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Geologic Interpretation of Gravity Data, Marenisco-Watersmeet Area, Northern Michigan

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1292–A, B

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CONTRIBUTIONS TO THE GEOLOGY OF THE LAKE SUPERIOR REGION

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A study of some of the oldest rocks in North America and their geologic setting

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CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGY, GEOCHEMISTRY, AND AGE OF ARCHEAN AND EARLY PROTEROZOIC ROCKS IN THE MARENISCO-WATERSMEET AREA, NORTHERN MICHIGAN

By P. K. SIMS, Z. E. PETERMAN, W. C. PRINZ, and F. C. BENEDICT

ABSTRACT

The Marenisco-Watersmeet area lies astride the boundary between the two Archean basement terranes recognized in the Lake Superior region. Rocks characteristic of the gneiss terrane are exposed sparsely in a gneiss dome at Watersmeet. They consist of a tonalitic augen gneiss (~3,560 m.y. old), which is unconformably overlain by a biotite gneiss succession of about the same age and a younger succession of interlayered amphibolite and biotite gneiss (~2,640 m.y. old). These rock types were intruded by biotite leucogranite 2,590 m.y. old. Greenstone-granite complexes, which are characteristic of the Archean greenstone-granite terrane, are exposed in the northwest part of the area. They consist of metavolcanic and metasedimentary rocks that are intruded by the Puritan Quartz Monzonite (~2,650 m.y. old). The major body of Puritan Quartz Monzonite composes the northeast part of the Puritan batholith; satellitic bodies of the granite cut similar, but more highly deformed and metamorphosed bedded rocks in a northeast-trending belt to the southeast of the batholith.

The Archean rocks of both terranes are overlain unconformably by a succession of metavolcanic and metasedimentary rocks assigned to the Marquette Range Supergroup. A basal volcanic unit of the Marquette Range Supergroup, named here the Blair Creek Formation, is overlain by metagraywacke and meta-argillite of the Copps and Michigamme Formations of the Baraga Group. Locally, quartzite and siliceous dolomite of the Chocolay Group are preserved beneath the Blair Creek Formation. The Blair Creek Formation thickens southeastward and is estimated to have a maximum thickness in the area of about 2,000 m. The Blair Creek and the older Archean rocks are intruded by numerous dikes of metadiabase (Early Proterozoic) and diabase (Keweenawan).

Major and trace element compositions reflect both primary chemical attributes and modifications attendant with the Early Proterozoic tectonism. The Early Archean tonalitic augen gneiss has a relatively high TiO_2 and P_2O_5 content for its silica content, a Na_2O/K_2O ratio near unity, a Rb/Sr ratio greater than unity, and a low K/Rb(<200) ratio. Leucogranite in the Watersmeet dome also has a Rb/Sr ratio greater than unity. The Late paragenesis of K-feldspar, its poikilitic habit, and its close association with cataclastic and recrystallized fabrics in the augen gneiss suggest that potassium was introduced during Penokean tectonism. Probably either rubidium was added or strontium was removed diffentially concurrently with the migration of potassium. The late Archean Puritan Quartz Monzonite has a high $FeO^*/(FeO^*+MgO)$ ratio, and many samples have uncommonly high amounts of thorium and (or) uranium. Similarly, the leucogranite in the gneiss dome has high thorium and uranium contents. The Archean metagraywacke is distinguished chemically from the Proterozoic graywacke in having lower CaO and higher MgO contents and a lower Rb/Sr ratio. The basalt in the Proterozoic Blair Creek Formation has a high Na_2O/K_2O ratio and shows an iron-enrichment trend in the tholeiite field. The protoliths of the Early Archean augen gneiss and the biotite gneisses of both terranes possibly were dacitic volcanic rocks; the amphibolites of both terranes also are of volcanic derivation. The composition of the Puritan Quartz Monzonite is consistent with its derivation by partial melting of short-lived graywacke at crustal depths.

Deformation during the Penokean orogeny produced open to tight folds overturned to the northwest or north in the Proterozoic bedded rocks. A southeast-dipping axial plane foliation accompanied the folding and was superposed on previously deformed rocks of Late Archean age along the southern margin of the greenstone terrane. The intensity of the deformation decreased northward, and the width of the tectonically deformed zone is about 25 km. The folding was followed shortly by a low-pressure metamorphism having a nodal distribution pattern centered on the Watersmeet dome.

The rocks within the core of the dome were metamorphosed to amphibolite facies; surrounding the core is a zone of epidote amphibolite facies about 15 km wide, which passes outward into greenschist facies. The metamorphism resulted from heat that accompanied reactivation and uplift of the Archean gneiss in the core of the dome. The deformation and metamorphism of the Archean rocks during the Penokean orogeny produced open systems that allowed substantial migration of strontium and probably also rubidium. The apparent isotopic homogenization was local and resulted from cataclasis and recrystallization. The resulting secondary whole-rock and mineral isochrons give ages of 1,750 to 1,800 m.y., which are thought to represent the approximate time span of the Penokean event in this area. Additionally, one sample of intensely sheared and recrystallized gneiss gave a U-Pb zircon age of 1,760 m.y. We interpret this zircon as a reconstituted mineral in which the U-(Th)-Pb system was completely reset as a consequence of the intense metamorphism. Isotopic systems in the Archean gneisses and granite in the deformed and metamorphosed belt southeast of the Puritan batholith also were highly disturbed during this event, whereas those in the Puritan Quartz Monzonite in the batholith were only moderately disturbed.

Faulting materially affected the distribution and structure of the Archean and Early Proterozoic rocks. A northwest-trending set, which probably was initiated in the Archean, had both strike-slip and dip-slip movements. An east-northeast set was initiated in Early Proterozoic time, as indicated by alined metadiabase dikes, but its principal movement was in Late Proterozoic time, when the Archean and Proterozoic rocks of the Gogebic Range were tilted steeply northward. A younger set trending northeast cuts and offsets the lower Keweenawan lavas in the area.

INTRODUCTION

The Marenisco-Watersmeet area, in the western part of the Upper Peninsula of Michigan, lies astride the boundary between the two major crustal segments that have been delineated in the Lake Superior region (Morey and Sims, 1976): a Late Archean greenstone-granite terrane and an older Archean gneiss terrane (fig. 1). The greenstone-granite terrane is composed of greenstone- granite complexes 2,600–2,750 m.y. in age that are typical of most of the Superior province of the Canadian Shield. The gneiss terrane is composed of migmatitic gneisses and amphibolite that are in part 3,560 m.y. old or older. The two basement terranes have been so designated because they appear to have evolved largely as separate crustal entities (Sims and Peterman, 1981) and had vastly different tectonic stabilities, especially during the Early Proterozoic (Sims and others, 1981). They strongly influenced crustal evolution in the Upper Midwest during Precambrian time. The boundary between the two basement terranes is marked by a distinctive zone of tectonism that has been named the Great Lakes tectonic zone (Sims and others, 1980).

The area is contiguous to the eastern end of the Gogebic Range, and because of its potential as a source of iron ore has been studied intermittently for nearly a century. Allen and Barrett (1915) summarized the results of iron ore exploration and presented reconnaissance geologic maps of parts of the area. Later, Fritts (1969) mapped the area in moderate detail, as a part of the U.S. Geological Survey cooperative program with the Geological Survey Division of the Michigan Department of Conservation. The area adjoining that mapped by Fritts on the west—the east end of the Gogebic Range—was mapped subsequently by Trent (1973), also as a part of the Federal-State cooperative program. The geologic structure of this part of the Gogebic Range was described earlier in an unpublished report by Hendrix (1960).

Since publication of the earliest reports concerning the region, interpretations of the geology have differed and, in part, have been contradictory. This confusion has resulted from the complexity of the geology, the inadequacy of bedrock exposures in critical areas, and a lack of radiometric data needed to distinguish the ages of various rock bodies. Without this powerful tool, interpretation of the geology was highly subjective.

The main purpose of our study, begun in 1974, was to determine critical geologic relationships in the tectonically disturbed zone at the juncture of the two Archean basement terranes. At an early stage in our reconnaissance mapping and radiometric studies we recognized that several aspects of the geology reported in the literature appeared to be erroneous. Accordingly, a regional reconnaissance map (scale 1:125,000) of a much larger area was prepared by Prinz (1981), and selected parts of the Marenisco, Thayer, and Watersmeet 15-minute quadrangles, previously mapped by Fritts (1969) and Trent (1973), were remapped. A generalized version of the revised map is given on figure 2. Concurrently, samples of granitic rocks, gneisses, and metagraywacke were collected for age determinations. Because of intense isotopic disturbance in the crystalline rocks of the area, the U-Pb zircon method has been required to date many of the rocks. Rb-Sr data on whole-rock and mineral samples are very informative, however, especially for dating isotopic disturbances recorded in the rocks. Some of the results of the geochronology study have been summarized by Sims and Peterman (1976), Sims and others (1977), and Peterman and others (1980). All ages are calculated using the isotopic and decay constants recommended by the IUGS Subcommission on Geochronol- and Jäger, 1977).

The following principal conclusions of our study differ from those of earlier studies: (1) The bedded rocks in the Marenisco-Watersmeet area are complexly folded and are of both Late Archean and Early Proterozoic ages. In previous publications, all the bedded rocks were considered to be of Proterozoic age. (2) Except for the Gogebic Range, the Marquette Range Supergroup consists essentially of two formations, a lower, dominantly volcanic unit, containing lenses of iron-formation, conglomerate, and wacke, herein named the Blair Creek Formation; and an upper graywacke-argillite unit, the Copps Formation in the west and its equivalent in the east, the Michigamme Formation. Previously (Fritts, 1969), the successions in the area were interpreted as a homoclinal, conformable sequence of Early Proterozoic rocks, younging eastward, having a stratigraphic thickness of at least 40,000 feet. (3) The Wolf Lake Granite of Allen and Barrett (1915) is a composite unit of gneiss, metavolcanic rocks, and granite of Archean age. It composes a gneiss dome that was reactivated during the Penokean event concurrently with metamorphism of the overlying bedded rocks of the Marquette Range Supergroup (Sims and Peterman, 1976). Both Fritts (1969) and Allen and Barrett (1915) interpreted the Wolf Lake Granite as being younger than the Early Proterozoic bedded rocks. (4) The granite and gneiss east of Marenisco, called the granite near Thayer by Fritts (1969), are Late Archean in age, and the granite is equivalent to the Puritan Quartz Monzonite exposed in the Puritan batholith west of Lake Gogebic. Fritts (1969) considered the granite near Thayer to be younger than the bedded rocks of the Marquette Range Supergroup, whereas Allen and Bar-

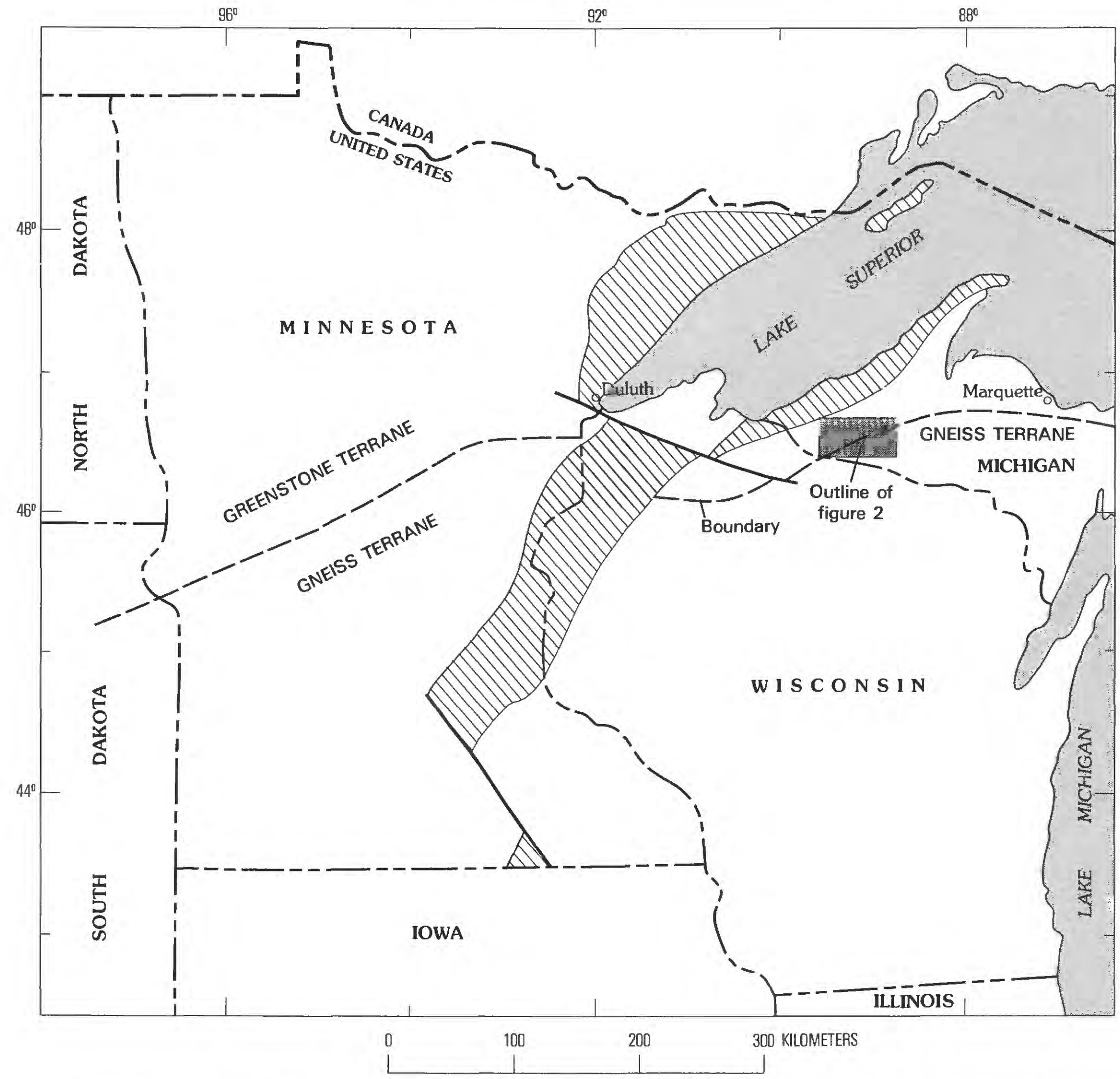


FIGURE 1.—Map of Lake Superior region showing location of study area relative to boundary between Archean basement terranes. Rocks of midcontinent rift system shown by diagonal rule pattern.

rett (1915) correlated it on the basis of similar lithology with the Puritan Quartz Monzonite (Presque Isle Granite of Allen and Barrett, 1915).

In addition, a local problem of long standing in the eastern Gogebic Range appears to have been resolved. Allen and Barrett (1915) and, later, Trent (1973) concluded that biotite schist and amphibolite in the southern part of T. 47 N., R. 43 W., are metamorphosed phases of the Palms Formation that were developed adjacent to the Puritan Quartz Monzonite (Presque Isle Granite of Allen and Barrett, 1915). Instead, we conclude that a major fault (Presque Isle fault, fig. 2) separates typical Palms, on the north, from the schist and amphibolite, and that the schist and amphibolite are Archean bedded rocks that were intruded by the granite.

On a regional scale, the study has produced a number of new discoveries about stratigraphic and tectonic patterns in the boundary zone between the two Archean basement terranes: (1) Metavolcanic rocks of Archean age were deposited unconformably on Early Archean gneiss, and these rocks were intruded by Late Archean granite. Thus the depositional history of the gneiss terrane is more complex than previously thought (Sims, 1980). (2) The Late Archean bedded rocks of the greenstone terrane adjacent to the boundary were deformed on axes subparallel to the boundary in Late Archean time. Elsewhere in the greenstone terrane, folding was mainly caused by the diapiric rise of Late Archean magmas, in a manner described by Schwerdtner and others (1979). (3) The boundary zone was tectonically active intermittently during the Early Proterozo-

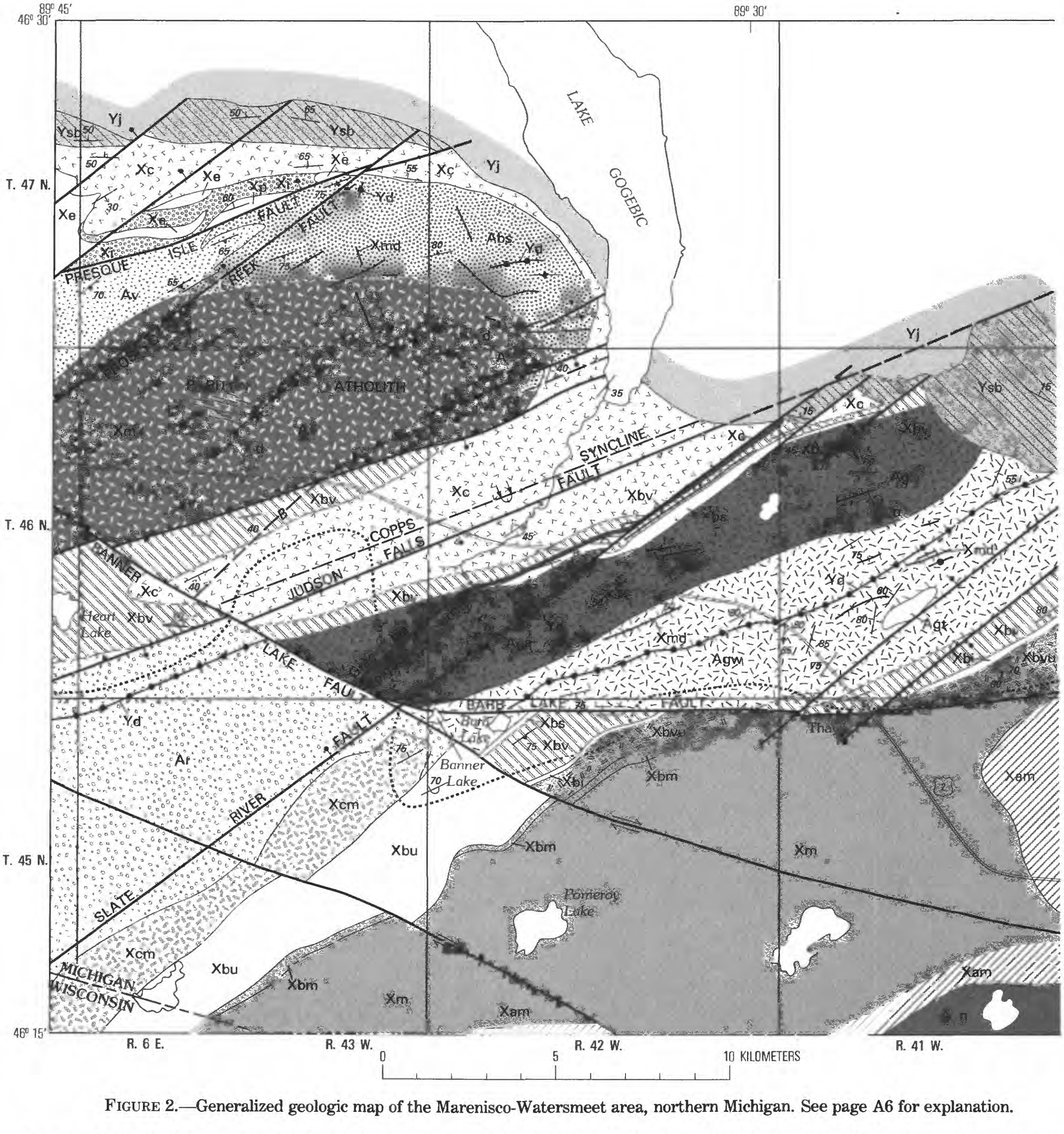
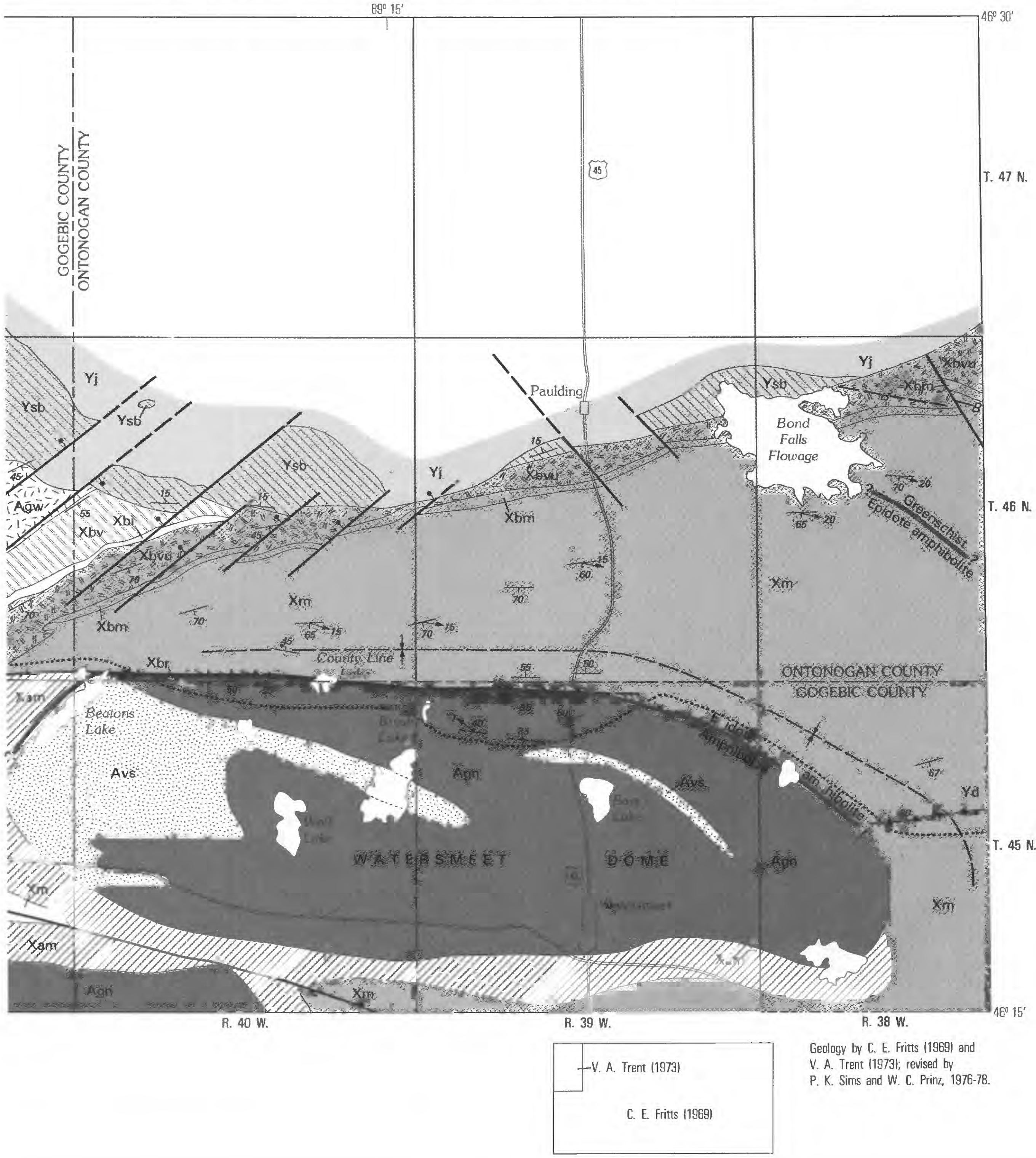


FIGURE 2.—Generalized geologic map of the Marenisco-Watersmeet area, northern Michigan. See page A6 for explanation.

ic, as indicated by the nondeposition or erosion of Chocolay Group strata of the Marquette Range Supergroup, the occurrence of locally derived conglomerate and grit at the base of the Proterozoic section, the extrusion of mafic volcanic rocks approximately contemporaneously with deposition of the major iron-formation in the area (the Ironwood Iron-formation), and the existence of overturned folds and a penetrative cleavage in rocks within the zone. The folds are overturned toward the northwest, apparently as a result of impingement of the Archean gneiss block against the more rigid greenstone- granite block.

ACKNOWLEDGMENTS

This report is based mainly on our reconnaissance geologic mapping and radiometric studies during the past five years. The published geologic maps of Fritts

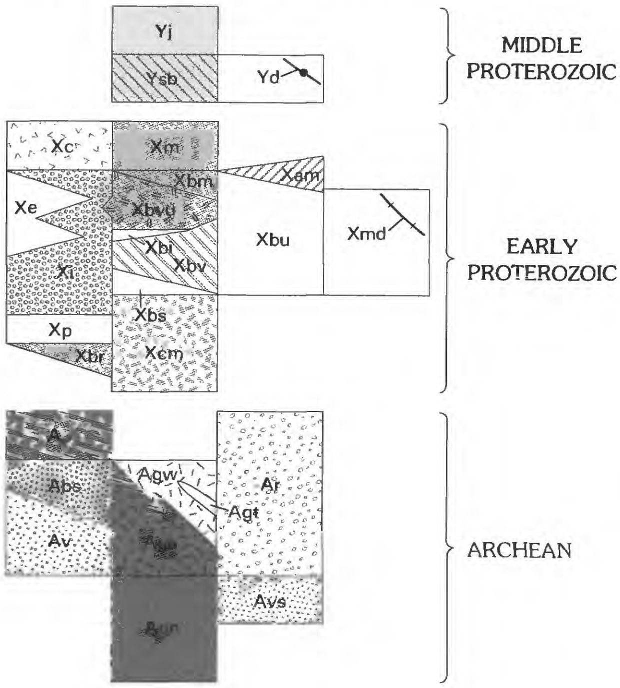


(1969) and Trent (1973) were extremely useful. The field and related studies were the responsibility of Sims and Prinz, Peterman was responsible for the geochronology, and Benedict assisted with the petrographic studies. Klaus J. Schulz and Steven F. Olson assisted in the fieldwork. The chemical analyses reported herein were done by the single-solution procedure described by Shapiro (1967). Analysts are credited specifically in the tables.

STRATIGRAPHY

It is useful to discuss the stratigraphy of the area with respect to a generalized section across the strike of the major units (fig. 3). The oldest known rocks are

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

MIDDLE PROTEROZOIC

- Yj — Jacobsville Sandstone
- Ysb — Siemens Creek Formation (basaltic lava flows) and Bessemer Quartzite (local basal quartzite)
- Yd — Diabase—Inversely polarized dikes

EARLY PROTEROZOIC

- Xc — Copps Formation
- Xm — Michigamme Formation
- Xi — Ironwood Iron-formation
- Xe — Emperor Volcanic Complex
- Blair Creek Formation
  - Xbu — Undivided
  - Xbm — Unexposed magnetic unit
  - Xbvu — Dominantly volcanic rocks
  - Xbi — Lean iron-formation
  - Xbv — Mafic volcanic rocks—Includes porphyritic lava
  - Xbs — Basal conglomerate, arkose, wacke, and felsite

EARLY PROTEROZOIC—continued

- Xam — Unexposed magnetic unit
- Xmd — Metadiabase
- Xp — Palms Formation
- Xbr — Bad River Dolomite
- Xcm — Chocolay and Menominee Groups, undivided—Sedimentary rocks known mainly from drill cores

ARCHEAN

- Puritan Quartz Monzonite of Puritan batholith—Approximately 2,650 m.y. old
- Abs — Biotite schist—Locally migmatized; contains some tonalite and amphibolite
- Agw — Metagraywacke—Includes lenses of dacite tuff
- Agt — Dacitic volcanic rocks
- Av — Metabasalt—In part pillowed
- Gneiss and amphibolite—Approximately 2,750 m.y. old. Includes local bodies of Puritan Quartz Monzonite
- Ar — Metavolcanic, metasedimentary, and sparse granitoid rocks
- Gneiss and granite, undivided—Possibly includes some rocks of Early Proterozoic age
- Avs — Unexposed magnetic rocks—In part may be of Early Proterozoic age

CONTACT—Approximately located

HIGH-ANGLE DIP-SLIP FAULT—Bar and ball on downthrown side

HIGH-ANGLE FAULT—Arrows show relative movement

SYNCLINE

OVERTURNED SYNCLINE

STRIKE AND DIP
- 40 Bedding
- 45 Overturned bedding
- 55 Foliation

10 BEARING AND PLUNGE OF LINEATION

METAMORPHIC FACIES BOUNDARY—Queried where location is uncertain

B BIOTITE ISOGRAD

APPROXIMATE SOUTHERN LIMIT OF OUTCROPS

FIGURE 2.—Generalized geologic map of the Marenisco-Watersmeet area, northern Michigan—Explanation.

