found between the serpentinite and gabbro.

STOP A2. Sturgeon Falls Dam, E1/2 sec. 27, T.39N., R.29W. Faithorn 7 1/2-minute quadrangle.

Outcrops of gabbro extend to the northwest and southeast and represent the major part of the Sturgeon Falls sill as presently exposed. Locally, the gabbro is cut by thin shear zones and contains basalt inclusions (near steps to dam). A major fault, which appears to truncate the top of the sill, passes southeastward along the river just west of these outcrops.

The gabbros consist of varying proportions of plagioclase and pyroxene, which are mostly replaced by saussurite and amphibole, respectively. Fresh clinopyroxene is locally preserved and shows abundant, fine exsolution lamellae. To the southeast, the top of the sill consists of magnetic, magnetite-rich (3%) gabbro.

Two gabbro analyses from this sill are given below; one an anorthositic gabbro and the other a magnetite-rich gabbro. The relative depletion in light REE and other trace-element characteristics shown by these samples are similar to those of the Quinnesec basalts, suggesting that they may be cogenetic. Also, the low trace-element abundances in both gabbro samples suggest that they are cumulate rocks.

Composition of Sturgeon Falls sill
gabbro samples

	<u>1</u>	<u>2</u>
SiO ₂	49.3	44.1
Al ₂ O ₃	21.6	13.2
Fe ₂ O ₃	1.4	7.0
FeO	3.8	11.4
MgO	7.2	7.2
CaO	13.0	10.9
Na ₂ O	1.7	1.9
K ₂ O	0.16	0.09
TiO ₂	0.13	1.6
P ₂ O ₅	0.06	0.06
MnO	0.11	0.20
H ₂ O ⁺	2.2	2.4
H ₂ O ⁻	0.18	0.16
CO ₂	0.01	0.10
Rb	4	<5
Sr	85	86
Ba	8	45
Zr	28	34
Y	12	12
Nb	<5	<5
Ta	--	--
Cr	124	3
Co	39	74
Sc	29.6	62
Hf	0.21	0.46
La	0.39	0.79
Ce	1.07	2.3
Sm	0.44	0.80
Eu	0.31	0.33
Tb	0.19	0.25
Yb	0.78	0.88
Lu	0.12	0.17

1 - Anorthositic gabbro
2 - Magnetite-rich gabbro

STOP B. N1/2 sec. 36, T.37N., R.20E., Pembine 7 1/2-minute quadrangle.

Outcrops of intermediate to felsic tuffs are exposed along both sides of the South Branch Pemebonwon River.

Rocks consist of very fine grained, grayish-green to light-green tuffs and interlayered quartz eye tuffs. The rocks have a strong foliation striking N.60°E. and dipping 75°SE. and have a lineation plunging 75°S.10°W. Locally, plagioclase crystal tuffs (or porphyritic flows?) are also present.

This unit strikes northeast, is intruded by the Newingham tonalite on the north, and is in apparent fault contact with the Quinnesec Formation basalts to the south. It is also intruded by quartz porphyries and granophyre. The unit is representative of felsic tuffs found within the Quinnesec Formation to the north and northwest.

STOP C. SW1/4NE1/4 sec. 27, T.37N., R.21E., Faithorn 7 1/2-minute quadrangle. Low open outcrop just south of road.

This outcrop is relatively lichen free and shows pillows of basalt (or andesite?) of the Quinnesec Formation. Outcrops to the northwest consist of similar pillowed flows and pillow breccia. Amygdules and variolites are locally observed. Pillows in this area strike about N.80°W. and generally face south. A sample from an outcrop to the northwest was analyzed and shows high SiO₂ (62.4 wt.%) and low MgO (4.3 wt.%) contents. However, the strong alteration of the sample (reflected in a very low CaO content - 3.3 wt.% - and high Na₂O and K₂O contents) makes this analysis suspect.