Early Archean gneisses in the core of the gneiss dome at Watersmeet. Younger basement rocks in the western part, Late Archean in age, consist of metavolcanic and metagraywacke units that are intruded by granite of Late Archean age. Unconformably overlying the Archean basement are bedded metavolcanic and

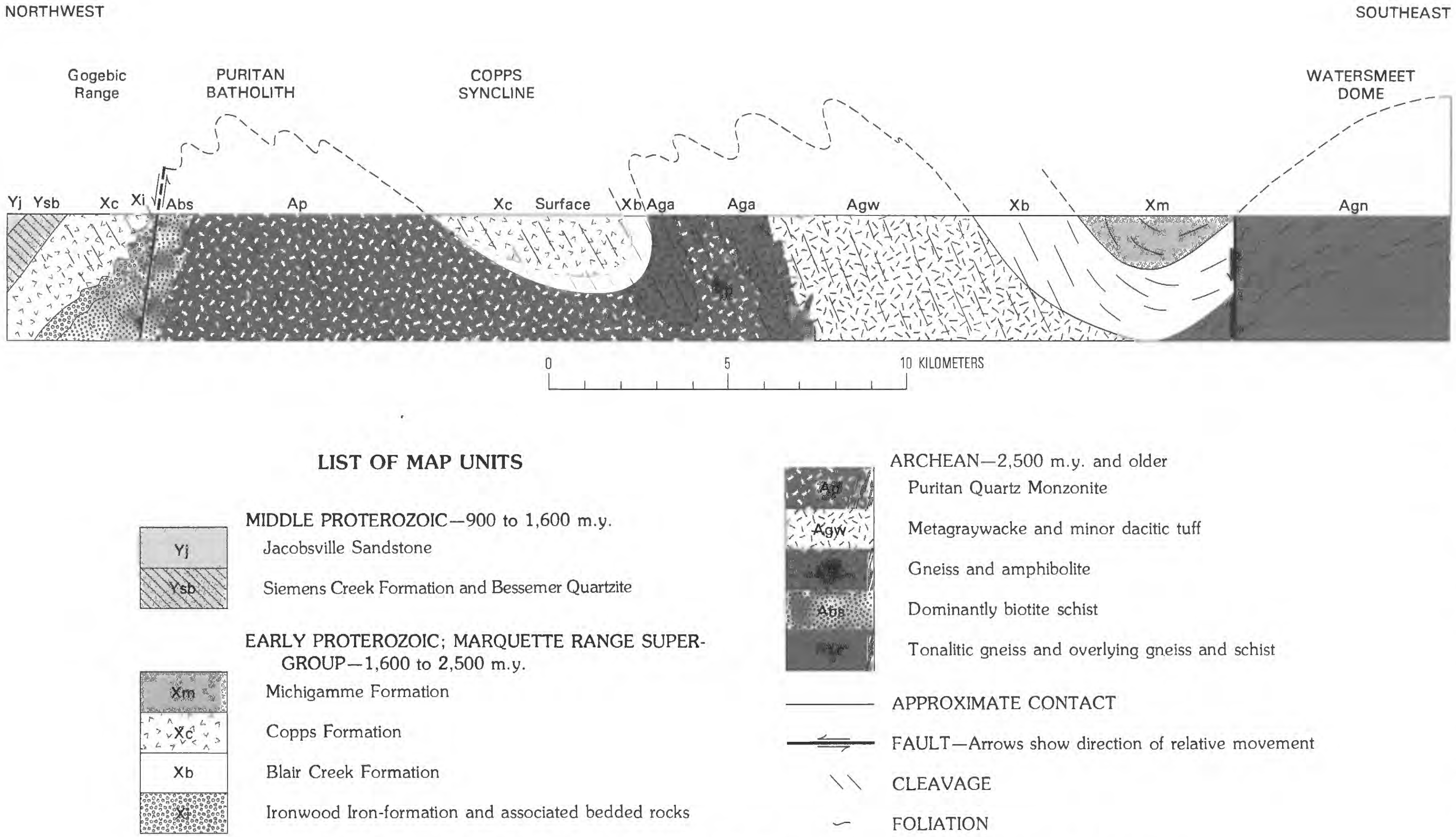


FIGURE 3.—Gross stratigraphy and structure of Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area.

metasedimentary rocks of the Early Proterozoic Marquette Range Supergroup. In the Marenisco-Watersmeet area, these rocks consist of a lower, dominantly volcanic unit, herein named the Blair Creek Formation, and an upper metagraywacke-argillite unit called the Copps Formation in the west and the Michigamme Formation in the east. The Copps Formation directly overlies the Ironwood Iron-formation and associated volcanic rocks (Emperor Volcanic Complex) at the east end of the Gogebic Range, as shown on figure 2. Both the Archean and the Early Proterozoic rocks are overlain unconformably along the north edge of the area (fig. 2) by lava and sandstone of Keweenawan (Middle Proterozoic) age. These younger Proterozoic rocks have been described by Hubbard (1975) and are not discussed in this report.

The stratigraphic nomenclature used in this report is compared with that of Fritts (1969) in table 1. As mentioned previously, Fritts considered the stratigraphic succession to be homoclinal and conformable, younging eastward. He arranged the bedded rocks, from oldest to youngest, as follows: strata near Cup Lake, strata near Banner Lake, strata near Blair Lake, and strata near Paulding. He assigned these rocks to the Animikie Series. Later Cannon and Gair (1970) named the Marquette Range Supergroup designating it as a replacement term for the Animikie in Michigan. It should be noted that the rock units on the east end of the Gogebic Range are omitted from table 1. Their stratigraphic relationship to those listed in table 1 can be seen by reference to the explanation for figure 2.

TABLE 1.—*Correlation of pre-Keweenawan rock units used in this report with those of Fritts (1969)*[1]

This report	Fritts (1969)
Early Proterozoic:	2,500-1,600 m.y.
Michigamme Formation------	Strata near Paulding.
Copps Formation-----------	Copps Formation.
Blair Creek Formation-----	Strata near Blair Lake, strata of the Marenisco range (part), strata near Cup Lake (part).
Iron-formation, schist, dolomite, and quartzite.	Strata near Banner Lake.
Archean:	>2,500 m.y.
Puritan Quartz Monzonite--	Granite near Nelson Creek, granite near Thayer.
Biotite schist------------	Gneiss near Mount Kimberly.
Metagraywacke-------------	Strata near Banner Lake.
Amphibolite---------------	Strata near Cup Lake (part).
Migmatitic gneisses-------	Wolf Lake Granite of Allen and Barrett (1915).

[1]Table omits Archean metavolcanic rocks and Proterozoic Palms Formation, Ironwood Iron-formation, and Emperor Volcanic Complex of the east Gogebic Range.

ARCHEAN ROCKS

Archean rocks belonging to both basement terranes crop out in the area. Rocks that represent the gneiss terrane are exposed in the Watersmeet gneiss dome, in the southeast part, and rocks that represent the greenstone-granite terrane crop out in the cores of anticlinal blocks in the northwest part. Except for the Puritan Quartz Monzonite, Archean rocks associated with the Puritan batholith, in the extreme northwest part of figure 2, are not described here. They resemble rocks mapped in areas to the west, which have been discussed by Schmidt (1976).

ROCKS IN THE WATERSMEET DOME

Three successions of Archean rocks are exposed in the Watersmeet dome. An older tonalitic augen gneiss, informally called the gneiss at Watersmeet (Peterman and others, 1980), is unconformably overlain in the northeast part of the dome by a succession of layered biotite gneisses. The third succession, composed of interlayered amphibolite and biotite gneiss and schist, crops out sporadically in the southern part of this area and apparently overlies the gneiss of the Watersmeet dome. All the layered rocks are cut by small bodies and dikes of biotite leucogranite. Exposures are limited to the northern part of the dome, and even here they are too widely separated to allow accurate mapping of the different rock successions. Accordingly, on the geologic map (fig. 2) all the rocks in the dome are included under a single map unit, gneiss and granite undivided (Agn); an exception is the unit of unexposed magnetic rocks (Avs), which is delineated separately. For the main area of outcrops in the northeast part of the dome, a more detailed map (fig. 4) was prepared in order to show areas underlain by each of the three rock successions. This map is essentially an outcrop map. The locations of specific outcrops are shown on the earlier published map (Fritts, 1969).

TONALITIC AUGEN GNEISS

Tonalitic augen gneiss is exposed sporadically in the northern part of the Watersmeet dome. The principal exposures are in a small window about 1 km^2 in area in secs. 4 and 5, T. 45 N., R. 39 W. (fig. 4). A small outcrop largely overlain by amphibolite is present in SW¼ SE¼ sec. 5, T. 45 N., R. 39 W.

The tonalitic gneiss, as exposed in the window (fig. 4), is a medium-gray, medium- to coarse-grained,

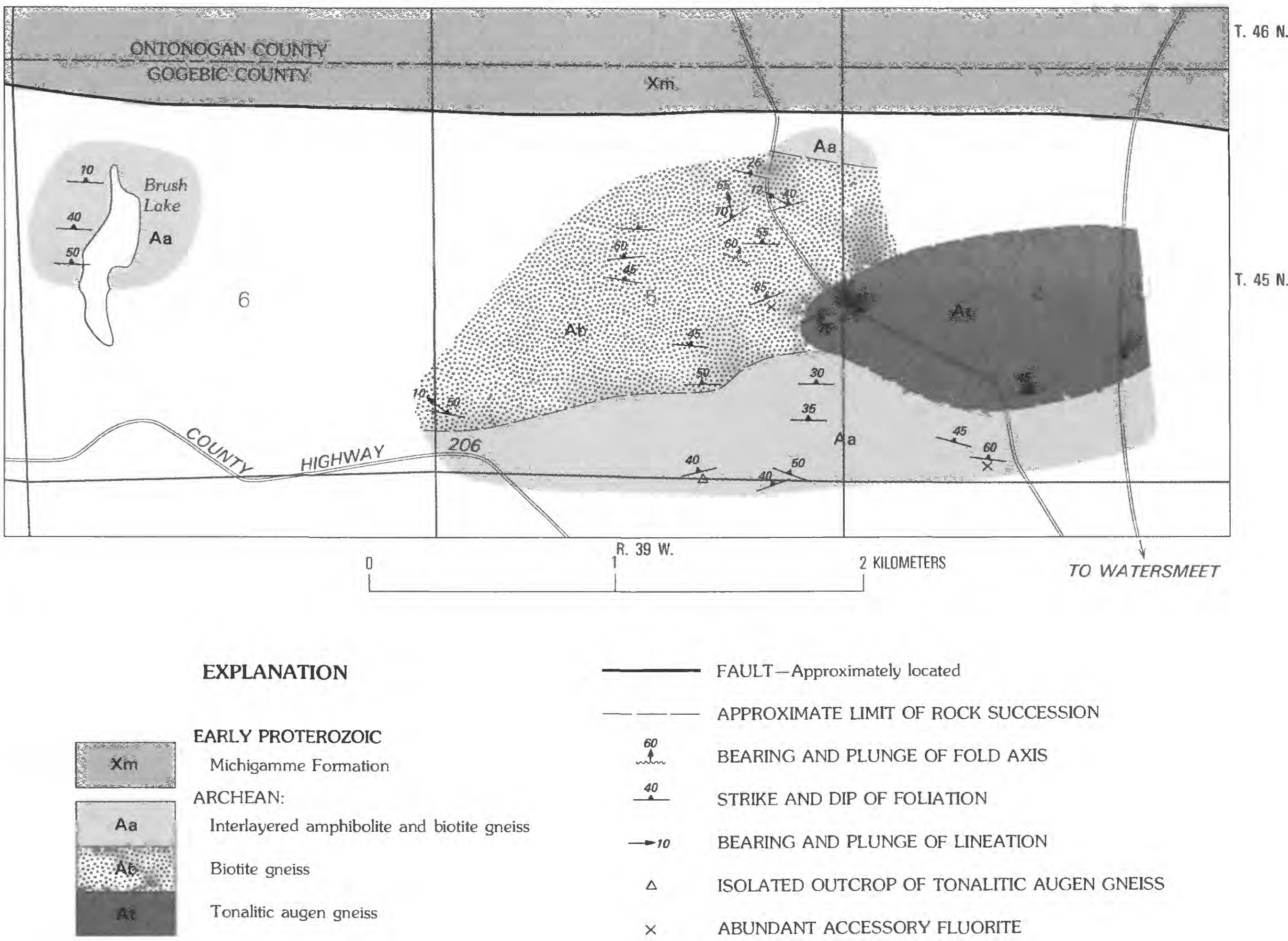


FIGURE 4.—Geologic map of part (T. 45 N., R. 39 W.) of northern margin of Watersmeet dome showing distribution and structure of Precambrian rocks.

irregularly layered rock containing sparse plagioclase augen. It contains rare layers and lenses of amphibolite at most a few meters thick. The layering is given by alternating feldspar-quartz and biotite-rich zones about a centimeter thick. The fabric of the gneiss as seen in thin sections is highly irregular. Generally, coarse plagioclase ($An_{25\text{-}33}$) and amoeboid aggregates of sutured quartz grains are crossed by irregular seams and braided zones of finer grained quartz, plagioclase, and biotite, resulting from recrystallization of finely granulated material. The plagioclase (as much as 2 mm in diameter) is anhedral, is in part weakly zoned, and is weakly to moderately altered to sericite, calcite, and epidote/clinozoisite. Biotite is recrystallized within the cataclastic zones and accordingly generally has two preferred orientations. It is olive brown and either clustered or strung out in foliation planes. Abundant (~1 percent) sphene and associated opaque oxides and lesser epidote/clinozoisite are associated with the biotite. Microcline is sparse to common, interstitial, slightly poikilitic, and commonly confined to the cataclastic and recrystallized zones. Characteristic accessory minerals are zircon, allanite, apatite, sphene, and opaque oxides.

The changes in fabric of the tonalite gneiss are interpreted as indicating progressively greater cataclasis and recrystallization of an originally coarse-grained rock of tonalitic composition. Petrographic studies suggest that potassium was mobile in these rocks subsequent to primary recrystallization. Representative modes and chemical analyses of the tonalitic gneiss are listed in table 2.

Amphibolite is interlayered with the tonalitic gneiss at places in sec. 4, T. 45 N., R. 39 W. The amphibolite occurs as lenses as much as a meter thick. It is a dark-gray, medium- to coarse-grained hornblende-plagioclase rock with a typical salt-and-pepper appearance. It has a moderate to strong foliation and lineation. A sample from the south-central part of sec. 4 has the following mode, in volume percent: hornblende, 68.5; plagioclase ($An_{25\text{-}30}$), 24; biotite, 5; other minerals, 2.5. The rock

TABLE 2.—*Approximate modes and chemical analyses of tonalitic augen gneiss from the Watersmeet dome*

[Leaders (—) indicate not determined. Tr, trace. Chemical analyses of sample M45L by Samuel Botts; samples D1042, 1042G, and 1042I by N. Skinner; and sample M83 by J. S. Wahlberg, J. Taggart, and J. Baker. U and Th analyses by H. T. Millard, Jr., and others]

Constituent	D1042	M45L	M83	D1042I	D1042G
Modal composition (volume percent)					
Plagioclase-------	55	44.5	48	--	--
Quartz------------	35	35	30	--	--
K-feldspar--------	0	3.5	8	--	--
Biotite-----------	5	15.5	13	--	--
Muscovite---------	3	Tr.	Tr.	--	--
Accessory minerals	2	1.5	1	--	--
Major oxides (weight percent)					
SiO_2-------------	70.8	68.6	66.8	72.1	69.7
Al_2O_3------------	13.7	15.2	14.2	13.7	13.9
Fe_2O_3------------	.63	1.1	.79	.64	.83
FeO--------------	2.9	3.2	4.75	1.8	3.5
MgO--------------	.97	1.7	2.0	.81	1.4
CaO--------------	1.8	2.4	2.46	1.4	2.0
Na_2O-------------	3.6	4.1	3.4	3.6	3.5
K_2O--------------	3.5	2.7	2.71	4.3	3.7
H_2O^+-------------	1.2	.87	--	.78	.84
H_2O^--------------	.13	.02	--	.00	.05
TiO_2-------------	.48	.74	.90	.43	.58
P_2O_5-------------	.14	.17	<.2	.12	.17
MnO--------------	.00	.05	<.08	.02	.02
CO_2--------------	1.0	.08	--	.66	.31
Loss on ignition	--	--	.88	--	--
Sum---------	101	101	100	100	101
Trace elements (parts per million)					
Rb---------------	149	184	216	147	183
Sr---------------	132	194	150	124	160
U----------------	--	1.8	--	--	--
Th---------------	--	8.7	--	--	--

SAMPLE DESCRIPTIONS AND LOCALITIES

D1042. Roadcuts along Michigan Highway 45. NW 1/4 SE 1/4 sec. 4, T. 45 N., R. 39 W. Irregular aggregates of plagioclase and quartz and alined biotite define a foliation. Plagioclase is partly granulated and recrystallized and is poorly twinned, partly because of strain; it is moderately altered to muscovite, epidote/clinozoisite, and calcite. Quartz forms amoeboid aggregates of sutured, recrystallized grains. Biotite is olive brown and weakly chloritized. Accessory minerals are zircon, apatite, sphene, opaque oxides, and allanite. Allanite is partly rimmed by epidote/clinozoisite.

M45L. Same locality as D1042. Microcline is interstitial to plagioclase and quartz. About 1 percent sphene is associated with biotite.

M83. NW 1/4 SW 1/4 sec. 4, T. 45 N., R. 39 W.

D1042G and D1042I. Same locality as D1042.

contains a trace of quartz and microcline, and small amounts of epidote, sphene, and opaque oxides. The hornblende is a dark-bluish-green variety. It is not known whether the protolith of the amphibolite was extrusive basalt or a dike. The amphibolite can be distinguished from the Early Proterozoic metadiabase and metagabbro dikes in the Watersmeet dome because it has (1) darker hornblende, (2) better twinned plagioclase that has a weak concentric zoning, (3) mosaic texture, and (4) partial alteration of plagioclase to epidote/clinozoisite.

BIOTITE GNEISS SUCCESSION

Unconformably overlying the tonalitic gneiss in the Watersmeet dome is a succession of layered biotite gneiss and schist. The unconformity is well exposed in small outcrops in the NE¼ SE¼ sec. 5, T. 45 N., R. 39 W. At this locality, folded biotite schist overlies steeply dipping tonalite augen gneiss. Both rock types are intruded by small bodies of biotite leucogranite.

The bedded rocks compose a folded, supracrustal succession that strikes generally northeastward and dips moderately northward toward the north margin of the gneiss dome. They are generally finer grained and more massive than the tonalitic gneiss. In the principal exposed area (fig. 4), the rocks are mainly interlayered, banded, and massive biotite-quartz-feldspar gneisses containing scattered layers and lenses of biotite schist. Some of the biotite schist is fine grained and massive. Interlayered cataclastic gneiss and fine-grained biotite schist that are exposed along Gogebic County Road 206 in secs. 3 and 4, T. 45 N., R. 40 W., are interpreted as belonging to this supracrustal succession.

The gneiss and schist have highly variable fabrics as a result of multiple deformations and recrystallization, and have a wide range in composition. Two foliations can be seen in thin sections of most rocks, and these are commonly cut by local fractures coated by biotite. Each of the foliations is marked by oriented biotite and elongate aggregates of quartz and feldspar. As a result of the multiple episodes of recrystallization, textures vary considerably even within a thin section, although the mineralogy developed during each event was similar. An exception was a late shearing, which is expressed by some retrograde metamorphism, including chloritization of biotite and sericitization of plagioclase.

The major rock type in the succession is a light-gray to medium-gray, medium-grained gneiss that megascopically resembles granite gneiss. It varies from a massive to a layered rock, and the two varieties are interlayered on scales of a few meters or a few tens of meters.

TABLE 3.—*Approximate modes and chemical analyses of representative samples of the biotite gneiss succession in the Watersmeet dome*

[Leaders (—) indicate not determined. Tr, trace. Chemical analyses of samples D1394, D1395, D1396, D2438, and D2439 by Z. A. Hamlin, sample M48L by S. Botts, and samples M95B, M109, M–93, and M199 by J. S. Wahlberg, J. Taggart, and J. Baker. U and Th analyses by H. T. Millard, Jr., and others]

Constituent	Biotite gneiss										Biotite schist	
	M95B	M109	D1394	D1395	D1396	M93	M193A	M321A	M48L	D2439	D2438	M199
					Modal analyses (volume percent)							
Plagioclase-----	17	38	42	65	52	36	36	42	40	--	--	--
Quartz----------	25	32	26	24	32	30	28	30	11	--	--	--
K-feldspar------	30	15	26	5	11	29.5	30	17	22	--	--	--
Biotite---------	22	10	6	6	5	2.5	5	11	20	--	--	--
Other minerals--	6	5	Tr.	Tr.	Tr.	2	1	Tr.	7	--	--	--
					Major oxides (weight percent)							
SiO_2------------	69.3	69.5	71.2	70.7	75.5	73.4	--	--	62.2	72.3	69.3	61.4
Al_2O_3-----------	13.0	15.0	13.7	14.7	12.9	13.6	--	--	16.3	12.7	14.7	17.8
Fe_2O_3-----------	5.86	3.66	.29	.42	.13	1.79	--	--	.30	.27	.79	6.58
FeO-------------		--	2.2	1.9	1.8		--	--	6.0	2.2	2.6	
MgO-------------	1.8	1.2	.56	.91	.54	.73	--	--	1.3	.5	.69	.97
CaO-------------	.60	2.25	.65	1.5	1.3	.54	--	--	1.9	2.3	2.4	2.11
Na_2O------------	3.3	3.4	4.8	4.6	4.8	4.2	--	--	5.3	3.6	4.3	6.5
K_2O-------------	4.31	3.39	4.0	2.6	1.8	4.38	--	--	4.1	3.5	2.7	2.55
H_2O^+------------	--	--	.86	.86	.62	--	--	--	.65	0.74	.65	
H_2O^-------------	--	--	.18	.28	.14	--	--	--	.02	0.03	.08	
TiO_2------------	.45	.41	.06	.08	.00	.13	--	--	.58	.38	.25	.35
P_2O_5------------	<.1	.1	.05	.05	.05	<.1	--	--	.10	.08	.10	<.1
MnO-------------	.07	.03	.04	.03	.03	<.02	--	--	.15	.08	.05	.08
CO_2-------------	--	--	.08	.08	.13	--	--	--	.52	1.1	.08	
Loss on ignition	.51	1.0	--	--	--	.41	--	--	--	--	--	.96
Sum--------	99	100	99	99	100	99	--	--	99	100	99	99
					Trace elements (parts per million)							
Rb--------------	116	104	95	89	57	105	--	--	96	87	314	98
Sr--------------	30.6	170	98	240	118	80	--	--	65	52	130	85
U---------------	12.2	2.0	2.4	1.4	14.3	3.9	--	--	6.8	5.2	6.6	6.9
Th--------------	63.1	14.3	18.5	20.4	29.9	32.4	--	--	35.9	18.9	30.9	45.7

SAMPLE DESCRIPTIONS AND LOCALITIES

M95B. NW 1/4 NE 1/4 sec. 5, T. 45 N., R. 39 W. Gray, fine-grained biotite gneiss with seams and clots of biotite; contains 6 percent muscovite.

M109. NE 1/4 NE 1/4 sec. 5, T. 45 N., R. 39 W. Gray, fine- to medium-grained biotite gneiss.

D1394. NE 1/4 sec. 5, T. 45 N., R. 39 W. Light-gray, fine- to medium-grained, weakly layered gneiss.

D1395. Same locality as D1394. Similar to D1394 but coarser grained and distinctly inequigranular.

D1396. Same locality as D1394.

M93. SW 1/4 NE 1/4 sec. 5, T. 45 N., R. 39 W. Light-gray, fine- to medium-grained, distinctly layered gneiss. Layering result of brittle deformation and recrystallization of biotite and cataclastic zones.

M193A. NE 1/4 NE 1/4 sec. 5, T. 45 N., R. 39 W. Gray, fine- to medium-grained, foliated rock. Biotite clots occur in foliation planes.

M321A. NE 1/4 NE 1/4 sec. 5, T. 45 N., R. 39 W. Gray, medium-grained layered biotite gneiss.

M48L. Same locality as D2438. Interlayered with biotite schist (D2438). Strongly cataclasized and recrystallized. Bimodal grain size, with larger plagioclase (An_{25-30}) and poikilitic microcline in a finer grained matrix. Contains 3 percent muscovite and 4 percent calcite.

D2439. NE 1/4 NW 1/4 sec. 4, T. 45 N., R. 40 W. Dark-gray, fine-grained biotite schist. Interlayered(?) with a coarser grained cataclastic biotite gneiss (M48L). Contains several percent of microcline and sparse garnet.

D2438. Same locality as D2439.

M199. NE 1/4 SE 1/4 sec. 5, T. 45 N., R. 39 W. Gray, fine-grained biotite schist. Contains about 15 percent biotite. Plagioclase is untwinned.

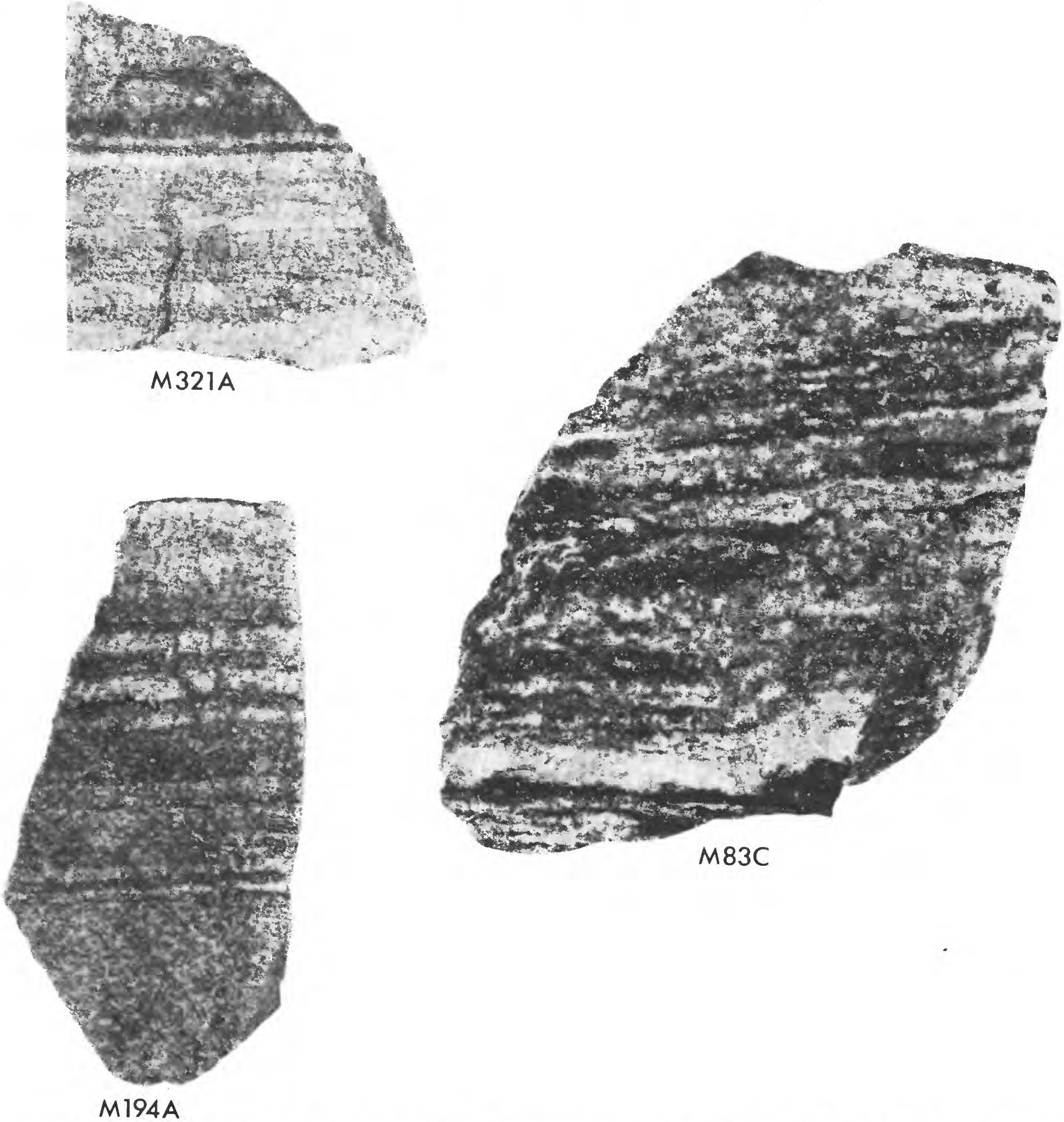


FIGURE 5.—Hand specimens of Early Archean gneisses from the Watersmeet dome, shown actual size. M321A and M194A are thinly layered phases in the biotite gneiss succession. Thin banding is sharply defined and continuous. M83C is the tonalitic augen gneiss showing the discontinuous layering imparted by feldspar-quartz- and biotite-rich zones.

Modes and chemical analyses of representative samples are given in table 3. Layering in the rock reflects both compositional differences and structural deformation. Rocks having a compositional layering (fig. 5, sample M194A) characteristically have a younger schistosity given mainly by alined biotite. Layering produced by deformation has resulted from cataclasis and recrystallization and is particularly shown by streaks of biotite and (or) chlorite. Textures in all the rocks are granoblastic and typically inequigranular. Biotite is brown, plagioclase has variably developed polysynthetic twinning and is oligoclase-andesine, and microcline tends to be poikilitic. Accessory minerals are apatite, allanite, opaque oxides, zircon, and, locally, fluorite. The zircon occurs as subrounded or subhedral crystals within biotite or scattered throughout the rock; most grains are less than 0.01 mm in diameter, but in some of the thinly banded gneiss the grains are somewhat larger. The fluorite is disseminated through the rocks but seems to be more abundant in coarser grained recrystallized zones. Quite commonly, the rocks have a pronounced schistosity marked by discontinuous lenses and clots of shiny biotite, which is somewhat coarser than the biotite in the remainder of the rock. We interpret this generation of biotite as having crystallized during the Penokean deformation.

Another common rock type is a fine-grained (~0.10-mm-diameter) biotite schist that megascopically resembles the graywacke or argillite of the Proterozoic Michigamme Formation and has been mistaken for it in the past (Fritts, 1969). This rock generally appears massive in outcrops, but it typically has a fine layering and a foliation given mainly by oriented biotite. It contains quartz, poorly twinned oligoclase, microcline, biotite, and, locally, small amounts of hornblende (table 3). Minor minerals are garnet, muscovite or sericite, epidote/clinozoisite, opaque oxides, apatite, zircon, and fluorite.

The cataclastic gneiss exposed in the northwest part of the Watersmeet dome is a medium-gray, medium-grained gneiss characterized by clots of strongly oriented, shiny biotite. Larger anhedral crystals of plagioclase (An_{25-30}) and microcline are scattered through a finer grained matrix of plagioclase, quartz, microcline, and biotite that was formed by cataclasis and recrystallization. Microcline commonly embays and replaces the larger plagioclase grains; it also occurs as interstitial, poikilitic grains. Sphene is locally associated with the biotite, which is grayish yellow to olive brown. Common accessory minerals are apatite, allanite, zircon, and fluorite. Analyses of a typical sample (M48L) are given in table 3.

INTERLAYERED AMPHIBOLITE AND BIOTITE GNEISS

The youngest recognized succession is exposed in the southern part of the outcrop area (fig. 4) and along the northern margin of the dome, mainly in the vicinity of Brush Lake. It consists dominantly of amphibolite but includes interlayers of biotite gneiss and schist and hornblende-biotite gneiss. The biotite gneiss layers generally are less than a meter or only a few meters thick. These rocks are structurally simpler than those of the two older successions; they strike nearly eastward and have a moderate or shallow northward-dipping foliation, as shown in figure 4. The deformation is interpreted as being Penokean, for the structures in these rocks are comparable to those observed in the Early Proterozoic metagabbro dikes.

The mafic bedded rocks range from relatively massive amphibolite to distinctly layered hornblende-plagioclase-quartz gneiss. The latter is mainly confined to the northwestern part of sec. 6, T. 45 N., R. 39 W., west of Brush Lake; it superficially resembles the tonalitic gneiss in fabric and structure but is considered to be a part of the younger succession of bedded rocks. The amphibolite is medium grained and has the typical salt-and-pepper appearance of this rock type. The plagioclase (oligoclase and andesine) and quartz (less than 5 percent) are variably granulated as a result of cataclasis and recrystallization at smaller grain sizes. The hornblende is green or bluish green and forms subhedral grains. Apatite, sphene, and opaque oxides are minor minerals. The layered gneiss has irregular, alternating quartz-plagioclase-biotite and hornblende-biotite-plagioclase layers. In outcrop, a foliation given mainly by oriented hornblende and biotite and rarely by quartz-feldspar lenses is seen to cross the compositional layering. The biotite in these rocks is a reddish-brown variety. The accessory minerals are the same as those in amphibolite, but garnet occurs rarely in biotitic zones. Modes of representative rocks and the chemical composition of one sample (M261) are given in table 4; this amphibolite contains more K_2O than the Archean amphibolite in the gneiss and amphibolite unit (table 6) in the Marenisco area.

The felsic gneiss and schist interlayered with the amphibolitic rocks are dominantly gray or pinkish-gray, fine- to medium-grained biotite gneisses and schists. Textures vary considerably, mainly because of sporadic cataclasis and recrystallization. The quartz-bearing rocks in the Brush Lake area (fig. 4) are in part at least rather sodic, for they locally contain riebeckite; they lack K-feldspar. Those in secs. 4 and 5 (fig. 4) typically contain considerable K-feldspar (table 4). Zircon in these rocks tends to be elongate, unzoned, and clear.

The younger succession of supracrustal rocks is interpreted as representing metamorphosed mafic and felsic volcaniclastic rocks deposited in a subaqueous environment. The mafic rocks are dominantly metamorphosed mafic and intermediate pyroclastic deposits, although some of the more massive amphibolite could have been basaltic lava.

BIOTITE LEUCOGRANITE

Biotite leucogranite, which intruded the tonalitic gneiss and the supracrustal bedded rocks, forms widely

TABLE 4.—*Approximate modes, in volume percent, of representative samples of the interlayered amphibolite and biotite gneiss succession in the Watersmeet dome*

[Tr., trace]

Constituent	M111A	M261	M202A	M113	M202B	M203B	M260
Plagioclase---	40.5	32	33	24	52.5	41	35
Quartz--------	Tr.	0	25	30	29.5	30	33
K-feldspar----	0	0	0	0	0	24	24
Biotite-------	12	Tr.	21	2	15.5	5	8
Hornblende----	42.5	63	17	41	Tr.	0	0
Sphene--------	Tr.	5	Tr.	0	Tr.	Tr.	0
Opaque oxides	3	0	0	Tr.	0	0	0
Other minerals	2	Tr.	4	3	2.5	Tr.	Tr.

SAMPLE DESCRIPTIONS AND LOCALITIES

M111A. SW 1/4 NW 1/4 sec. 6, T. 45 N., R. 39 W. Massive, medium- to coarse-grained biotitic amphibolite. Apatite is uncommonly abundant.

M261. SE 1/4 SE 1/4 sec. 5, T. 45 N., R. 39 W. Foliated, medium-grained amphibolite. Small grains of brown biotite occur sparsely in plagioclase. Chemical analysis: SiO_2, 50.5; Al_2O_3, 14.4; total Fe as Fe_2O_3, 13.4; MgO, 5.8; CaO, 10.0; Na_2O, 2.3; K_2O, 1.28; TiO_2, 1.66; P_2O_5, <0.2; MnO, 0.26; loss on ignition, 0.76; sum, 100; Rb, 46 ppm; Sr, 255 ppm. Analysts: J. S. Wahlberg, J. Taggart, and J. Baker.

M202A. SW 1/4 SW 1/4 sec. 4, T. 45 N., R. 39 W. Hornblende-biotite schist.

M113. NW 1/4 NW 1/4 sec. 6, T. 45 N., R. 39 W. Garnetiferous hornblende schist. Opaque oxides have sphene rims.

M202B. SW 1/4 SW 1/4 sec. 4, T. 45 N., R. 39 W. Gray, medium-grained biotite gneiss.

M203B. SE 1/4 SW 1/4 sec. 4, T. 45 N., R. 39 W. Pinkish-gray, medium-grained biotite gneiss.

M260. SE 1/4 SE 1/4 sec. 5, T. 45 N., R. 39 W. Pink, fine- to medium-grained biotite gneiss.

scattered, small bodies. The bodies range in size from dikes a meter or less thick to dikes several meters thick. They generally crosscut the older rocks and were emplaced after the bedded rocks were deformed. They range in structure from nearly massive to foliated rocks and in texture from nearly equigranular, fine- to medium-grained rocks to inequigranular, dominantly fine-grained rocks. The variable fabric has resulted from recrystallization under different stress environments; the more equigranular rocks crystallized in a virtually static stress field and the strongly foliated rocks crystallized in a high-stress environment. Cataclasis followed by recrystallization at a finer grain size was the dominant mechanism for development of the foliation in the rocks.

The biotite leucogranite is a light-gray rock containing roughly equal amounts of oligoclase (An_{25-28}), quartz, and K-feldspar (table 5). The plagioclase is bimodal, forming anhedral, rarely zoned crystals a millimeter or more in diameter and smaller crystals within cataclasized and recrystallized zones. The larger crystals commonly have a distinct mortar structure. The quartz tends to form elongate aggregates or scattered anhedral crystals and commonly has strain shadows. The biotite is yellowish gray to yellowish brown and generally fine grained; it occurs in clusters as unoriented grains and in thin streaks within cataclastic zones. The K-feldspar is well-twinned microcline, which is poikilitic. It includes quartz, plagioclase, and, locally,

TABLE 5.—*Approximate modes and chemical analyses of biotite leucogranite in the Watersmeet dome*

[Leaders (---) indicate not determined. Tr., trace. Chemical analyses of sample M45H by Samuel Botts, samples D1042B, D1042H, and D1042J by N. Skinner. U and Th analyses by H. T. Millard, Jr., and others]

Constituent	M45H	M45C	D1042B	D1042H	D1042J
Modal analyses (volume percent)					
Plagioclase---	33.5	32	--	--	--
Quartz--------	28	30	--	--	--
K-feldspar----	32	33	--	--	--
Biotite-------	5	5	--	--	--
Other minerals	1.5	Tr.	--	--	--
Major oxides (weight percent)					
SiO_2----------	74.1	--	75.0	74.6	74.2
Al_2O_3---------	14.2	--	13.6	12.8	13.1
Fe_2O_3---------	.30	--	.7	.31	.18
FeO-----------	.76	--	.98	1.4	1.1
MgO-----------	.59	--	.8	.59	.44
CaO-----------	.46	--	.45	1.1	.83
Na_2O----------	3.6	--	3.8	3.6	3.6
K_2O-----------	5.2	--	5.0	4.4	4.6
H_2O^+----------	.64	--	.45	.66	1.0
H_2O^- ---------	.05	--	.05	.00	.20
TiO_2----------	.21	--	.18	.26	.08
P_2O_5----------	.06	--	.10	.11	.06
MnO-----------	.01	--	.00	.00	.02
CO_2-----------	.07	--	.07	.47	.02
Sum------	100	--	101	100	99
Trace elements (parts per million)					
Rb------------	136	--	168	143	176
Sr------------	46.6	--	57.7	56.8	94.6
U-------------	17.6	--	--	--	1.7
Th------------	67.4	--	--	--	10.1

SAMPLE DESCRIPTIONS AND LOCALITIES

M45H. Roadcut on Michigan Highway 45 in NW 1/4 SE 1/4 sec. 4, T. 45 N., R. 39 W. Light-gray, fine- to medium-grained, weakly foliated granite. Rock traversed by local, irregular fractures coated by biotite. Cuts tonalite gneiss.

M45C. Thin dike that cuts tonalite gneiss. Same locality as M45H.

D1042B. Same locality as M45H.

D1042H. Same locality as M45H.

D1042J. Same locality as M45H.

biotite, and it undoubtedly crystallized late paragenetically. Alteration is variable; muscovite or sericite and calcite are associated with the plagioclase, and the biotite is partly altered to chlorite and rutile(?). Epidote/clinozoisite is a local alteration product of biotite. Accessory minerals are relatively sparse and include zircon, allanite, apatite, and sphene.

GNEISS AND AMPHIBOLITE

Interlayered gneiss and amphibolite compose a northeast-trending belt about 2.5 km wide southeast of Marenisco (fig. 2, Aga). The rocks are intruded sporadically by relatively small bodies of Puritan Quartz Monzonite, which are not shown separately on figure 2. The gneiss and amphibolite appear to grade laterally southeastward into metagraywacke, but probably are mainly older than it. Presumably correlative metavolcanic rocks—metabasalt and biotite schist (Av and Abs, fig. 2)—on the north side of the Puritan batholith have a somewhat lower metamorphic grade, and pillows are preserved locally in the metabasalt. The gneiss and amphibolite were included by Fritts (1969) in his map unit "strata near Cup Lake"; he also included rocks that we assign to the Blair Creek Formation in this unit. He assigned the granite that cuts the bedded rocks to an informal unit called "granite near Thayer."

The gneiss and amphibolite are interlayered on scales ranging from about 3 meters to several hundred meters, and contacts generally are sharp. Exposures are not adequate to map the larger bodies of each rock type separately. Small bodies of Puritan Quartz Monzonite cut the bedded rocks in the Cup Lake area (fig. 2).

The gneiss and amphibolite were deformed twice. During an earlier deformation, the rocks were folded on northeast-trending axes, as indicated by folded layering in the rocks and the existence of an older foliation. Later, a nearly pervasive east-northeast-trending foliation that did not destroy the older foliation was superposed on the layered rocks. This foliation is marked by oriented biotite and associated fine-grained granulated quartz and plagioclase. A pronounced lineation that plunges steeply south or southwest was produced by superposition of the younger foliation on an older compositional layering and foliation.

The gneiss is a pinkish-gray to medium-gray, medium-grained, generally inequigranular biotite gneiss that ranges in composition from granite to tonalite (table 6). Neither the distribution nor the relationship between rocks of the two compositions is known, although tonalite seems to be dominant. The gneisses range from massive rocks having a cataclastic foliation to conspicuously layered rocks, which also have cataclastic textures. The cataclastic foliation is given by oriented biotite and aggregates of quartz and plagioclase, which are finer grained than the remainder of the rock. Differences in the intensity and nature of the cataclastic structures can be observed in the blasted outcrop along the U.S. Forest Service road in sec. 36, T. 46 N., R. 43 W. Plagioclase (An_{25-30}) commonly occurs as megacrysts, which are granulated to different degrees; the biotite in the rocks is a reddish-brown variety. Alteration minerals that accompany the granulation and recrystallization are muscovite or sericite, epidote/clinozoisite, and chlorite. Zircon is a common accessory mineral. Other accessory minerals are allanite (commonly rimmed by epidote), apatite, and opaque oxides. Garnet and staurolite are rare metamorphic minerals. A fine-grained biotite schist is intercalated with the coarser grained gneisses in the Cup Lake area.

The amphibolite in this unit is a fine- to medium-grained, layered to massive rock composed of hornblende, plagioclase, and lesser quartz. At places it contains subrounded clasts of dacite or dacite porphyry as much as 4 cm in diameter. It is strongly foliated and lineated. The hornblende is a green or bluish-green variety. Clinopyroxene is intergrown with hornblende in one sample (M71D, table 6) from the Cup Lake area. Chemical compositions of selected samples are given in table 6.

The gneiss and amphibolite are interpreted as metamorphosed felsic- intermediate pyroclastic deposits and mafic volcanic rocks, respectively. Evidence of primary textures has been destroyed by the multiple deformations and metamorphism, but the interlayering of the two contrasting rock types and their mineral and chemical compositions support a volcanic derivation. Also, they appear to grade eastward into metagraywacke and associated tuffs, which have preserved some primary bedding features indicative of turbidites.

METAGRAYWACKE

Metagraywacke is a major rock unit, composing a northeast-trending belt as much as 3 km wide north of Thayer (fig. 2). The unit contains thin intermediate tuff beds and lenses—one of which is mapped on figure 2—and rare, thin iron-formation. The metagraywacke is folded on tight north- northeast-trending axes; its stratigraphic thickness probably does not exceed 1 km. The rock grades into gneiss and amphibolite to the west through a broad zone of intercalated amphibolite and metagraywacke, and the contact between these two units is rather arbitrarily located. It appears to be overlain unconformably to the east by the Early Proterozoic Blair Creek Formation. The metagraywacke was mapped by Fritts (1969) as "strata near Banner Lake."

The metagraywacke is a medium-gray, fine-grained,

TABLE 6.—*Approximate modes and chemical analyses of selected rocks in the gneiss and amphibolite unit*

[Leaders (—) indicate not determined. Tr., trace. Chemical analyses of sample M68 by Samuel Botts, samples M147–1A, M147–1B, M147–2, and M150, by H. Smith, sample M89X by N. Skinner and D. Kobilis, sample M324A by J. S. Wahlberg, J. Taggart, and J. Baker, and sample D1392 by Z. A. Hamlin. U and Th analyses by H. T. Millard, C. M. Ellis, and V. C. Smith]

Constituent	M68	D1043	M69	M150	M147-1A	M147-1B	M147-2	M89X	M71D	D1392	M324A
Modal analyses (volume percent)											
Plagioclase	22	37	42	64	59	--	70	--	Tr.	--	41
Quartz	45	32	50	32	29	--	21.5	--	0	--	0
K-feldspar	22	20	Tr.	0	0	--	0	--	0	--	0
Biotite	8.5	8	4.5	3	10	--	8	--	Tr.	--	0
Hornblende	Tr.	Tr.	1.5	0	0	--	0	--	58.5	--	55
Clinopyroxene	0	0	0	0	0	--	0	--	3	--	0
Alteration minerals	1.5	2	1	1	.5	--	Tr.	--	38.5	--	Tr.
Accessory minerals	1	1	1	Tr.	1.5	--	.5	--	Tr.	--	4
Major oxides (weight percent)											
SiO_2	70.6	--	--	72.6	67.8	67.7	72.35	50.9	--	47.1	52.5
Al_2O_3	13.1	--	--	15.2	15.1	15.8	14.2	13.2	--	21.3	14.1
Fe_2O_3	1.1	--	--	.09	.35	.92	.31	2.9	--	2.0	12.4
FeO	3.2	--	--	1.5	3.2	3.0	2.0	10.6	--	6.9	--
MgO	.30	--	--	.79	2.2	1.6	.95	5.8	--	3.6	5.77
CaO	1.7	--	--	2.6	2.5	2.6	2.	9.6	--	10.1	8.70
Na_2O	3.0	--	--	6.8	4.2	5.6	5.5	2.0	--	2.9	3.1
K_2O	4.4	--	--	.54	1.8	1.3	.92	.71	--	1.9	.93
H_2O^+	.75	--	--	.52	1.2	0.65	.53	1.6	--	1.9	--
H_2O^-	.02	--	--	.11	.04	0.18	.14	.11	--	.14	--
TiO_2	.56	--	--	.18	.41	0.41	.22	1.2	--	.57	1.20
P_2O_5	.12	--	--	.06	.13	0.13	.08	.18	--	.05	.2
MnO	.04	--	--	.03	.06	0.06	.05	.23	--	.12	.21
CO_2	.27	--	--	.07	.05	0.07	.28	.14	--	.18	--
Loss on ignition	--	--	--	--	--	--	--	--	--	--	.95
Sum	99	--	--	--	99	100	99	99	--	99	100
Trace elements (parts per million)											
Rb	102	118	--	15	51.4	28.6	17.4	--	--	91	16
Sr	136	119	--	275	304	239	190	--	--	243	197
U	4.1	--	--	.6	1.1	1.2	.5	.6	--	.5	--
Th	26.3	--	--	4.0	21.3	13.5	13.2	2.7	--	.0	--

SAMPLE DESCRIPTIONS AND LOCALITIES

M68. NE 1/4 NE 1/4 sec. 36, T. 46 N., R. 43 W. Pinkish-gray, medium-grained flaser gneiss. Foliation given by streaks of mafic minerals, which wrap around feldspar augen.

D1043. Same locality as M68. Mode shows difference in mineralogy from layer to layer.

M69. NW 1/4 SW 1/4 sec. 30, T. 46 N., R. 42 W. Gray tonalitic gneiss. Foliation given by irregular streaks of mafic minerals.

M150. East-center sec. 30, T. 46 N., R. 42 W. Pinkish-gray, medium-grained, slightly inequigranular, weakly foliated gneiss.

M147-1A. SE 1/4 SW 1/4 sec. 21, T. 46 N., R. 42 W. Medium-gray, medium-grained, layered tonalite gneiss. Layering given by alternating biotite-rich and quartz- and plagioclase-rich bands. Biotite is alined in cataclastic zones.

M147-1B. Same locality as M147-1A. Similar in composition and structure to M147-1A.

M147-2. Same locality as M147-1A.

M89X. NE 1/4 NW 1/4 sec. 27, T. 46 N., R. 42 W. Thinly layered metabasalt with pronounced lineation.

M71D. SW 1/4 SW 1/4 sec. 17, T. 46 N., R. 41 W. Collected from cut along abandoned railway. Dark-gray foliated amphibolite; has streaks of feldspar. Epidote (23 percent) and muscovite (12 percent) are major alteration minerals. Amphibolite is included in foliated granite.

D1392. Same locality as M71D.

M324A. NW 1/4 SW 1/4 sec. 30, T. 46 N., R. 42 W. Fine-grained amphibolite; contains 4 percent sphene.

thin- to thick-bedded rock having a nearly pervasive northeast-trending schistosity. Graded beds are common; they indicate the existence of folds having widths on the order of 100–200 m. The graywacke consists mainly of plagioclase, quartz, and biotite but also contains chlorite, muscovite, and, locally, garnet. Zircon and opaque oxides are sparse accessory minerals. Epidote is a sparse secondary mineral. Two generations of biotite are present: an older, generally finer- grained variety and a younger, generally coarser variety. The older generation defines an older schistosity (S_1), which is nearly parallel to bedding, and the younger generation defines a younger schistosity (S_2). Both generations of biotite are weakly altered to chlorite. The plagioclase forms small anhedral, generally untwinned grains that are difficult to distinguish from quartz, and it is weakly altered to muscovite.

Although the metagraywackes of both Archean and Early Proterozoic ages are similar in composition, they are clearly distinguished by subtle differences in some of the major elements and larger differences in rubidium and strontium (table 7). The Archean rocks are slightly lower in CaO and higher in MgO than the Proterozoic rocks and give consistently higher MgO/CaO ratios. The substantially lower rubidium in the Archean metagraywackes (fig. 6) results in generally

TABLE 7.—*Chemical analyses of Archean and Proterozoic metagraywacke, Marenisco-Watersmeet area*

[Chemical analyses by Z. A. Hamlin; U and Th analyses by H. T. Millard, C. M. Ellis, and V. C. Smith]

Constituent	Archean metagraywacke unit						Michigamme Formation						Copps Fm.	Blair Creek Fm.
	M91	M97	M99	M115	M98-1	M124	D2433	D2434	D2435	D2436	D2437	D2440	M108	M106
							Major oxides (weight percent)							
SiO_2	62.0	63.1	60.0	62.1	63.8	61.9	63.2	58.5	67.6	60.1	63.3	66.4	66.0	53.9
Al_2O_3	15.8	16.0	16.7	16.1	15.7	19.4	16.4	16.4	14.6	16.0	16.8	14.9	14.7	13.5
Fe_2O_3	.83	1.1	.54	.76	.95	.64	1.2	.33	.61	2.0	1.3	.82	.76	8.0
FeO	6.2	4.8	6.3	4.8	4.1	1.8	3.7	9.3	6.0	7.1	5.9	5.4	5.2	5.8
MgO	4.0	3.3	3.8	3.1	2.9	1.7	1.6	3.0	2.4	3.0	2.7	2.3	2.2	3.5
CaO	1.8	1.7	1.8	2.3	1.3	4.2	3.9	2.0	1.8	2.9	1.9	1.7	1.4	4.1
Na_2O	3.6	3.5	5.1	3.4	6.4	5.4	4.4	3.1	3.4	2.8	3.4	4.6	3.8	4.0
K_2O	2.6	2.7	0.92	3.1	1.0	2.5	2.4	2.0	1.5	1.9	2.6	.51	1.9	1.9
H_2O^+	1.8	1.7	2.7	2.0	1.6	1.2	.98	2.8	1.8	1.7	1.9	2.0	1.8	1.2
H_2O^-	.18	.09	.08	.09	.11	.08	.08	.05	.05	.07	.06	.07	.03	.04
TiO_2	.59	.42	1.4	.52	.48	.32	.70	.87	.70	.85	.79	.70	.56	2.1
P_2O_5	.2	.18	.17	.19	.19	.19	.24	.14	.13	.13	.19	.12	.13	.49
MnO	.06	.04	.05	.07	.03	.02	.06	.06	.04	.09	.03	.03	.07	.09
CO_2	.00	.02	.01	.00	.04	.83	.02	.08	.02	.08	.01	.02	.00	.10
Sum	100	99	100	99	99	100	99	99	101	99	101	100	99	99
							Trace elements (parts per million)							
Rb	58.5	66.7	23	83	17.6	46	114	95	76	98	115	20	91	26.5
Sr	337	450	306	520	166	646	271	280	341	211	274	316	277	173
U	2.8	3.8	2.1	2.4	2.5	1.4	2.5	2.9	2.2	2.5	3.5	2.5	2.1	1.8
Th	8.6	9.5	6.3	7.1	9.0	4.5	6.5	5.8	5.3	6.9	4.9	5.9	4.0	5.9

SAMPLE DESCRIPTIONS AND LOCALITIES

M91. SE 1/4 SW 1/4 sec. 30, T. 46 N., R. 41 W.
M97. SE 1/4 NE 1/4 sec. 31, T. 46 N., R. 41 W.
M99. SE 1/4 SW 1/4 sec. 30, T. 46 N., R. 41 W
M115. SE 1/4 sec. 29, T. 46 N., R. 41 W.
M98-1. West-center sec. 32, T. 46 N., R. 41 W. Intermediate tuff containing 1 mm plagioclase crystals. Adjacent to thin iron-formation.
M124. SE 1/4 NW 1/4 sec. 28, T. 46 N., R. 41 W.. Dacitic tuff.
D2433. SW 1/4 SW 1/4 sec. 34, T. 46 N., R. 39 W.
D2434. SE 1/4 SE 1/4 sec. 21, T. 46 N., R. 39 W.
D2435. NE 1/4 sec. 33, T. 46 N., R. 39 W.
D2436. SE 1/4 NE 1/4 sec. 29, T. 46 N., R. 39 W.
D2437. NE 1/4 sec. 34, T. 46 N., R. 40 W.
D2440. SE 1/4 NE 1/4 sec. 32, T. 46 N., R. 40 W.
M108. SW 1/4 NW 1/4 sec. 18, T. 46 N., R. 42 W.
M106. NW 1/4 SE 1/4 sec. 26, T. 46 N., R. 41 W.. Iron-rich metasediment.