STOP D. NW1/4NE1/4 sec. 22, T.37N., R.21E. Faithorn 7 1/2-minute quadrangle. Outcrops extend both west and east of road.

This stop is to examine some of the gabbroic and diabasic rocks associated with the large peridotite body in the north-central part of the map area. The peridotite is not exposed in these outcrops but occurs about 1/4 mile to the northwest.

One of the most distinctive rock types exposed here is a strongly foliated gabbro (outcrop to left (west) of road). The gabbro is altered, and plagioclase is replaced by saussurite and pyroxene is replaced by amphiboles. The foliation strikes N.10°-20°E. and dips 70°NW.; it is almost at right angles to the strike of the ultramafic-mafic body and the strike of foliations in surrounding rocks. Locally in other outcrops, banded gabbros having mineral layering are present; this banding also strikes at a high angle to the trend of the body.

Another distinctive rock type present in this outcrop is a fine-grained, gray, mottled diabase. The mottled appearance results from small (2-3 mm) oikocrysts of quartz (this is the myrmikitic basalt of G. I. Hall (1971, M. S. thesis, Univ. Wis., Milwaukee). More normal textured diabases of somewhat varying grain size are also present. These rocks lack the strong foliation of the gabbro but are similarly altered.

In the outcrop area to the right of the road (east), the generally massive diabases are cut by thin (15 cm wide) dikes of diabase and pyroxenite(?). These dikes weather to a reddish brown and strike northwest. Similar dikes have been observed to the west but have not been recognized outside this ultramafic-mafic body.

The relationship between the various gabbroic and diabasic rocks of these outcrops and elsewhere within this body remains uncertain. Could the diabases represent dikes cutting the foliated gabbro? Diabase is found crosscutting the ultramafic rocks of this body in outcrops to the northwest. Could they represent a system of sheeted dikes?

Ultramafic rocks (not exposed at this stop) occur predominately along the north side of the body and at its western end. The ultramafic rocks are all highly altered but locally show some preserved primary textures. Peridotite and pyroxenite appear to have been the main lithologies. At the western end of the body, large dikes(?) of coarse-grained, altered pyroxenite appear to cut and include serpentinite.

Both the structural features of the rocks of this ultramafic-mafic body and the apparent restriction of dikes within it suggest that this body was tectonically emplaced. Could this ultramafic-mafic body represent a slice of Early Proterozoic ocean floor or is it just a disrupted differentiated sill? Samples have been submitted for chemical analysis, however, the altered nature of many of these rocks may preclude meaningful results.

STOP E. Quiver Falls on the Menominee River. S1/2, sec. 24, T.37N., R.21E., Faithorn 7 1/2-minute quadrangle. Outcrops exposed mainly along river bank.

Follow road north to the river bank. Outcrops of largely undeformed pillow basalt of the Quinnesec Formation are exposed along the bank. This is one of the few places in the area where pillows can be viewed in three dimensions. They face south and appear to be slightly overturned. The basalt is very fine grained, is light gray-green, and contains small, skeletal pseudomorphs of olivine.

Return to parking area and take trail going south to river bank. Outcrop on the left (north) side of the trail presents one of the petrologic wonders of this area. At the top of the slope is a variolitic basalt in which the varioles are generally small. Down slope, these varioles are much larger (cm size) and compose the bulk of the flow. These structures are more resistant to weathering than their surrounding matrix. The variolitic structures are round to ovoid, are pink, and are concentrically zoned. The zoning consists of a thin reddish-brown rim followed inward by a white zone and a pink core. The varioles consist of albite, an altered skeletal mafic phase (pyroxene?), microcrystalline material, quartz, and secondary carbonate minerals with hematite staining.

Varioles found in basaltic rocks generally consist of radial growths of plagioclase formed as a result of rapid growth in cooling pillows or later devitrification of glass. In composition, these are similar to their host basalt. The varioles observed here, however, are more siliceous than their matrix and have textural features distinct from normal basaltic varioles. They most resemble the siliceous varioles described from Archean basalts of the Abitibi Belt of Ontario (Gelinas and others, 1976, Canadian Jour. Earth Sci., v. 13, p. 210-230), which have been interpreted as quenched immiscible liquids. Samples of the matrix and varioles from this outcrop are being analyzed to test this possibility.