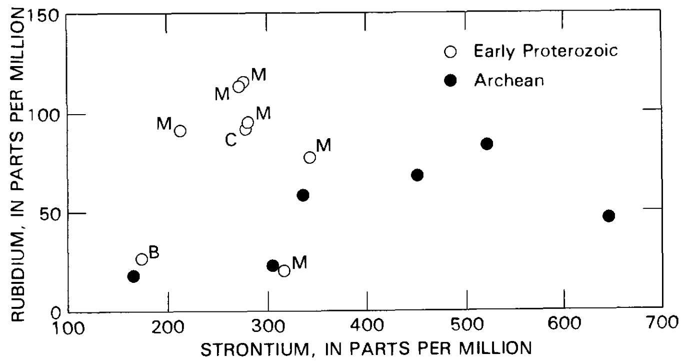


FIGURE 6.—Rb-Sr plot for Archean and Early Proterozoic metagraywacke. For the Proterozoic samples, letters designate the formation: M, Michigamme; C, Copps; and B, Fe-rich metasediment in the Blair Creek. The Archean sample with the highest Sr content is a metavolcanic rock (M–124) associated with the metagraywackes.

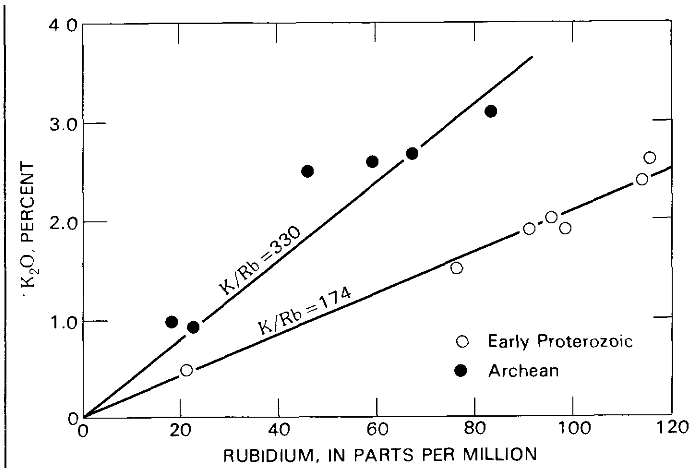


FIGURE 7.—K/Rb ratios of Archean and Early Proterozoic metagraywacke. The Archean sample at 2.5 percent K_2O and 46 ppm Rb is a metavolcanic rock (M–124) and is not used in calculating the average K/Rb ratio.

lower Rb/Sr ratios. A striking difference is seen in the K/Rb ratios of the two rocks of different ages (fig. 7). Over a range of K_2O from 0.5 to 2.6 percent, K/Rb ratios of the Early Proterozoic metagraywackes are unusually low, varying little from their average value of 174. Within a similar range in K_2O, K/Rb ratios of the Archean metagraywackes are nearly double this figure, their average being 330.

These geochemical differences are considered to be primary features related to the source material and the primary mineralogic composition. The lower K/Rb ratios in the Early Proterozoic metagraywacke may reflect a greater proportion of original clay matrix in these rocks, perhaps related to more intense weathering of the source rocks.

PURITAN QUARTZ MONZONITE

Rocks that are similar in appearance and composition to the Puritan Quartz Monzonite in the Puritan batholith (fig. 2, Ap) and presumably are equivalent occur in the belt of Archean gneiss and amphibolite southeast of Marenisco. Contact relations are poorly exposed, and the extent of the granitic rocks is not known accurately; accordingly, these outlying bodies of the Puritan are not mapped separately on figure 2. The rocks have been deformed and have widespread cataclastic textures, especially a mortar structure; the deformation is Penokean in age.

The principal bodies of Puritan Quartz Monzonite within the gneiss belt are in the Cup Lake area (fig. 2), mainly in secs. 16 and 17, T. 46 N., R. 41 W. They consist of pinkish-gray, medium- to coarse-grained, somewhat inequigranular, massive to weakly foliated leucocratic biotite granite and coarse-grained leucogranite. Much of the coarse-grained granite grades into syenitic or granitic pegmatite. A less common facies is fine to medium grained and has a moderate to strong foliation given by alined biotite. The coarse granite and pegmatite are widely scattered in secs. 16 and 17, as noted above, and are abundant in the eastern part of sec. 23, T. 46 N., R. 42 W. Samples M72, M78, and M85 (table 8) are representative of this facies. Possibly, some of these coarse-grained rocks are not intrusive, but instead have a volcanic protolith and should be grouped with the felsic gneiss.

The granitic rocks contain variable amounts of sodic plagioclase, quartz, and microcline (table 8), but in general their compositions are within the limits for granite defined by Streckeisen (1976). Biotite is sparse and tends to occur as frayed aggregates of small brown grains. Some of the biotite contains tiny barrel-shaped blebs of K-feldspar.

As can be seen from figure 8, the modal mineralogy of the bodies in the gneiss belt is similar to that of the Puritan Quartz Monzonite in the Puritan batholith. The modes and chemical analyses of the Puritan from the batholith, given in table 9, are of samples dated previously by the Rb-Sr isochron method (Sims and others, 1977).

The occurrence of Puritan Quartz Monzonite in the gneiss belt that is virtually identical compositionally to that in the Puritan batholith suggests that the bodies in the gneiss belt are satellitic bodies related to the main batholithic mass, as shown diagrammatically on figure 3.

AGE AND CORRELATION

The Archean rocks exposed in the area are representative of the two tectono-stratigraphic environments recognized in the Lake Superior region, as shown on figure 1.

TABLE 8.—*Approximate modes and chemical analyses of Puritan Quartz Monzonite from bodies in the gneiss and amphibolite unit*

[Leaders (—) indicate not determined. Tr., trace. Chemical analyses of samples D1389 and D1391 by Z. A. Hamlin, sample M85 by H. Smith, and sample M71 by Samuel Botts. U and Th analyses by H. T. Millard, Jr., and others]

Constituent	M71A	M71C	D1389	D1390	D1391	M78	M85	M72
			Modal analyses (weight percent)					
Plagioclase	30	38.5	24	20	46	27	48	40
Quartz-----	39	31.5	26	30	34	33	6	22
K-feldspar-	28.5	23.5	45	47	16	33	44	33
Biotite----	2.5	5.5	5	3	4	7	0.2	5
Alteration minerals	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Accessory minerals	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
			Major oxides (weight percent)					
SiO_2-------	72.4	--	71.7	--	72.3	--	76.1	--
Al_2O_3------	14.6	--	14.0	--	13.8	--	13.2	--
Fe_2O_3------	.40	--	.27	--	.00	--	.19	--
FeO--------	.76	--	1.9	--	2.2	--	1.2	--
MgO--------	.16	--	.21	--	.35	--	.09	--
CaO--------	1.4	--	.81	--	1.0	--	.73	--
Na_2O-------	3.5	--	3.2	--	3.7	--	4.3	--
K_2O--------	4.8	--	5.8	--	4.1	--	3.3	--
H_2O^+-------	.50	--	.56	--	.74	--	.32	--
H_2O^--------	.02	--	.18	--	.19	--	.08	--
TiO_2-------	.11	--	.00	--	.05	--	.02	--
P_2O_5-------	.04	--	.04	--	.03	--	.05	--
MnO--------	.00	--	.01	--	.02	--	.12	--
CO_2--------	.08	--	.06	--	.06	--	.04	--
Sum---	99	--	99	--	99	--	100	--
			Trace elements (parts per million)					
Rb---------	101	--	135	--	99	--	93	--
Sr---------	94	--	111	--	164	--	61.7	--
U----------	20.5	--	10.2	--	2.0	--	17.4	--
Th---------	28.9	--	48.7	--	5.2	--	5.0	--

SAMPLE DESCRIPTIONS AND LOCALITIES

M71A. SW 1/4 SW 1/4 sec. 17, T. 46 N., R. 41 W. Collected from cut along abandoned railway. Pinkish-gray, medium- to coarse-grained, inequigranular, weakly foliated granite. Plagioclase has weak concentric zoning.

M71C. Same locality as M71A. Light-gray, fine- to medium-grained foliated granite. Intercalated with M71A. Foliation given by alined biotite and recrystallized quartz aggregates.

D1389. Same locality as M71A. Pinkish-gray, coarse-grained, weakly foliated granite similar to M71A.

D1390. Same locality as M71A. Pink, medium-grained, inequigranular, weakly foliated granite.

D1391. Same locality as M71A. Pinkish-gray, fine-grained, foliated granite. Foliation given by thin zones of oriented biotite, similar to M71C.

M78. NE 1/4 NW 1/4 sec. 17, T. 46 N., R. 41 W. Pink, coarse-grained massive granite.

M85. NW 1/4 SW 1/4 sec. 23, T. 46 N., R. 42 W. Pinkish-gray, coarse-grained, inequigranular, massive syenite. Contains sparse garnet.

M72. SW 1/4 SW 1/4 sec. 17, T. 46 N., R. 41 W. Pinkish-gray, coarse-grained, weakly foliated granite.

The rocks exposed in the Watersmeet dome, which belong to the gneiss terrane, were formed during three rock-forming episodes. Analyses of two samples of the tonalitic gneiss give a firm minimum U-Th-Pb age of 3,400 m.y. and a concordia-intercept age of about 3,560 m.y. (fig. 9; Peterman and others, 1980). Analyses of zircon from one sample (M321) of the supracrustal biotite gneiss in the dome indicate an age virtually identical to that of the tonalitic gneiss (U-Pb zircon method). The third succession, interlayered amphibolite and biotite gneiss, has an apparent age of about 2,640 m.y. (fig. 9); this is based on zircon from sample M203. These rocks are cut by dikes of leucogranite having a U-Pb zircon age of about 2,590 m.y. (fig. 9). All the Archean rocks in the Watersmeet dome were strongly deformed and metamorphosed during the Penokean event. As a consequence, the Rb-Sr whole rocks and mineral systems were reset about 1,750 m.y. ago, as shown by the secondary isochrons on figure 10. The analytical data for these and other dated samples are given in table 10. Biotite gneiss whole-rock and mineral samples from the M-48 locality (including M-48, D2438, and D2439) define a relatively precise isochron of 1,750 m.y. Similarly, the array of points for biotite leucogranite at the D1042 locality, including microcline and plagioclase, is consistent with an isochron of the same slope. The other samples do not define linear arrays but plot between these two isochrons, indicating isotopic homogenization on a limited scale. Reference isochrons at 3,500 and 2,700 m.y. are shown for comparison (fig. 10). Whole-rock samples of the tonalitic augen gneiss and of the leucogranite plot to the right of the 3,500 m.y. and 2,700 m.y. isochrons, respectively, suggesting that the discordances observed may

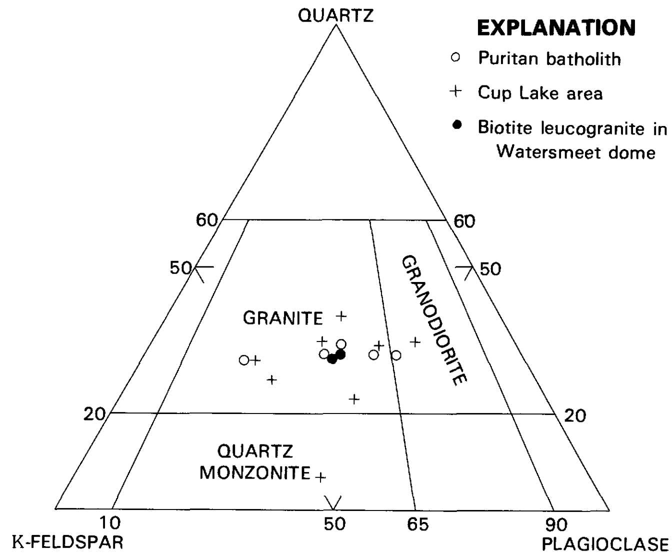


FIGURE 8.—Quartz-K-feldspar-plagioclase diagram showing modal composition of Late Archean granitoid rocks. Except for the biotite leucogranite in the Watersmeet dome, all are assigned to the Puritan Quartz Monzonite. Lines are compositional boundaries established by Streckeisen (1976).

TABLE 9.—*Approximate modes and chemical analyses of Puritan Quartz Monzonite in the Puritan batholith*

[Tr., trace. Chemical analyses by Z. A. Hamlin. U and Th analyses by H. T. Millard, Jr., C. M. Ellis, and V. C. Smith]

Constituent	D1729	D1730	D1732	D2492	D2493
Modal analyses (volume percent)					
Plagioclase---	43	40	31	36	52
Quartz--------	31	31	31	30	20
K-feldspar----	22	26	34	28	23
Biotite-------	4	3	3	5	5
Other minerals	Tr.	Tr.	1	1	Tr.
Major oxides (weight percent)					
SiO_2----------	71.0	70.7	71.4	71.2	68.5
Al_2O_3---------	13.5	13.6	13.7	13.8	16.0
Fe_2O_3---------	1.1	0.79	0.34	0.42	0.50
FeO-----------	3.2	2.9	2.5	2.0	1.5
MgO-----------	0.50	.44	.45	.44	.40
CaO-----------	1.9	1.3	.49	.71	1.7
Na_2O----------	4.3	4.1	4.3	3.6	5.3
K_2O-----------	4.0	4.0	4.8	5.0	3.6
H_2O^+----------	.84	.51	.42	.88	.67
H_2O^-----------	.07	.04	.08	.21	.16
TiO_2----------	.09	.15	.03	.13	.05
P_2O_5----------	.06	.04	.03	.06	.05
MnO-----------	.11	.05	.04	.03	.03
CO_2-----------	.12	.08	.16	.10	.08
Sum------	101	99	99	99	99
Trace elements (parts per million)					
Rb------------	119	118	54.4	233	104
Sr------------	180	174	79.7	158	640
U-------------	7.4	6.0	7.7	2.5	1.2
Th------------	32.4	29.7	62.1	26.2	3.4

SAMPLE LOCALITIES

D1729. Sec. 7, T. 46 N., R. 43 W.
D1730. Sec. 7, T. 46 N., R. 43 W.
D1732. Sec. 9, T. 46 N., R. 43 W.
D2492. Sec. 24, T. 47 N., R. 47 W.
D2493. Sec. 5, T. 46 N., R. 45 W.

be related to increases in the $^{87}Rb/^{86}Sr$ ratios rather than simple redistribution of radiogenic Sr at 1,750 m.y. ago. The radiometric data indicate that the tonalitic augen gneiss and the overlying biotite gneiss in the Watersmeet dome are approximately the same age as the Early Archean gneisses in the Minnesota River valley in southwestern Minnesota (Goldich and others, 1980; Goldich and Wooden, 1980), which has been designated as the type area for the Archean gneiss terrane in the Lake Superior region (Sims, 1980; Sims and Peterman, 1982). The 2,590-m.y.-old leucogranite that cuts the supracrustal rocks in the dome is similar lithologically and chemically to the granite facies of the Puritan Quartz Monzonite; possibly, the two granites are comagmatic.

The rocks in the area that are representative of the greenstone-granite terrane are all Late Archean in age. The gneiss and amphibolite unit in the belt southeast of Marenisco is considered approximately correlative with the metabasalt (Ramsay Formation) and biotite schist associated with the Puritan batholith; it differs from the rocks associated with the batholith mainly in having been deformed and metamorphosed twice, once in the Late Archean and again during the Penokean event. The Puritan Quartz Monzonite that intrudes the gneiss and amphibolite also differs from that in the batholith in having been tectonically disturbed during the Penokean event. The Puritan in the batholith has been dated by the Rb-Sr isochron method as being 2,650 ± 140 m.y. old (Sims and others, 1977). Rb-Sr data for samples of Puritan Quartz Monzonite in small bodies that cut gneiss and amphibolite show considerable scatter, but are consistent with the 2,650-m.y. isochron for the main batholith (fig. 11). Rb-Sr data on samples of gneiss that are cut by the Puritan indicate a severe disturbance and define an isochron of 1,750 m.y. with a high initial $^{87}Sr/^{86}Sr$ of 0.7101. This array includes biotite from sample M–68. The isotopic disturbance of these systems accords with the strong ductile deformation and recrystallization seen in samples of the analyzed gneiss.

Zircons from two samples of gneiss and one of the Puritan Quartz Monzonite were dated by the U-Th-Pb method (fig. 12). Three size fractions of zircon from one sample (M147) give a concordia-intercept age of 2,750 m.y. Zircons from sample M68, a flaser gneiss, and from M71, Puritan Quartz Monzonite from the Cup Lake area, have unusually high U contents, and their isotopic ages are extremely discordant. Both plot near the lower end of the discordia defined by M147, indicating an intercept at about 650 m.y. Presumably, these zircons have become metamict as a consequence of their high U contents and have suffered substantial Pb loss. The Late Archean ages determined for gneiss in the belt southeast of Marenisco and for the Puritan Quartz Monzonite are indistinguishable from ages obtained by both Rb-Sr and U-Pb methods on metavolcanic and associated intrusive rocks from greenstone belts in northern Minnesota (Peterman, 1979).

Rb-Sr whole-rock analyses of samples of Archean metagraywacke have not provided unique age information because of their low Rb/Sr ratios and the excessive scatter of data points (fig. 13). However, relative to the isochron defined by the Early Proterozoic metagraywacke, three of the Archean samples have significantly higher $^{87}Sr/^{86}Sr$ ratios. A reference isochron of 2,750 m.y. bisects the field defined by data points for

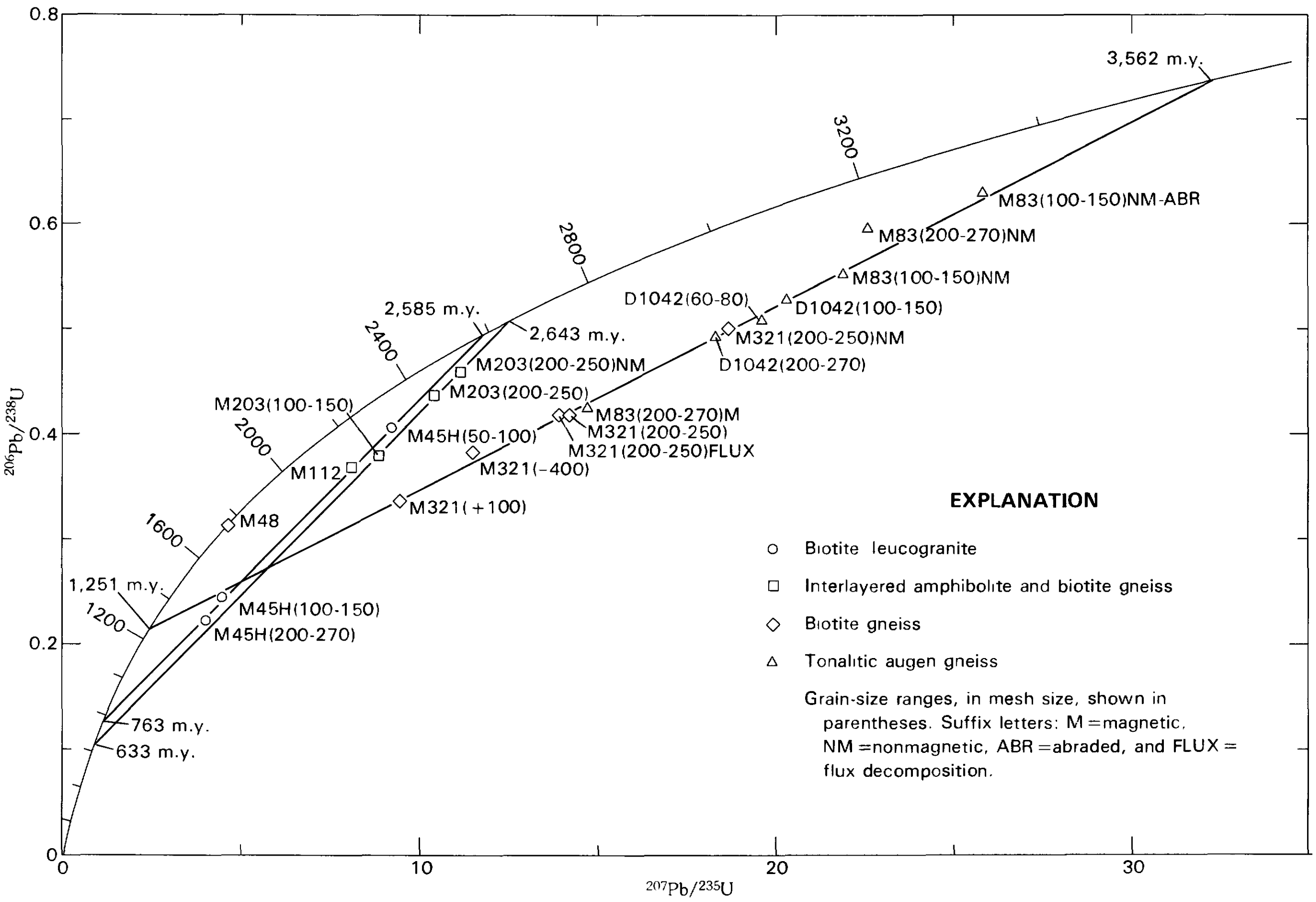


FIGURE 9.—Concordia plot of zircon data for samples of granitoid rocks in the Watersmeet dome. Upper and lower intercepts, respectively, are 3,562 m.y. and 1,251 m.y. for augen gneiss and biotite gneiss (M83(200–270)NM excluded from regression); 2,643 m.y. and 633 m.y. for the interlayered amphibolite and biotite gneiss (M112 excluded from the regression); and 2,585 m.y. and 763 m.y. for the biotite leucogranite. Data for M321 and M203 from Peterman and others (in press).

the Archean rocks. As shown by petrographic data, the Archean metagraywacke was subjected to a pre-Penokean metamorphism of at least garnet grade. The scatter shown by the Rb-Sr data probably reflects the second metamorphism imposed on the earlier mineral systems. Even though a precise age is not defined by the Rb-Sr results, the data strongly suggest that the graywacke is older than that of the Michigamme and Copps Formations, and thus are consistent with other evidence indicating an Archean age for these rocks.

EARLY PROTEROZOIC ROCKS

The classic sedimentary sequence (Marquette Range Supergroup) of the main part of the Gogebic Range (Schmidt, 1980; Cannon and Gair, 1970; this report, fig. 3) gives way at the east end to a grossly correlative succession containing a substantial thickness of volcanic rocks (Emperor Volcanic Complex) and cogenetic(?) sills and dikes. The change in character of the rocks from west to east reflects a transition from a shallow-water platform environment to deeper water conditions in a less stable tectonic environment. At the east end of the Gogebic Range, the Emperor Complex is interbedded with and overlies the Ironwood Iron-formation (Trent, 1973), which in this area is composed mainly of tuffaceous rocks and, at least locally, of relatively nonmagnetic black slate (Hendrix, 1960). As shown on figure 2, the Ironwood locally overlies the Palms Formation. The Ironwood and Emperor are overlain, apparently unconformably, by the Copps Formation. The Early Proterozoic rocks in the eastern part of the Gogebic Range have been described by Van Hise and Leith (1911) and by Schmidt (1980) and are not described here.

East of the Gogebic Range, the Ironwood Iron-formation is not recognized as a discrete stratigraphic unit, but magnetic iron-formation occurs at approximately the same stratigraphic position within the lowermost Proterozoic unit distinguished in this area, the Blair Creek Formation. The iron-formation is magnetic,

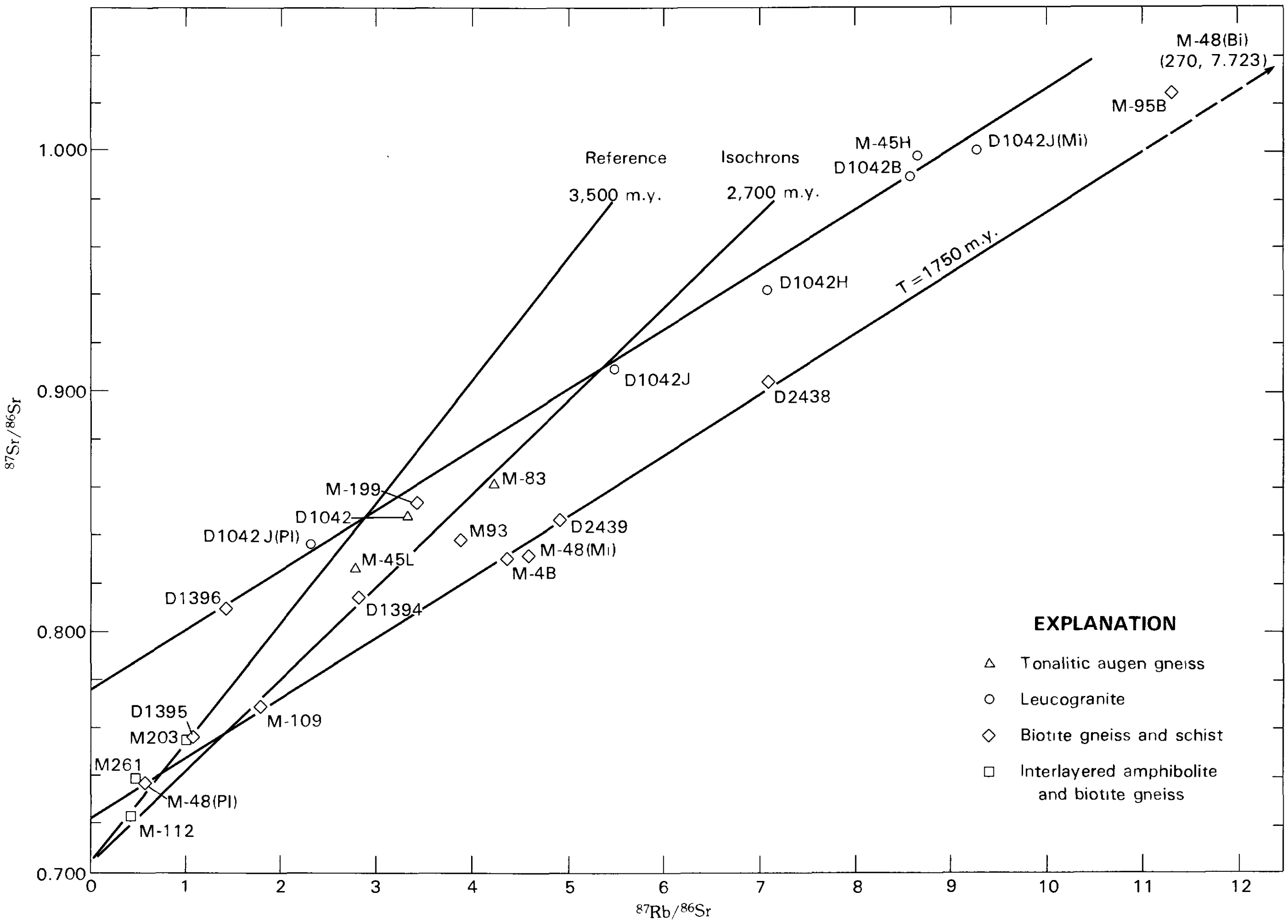


FIGURE 10.—Rb-Sr isochron plot for samples of gneiss, schist, and leucogranite from the Watersmeet dome. Mineral analyses are designated by suffix abbreviations in parentheses: Pl, plagioclase; Mi, microcline; and Bi, biotite. The remaining points represent whole-rock analyses. The 1,750-m.y. isochron is derived from whole-rock and mineral data for the M-48 locality. A regression of these points yields an age of 1,750±90 m.y. with an initial $^{87}Sr/^{86}Sr$ of 0.7217±0.0019 (uncertainties at the 95-percent confidence level). A parallel reference isochron is drawn through the array of points for the leucogranite. The 2,700- and 3,500-m.y. isochrons are shown for comparison.

thin, and apparently discontinuous. The Blair Creek is overlain by graywacke-slate called Copps Formation in the west and Michigamme Formation in the east (fig. 2). These rocks unconformably overlie Archean basement rocks.

The local occurrence of rocks typical of the Chocolay Group of the Marquette Range Supergroup suggests that these strata underlie the Blair Creek Formation, at least at places, in the area. Drilling at two localities in T. 45 N., R. 43 W., in the southwest part of the map area (fig. 2), has disclosed thick quartzite and dolomite successions overlain by iron-formation and slate (Allen and Barrett, 1915). These rocks are interpreted as being correlative with the lowermost exposed rocks of the Marquette Range Supergroup in the Gogebic Range. Also, interlayered quartzite and tremolitic dolomite are exposed as an isolated body in a roadcut on Gogebic County Highway 206 in sec. 4, T. 45 N., R. 40 W. These rocks are tentatively considered to be equivalent to the Bad River Dolomite; they probably lie directly on Archean rocks along the northwestern margin of the Watersmeet dome.

Mafic dikes of two ages cut all the rocks in the map area (fig. 2) except the Copps and Michigamme Formations. The older set is Early Proterozoic; these dikes are composed of metadiabase and metagabbro and in the northwest part of the region are mainly oriented northeastward, subparallel to the structural grain in the Archean and Proterozoic rocks. Sparse exposures in the Watersmeet dome suggest that here they trend northwestward. (See Fritts, 1969.) The younger dike set is presumed to be Keweenawan in age. It consists of tholeiitic gabbro that is neither deformed nor metamorphosed. The dikes trend subparallel to the older metamorphosed dikes. Only the Early Proterozoic metadiabasic dikes are described in this section.

BLAIR CREEK FORMATION

The Blair Creek Formation is named herein to include the succession of mafic volcanic rocks and lesser

TABLE 10.—*Analytical data for samples dated by the Rb-Sr method*

[Data for metagraywackes and M83, M93, M95B, M109, and M199 are new analyses. Other data have been reported previously in Sims and Peterman (1976), Sims and others (1977), and Peterman and others (1980). Abbreviations in parentheses denote minerals: Pl, plagioclase; Mi, microcline; Bi, biotite]

Sample No.	Rock type	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
	Watersmeet dome				
D1042------	Augen gneiss-----	149	132	3.32	0.8478
M45L-------	---do------------	184	194	2.78	.8256
M83--------	---do------------	216	150	4.22	.8605
M48--------	Biotite gneiss---	96.3	64.8	4.36	.8303
M48 (Pl)---	---do------------	18.4	91.2	.585	.7365
M48 (Mi)---	---do------------	89.1	56.9	4.59	.8305
M48 (Bi)---	---do------------	356	6.43	270	7.723
D2439------	---do------------	87.2	52.3	4.89	.8466
D1394------	---do------------	95.2	98.2	2.81	.8139
D1395------	---do------------	89.1	240	1.08	.7560
D1396------	---do------------	57.3	118	1.42	.8087
M93--------	---do------------	105	79.5	3.87	.8380
M1D9-------	---do------------	104	170	1.78	.7686
M203-------	---do------------	104	284	1.07	.7548
M112-------	Hornblende-biotite gneiss---	33.0	218	.439	.7224
M261-------	Amphibolite------	45.6	262	.505	.7377
D2438------	Biotite schist---	314	130	7.10	.9044
M958-------	---do------------	116	30.6	11.3	.8535
M199-------	---do------------	98.2	84.5	3.411	1.0249
D1042------	Leucogranite-----	176	94.6	5.46	.9096
D1042J (Pl)	---do------------	25.9	32.7	2.29	.8363
D1042J (Mi)	---do------------	369	115	9.26	1.0022
D1042H-----	---do------------	167	69.5	7.07	.9430
D1042B-----	---do------------	168	57.7	8.55	.9901
M45H-------	---do------------	136	46.6	8.65	.9986
	Gneiss belt				
D1043------	Flaser gneiss----	118	119	2.88	.7829
M68--------	---do------------	102	136	2.19	.7659
M68 (Bi)---	---do------------	474	26.4	59.4	2.1655
M147-1A----	Tonalite gneiss--	51.4	304	.491	.7226
M147-1B----	---do------------	28.6	239	.346	.7197
M150-------	Biotite gneiss---	14.8	275	.156	.7128
D1392------	Amphibolite inclusion------	91.0	243	1.09	.7413
M324A------	Amphibolite------	15.0	203	.214	.7118
	Puritan Quartz Monzonite				
D1389------	Biotite granite--	135	111	3.50	.8391
D1390------	---do------------	126	88.7	4.10	.8538
D1391------	---do------------	99.3	164	1.75	.7723
M71--------	---do------------	101	94.3	3.15	.8312
M712 (Bi)--	---do------------	144	38.7	11.05	1.0012
M85--------	Syenite----------	93.3	61.7	4.45	.8867
	Archean metagraywacke				
M91--------	Metagraywacke----	58.5	337	.503	.7239
M97--------	---do------------	66.7	450	.430	.7191
M98-1------	Metadacite-------	17.6	166	.307	.7137
M99--------	Metagraywacke----	22.9	306	.226	.7136
M115-------	---do------------	83.1	520	.463	.7178
M124-------	Metadacite-------	45.9	646	.206	.7092
	Proterozoic metagraywacke				
D2433------	Metagraywacke----	114	271	1.22	.7438
D2434------	---do------------	95.1	280	.985	.7325
D2435------	---do------------	76.0	341	.646	.7213
D2436------	---do------------	98.1	211	1.35	.7414
D2437------	---do------------	115	274	1.22	.7369
D2440------	---do------------	20.3	316	.186	.7098
M106-------	Iron rich--------	26.5	173	.443	.7169
M108-------	Metagraywacke----	91.1	277	.956	.7302

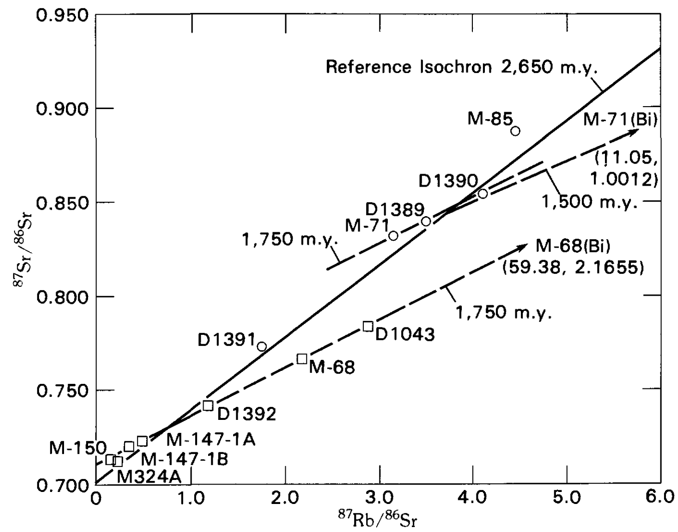


FIGURE 11.—Rb-Sr isochron plot for samples of Puritan Quartz Monzonite (circles) and biotite gneiss (squares) from the Archean gneiss belt southeast of Marenisco. An isochron through points representing the biotite gneiss, including biotite from M–68, gives an age of 1,750±35 m.y. with an initial $^{87}Sr/^{86}Sr$ of 0.7101±0.0005 (uncertainties at 95-percent confidence limits). A reference isochron with this slope is drawn through granite samples M–71, D1389, and D1390. The 2,650-m.y. isochron corresponds in slope and intercept to that defined by samples from the main body of Puritan Quartz Monzonite north of Marenisco (Sims and others, 1977).

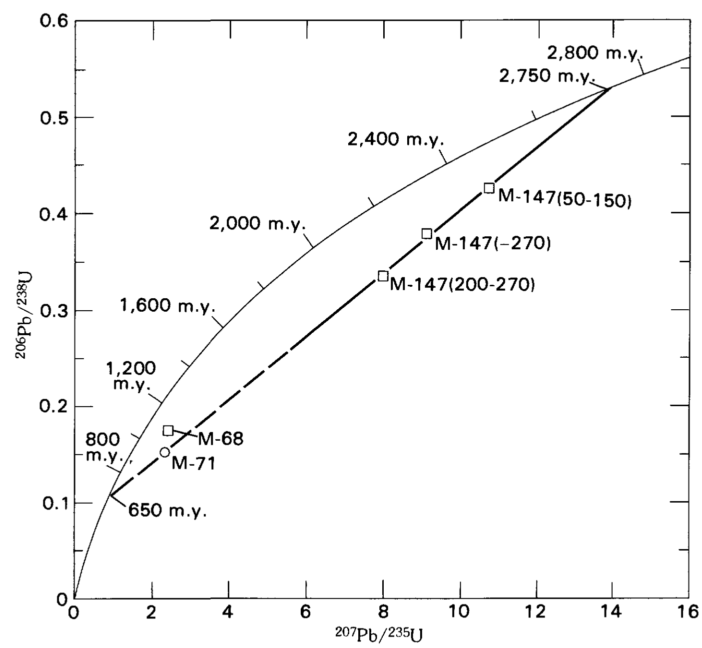


FIGURE 12.—Concordia plot of zircon data for samples of biotite gneiss (squares) and associated Puritan Quartz Monzonite (circle) from gneiss belt southeast of Marensico. Intercepts defined by three fractions of zircon from biotite gneiss sample M–147 are 2,750 and 650 m.y. Zircons M–68 (flaser gneiss) and M–71 (Puritan Quartz Monzonite) are extremely discordant, probably as a result of metamictization due to their high uranium contents.

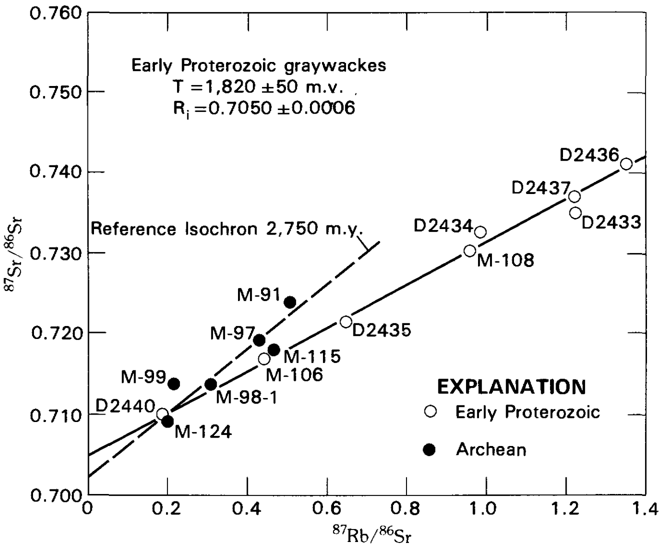


FIGURE 13.—Rb-Sr isochron plot for samples of Archean and Early Proterozoic metagraywackes and associated rocks. The sample of metavolcanic rock, M–124, is included with the Archean metagraywackes.

conglomerate, wacke, and iron-formation that compose the lower part of the Marquette Range Supergroup in the region southeast of the Gogebic Range (fig. 2). The type area is the area of sporadic exposures in the vicinity of Blair Creek in T. 46 N., R. 40–41 W. Additional exposures of the formation are present in secs. 1–6, T. 45 N., R. 42 W., east of Barb Lake; in the vicinity of Marenisco; and in the narrow belt extending from sec. 30, T. 46 N., R. 42 W. northwestward to sec. 7, T. 46 N., R. 41 W. The rocks within this narrow belt are on the overturned, southeast limb of the Copps syncline (fig. 3); they unconformably overlie and truncate Archean gneiss.

The Blair Creek is divided into five map units on figure 2, but because of poor exposures only three of the units represent known lithotypes. The basal unit (Xbs, fig. 2) is exposed on the southeast limb of the Copps syncline. In sec. 21, T. 46 N., R. 42 W., it is composed of arkosic grit, conglomerate, wacke, and local iron-formation and is a maximum of 200 m thick. The arkose and conglomerate were derived locally from underlying granitoid rocks. In secs. 9, 13, 14, and 22, T. 46 N., R. 42 W., the basal unit consists dominantly of granite-pebble conglomerate of local derivation, quartz-pebble conglomerate, arkosic grit, and iron-formation. Overlying the basal unit on the southeast limb of the overturned syncline is a mafic volcanic rock unit (Xbv, fig. 2) as much as 400 m thick composed of massive metabasalt and porphyritic metabasalt. On the southeast side of the belt of Archean rocks southeast of the Copps syncline, the Blair Creek Formation is much thicker than to the west. On the south side of the Barb Lake fault, the Blair Creek is exposed across a width of about 1.5 km. Fritts (1969) noted a quartz-bearing conglomerate at the base, and we assign this bed to the basal unit. It is overlain stratigraphically by about 1,500 m of massive and porphyritic metabasalt. Equivalent rocks in the mafic volcanic rock unit on the north side of the Barb Lake fault, extending northeastward from the vicinity of Thayer, are described by Fritts (1969) as consisting mainly of porphyritic lava and massive or pillowed lavas. He delineated quartz-conglomerate beds near the base of the formation, but it is uncertain whether or not these are its basal beds. Unless additional northeast-trending faults have repeated the succession, it seems probable that the conglomerate beds are higher in the section, intercalated with lavas. The lean iron-formation unit (Xbi, fig. 2) in the approximate middle of the formation in the Barb Lake and Thayer areas was mapped mainly from aeromagnetic anomalies, but the iron-formation unit is exposed along Blair Creek adjacent to the Gogebic-Ontonagon County line (Fritts, 1969). The upper part of the formation, mapped as dominantly volcanic rocks (Xbvu unit on fig. 2), is poorly exposed, but outcrops along Blair Creek are described by Fritts as consisting mainly of layered metatuff and tuffaceous metagraywacke. The unexposed magnetic unit (Xbm, fig. 2) at the top of the formation, presumably contains thin beds of iron-formation. A similar magnetic unit (Xam) outlines most of the gneiss dome at Watersmeet; probably it is equivalent to a part of the Blair Creek Formation, but it is not necessarily correlative with the unexposed magnetic unit at the top of the formation near Blair Lake. The formation thickens southeastward from 0 to an estimated 2,000 m.

In thin section, weakly metamorphosed parts of the porphyritic lava have an ophitic texture. This texture was destroyed during higher grade metamorphism, and the amphibole (hornblende or actinolitic hornblende) throughout the rock was conspicuously lineated. Biotite is commonly associated with the hornblende. Some of the porphyritic lava has visible pillow structures, as do some of the more massive lavas. Chemical analyses of representative samples of the porphyritic lava and associated lavas (table 11) indicate that the volcanics have the composition of tholeiitic basalt.

COPPS AND MICHIGAMME FORMATIONS

The Copps and Michigamme Formations are considered correlative, for they both are composed of metagraywacke and slate and directly overlie the Blair Creek Formation. Presumably the contact between the Copps and Blair Creek units is subconformable. The Copps Formation occupies the keel of an overturned syncline east of Marenisco, forms a narrow belt of

TABLE 11.—*Chemical analyses of lavas from the Blair Creek Formation*

[Chemical analyses by N.Skinner and D. Kobilis. U and Th analyses by H. T. Millard, Jr., and others]

Lab. No.------	D216361	D216362	D216364	D216365
Field No.-----	M96X	M96Y	M179	M179-1
Major oxides (weight percent)				
SiO_2---------	47.8	47.6	51.1	49.3
Al_2O_3--------	14.2	14.0	13.9	18.3
Fe_2O_3--------	2.1	2.6	1.7	1.5
FeO----------	9.0	11.2	9.5	6.0
MgO----------	6.9	5.5	5.9	6.0
CaO----------	11.4	9.4	9.4	12.2
Na_2O---------	2.7	3.2	2.7	2.2
K_2O----------	.49	.36	.63	.46
H_2O^+---------	1.4	1.5	1.6	1.2
H_2O^----------	.12	.27	.13	.09
TiO_2---------	1.6	2.3	1.6	.65
P_2O_5---------	.27	.74	.19	.07
MnO----------	.16	.23	.23	.14
CO_2----------	.88	.52	.79	.48
Sum-----	99	99	99	99
Trace elements (parts per million)				
U------------	0.9	1.0	0.95	0.2
Th-----------	2.1	5.6	3.5	1.5

SAMPLE DESCRIPTIONS AND LOCALITIES

M96X. SE 1/4 SW 1/4 sec. 32, T. 46 N., R. 41 W. Collected adjacent to U.S. Hwy. 2. Dark-gray, medium-grained basalt with conspicuous foliation and lineation.

M96Y. Same locality as M96X. Pillow basalt.

M179. West-center sec. 21, T. 46 N., R. 42 W. Probably pillow basalt.

M179-1. Same locality as M179. Porphyritic basalt. Has ophitic texture.

steeply dipping strata adjacent to the Puritan batholith and associated biotite schist, and overlies somewhat folded strata of the Ironwood Iron-formation and the associated Emperor Volcanic Complex at the eastern end of the Gogebic Range (Hendrix, 1960; Trent, 1973). It stratigraphically overlies the Blair Creek Formation throughout most of the syncline, but to the northwest it lies directly on the Archean Puritan batholith; further west, it overlies strata on the East Gogebic Range that are approximately correlative with the Blair Creek Formation. Where it overlies the Archean batholithic rocks, it has a local basal conglomerate derived from the underlying basement rocks (Allen and Barrett, 1915). The Copps thins westward because of erosion, and it pinches out beneath Keweenawan (Middle Proterozoic) lavas near Wakefield, Mich., 15 km west of the map area. The formation is composed dominantly of thick-bedded graywacke and argillite, the beds typically being 1 to 3 m thick. Graded beds are common and are distinguished most readily by diffraction of cleavage as it passes from the coarser to finer parts of a bed. This relationship is well illustrated in outcrops on Ice House Bay, at the southern end of Lake Gogebic. Carbonate lenses, generally rotated into the cleavage, are common. Mineralogically, the Copps consists mainly of grains of plagioclase, quartz, and biotite.

The Michigamme Formation is exposed sporadically in the area north and northeast of the gneiss dome at Watersmeet, where it occupies the keel of a syncline between the gneiss dome and the south-dipping beds of the Blair Creek Formation (fig. 2). The Michigamme resembles the Copps Formation. It is both thick and thin bedded, has weakly graded beds, and contains impure carbonate lenses. It is composed dominantly of quartz, plagioclase, and biotite; garnet is present adjacent to the gneiss dome.

As noted earlier, the Copps and Michigamme differ in major element chemistry from the Archean metagraywacke in having higher CaO and slightly lower MgO and Na_2O (table 7). Chemical differences are particularly indicated by rubidium and strontium contents and by K/Rb ratios; the Copps and Michigamme have much higher rubidium contents and generally lower strontium contents (fig. 6) and higher K/Rb ratios (fig. 7) than the Archean metagraywacke. Rb-Sr data for samples of the Michigamme and Copps Formations and a single sample of an iron-rich sedimentary rock from the Blair Creek Formation scatter somewhat on an isochron diagram (fig. 13) but define a slope corresponding to an age of $1{,}820 \pm 50$ m.y. and an intercept $^{87}Sr/^{86}Sr$ value of 0.7050 ± 0.0006. Within this array, only two of the samples (D2433 and D2434) depart from the isochron by an amount significantly greater than analytical error. These variations could reflect either open-system behavior, variation in initial strontium-isotope ratios, or both. Exclusion of these points does not alter the slope of the isochron appreciably, although petrographic evidence does not indicate that these samples are different than the others. Based on previous studies dealing with the Rb-Sr systems in metasedimentary rocks, we consider the isochron age as a close approximation of the time of metamorphism.

METADIABASE DIKES

Metadiabase dikes of Early Proterozoic age are abundant in the northwest part of the area (fig. 2), especially in the Archean rocks belonging to the greenstone-granite terrane. Most of the dikes shown on figure 2 were mapped by Fritts (1969) and Trent (1973). The dikes are dominantly oriented northeastward, subparallel to the structural fabric of the country rock and, as noted earlier, subparallel to the boundary between the two basement terranes (Sims, 1980, fig. 5). Most are only a few meters thick, but some are several tens of meters thick. We estimate that they make up as much as 5 percent by volume of the rocks near the boundary zone.

The dikes have a general basaltic composition, and have been metamorphosed and deformed differently, depending on their geographic distribution. The mafic dikes in the gneiss belt in the northwest part of the area (fig. 2) locally have chilled margins and relict ophitic textures; they are dark gray and fine to medium grained. Modally, they consist mainly of an amphibole (mainly hornblende), lesser plagioclase, and a few percent of biotite and quartz. Sphene, opaque oxides, epidote, and calcite are conspicuous alteration minerals. The color of the hornblende and the composition of the plagioclase depend on the grade of metamorphism. The dikes have a weak to moderate foliation and lineation but are not folded, so far as known.

Within the Watersmeet dome, the mafic dikes are deformed as well as metamorphosed. They are dark gray to nearly black and coarser grained than those to the west. Relict ophitic textures are rare. The hornblende is bluish green or green, strongly poikilitic, and associated with a few percent of sphene and opaque oxides. The plagioclase (An_{25-35}) is poorly twinned, typically contains subrounded quartz blebs, and is partly replaced by biotite, epidote, and calcite. Much of it has been granulated and recrystallized on a fine scale. Biotite composes 5 to 15 percent of the rock. Garnet is a local metamorphic mineral. At several places, small-scale folds that have northward-dipping axial surfaces and a north- to northeast-plunging lineation can be seen. The folds resulted from the deformation associated with the rise of the gneiss dome during the Penokean event. Exposures of such folds are present in the NE¼ sec. 5, T. 45 N., R. 39 W.

The mineralogy of the metadiabase dikes is similar to that of the mafic lavas in the Blair Creek Formation; possibly the dikes and lavas are cogenetic.

GEOCHEMISTRY

CHARACTERISTIC FEATURES

Because of the long time interval between the ages of the Early Archean gneisses in the Watersmeet dome and the Late Archean intrusive and metamorphic rocks, compositional differences between these rocks are to be expected. Major- and trace-element analyses given in the previous tables show that most of the units have certain characteristic compositional features. These are discussed below.

Variations in major elements are illustrated on K_2O-Na_2O-CaO and AFM diagrams (figs. 14 and 15). The range in composition of the intrusive rocks and gneisses from trondhjemitic and tonalitic to granitic is shown on the K_2O-Na_2O-CaO diagram (fig. 14). Samples of the Puritan Quartz Monzonite from the batholith and from the Cup Lake area are granitic, both modally (fig. 8) and chemically (table 8). Data for the four samples of biotite leucogranite from the Watersmeet dome cluster closely; they have Na_2O/K_2O ranging from 0.69 to 0.82 and $(Na_2O+K_2O)/CaO$ ranging from 7.3 to 20. They are contained in the broader field defined by samples of Puritan Quartz Monzonite. Modally, the Early Archean augen gneiss is tonalitic and contains more biotite than samples of the Puritan Quartz Monzonite (table 2). These differences are not pronounced on the K_2O-Na_2O-CaO plot, which shows that the Early Archean gneiss is relatively potassic and similar in Na_2O/K_2O ratios to many of the samples of Late Archean granite. Much of the K_2O in the augen gneiss is in biotite and sericite rather than microcline, and this difference can account for the modal differences and chemical similarities between the two rock types. Biotite gneisses and schists both within and outside of the Watersmeet dome—derived from volcanic rocks—vary widely in Na_2O/K_2O ratios and in the proportion of total alkalies to CaO. Within the dome, potassium may have been introduced into these rocks after crystallization. Three samples of amphibolite from the gneiss belt and one from the dome plot near the CaO apex. Rocks intermediate in composition between the amphibolite and felsic gneisses have not been recognized, suggesting that collectively the assemblage may be bimodal in composition, a common volcanic association in many Archean terranes (Barker and Peterman, 1974).

The metagraywackes of Early Proterozoic and Late Archean ages are only partially separated on the alkali-lime plot (fig. 14). They have the characteristic features of most graywackes; in specific, their Na_2O/K_2O, MgO/CaO, and FeO/Fe_2O_3 ratios are greater than unity (Pettijohn and others, 1973). Metabasalt of the Blair Creek Formation is characterized by high Na_2O/K_2O ratios, which is consistent with its tholeiitic character; the samples plot near the CaO apex in accord with their basaltic compositions.

The Archean granitic and gneissic rocks plot closest to the alkali apex of the AFM diagram (fig. 15) because of their felsic nature. Significant differences among the units are evident, notably in the proportions of FeO* (total iron expressed as FeO) and MgO. Samples of the Puritan Quartz Monzonite from the batholith and from the smaller bodies near Cup Lake have similar and un-

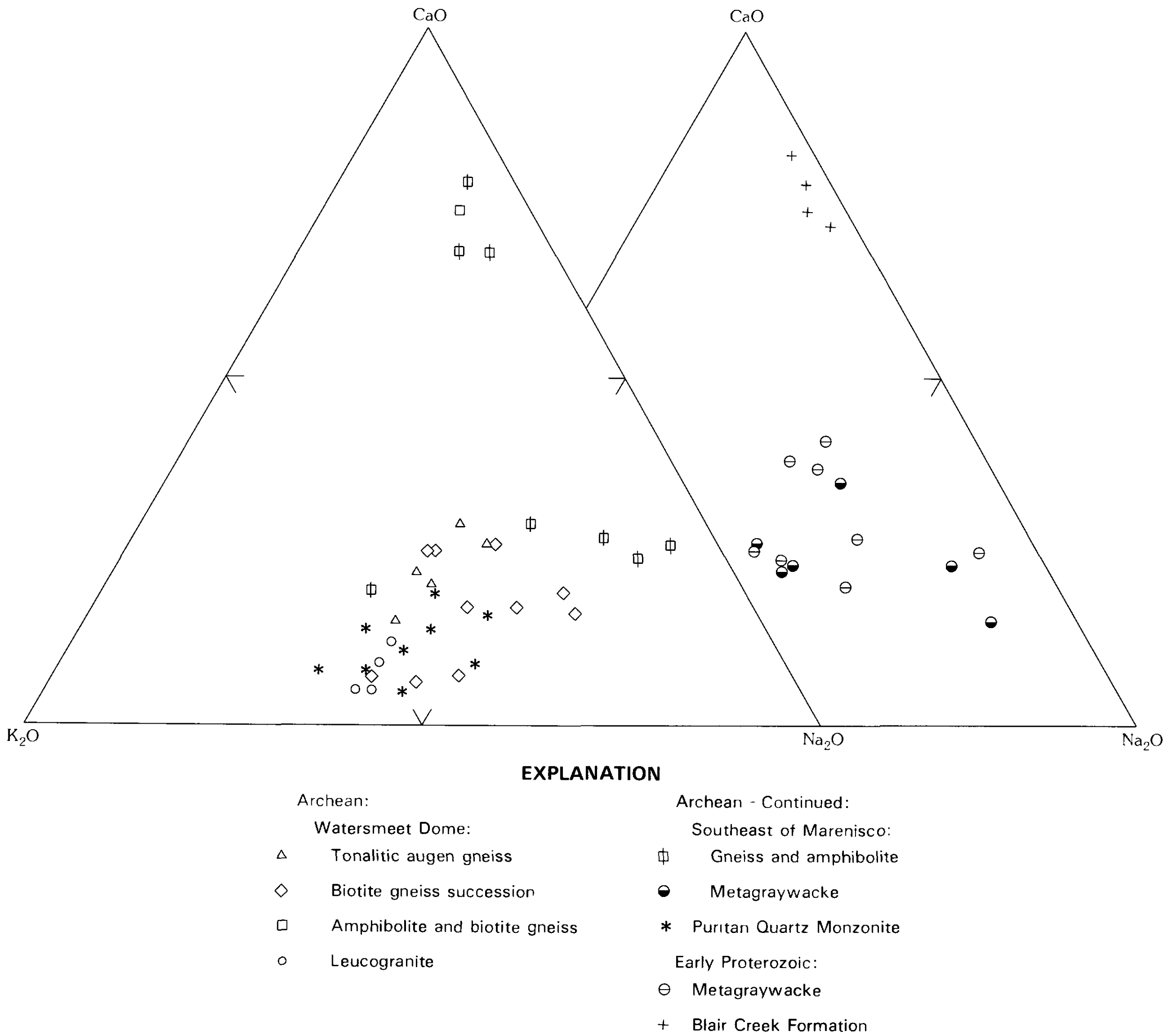


FIGURE 14.—K_2O-Na_2O-CaO diagram for selected Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area.

commonly high FeO*/(FeO* MgO) ratios, averaging 0.89 and 0.90, respectively. The augen gneiss samples from the Watersmeet dome have significantly lower FeO*/(FeO* MgO) ratios, their mean being 0.75. In this respect, they are similar to the Late Archean leucogranite dikes, but the latter are lower in FeO* and MgO relative to total alkalies and generally are more siliceous. The biotite gneisses from both tectonic environments are highly variable in FeO*/(FeO* +MgO).