STOP F. NE1/4NE1/4 sec. 22, T.36N., R.21E., Miscauno Island 7 1/2-minute quadrangle. Small hill on east side of road.

This stop is to examine a typical exposure of the McAllister formation. The rock is a breccia consisting of porphyritic vesicular andesite fragments in a tuffaceous matrix. The fragments are characterized by 1-5-mm-long,

dark-green hornblende pseudomorphs after clinopyroxene. Units tend to be massive and lack flow structures. Fragments appear to increase in size (>15 cm) in outcrops to the east, suggesting that a vent area is across the river in Michigan.

STOP G. NW1/4NW1/4 sec. 26, T.36N., R.21E., Miscauno Island 7 1/2-minute quadrangle. Outcrop on hill on east side of road.

This outcrop shows typical lithologies of the upper part of the Beecher formation. Lithologies range from fine-grained tuffs and crystal tuffs to coarser fragmental units. The coarser units contain rounded to sub-angular pink to white felsite and gray porphyritic dacite fragments in a pale to dark-green matrix. Crystal tuffs mostly contain albitized feldspar and a few quartz fragments. In some tuff beds that show grading, tops are to the north. The lower part of this formation consists mostly of dark-green porphyritic andesites and gray porphyritic dacites.

STOP H. Pemene Falls, SW1/4SW1/4 sec. 16, T.37N., R.28W., Miscauno Island 7 1/2-minute quadrangle. Outcrop along river bank.

Exposed along the bank of the Menominee River at Pemene Falls are rhyolites of the Pemene formation. The rocks are dark gray to reddish gray, contain few phenocrysts, and are generally microspherulitic. Phenocrysts, many of which are glomeroporphyritic, consist of euhedral to subhedral albite. The microspherules consist of radial intergrowths of quartz and albite. Flow banding and breccias (flow breccia?) are observed in some outcrops west of this stop and probably represent upper and lower parts of rhyolite flows. Locally, thin felsite dikes can be seen cutting the rhyolites.

Suggested additional stop (will not be visited on this trip unless time permits).

STOP I. Low, open outcrop east side of U.S. Highway 141, NW1/4SW1/4 sec. 10, T.35N., R.20E., Amberg 7 1/2-minute quadrangle.

Outcrop consists of Athelstane Quartz Monzonite cut by dikes of Amberg Granite (after Medaris and others, 1973, 19th Annual Inst. Lake Superior Geology field guide). The Athelstane Quartz Monzonite intrudes the Beecher formation north of this stop and extends for several kilometers to the south and west. It is pink, medium to coarse grained, and allotriomorphic granular, and it contains both biotite and hornblende. Its distinctive appearance is due to the presence of pink perthitic microcline and white plagioclase. In the road cut, the Athelstane shows a cataclastic foliation. Small metavolcanic inclusions are also locally present in the outcrop. The Athelstane was dated by P. O. Banks and J. A. Cain (1969, Jour. Geol., v. 77, p. 208-220) as $1,836 \pm 15$ Ma, which is similar to the age of the Hoskin Lake Granite to the north. The Athelstane Quartz Monzonite is compositionally distinct from other granitoid rocks of the area in being significantly lower in Rb and having lower Rb/Sr and higher K/Rb ratios.

The Amberg Granite is gray, medium to fine grained, and hypidiomorphic granular; it contains mainly biotite as the major ferromagnesian phase. Van Schmus (1980, Geol. Soc. America Special Paper 182, p. 159-168) determined the age of the Amberg as $1,756 \pm 19$ Ma. Thus, it is equivalent in age to the high-level granitoids and felsic volcanic rocks in central Wisconsin.