The Early Proterozoic and Late Archean graywackes are clearly separated on the AFM diagram (fig. 15). The Early Proterozoic rocks are uniformly higher in FeO*/(FeO*+MgO) than the Archean rocks. The near-linear trends of decreasing FeO*+MgO with increasing alkalies are similar to those defined by differentiated rock series. If the graywackes are dominantly volcanogenic in origin, as we suspect, these trends may reflect the nature of the volcanic series from which they were derived. The Early Proterozoic graywackes suggest an iron-enrichment trend of tholeiitic character, whereas the trend defined by the Archean graywackes is more calc-alkaline.

The four samples of metabasalt from the Blair Creek Formation are alined along an iron-enrichment trend in the tholeiitic field. The Early Proterozoic graywacke that has the highest relative FeO* content is an iron-rich sample intercalated with metabasalt in the Blair Creek Formation. Collectively, the Early Proterozoic graywacke and basalt are strongly suggestive of a tholeiitic series that has a moderate iron enrichment.

Significant differences among some of the units are shown by oxides of the minor elements titanium and phosphorus (fig. 16). Samples of the Puritan Quartz Monzonite are low in both elements and define a field

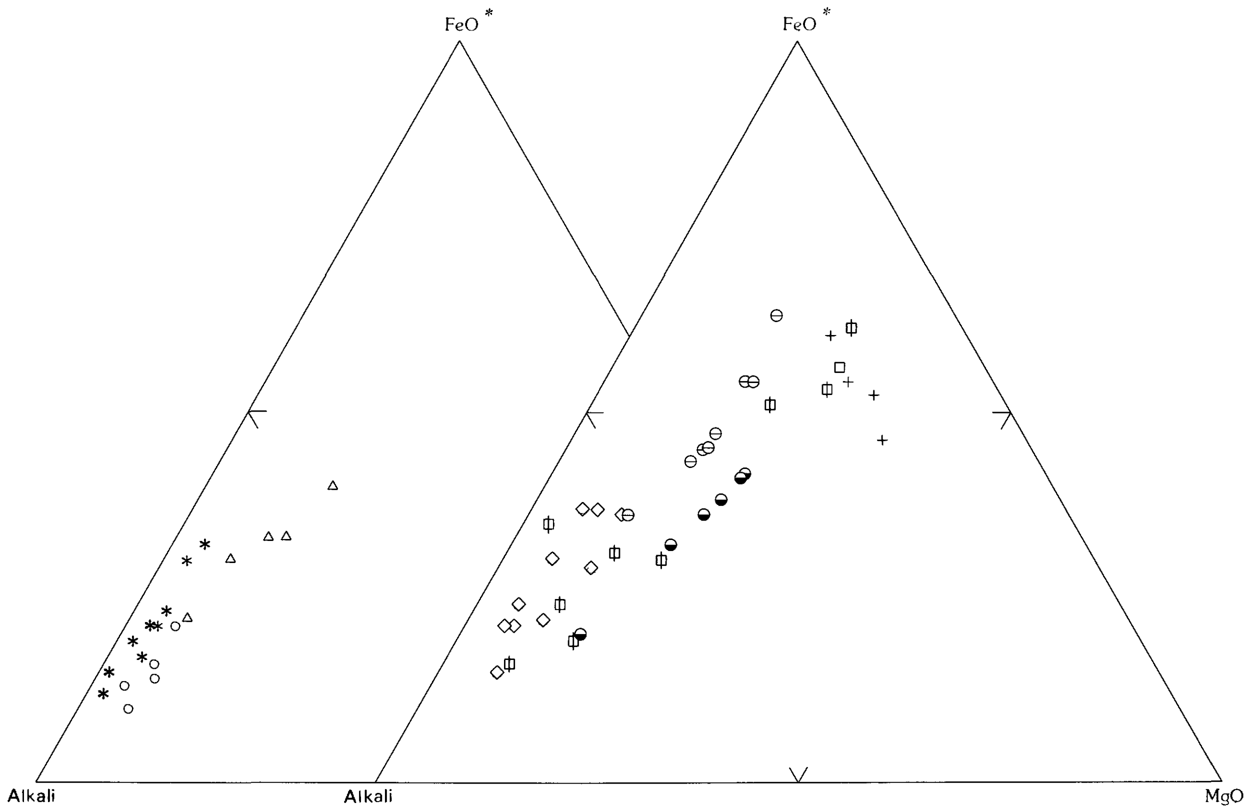


FIGURE 15.—AFM diagram for selected Archean and Early Proterozoic rocks in the area. Symbols are the same as on figure 14.

fairly distinct from the other units. Relative to these rocks, the tonalitic augen gneiss contains substantially more TiO_2 and P_2O_5 and has a limited range of values. The leucogranite dikes are intermediate between these two groups. Graywackes of both ages are relatively high in TiO_2 and P_2O_5, and although there is some overlap, the Archean graywacke tends to have lower TiO_2/P_2O_5 ratios than the Early Proterozoic graywacke. The iron-rich metasediment in the Blair Creek Formation has contents of these elements that are indistinguishable from those in the associated basalt.

Thorium and uranium vary considerably within and among units (fig. 17). Some of the scatter may be a consequence of surficial processes, for mobility of uranium in crystalline rocks through leaching is well established. The most coherent groups of data are formed by the values for the graywackes. Uranium content in the two groups is approximately the same, but the Late Archean rocks have higher thorium values, resulting in higher Th/U ratios. (Averages are 3.0 for the Archean rocks and 2.4 for the Proterozoic rocks.) Several samples are significantly enriched in both uranium and thorium above values considered to be average for granitic rocks (4 ppm U and 18 ppm Th; Rogers and Adams, 1969). One sample of leucogranite has high uranium and thorium contents of 17.6 and 67.4 ppm, respectively. Field measurements with a scintillometer indicate that these dikes are commonly above average in their total radioactivity. Values for samples of the Puritan Quartz Monzonite scatter widely, but several show uncommonly high contents of thorium and (or) uranium.

Although rubidium and strontium contents also vary widely, the intrusive rocks and gneisses collectively show the common pattern of increasing Rb/Sr ratios with increasing K_2O as the compositions trend from tonalitic or trondhjemitic to granitic (fig. 18). Samples of the leucogranite dikes tend to have high Rb/Sr ratios, mainly as a result of their lower strontium contents. Rb/Sr ratios of the tonalitic augen gneiss are limited to a range between about 1.0 and 1.5. Biotite gneiss and schist within the Watersmeet dome illustrate an unusual trend in that their rubidium content is roughly constant and their strontium content ranges by an order of magnitude. This is not a common differentiation trend, for increasing rubidium is usually associated with decreasing strontium. This feature probably reflects unusual mobility of rubidium and strontium in these fine-grained rocks during the Penokean metamorphism. The graywackes are among the samples having lower Rb/Sr ratios and show some differences related to age as noted earlier. Samples of the

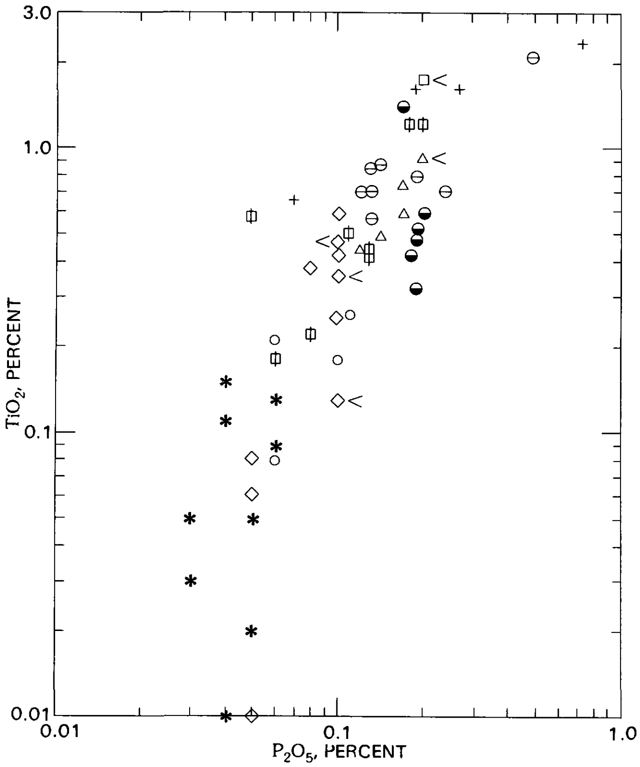


FIGURE 16.—TiO_2-P_2O_5 log-log plot for selected Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area. Symbols are the same as on figure 14. The less-than symbols (<) adjacent to certain points indicate that the P_2O_5 values are equal to or less than the values indicated.

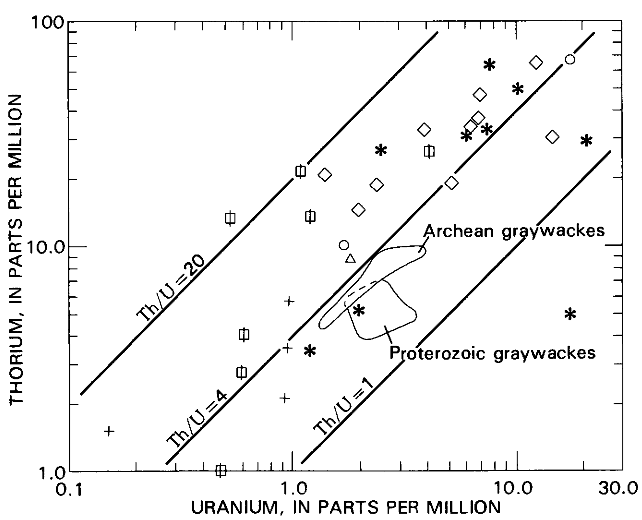


FIGURE 17.—Th-U log-log plot for selected Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area. Symbols are the same as on figure 14. Lines representing Th/U ratios of 1, 4, and 20 are shown for reference.

Puritan Quartz Monzonite scatter considerably and define no particular trend or pattern. Samples of the Early Archean tonalitic augen gneiss have unusually

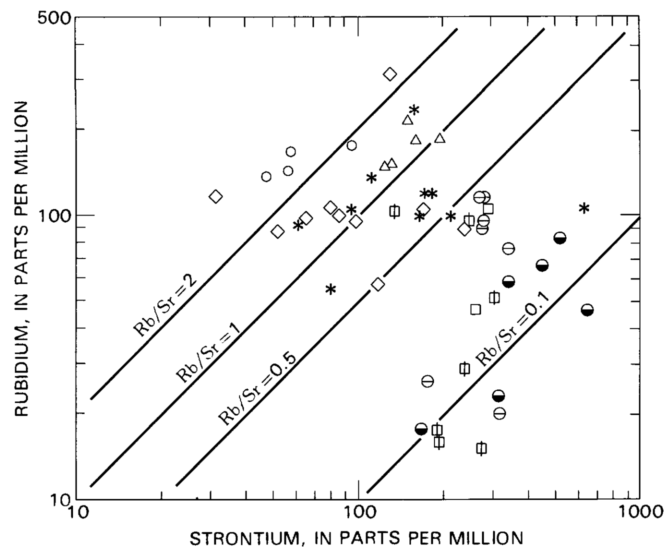


FIGURE 18.—Rb-Sr log-log plot for selected Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area. Symbols are the same as on figure 14.

low K/Rb ratios (less than 200; table 2). With few exceptions, K/Rb ratios of the other granitic and gneissic units are between 200 and 400.

GENETIC SIGNIFICANCE

Limited variations within the major granitic and gneissic units and the possibility of metamorphic effects make genetic deductions highly speculative. Nevertheless, some observations, based largely on comparison with units of other regions, seem appropriate.

The Puritan Quartz Monzonite is similar in age, composition, and geologic setting to the Late Archean granitic batholiths of northern Minnesota, where detailed geochemical studies have been completed. Arth and Hanson (1975) concluded that granites of the Vermilion Granitic Complex and the Giants Range Granite (a batholith) originated through partial melting of short-lived graywacke at crustal depths. Although our chemical data are not as complete as those of Arth and Hanson, the general compatibility of features is consistent with a similar origin for the Puritan Quartz Monzonite. The predominance of granitic rocks in the Puritan Quartz Monzonite and their uncommonly high $FeO^*/(FeO^*+MgO)$ ratios do not favor an origin based on fractional crystallization of a more mafic parental magma. Three of the four known Early Archean terranes in the North American shield—Greenland, Labrador, and northern Michigan—contain intermediate to felsic augen gneisses as major components. The significance of these units in the evolutionary history of these terranes is not clearly established, but some similarities

TABLE 12.—*Average compositions of Early Archean augen gneisses from northern Michigan, Greenland, and Labrador*

[Compositions normalized to 100 percent on a CO_2- and H_2O-free basis. Total iron expressed as FeO*. Data for major oxides in percent]

Constituent	Watersmeet dome[1]	Gothab, Greenland[2]	Saglek, Labrador[3]
SiO_2	70.4	66.4	68.7
Al_2O_3	14.3	14.6	13.9
FeO*	3.99	5.86	5.26
MgO	1.39	1.11	1.20
CaO	2.03	3.64	2.78
Na_2O	3.68	3.54	3.72
K_2O	3.42	3.43	3.34
TiO_2	.63	1.00	.78
P_2O_5	.13	.31	.22
MnO	.03	.09	.09
Rb, ppm	176	86	155
Sr, ppm	152	220	299
Rb/Sr	1.16	.39	.52
K/Rb	161	328	176
Alkalies/CaO	3.5	1.9	2.5
FeO*/(FeO*+MgO)	.75	.84	.81

[1]Average for samples D1042, M-45L, D1042G, M83, and D1042I.
[2]Average for Amitsoq augen gneiss, from McGregor (1979).
[3]Average for Uivak II augen gneisses, from Collerson and Bridgwater (1979).

in composition warrant a brief discussion. Compositional attributes of the augen gneisses in Greenland and Labrador have been discussed in detail (McGregor, 1979; Collerson and Bridgwater, 1979). Average compositions for the augen gneisses are shown in table 12. Whereas the limited sampling of the augen gneiss in the Watersmeet dome has not identified any compositional variations attributable to wide ranges in primary composition, the Amitsoq and Uivak II augen gneisses from Greenland and Labrador, respectively, do show significant variations in both major and trace elements. These variations are not apparent in table 12, however, as it only shows averages.

Although there are significant differences among the average compositions of the augen gneisses, certain features are in common. The augen gneisses are relatively high in TiO_2 and P_2O_5 for their SiO_2 contents. All of the units have average Na_2O/K_2O ratios near unity. K/Rb ratios are exceptionally low in the Uivak II gneisses and the augen gneiss at Watersmeet. Collerson and Bridgwater (1979) attribute the low ratio for the Uivak II gneisses to metamorphism. We suggest also that differential mobility of lithophile elements during the Penokean event can account for the low K/Rb ratio in the tonalitic augen gneiss at Watersmeet.

The protolith of the augen gneisses is problematic. McGregor (1979) and Collerson and Bridgwater (1979) draw analogies with anorogenic granitic rocks commonly associated with gabbros and anorthosites. Collerson and Bridgwater (1979) suggest that the Uivak II gneisses were formed by partial melting of tonalite and trondhjemite at granulite facies conditions followed by some fractional crystallization. McGregor (1979) appears to favor a similar origin for the Amitsoq augen gneisses. The Uivak II gneisses and the Amitsoq augen gneisses are considered to be intrusive igneous rocks. With respect to the augen gneiss in the Watersmeet area, evidence for establishing either the origin or the early crustal history of the augen gneiss is lacking. However, the presence of relatively large plagioclase crystals in a generally finer grained matrix is compatible with a volcanic protolith of intermediate composition.

However, consideration of the augen gneiss protolith as a volcanic rock requires explanation of some of its chemical features. For the most part, the major element composition can be matched with that of some calc-alkaline rhyodacites, although these rocks rarely attain such high Rb/Sr ratios. However, more extreme differentiates are typically lower in iron, magnesium, and calcium. The low K/Rb ratios, as noted by Collerson and Bridgwater (1979), are suggestive of differential mobility of these elements, probably during metamorphism. The rubidium content of the average augen gneiss (table 2) would have to be reduced to about 100 ppm to form a normal K/Rb ratio of 300. Addition of a potassium-free, rubidium-rich phase seems unlikely, but modification of K/Rb ratios could also occur by mobilization and removal of a K-feldspar-rich phase, leaving a biotite-enriched restite, because these two minerals effectively fractionate K/Rb ratios (Goldich and others, 1970). If this process occurred, the present composition of the augen gneiss has been severely modified from the composition of the protolith, and this possibility greatly complicates the task of determining the original rock type.

The limited data available for the Early Proterozoic rocks are compatible with a rift tectonic setting, as proposed earlier (Sims and Peterman, 1983). Metabasalts from the Blair Creek Formation are clearly tholeiitic in character, a feature that is common in more modern regimes developed in rift zones.

STRUCTURE

Deformation in the area was complex and involved at least three and probably four episodes of folding in the gneiss terrane and two episodes in the greenstone-granite terrane: one during the Archean and another during the Early Proterozoic Penokean event. Moreover, in both terranes, faulting began in the Archean and continued intermittently until well into Proterozoic Y (Keweenawan) time.

ARCHEAN DEFORMATION

Deformation in the gneiss terrane, as recorded by the gneisses and associated rocks in the Watersmeet dome, was more involved and prolonged than that in the greenstone-granite terrane. The oldest recognized deformation involved the development of a generally steep foliation in the tonalitic augen gneiss and an accompanying metamorphism, apparently at least to amphibolite grade. This deformation preceded deposition of the supracrustal biotite gneiss succession, which subsequently was deformed on northeast-trending axes, again under amphibolite-facies conditions. Apparently, a third episode of folding followed deposition of the Late Archean succession of interlayered amphibolite and biotite gneiss and schist, for these rocks contain two generations of biotite and associated planar features, which are indicative of polydeformation. Inasmuch as the Late Archean leucogranite shows evidence for only a single deformation, of Penokean age, the older foliation in the amphibolite-biotite gneiss succession must be Archean. The attitude and pattern of this deformation is poorly known, but folding must have been on roughly east-west axes and under amphibolite-grade conditions. Further detailed studies are warranted. The oldest deformation took place about 3,560 m.y. ago, if the U-Pb zircon age of the tonalitic augen gneiss is indicative of its primary age. The second episode of folding occurred between about 3,560 m.y. ago and 2,700 m.y. ago. The youngest deformation must have taken place shortly before emplacement of the 2,590-m.y.-old leucogranite; it could have been concurrent with the Late Archean episode in the greenstone terrane. All the rocks in the dome, including the Early Proterozoic metadiabase, were strongly deformed and metamorphosed during the Penokean event, and this episode partly obscured the record of the older events.

The Precambrian rocks to the northwest of the gneiss dome, which belong to the Archean greenstone-granite terrane, were deformed during a Late Archean event, about 2,700 m.y. ago. The biotite gneiss and amphibolite in the Archean belt southeast of Marenisco were deformed into steep, moderately tight, north-northeast- to east-trending folds. In the same way, the Archean metagraywacke was deformed on steep north-northeast-trending fold axes. The axial planes of these folds commonly have quartz lenses. Judged from reversals in stratigraphic facing directions in the graywacke, the fold crests are approximately 200 m apart. The structure in the biotite schist unit adjacent to the Puritan batholith (fig. 2) was not studied in detail, but according to Fritts (1969), the foliation in these rocks strikes nearly east and is steep. West of the Prospector Creek fault (fig. 2), the foliation in these rocks and the apparently intertonguing metabasalt trends about N. 60° E. and dips uniformly about 60° SE. In both areas of Archean bedded rocks, the intrusive rocks of the Puritan Quartz Monzonite were not deformed during the Late Archean tectonism. The foliation and fold axes in the belt southeast of Marenisco are subparallel to the boundary between the two Archean terranes; presumably, they resulted from compression caused by the impingement of the Archean gneiss segment against the greenstone-granite segment.

PENOKEAN DEFORMATION

The Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area were deformed to different degrees in Early Proterozoic time by a deformation assigned to the Penokean orogeny. The major tectonic elements were folding of the Proterozoic rocks on northeast- to east-trending axes and the development of a strong to weak foliation in both Early Proterozoic and Archean rocks. The foliation is axial planar to the folds. This deformation decreased in intensity northwestward. A slightly younger, more local deformation, also assigned to the Penokean, resulted from the uplift of the gneiss dome at Watersmeet; it produced a rim syncline in the previously deformed overlying Proterozoic rocks and folds and a penetrative foliation in the Precambrian rocks in the core of the dome. The approximate trace of the axis of the rim syncline is shown on figure 2.

The style and nature of the larger scale regional folds in the Early Proterozoic rocks are shown on figure 3. The northeast-trending folds, as exemplified by the Copps syncline, just east of Marenisco, are overturned toward the northwest, have an axial-plane S_2 (Penokean) cleavage dipping 45°–70° SE., and plunge gently or moderately northeast. The subjacent Archean basement rocks have a penetrative schistosity that is subparallel to the cleavage in the younger supracrustal rocks. The east-trending folds in the Michigamme Formation on the north side of the Watersmeet dome, which presumably formed at the same time as the northeast-trending folds to the west, similarly are overturned to the north and have a steeply dipping penetrative S_2 cleavage. Observed folds in the Michigamme are small in scale; they plunge about 15° E.

The regional foliation related to the Penokean folding in both Archean and Early Proterozoic rocks is shown by the Schmidt net plots on figure 19. The foliation varies slightly in both strike and dip from one area to

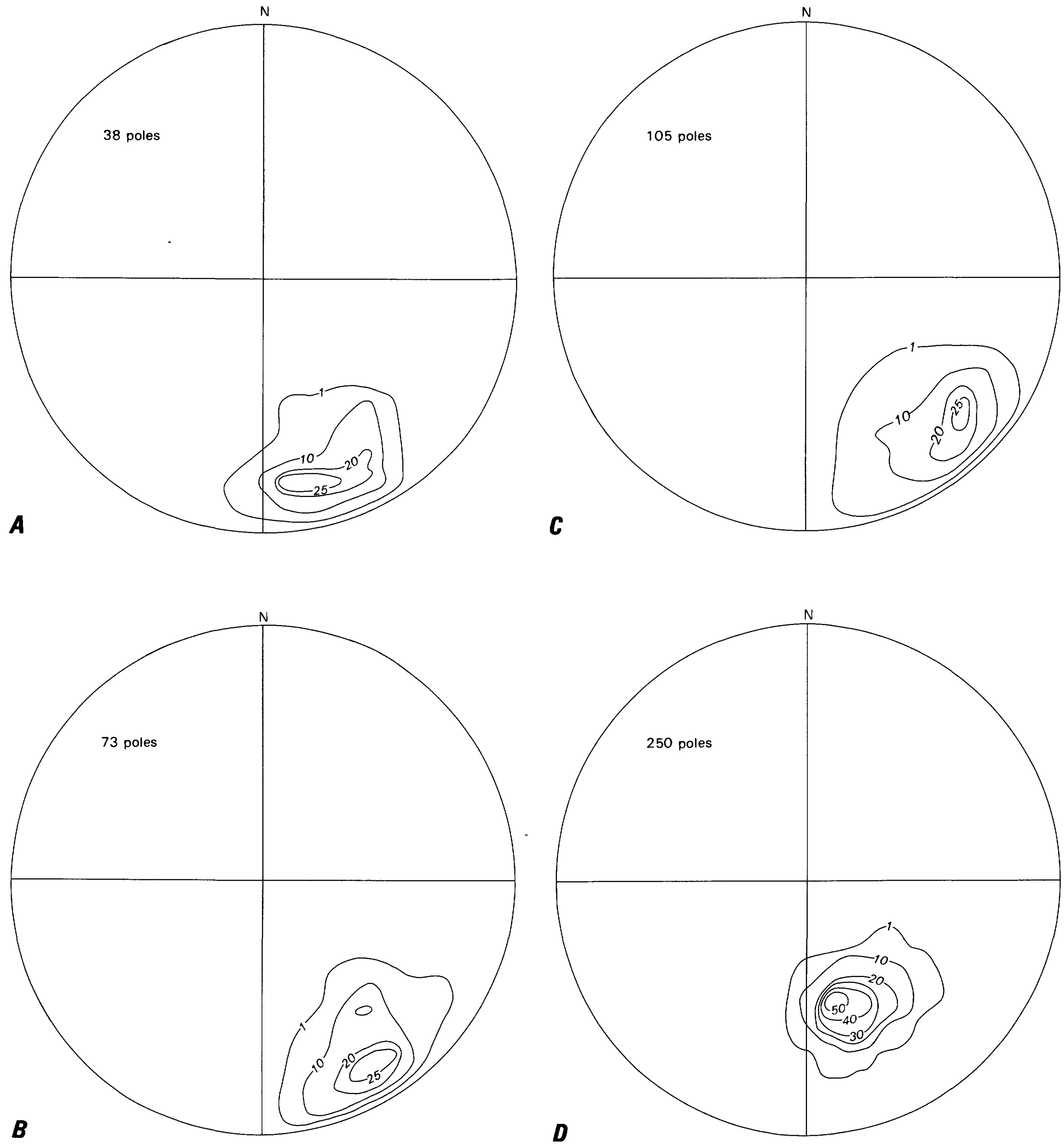


FIGURE 19.—Contour plots (in percent) of poles to foliation related to Penokean folds in the Marenisco area; upper hemisphere projection. *A*, Foliation in Copps and Blair Creek Formations and in Archean amphibolite and metagraywacke units in the northeast-trending belt east of Marenisco. *B*, Foliation in Archean granitic rocks in Puritan batholith. (Data from Trent, 1973.) *C*, Foliation in Archean metavolcanic unit on northwest side of Puritan batholith. (Data from Trent, 1973.) *D*, Axial-plane cleavage in Emperor Volcanic Complex, sections 14, 15, 22, and 23, T. 47 N., R. 43 W. (after Hendrix, 1960).

another and from one rock type to another but does not differ greatly in orientation. The intensity of the foliation decreases to the northwest, but according to Hendrix (1960) the foliation persists to the center of T. 47 N., R. 44 W., which is about 20 km west of Lake Gogebic.

In contrast, in the Archean rocks and Early Proterozoic metagabbro dikes in the core of the Watersmeet dome, the foliation trends easterly and dips moderately northward. This foliation is axial planar to recumbent folds, apparently of small scale, that can be observed in the bedded rocks and the metagabbro. These folds plunge northward or northeastward where observed within the area of figure 4. The metagraywacke and slate of the Michigamme Formation on the north margin of the dome also have a gently north-dipping schistosity, which is axial planar to recumbent folds. These structures largely obliterate the older (S_2) foliation in the area south of the rim syncline. Thus, uplift of the gneiss dome was accompanied by recumbent folding of the Late Archean and Early Proterozoic bedded rocks that unconformably overlie the Archean basement gneiss. This mode of deformation was restricted to the gneiss dome itself and reflects inhomogeneous deformation of the basement rocks. These data suggest that changes in the direction of dip of foliation throughout the region can be related to different strain patterns within separate basement crustal blocks, resulting from both vertical and horizontal movements.

The vergence of the regional Penokean folds in the Proterozoic rocks and the related cleavage and schistosity indicate maximum compressive stresses in a northwest-southeast direction and, in the area north of the Watersmeet dome, stresses in a north-south direction. Presumably the axis of maximum finite shortening was subhorizontal and was directed northwestward and northward. Judged from the radiometric data, the principal deformation and accompanying metamorphic recrystallization in this area took place 1,800–1,750 m.y. ago.

The Penokean-age foliation in the Archean rocks of the greenstone-granite terrane, so far as known, is restricted to its southern margin adjacent to the gneiss terrane. In this area, the width of this tectonized zone is about 25 km.

FAULTS

Three main sets of high-angle faults of different ages have been distinguished in the Marenisco-Watersmeet area (fig. 20). These are (1) a northwest-trending set, represented by the Banner Lake fault; (2) an east-northeast-trending set, represented by the Presque Isle fault; and (3) a northeast-trending set, represented by the Slate River fault. A fourth set of northwest-trending faults in the eastern part of the map area appears to cut and offset lower Keweenawan lavas (Ysb unit, fig. 2).

NORTHWEST FAULT SET

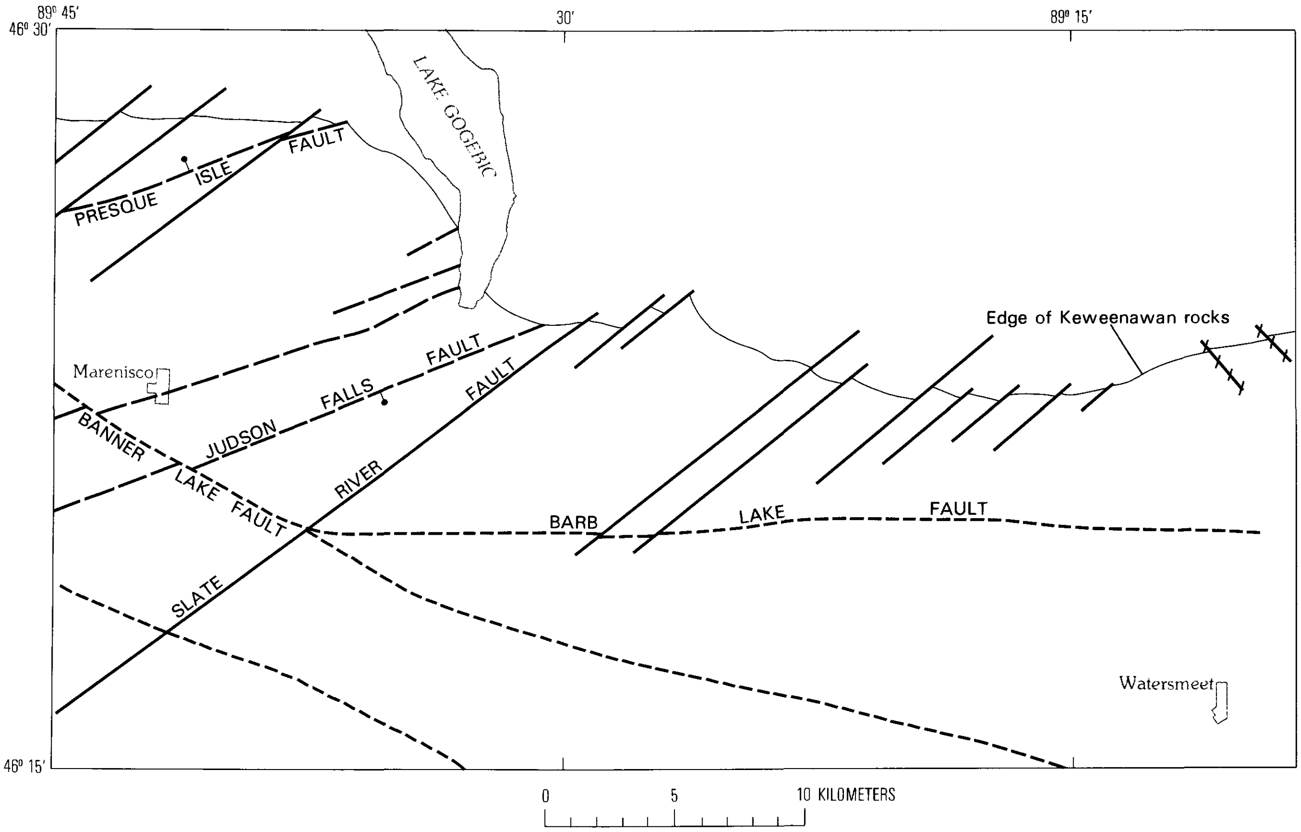
The principal northwest-trending fault, here named the Banner Lake fault, extends from the western margin of the map area (fig. 2) to the south side of the gneiss dome at Watersmeet. Evidence for the fault in this area is mainly the right-lateral apparent offset of magnetic anomalies given by the Blair Creek Formation. West of the map area, in T. 46–47 N., R. 44 W., the fault separates Archean metavolcanic rocks of the Ramsay Formation from the Puritan Quartz Monzonite; it probably connects with the Sunday Lake fault in the Wakefield area (Prinz and Hubbard, 1975). Movement on the fault seems to have been both strike-slip and dip-slip, and probably took place intermittently from late Archean to at least Proterozoic Y time. The Sunday Lake fault does not cut the Proterozoic Y (Keweenawan) lavas in the Wakefield area (Prinz and Hubbard, 1975).

An apparent eastward branch from the Banner Lake fault, the Barb Lake fault (fig. 10), trends eastward from the vicinity of Banner Lake and appears to form the north, faulted edge of the Watersmeet gneiss dome. This fault has an apparent right-lateral displacement of about 6.5 km as indicated by offset of the Blair Creek Formation. (See fig. 2.)

The northwest-trending faults probably belong to a family of faults that includes many faults in northern Wisconsin (Sims and others, 1978). The major fault in this system, the Mineral Lake fault (Sims, 1980), has had an apparent right-lateral displacement of about 16 km.

EAST-NORTHEAST FAULT SET

East-northeast-trending faults have had a major effect on the distribution of rock units in the area. The principal fault, named the Presque Isle fault by Hendrix (1960) and called the Presque Isle wrench fault by Trent (1973), forms a conspicuous N. 70° E. lineament in T. 46 N., R. 44 W., southeast of Wakefield; in the map area (fig. 2), it separates downdropped, steeply north-dipping Early and Late Proterozoic rocks of the Gogebic Range and vicinity from Archean rocks to the south. It is inferred that the Presque Isle fault continues along the same strike to the southwest for a distance of at least 22 km and that it closely follows the boundary between amphibolite-facies metamorphic



EXPLANATION

Northeast-trending fault (known or inferred to have formed in late Keweenawan time)

East-northeast-trending fault—Bar and ball on downthrown side. (known or inferred to have formed in Early Proterozoic time and to have been rejuvenated in late Keweenawan time)

Northwest-trending fault (known or inferred to have formed in Archean time)

Fault of uncertain age (probably formed in Keweenawan time)

FIGURE 20.—Traces of faults in the Marenisco-Watersmeet area, northern Michigan.

rocks on the south and greenschist-facies rocks in the Ironwood, Mich., area, as mapped by Schmidt (1976). The apparent movement on the fault in the map area is dip-slip, the north side having moved downward. The possibly related Whitney Creek–Palms Creek lineament, mapped by Schmidt, is subparallel to the Presque Isle fault and 3.3 km north of it. Another possible fault in this set, the Judson Falls fault, is inferred from regional geologic relationships to be present about 10 km south of the Presque Isle fault. It is inferred to truncate the Keweenawan lavas east of Lake Gogebic, and accordingly is interpreted as having dominant dip-slip movement, with the north side having moved relatively upward. Under this interpretation, lower Keweenawan lavas in the horst between the Presque Isle and Judson Falls faults either were completely removed by erosion, as suggested by the map pattern (fig. 2), or were eroded downdip to the northeast and now are covered by the Jacobsville Sandstone. Possibly the broad magnetic anomaly in the center of T. 47 N., R. 42 W. (U.S. Geological Survey, 1972) reflects the buried downdip erosional remnant of the lavas. Other faults in this set were mapped by Fritts (1969) from displacements visible in outcrops just west of the south end of Lake Gogebic, and three of these are shown on figure 2.

Movement on fractures in this fault set apparently began during, or before, Early Proterozoic time, for abundant metadiabase dikes trend parallel to the fault set and probably occupy fractures related to it. The dikes cut rocks as young as the Ironwood Iron-formation and the Emperor Volcanic Complex in the eastern part of the Gogebic Range and the Blair Creek Formation to the southeast. The last movement recorded by the rocks in the map area (fig. 2) was after deposition of the basaltic lava flows of Middle Precambrian (Keweenawan) age. The faults of this set, and the Presque Isle fault in particular, appear to have been the principal structures responsible for the regional northward tilting of Proterozoic rocks along the Gogebic Range. Presumably the Jacobsville Sandstone covers the Presque Isle fault and is younger.

NORTHEAST FAULT SET

Abundant faults that trend N. 50°–55° E. and cut and displace rocks as young as the lower Keweenawan lavas (fig. 2) are known and inferred in the Marenisco-Watersmeet area. This fault set was first recognized (Sims and others, 1978) during interpretation of the aeromagnetic map of northern Wisconsin (Zietz and others, 1977). Some of the faults have been extended into the Marenisco-Watersmeet area, mainly on the basis of magnetic lineaments, apparent displacement of magnetic anomalies, and displacement of the lower Keweenawan lavas (Ysb unit, fig. 2). The pattern of northeast-trending faults shown on figure 2 is a modification of the fault pattern interpreted previously by Fritts (1969). The faults of this set offset the Keweenawan lavas, and one of them, herein named the Slate River fault, clearly offsets and repeats the Blair Creek Formation in the vicinity of Slate Creek, in sec. 22, T. 46 N., R. 42 W. A steep cataclastic foliation on the west bank of the river supports the interpretation of a fault. Judged from the displacement of the Blair Creek Formation at the Slate River locality, noted above, and of the gently north-dipping Keweenawan lavas east of Lake Gogebic (fig. 2), movement on the faults was mainly dip-slip, the southeast side having moved relatively upward. Similar northeast-trending faults that displace the lower Keweenawan lavas have been mapped west of the map area (fig. 2) and extend westward to the vicinity of Wakefield (Trent, 1973; Prinz and Hubbard, 1975). The fault set is interpreted as being late Keweenawan in age, although some faults of this trend may have been initated in Early Proterozoic time.

METAMORPHISM

A major metamorphism was approximately synchronous with the deformation (Penokean) that affected all the Early Proterozoic (formerly called Proterozoic X) and most of the Archean rocks in the area. This metamorphism was nodal in distribution and was centered on the gneiss dome at Watersmeet, which James (1955) called the Watersmeet metamorphic node. The metamorphic intensity decreased outward from the amphibolite facies (staurolite zone) to the chlorite zone of the greenschist facies. Except within the core of the gneiss dome, the metamorphism that was superposed on the previously metamorphosed Archean rocks was retrogressive.

Because mafic rocks are at least as abundant as argillaceous rocks in the area, the metamorphic facies classification is used here rather than the metamorphic isograds of James (1955). The approximate boundaries between amphibolite, epidote amphibolite, and greenschist facies are shown on figure 2. In addition, the greenschist facies is divided into biotite and chlorite zones. The boundaries shown on the map (fig. 2) are only approximately located because of the sparsity of outcrops in many critical areas.

The data from the area are consistent with the mineral assemblages listed by James (1955, table 2) for the metamorphic zones in northern Michigan. The amphibolite facies approximately equates with the staurolite zone, the epidote amphibolite facies with the upper part of the biotite zone and the lower part of the garnet zone, and the greenschist facies with the lower part of the biotite zone and the chlorite zone. Subgreenschist facies have not been recognized.

All the mafic rocks in the area, regardless of origin, have a similar metamorphic mineralogy. Within the chlorite zone of the greenschist facies, they contain the assemblage chlorite, pale-green hornblende (actinolitic hornblende), actinolite, epidote/clinozoisite, and albite; less abundant constituents are leucoxene, calcite, opaque oxides, and quartz. Except in areas of great deformation, primary textures are largely preserved. In the biotite zone of the greenschist facies, the appearance of a greenish-brown biotite distinguishes this metamorphic facies from the chlorite zone. Primary labradorite occurs in some of the mafic lavas of the Blair Creek Formation. In the epidote amphibolite facies, the mafic rocks have characteristic assemblages containing bluish-green hornblende, albite or sodic oligoclase, brown biotite, epidote, and sphene, as well as many minerals characteristic of the greenschist facies. In the amphibolite facies, the mafic rocks contain a bluish-green or green hornblende and andesine or calcic oligoclase. Brown or reddish-brown biotite, epidote, and sphene are common minerals, as are opaque oxides and quartz; almandine garnet occurs in some bedded rocks and in Early Proterozoic metagabbro.

Late, retrograde alteration characterized by chloritization of biotite, sericitization of plagioclase, and the development of calcite is widespread and apparently related to late Penokean or younger fracturing.

ARCHEAN METAMORPHISM

All the Archean rocks except the Puritan Quartz Monzonite and the leucogranite in the Watersmeet dome were metamorphosed in Archean time. The tonalitic augen gneiss and overlying gneiss and schist were metamorphosed at least to amphibolite facies, apparently during several episodes of deformation.

The Late Archean volcanic-sedimentary rocks in the northwest part of the map area (fig. 2), within the greenstone-granite terrane, were metamorphosed concurrently with their deformation in Late Archean time. The metavolcanic rocks in the gneiss and amphibolite unit within the Archean block southeast of Marenisco were mainly metamorphosed to the amphibolite facies, as indicated by the occurrence of assemblages containing a green or greenish-brown hornblende, clinopyroxene (local), staurolite, almandine garnet, oligoclase or andesine, and brown or reddish-brown biotite. The associated graywacke to the east was metamorphosed at least to garnet grade, as indicated by the widespread presence of relict garnet in these rocks. A Late Archean age for this garnet is indicated by its breakdown to epidote and chlorite during the recrystallization of biotite associated with the S_2 (Penokean) cleavage. The garnet is preserved where it was armored by quartz. The Late Archean volcanic and sedimentary rocks associated with the Puritan batholith, west of Lake Gogebic (fig. 2), also were metamorphosed to the amphibolite or epidote amphibolite facies during a Late Archean event. To the west, probable equivalent bedded rocks of the Ramsay Formation show an increase in metamorphic grade toward bodies of Puritan Quartz Monzonite and contain amphibolite-facies assemblages adjacent to these bodies (Schmidt, 1976; Sims and others, 1977).

The Archean rocks were affected to different degrees by the younger, Penokean metamorphism. This metamorphism decreased in intensity away from the Watersmeet node and did not materially affect the Archean rocks associated with the Puritan batholith.

EARLY PROTEROZOIC (PENOKEAN) METAMORPHISM

The metamorphism during the Early Proterozoic followed deposition of the Early Proterozoic bedded rocks and emplacement of the metadiabase dikes and sills, and apparently took place during two closely spaced stages. This is indicated by the wide distribution of greenschist-facies metamorphsm, as noted earlier by James (1955), and by the more local, definitely nodal pattern superposed on the regional low-grade pattern. In this area, the regional greenschist-facies metamorphism apparently accompanied development of S_2 schistosity, for biotite and chlorite are alined on these surfaces. In the area north of the Watersmeet dome, garnet is seen to have formed after the S_2 schistosity, and the schistosity, as well as the bedding, was deformed during the rise of the gneiss dome. Quite probably, the northeast-trending S_2 foliation in the rocks northwest of the gneiss dome formed more or less contemporaneously with the regional schistosity in the area to the east, but we have not been able to discern two distinct stages of Proterozoic metamorphism in the rocks of the northwestern area.

The metamorphism associated with the Watersmeet node is characterized by roughly concentric metamorphic zones (James, 1955) delineated by metamorphic changes in the Proterozoic bedded rocks and metadiabase and to a lesser degree by changes in the Archean rocks. Amphibolite-facies metamorphic rocks in the core of the Watersmeet dome are surrounded by successive envelopes of epidote amphibolite and greenschist facies. The width of the epidote amphibolite zone is about 15 km.

Amphibolite-facies metamorphism is confined to the core of the Watersmeet dome. Here, Proterozoic metagabbro and metadiabase in the form of dikes contain a green or bluish-green hornblende and andesine. A dike in the north-central part of sec. 5, T. 45 N., R. 39 W., mapped by Fritts (1969) but not shown on figure 4, contains garnet in addition to the above minerals. The Archean rocks contain mineral assemblages compatible with those in the Proterozoic mafic dikes. At least two episodes of recrystallization are indicated in most of these rocks by oriented biotite, hornblende, and quartz-feldspar aggregates. The minerals associated with the two foliations, one of which is Penokean, are similar. In the tonalitic gneiss, microcline is typically interstitial, confined to granulated and recrystallized zones, and has a poikilitic texture, containing inclusions of plagioclase, quartz, and biotite. It is probable that it was introduced or, alternatively, was developed by a metamorphic reaction during the recrystallization accompanying either an Archean event or the Penokean event. Garnet is common in the gneiss and biotite schist, and riebeckite occurs in porphyroblasts within a biotite-garnet schist interlayered with dominant amphibolitic rocks in the Brush Lake area. The associated amphibolite contains a green or bluish-green hornblende and oligoclase or andesine.

A broad zone of epidote-amphibolite metamorphism, reflected by mineral assemblages in bedded rocks of the Michigamme and Blair Creek Formations and the metadiabase in dikes and sills, surrounds the amphibolite-grade node. The argillaceous rocks of the Michigamme Formation have a well-developed mosaic texture and lack evidence of appreciable cataclasis. Aside from samples obtained near the margins of the Watersmeet dome, where the regional schistosity was deformed by diapiricrise of the dome, the rocks have a single schistosity. Near the dome, two schistosities are given by alinement of biotite. Typical assemblages are almandine garnet, brown biotite, albite or oligoclase, and quartz. At places, muscovite is intergrown with biotite, and chlorite, opaque oxides, clinozoisite, and rutile are present. In the same way as the

Michigamme Formation, the rocks of the Blair Creek Formation have simple mosaic textures and lack evidence of multiple metamorphism. Mafic volcanic rocks contain bluish-green hornblende, albite or oligoclase, epidote/clinozoisite, brown biotite, and minor quartz and opaque oxides. Ophitic textures are preserved in the porphyritic lavas. Iron-formation within the Blair Creek contains the assemblage quartz–magnetite–brown biotite–green hornblende–epidote (local). Proterozoic metadiabase dikes contain bluish-green hornblende, albite or oligoclase, quartz, brown biotite, epidote, sphene, and opaque oxides.

The Archean rocks within the zone of Penokean epidote-amphibolite metamorphism have retrograde metamorphic assemblages. Conspicuous retrograde metamorphism is indicated in Archean metagraywacke by the breakdown of garnet to chlorite+muscovite+lesser epidote and opaque oxides. The breakdown is most evident in streaks of coarse-grained brown biotite, which was developed along S_2 (Penokean) cleavage surfaces. Garnet persisted through the metamorphism where it was sheathed by quartz. Grunerite is a local mineral that was formed in iron-rich rocks during the Penokean metamorphism. It should be noted that Fritts (1969) implied that the garnet in the graywacke (strata near Banner Lake unit of Fritts) was Penokean in age. Rocks within the Archean gneiss and amphibolite unit, east of Marenisco, were cataclastically deformed to different degrees and partly refoliated as a result of the Penokean deformation. These deformed zones characteristically contain muscovite, chlorite, and some epidote/clinozoisite as well as biotite. Also, primary plagioclase is slightly to moderately altered to sericite and commonly has albite rims. Calcite is a local alteration mineral. In one sample, staurolite is largely altered to chlorite as a result of the retrograde metamorphism.

An outer zone of greenschist metamorphism is delineated from mineral assemblages in the mafic lavas of the Blair Creek Formation, the metadiabase dikes (Proterozoic X), and the Copps Formation. Within the biotite zone of the greenschist facies, the lavas typically contain a pale-green hornblende, minor brown biotite, epidote, albitic plagioclase, and minor quartz. Primary labradorite locally is preserved. Within the chlorite zone of this facies, the lavas consist dominantly of actinolite, chlorite, and albite.

DISCUSSION

The metamorphic zonation associated with the Watersmeet node is similar to that in other metamorphic nodes in northern Michigan (James, 1955). James ascribed the nodal pattern to heat derived from subjacent bodies of magma, by means of which heat acquired at a greater depth was transferred by mass movement to higher levels in the crust. The later recognition of the Watersmeet dome as a mantled gneiss dome and isotopic dating of the rocks within the core and the supracrustal cover led Sims and Peterman (1976) to propose that the metamorphism in the Watersmeet node was related to heat transfer during remobilization and rise of the Archean gneiss in the core of the dome. Metamorphic aureoles of comparable shape and intensity are characteristic of mantled gneiss domes, as for example, the Proterozoic Y Baltimore Gneiss domes in Maryland (Southwick, 1969).

With respect to temperature-pressure conditions during the metamorphism, the mineralogy of the highest grade rocks (amphibolite facies) indicates that they were formed under moderate temperatures and pressures.

GEOLOGIC HISTORY

The stratigraphic-tectonic evolution of the Marenisco-Watersmeet area can be discussed in the context of the regional geologic framework, inasmuch as the area lies astride the boundary between the two Archean crustal segments that have been delineated in the Lake Superior region. The two crustal segments have had different histories, both prior to and subsequent to their being joined together into a single continental mass near the end of the Archean (table 13).

The area (fig. 1) spans the northern margin of the gneiss terrane and the deformed margin of the juxtaposed greenstone-granite terrane. This belt of tectonized Archean and Early Proterozoic rocks has been named the Great Lakes tectonic zone (Sims and others, 1980). That part of the greenstone-granite terrane discussed in the left column of table 13 characterizes the area along and adjacent to the central or main part of the Gogebic Range, west of Wakefield, Mich.

The Late Archean greenstone-granite complexes in the area were formed as a part of the vast tectonic-igneous episode that yielded much of the Archean crust now composing the core of the North American craton. The tectonic environment in which these rocks were formed is little understood, but from regional geologic relations it seems probable that they accumulated, at least in this area, adjacent to the older sialic crustal block, which 2,700 m.y. ago had an area of at least 150,000 km^2 (Sims and Peterman, 1981). Possibly, the Late Archean supracrustal metavolcanic rocks in the Watersmeet dome were deposited at about the same time on at least the northern fringe of the sialic gneissic crust. The environment may have been analogous to modern continental borderlands or island arcs. Following this volcanism, the volcanic rocks were intruded by

TABLE 13.—*Precambrian stratigraphic-tectonic evolution, western Upper Michigan*

Approx. age	Greenstone-granite terrane		Gneiss terrane
	Main body	Tectonized zone (Great Lakes tectonic zone; width 25 km)	
	----------Erosion----------		
1,100	Continental rifting across both basement terranes, with deposition of mafic volcanic rocks, emplacement of gabbroic layered bodies, and deposition of epiclastic sedimentary rocks.		
		----------Penokean orogeny----------	
1,750		Uplift of Puritan batholith and associated Archean bedded rocks, with resultant doming of younger supracrustal rocks.	Diapiric rise of gneiss, forming mantled gneiss domes, and attendant thermal nodal metamorphism of supracrustal and basement rocks; differential mobility of lithophile elements.
1,900	Weak deformation and metamorphism.	Development of northward-facing folds and a penetrative cleavage; brittle deformation of Archean greenstone-granite complexes. Greenschist-amphibolite metamorphism.	Development of regional steep folds and a penetrative cleavage; greenschist-facies metamorphism.
	Deposition of quartzite, carbonate rocks, iron-formation, graywacke and shale in shallow-water environment.	Deposition of quartzite, carbonate rocks, iron-formation, basaltic lavas and pyroclastics, graywacke and shale in an unstable environment.	Deposition of volcanic rocks, graywacke and shale in an unstable environment.
2,100(?)		Initiation of early Proterozoic structural basin over boundary between greenstone and gneiss terranes by rifting(?).	
2,600	Crust is stable.		Intrusion of anorogenic leucogranite dikes.
2,650	Diapiric rise of granitoid plutons accompanied by intense deformation and thermal metamorphism (steep gradients) of volcanogenic rocks.		Ductile deformation and, probably, amphibolite-facies metamorphism.
			Submarine eruption of basalt and pyroclastics.
	----------Intrusion of Puritan Quartz Monzonite----------		
2,750	Submarine eruption of tholeiitic basalt in orogenic ensimatic environment, followed by eruption of felsic-intermediate pyroclastics that formed graywacke.		
Uncertain			Ductile deformation and amphibolite-facies metamorphism.
			Submarine eruption of felsic and intermediate-composition rocks in ensialic environment.
3,500			Development of tonalitic gneiss; protolith probably of igneous origin.

voluminous granitoid bodies, which rose diapirically upward into the pile, deforming the bedded rocks into tight, steep folds and metamorphosing them to lower amphibolite grade, in a manner similar to that described by Schwerdtner and others (1979). At about the same time in the gneiss terrane, sparse anorogenic granite in the form of dikes was emplaced into the older Archean gneisses, at least in the area now composing the Watersmeet dome. The lack of gravity-induced tectonics in the gneiss terrane at this time suggests that this segment of the crust was stronger and more stable than that beneath the greenstone belts to the north during Late Archean time.

In the Early Proterozoic (ca. 2,000 m.y. ago), the structural basin that now contains the sedimentary-volcanic sequence assigned to the Marquette Range Supergroup was formed over and along the zone of weakness between the two Archean crustal segments (Sims, 1976; Sims and others, 1981). Presumably, the basin was initiated by rift-faulting (Sims and Peterman, 1983), which was concentrated along the boundary zone and produced local troughs within a broad platform (Larue and Sloss, 1980). The faulting was controlled to a substantial degree by Archean basement structures. The fault troughs and other irregularities in basin topography, together with partial erosion of some of the supracrustal rocks, can account for the lenticularity that exists in the stratigraphy of the lower part of the Marquette Range Supergroup in the area of this report. It is clear that the Archean antiformal blocks were topographic highs during part of the time of deposition of the sequence, for the lower part of the sequence is missing in most of this area, and conglomerates of local derivation occur locally at the base of the Blair Creek and Copps Formations. Also, it is clear that the Puritan batholith and associated Archean bedded rocks rose as a diapiric dome after deposition of the Copps, as recorded by the steep dips in the rocks adjacent to the Archean core. Evidently, tectonic reconstitution of this granitoid body took place under essentially nonmetamorphic conditions (Sims and Peterman, 1976), for internal cataclasis is minimal, there is no thermal aureole surrounding the body, and the whole-rock Rb-Sr system in the granitic rocks was not highly disturbed (Sims and others, 1977). Possibly this doming occurred approximately contemporaneously with the formation of the gneiss dome at Watersmeet, which occurred under much more intense temperature-pressure conditions, as a result of the impingement of the gneiss crustal block against the greenstone-granite block. The supracrustal strata adjacent to the gneiss dome were metamorphosed to staurolite grade, and the Rb-Sr and K-Ar whole-rock and mineral systems in the Archean rocks within the core were reset at the time of the doming, about 1,800–1,750 m.y. ago. The reactivation of the gneiss dome during the Penokean event was accompanied by differential mobility of potassium and other lithophile elements, as indicated by the petrology and chemistry of the Archean rocks within the core.

Most faulting in the Marenisco-Watersmeet area resulted from the midcontinent rifting during the Keweenawan, although the Banner Lake fault and others in the same fault set probably were initiated late in Archean time and were recurrently active thereafter. The Presque Isle fault and related east-northeast-trending faults appear to have resulted from extension in approximately a N. 20° W.–S. 20° E. direction. Apparently the faulting was part of a tectonic continuum that began in the Early Proterozoic and continued into Keweenawan time, for abundant Proterozoic X metadiabase dikes having the same trend occur within the zone of faulting, and the faults themselves cut the lower Keweenawan lavas (fig. 2). The Presque Isle fault not only separates Archean from Early Proterozoic rocks in the map area (fig. 2), but apparently also was a major structure related to the steep, northwest tilting of the Proterozoic rocks in the Gogebic Range area in Keweenawan time. The Keweenawan lavas east of the other major fault in this set, the Judson Falls fault, dip only 5°–15°N., indicating that the hinge line for the tilting was northwest of this fault, possibly coinciding with the Presque Isle fault.

The northeast-trending faults apparently are somewhat younger than the east-northeast set, but this conclusion is equivocal. These faults also cut and displace the lower Keweenawan lavas, and mainly had dip-slip movements.

OCCURRENCE OF FLUORITE AND COPPER IN ROCKS WITHIN THE WATERSMEET DOME

Fluorite and apatite are uncommonly abundant accessory minerals in the Archean supracrustal rocks in the core of the Watersmeet dome, and concentrations of copper occur in a quartzite layer within a small outcrop of probable Bad River Dolomite along the northwest edge of the dome.

The principal occurrences of fluorite and apatite noted in the Archean metavolcanic rocks during studies of thin sections are shown on figure 4. At these localities, fluorite and apatite compose as much as 5 percent by volume of the rocks. Fluorite also was noted as a common accessory mineral in a fine-grained metavolcanic rock, which is cut by leucogranite, in road cuts along Gogebic County Highway 206, north-central part of sec. 4, T. 45 N., R. 40 W. At this locality, galena and sphalerite locally occur as coatings on late fractures that cut the Archean rocks. The fluorite is colorless or purple and forms irregular, disseminated grains. It is most common in coarser grained, recrystallized zones seen in the thin sections. The apatite is associated mainly with biotite. Both minerals also are locally common in the leucogranite that cuts the metamorphosed volcanic rocks. The association of fluorite and apatite with both metavolcanic and granitic rocks possibly indicates a volatile-rich primary environment for these rocks. Alternatively, the fluorine in the fluorite and apatite could have been released from biotite in the host rocks during the recrystallization, in the presence of water, that accompanied the Penokean metamorphism.

The copper occurrence has been described by Cannon (1980). Visible chalcopyrite and malachite are present in two beds of vitreous quartzite between 0.25 and 0.5 m thick that are interlayered with tremolite-bearing marble. The copper is clearly of the stratabound type. Because exposures are scarce in much of the region, the true extent of these rock units is not known; they could be more widespread than now thought and should be considered as a potential host for sedimentary copper deposits.

REFERENCES CITED

Allen, R. C., and Barrett, L. P., 1915, Contributions to the pre-Cambrian geology of northern Michigan and Wisconsin: Michigan Geological Survey Publication 18, Geologic Series 15, p. 13–164.

Arth, J. G., and Hanson, G. N., 1975, Geochemistry and origin of the early Precambrian crust of northeastern Minnesota: Geochimica et Cosmochimica Acta, v. 39, p. 325–362.

Barker, Fred, and Peterman, Z. E., 1974, Bimodal tholeiitic-dacitic magmatism and the early Precambrian crust: Precambrian Research, v. 1, p. 1–12.

Cannon, W. F., 1980, Copper-bearing quartzite near Watersmeet, Michigan: U.S. Geological Survey Open-File Report 80–390, 6 p.

Cannon, W. F., and Gair, J. E., 1970, A revision of stratigraphic nomenclature for middle Precambrian rocks in northern Michigan: Geological Society of America Bulletin, v. 81, p. 2843–2846.

Collerson, K. D., and Bridgwater, D., 1979, Metamorphic development of early Archean tonalitic and trondhjemitic gneisses, Saglek area, Labrador, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Amsterdam-Oxford-New York, Elsevier Scientific Publishing Company, p. 205–273.

Fritts, C. E., 1969, Bedrock geologic map of the Marenisco-Watersmeet area, Gogebic and Ontonagon Counties, Michigan: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–576, scale 1:48,000.

Goldich, S. S., Hedge, C. E., and Stern, T. W., 1970, Age of the Morton and Montevideo Gneisses and related rocks, southwestern Minnesota: Geological Society of America Bulletin, v. 81, p. 3671–3696.

Goldich, S. S., Hedge, C. E., Stern, T. W., Wooden, J. L., Bodkin, J. B., and North, R. M., 1980, Archean rocks of the Granite Falls area, southwestern Minnesota, *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 19–43.

Goldich, S. S., and Wooden, J. L., 1980, Origin of the Morton Gneiss, southwestern Minnesota, Part III, Geochronology, *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 77–94.

Hendrix, T. E., 1960, Structural history of the East Gogebic iron range: University of Wisconsin, Madison, Ph. D. thesis, 84 p.

Hubbard, H. A., 1975, Lower Keweenawan volcanic rocks of Michigan and Wisconsin: U.S. Geological Survey Journal of Research, v. 3, p. 529–541.

James, H. L., 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geological Society of America Bulletin, v. 66, p. 1455– 1487.

Larue, D. K., and Sloss, L. L., 1980, Early Proterozoic sedimentary basins of the Lake Superior region—Summary: Geological Society of America Bulletin, pt. 1, v. 91, p. 450–452.

McGregor, V. R., 1979, Archean gray gneisses and the origin of the continental crust—Evidence from the Godthåb region, west Greenland, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Amsterdam-Oxford-New York, Elsevier Scientific Publishing Company, p. 169–204.

Morey, G. B., and Sims, P. K., 1976, Boundary between two Precambrian W terranes in Minnesota and its geologic significance: Geological Society of America Bulletin, v. 87, p. 141–152.

Peterman, Z. E., 1979, Geochronology and the Archean of the United States: Economic Geology, v. 74, p. 1544–1562.

Peterman, Z. E., Zartman, R. E., and Sims, P. K., 1980, Early Archean tonalitic gneiss from northern Michigan USA, *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean and lower Proterozoic rocks, southern Canadian Shield: Geological Society America Special Paper 182, p. 125–134.

———1984, A protracted Archean history in the Watersmeet gneiss dome, northern Michigan *in* Peterman, Z. E., ed., Shorter contributions to isotope research: U.S. Geological Survey Professional Paper.

Pettijohn, F. J., Potter, P. E., and Siever, Raymond, 1973, Sand and sandstone: New York-Heidelberg-Berlin, Springer-Verlag, 618 p.

Prinz, W. C., 1981, Geologic map of the Gogebic Range-Watersmeet area, Gogebic and Ontonagon Counties, Michigan: U.S. Geological Survey Miscellaneous Investigations Series Map I–1365, scale 1:125,000.

Prinz, W. C., and Hubbard, H. A., 1975, Preliminary geologic map of the Wakefield quadrangle, Gogebic County, Michigan: U.S. Geological Survey Open-File Report 75–119, scale 1:24,000.

Rogers, J. J. W., and Adams, J. A. S., 1969, Abundances in common igneous rocks, *in* Uranium, chap. 92 *of* Wedepohl, K. H., ed., Handbook of geochemistry: Berlin, Springer-Verlag, p. 92–E–1 to 92–E–8.

Schmidt, R. G., 1976, Geology of the Precambrian W (Lower Precambrian) rocks in western Gogebic County, Michigan: U.S. Geological Survey Bulletin 1407, 40 p. (includes 1:48,000 scale map).

———1980, The Marquette Range Supergroup in the Gogebic iron district, Michigan and Wisconsin: U.S. Geological Survey Bulletin 1460, 96 p.

Schwerdtner, W. M., Stone, D., Osadetz, K., Morgan, J., and Stott, G. M., 1979, Granitoid complexes and the Archean tectonic record in the southern part of northwestern Ontario: Canadian Journal of Earth Sciences, v. 16, p. 1965– 1977.

Shapiro, Leonard, 1967, Rapid analysis of rocks and minerals by a single-solution method, *in* Geological Survey research 1967: U.S. Geological Survey Professional Paper 575–B, p. B187–B191.

Sims, P. K., 1976, Precambrian tectonics and mineral deposits, Lake Superior region: Economic Geology, v. 71, p. 1092–1118.

———1980, Boundary between Archean greenstone and gneiss terranes in northern Wisconsin and Michigan, *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 113–124.

Sims, P. K., Cannon, W. F., and Mudrey, M. G., Jr., 1978, Preliminary geologic map of Precambrian rocks in part of northern Wisconsin: U.S. Geological Survey Open-File Report 78–318, scale 1:250,000.

Sims, P. K., Card, K. D., and Lumbers, S. B., 1981, Evolution of early Proterozoic basins of the Great Lakes region, *in* Campbell, F. H. A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81–10, p. 379–397.

Sims, P. K., Card, K. D., Morey, G. B., and Peterman, Z. E., 1980, The Great Lakes tectonic zone—A major crustal structure in central North America: Geological Society of America Bulletin, pt. I, v. 91, p. 690–698.

Sims, P. K., and Peterman, Z. E., 1976, Geology and Rb-Sr ages of reactivated Precambrian gneiss and granite in the Marenisco-Watersmeet area, northern Michigan: U.S. Geological Survey Journal of Research, v. 4., p. 405–414.

———1981, Archean rocks in the southern part of the Canadian Shield—A review, *in* Glover, J. E., and Groves, D. I., eds., Archaean Geology—Second International Symposium, Perth, 1980: Geological Society of Australia Special Publication No. 7, p. 85–98.

———1983, Evolution of Penokean foldbelt, Lake Superior region, and its tectonic environment, *in* Medaris, L. G., Jr., ed., Early Proterozoic geology of the Great Lakes region: Geological Society of America Memoir 160, p. 3–14.

Sims, P. K., Peterman, Z. E., and Prinz, W. C., 1977, Geology and Rb-Sr age of Precambrian W Puritan Quartz Monzonite, northern Michigan: U.S. Geological Survey Journal of Research, v. 5, p. 185–192.

Southwick, D. L., 1969, Crystalline rocks of Harford County, *in* The geology of Harford County, Maryland: Baltimore, Md., Maryland Geological Survey, p. 1–76.

Steiger, R. H., and Jäger, E., 1977, Subcommission on Geochronology—Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362.

Streckeisen, A. L., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1–33.

Trent, V. A., 1973, Geologic map of the Marenisco and Wakefield NE quadrangles, Gogebic County, Michigan: U.S. Geological Survey open-file report, scale 1:20,000.

U.S. Geological Survey, 1972, Aeromagnetic map of northwestern Ontonagon County, Michigan: U.S. Geological Survey Geophysical Investigations Map GP–834, scale 1:62,500.

Van Hise, C. R., and Leith, C. K., 1911, The geology of the Lake Superior region: U.S. Geological Survey Monograph 52, 641 p.

Zietz, Isidore, Karl, J. H., and Ostrom, M. E., 1977, Preliminary aeromagnetic map covering most of the exposed Precambrian terrane in Wisconsin: U.S. Geological Survey Miscellaneous Field Studies Map MF–888, scale 1:250,000.

Geologic Interpretation of Gravity Data, Marenisco-Watersmeet Area, Northern Michigan

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CONTRIBUTIONS TO THE GEOLOGY OF THE LAKE SUPERIOR REGION

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A study of crustal structure in the boundary zone between two Archean basement terranes

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CONTENTS

ILLUSTRATIONS

TABLE

GEOLOGIC INTERPRETATION OF GRAVITY DATA, MARENISCO-WATERSMEET AREA, NORTHERN MICHIGAN

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ABSTRACT

Gravity measurements have been made in the western part of northern Michigan to aid in determining the crustal structure of the tectonic zone marking the boundary between the two Archean crustal segments recognized in the Lake Superior region: a greenstone-granite terrane on the north and a gneiss terrane on the south. The gravity anomalies generally correspond closely with mapped geologic units. Pronounced lows overlie the Puritan batholith, composed mainly of Late Archean granitic rocks, and a gneiss dome at Watersmeet, which has a core of Archean rocks. Most positive anomalies are associated with synclinal basins of Early Proterozoic rocks, and mainly reflect dense volcanic rocks and local iron-formation in units of the Marquette Range Supergroup. A north-sloping gravity gradient of about 5 milligals per kilometer coincides with the position of the boundary zone between the two Archean basement terranes and reflects density increases from north to south in rocks of both the upper and lower crusts.

The gravity data support the earlier interpretation that, during the Early Proterozoic, the boundary zone between the two Archean crustal segments was an intracratonic feature which localized the deposition of thick sedimentary and volcanic rocks now assigned to the Marquette Range Supergroup.

INTRODUCTION

A major crustal feature in the Lake Superior region is the boundary between the terrane of Late Archean greenstone-granite complexes, which compose the southern part of the Superior province, and an older Archean gneiss terrane to the south of this province (fig. 1). These two basement terranes have been delineated on both the west (Morey and Sims, 1976) and east (Sims, 1980) sides of the midcontinent rift system. Because of the great length (>1,200 km) of the boundary zone and the distinctive tectonic deformation of both the Archean and Early Proterozoic rocks within it, the feature has been named the Great Lakes tectonic zone (Sims and others, 1980).

Rocks within the boundary zone are rather well exposed in the Marenisco-Watersmeet area in northern Michigan, and accordingly this area has been studied in moderate detail to determine their stratigraphy, structure, and geologic history. Details of the general geology are described by Sims and others (this volume). Earlier reports presented data on the radiometric ages of the rocks (Sims and others, 1977; Peterman and others, 1980) and on the tectonic evolution of Archean rocks in the cores of gneiss domes in the area that were rejuvenated in the Early Proterozoic (Sims and Peterman, 1976).

To help understand the crustal structure, a gravity survey of the area was made in 1978, and detailed gravity profiles were measured along three traverses across the Archean boundary zone. The gravity study was part of a broader survey of the Iron River 1°×2° quadrangle (Klasner and Jones, 1979).

The main purposes of this paper are to relate observed gravity anomalies to the geology and to interpret the structure of the upper crust in the boundary zone from combined geological and gravity data. We also briefly discuss the significance of the regional gravity with respect to the two Archean crustal segments.

Klasner is responsible for the gravity data obtained in the region, and Sims is responsible for the geology. Both of us were involved in interpreting the gravity data. S. A. Jankowski assisted in the gravity modeling while she was a student at Western Illinois University. A. E. Grosz and P. J. Gerasi assisted in making gravity observations along the detailed profiles, and E. L. Coward, Christopher French, S. A. Jankowski, and W. A. O'Niell assisted in gathering the regional gravity data.

GEOLOGY

The Marenisco-Watersmeet area lies astride the boundary between the two Archean crustal segments that have been delineated in the Lake Superior region. In the northwestern part of the area (fig. 2), greenstone-granite complexes of Late Archean age (~2,700 m.y. old; Sims and others, 1977; Peterman and others, 1980) compose the basement; and in the southeastern part, the basement consists of tonalitic augen

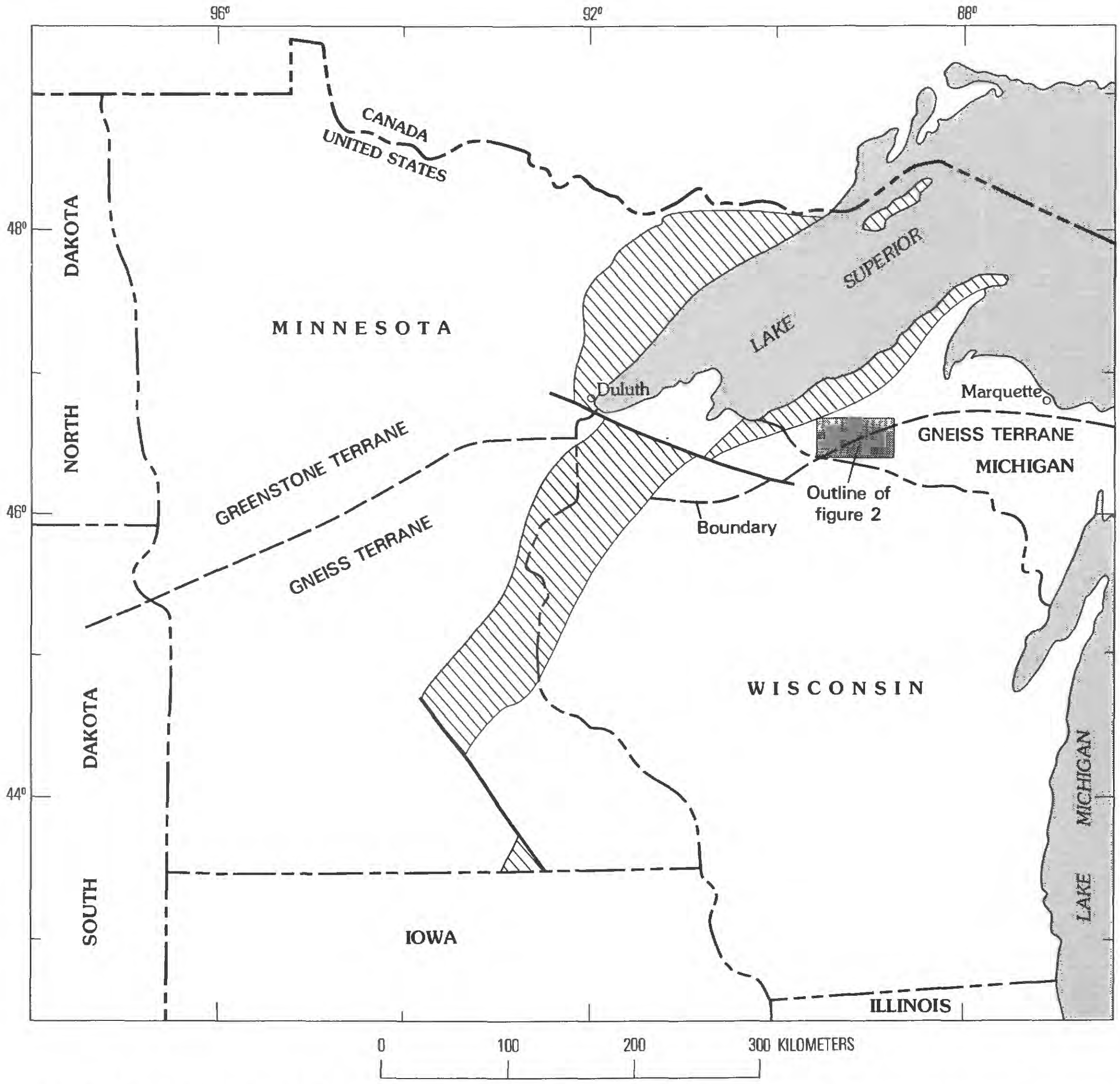


FIGURE 1.—Distribution of Archean basement terranes in the Lake Superior region. Younger rocks omitted, except for the lava and gabbro of the midcontinent rift system (Proterozoic Y), shown by ruled pattern.

gneiss of Early Archean age (3,560 m.y. old) and supracrustal gneiss and amphibolite that were intruded by 2,590-m.y.-old granite. The Archean basement rocks of both terranes are overlain in part by infolded and faulted sedimentary and volcanic rocks of the Early Proterozoic Marquette Range Supergroup (Sims and others, this volume; Schmidt, 1980). Except for the youngest units of this supergroup, the equivalent Copps and Michigamme Formations (western and eastern parts of the area, respectively), the bedded Proterozoic rocks and older basement rocks are intruded by abundant Early Proterozoic metadiabase dikes. In addition, all these rocks are intruded by Middle Proterozoic diabase dikes, most of which are oriented subparallel to the buried boundary between the two basement terranes. Mafic lavas and younger sandstone of Middle Proterozoic (Keweenawan) age, deposited in the midcontinent rift system, overlap the north side of the older Proterozoic and Archean rocks. The Archean and Early Proterozoic rocks are described by Sims and others (this volume), and accordingly are discussed only briefly here.

The Late Archean basement rocks in the northwest part of the map area consist of metabasalt and metagraywacke and equivalent amphibolite and biotite schist (Abs, fig. 2) that are intruded by granitoid rocks of the Puritan Quartz Monzonite (Ap, fig. 2). The granitic rocks compose the eastern part of the Puritan batholith, which is an elongate body as much as 20 km wide that extends southwest for a distance of more than 100 km, to the vicinity of Mellen, Wis. Small granitic bodies, not shown on figure 2, which are believed to be connected at depth with the granitic rocks of the Puritan batholith, intrude the gneiss and amphibolite in the northeast-trending belt east of Marenisco. The metamorphosed basaltic lavas associated with the Puritan batholith are correlative with the Ramsay Formation (Schmidt, 1976) as delineated in areas to the west in northern Michigan. Metagraywacke and equivalent biotite schist are moderately abundant within the map area (fig. 2) but are sparse to the west. The granitoid rocks in the Puritan batholith are dominantly granite, as defined by Streckeisen (1976).

Archean basement rocks that are characteristic of the gneiss terrane are exposed in the core of the Watersmeet dome, along its north margin. The oldest unit, a tonalitic augen gneiss, crops out within an area of about a square kilometer along and near Michigan Highway 45 (secs. 4 and 5, T. 45 N., R. 39 W.). It is overlain unconformably by bedded biotite gneiss, biotite schist, and amphibolite that dip moderately to the north. These bedded rocks and the tonalitic gneiss are both intruded by dikes of biotite leucogranite that has a U-Pb zircon age of 2,590 m.y. (Peterman and others, 1980).

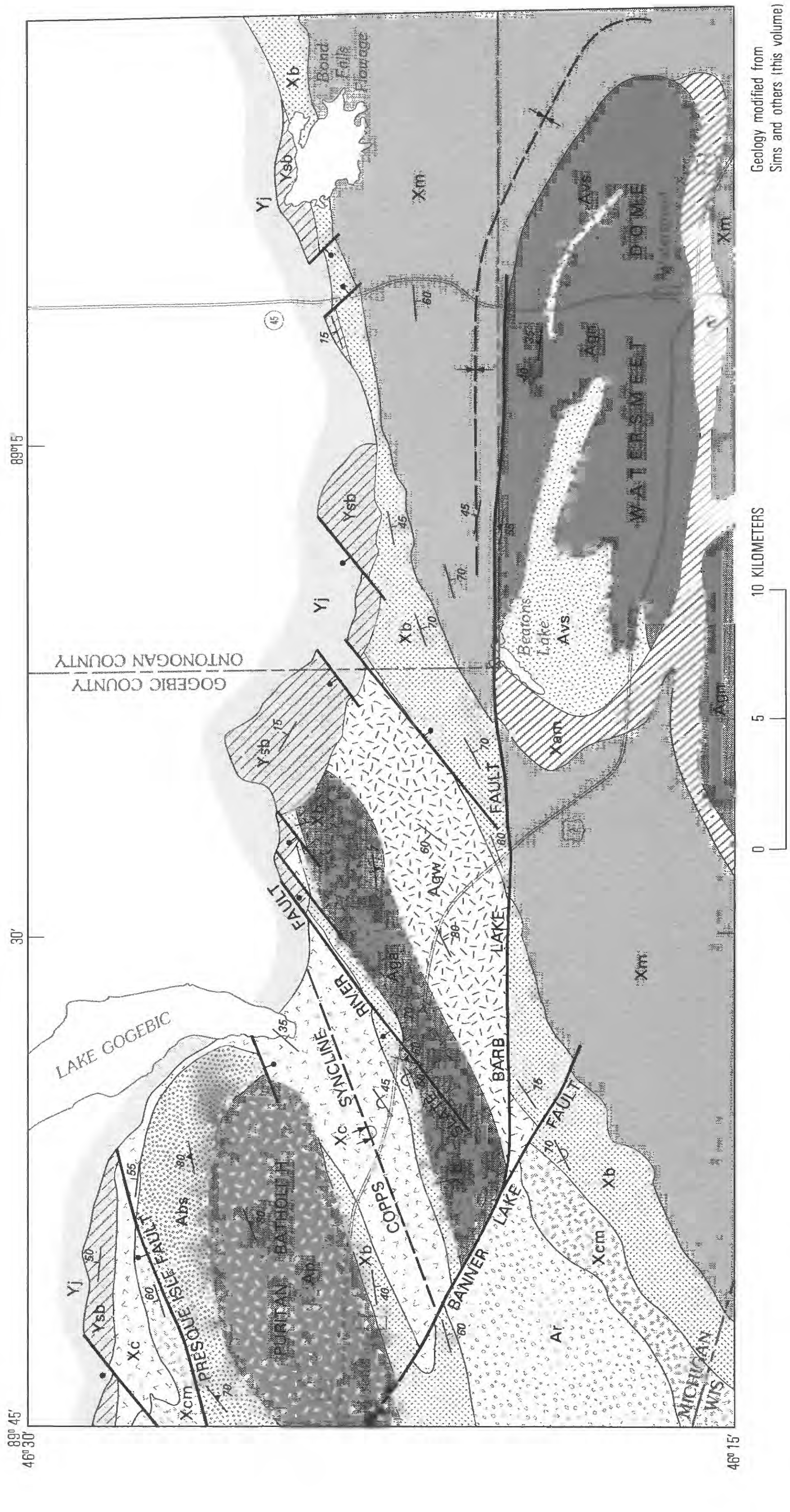
The bedded rocks of the Proterozoic Marquette Range Supergroup mainly consist of a basal metavolcanic unit that increases in thickness eastward—the Blair Creek Formation (Sims and others, this volume)—and a conformably(?) overlying unit of metagraywacke and meta-argillite, assigned to the Copps and Michigamme Formations. Older rocks of the Chocolay Group occur locally in the Gogebic Range, in a largely buried body in the southwest part of the map area, and at one locality along the north margin of the Watersmeet dome, about a kilometer east of the north end of Beatons Lake (fig. 2).

The structure of the rocks is complex. The Early Proterozoic rocks were folded during the Early Proterozoic Penokean orogeny. Also, within the area, an accompanying Penokean penetrative foliation was superposed on the previously deformed Archean basement rocks.

Within the gneiss terrane, at least two and probably three Archean deformations have been delineated in rocks in the Watersmeet dome. The oldest recognized deformation, about 3,500 m.y. ago, produced a steep foliation in the tonalitic augen gneiss and probably was accompanied by amphibolite-facies metamorphism. A second deformation followed deposition of the supracrustal biotite gneisses and, probably, a third, younger deformation followed deposition of a Late Archean succession of interlayered amphibolite and biotite gneiss. The age of the second deformation has not been determined, but it occurred during the interval between about 3,500 m.y. ago and deposition of the younger amphibolite and biotite gneiss, which has been dated by the U-Pb zircon method at about 2,640 m.y. The probable third deformation took place before emplacement of the 2,590-m.y.-old biotite leucogranite. The two younger deformations were also accompanied by amphibolite-facies metamorphism.

The rocks in the greenstone terrane, as reflected by structures in the Archean rocks in the northwest part of the map area, were deformed during a Late Archean (~2,700-m.y.-old) tectonic event. This event produced folds in the bedded rocks with steep axial surfaces and was accompanied by upper greenschist- to lower amphibolite-facies metamorphism. Presumably, the folding was accomplished by diapiric rise of the Late Archean granitoid rocks, a mechanism generally favored to account for deformation of the Archean bedded rocks within the Superior province. (See Schwerdtner and others, 1979.) Also at this time, the Archean paragneiss and amphibolite unit and metagraywacke unit (Aga and Agw, fig. 2) in the belt east of Marenisco were deformed. These rocks were folded on steep northeast-trending axial surfaces, which are subparallel to the boundary between the two Archean terranes. Presumably, this deformation resulted from impingement of the gneiss terrane against the greenstone terrane; it preceded emplacement of the Late Archean batholithic rocks, for the Puritan Quartz Monzonite in the belt of gneiss and amphibolite east of Marenisco was not deformed at this time.

The Early Proterozoic deformation affected all the Early Proterozoic and Archean rocks in the area and apparently involved two separate episodes of tectonism assigned to the Penokean orogeny (Cannon, 1973). The major and most widespread tectonic episode involved folding of the Early Proterozoic bedded rocks on axial surfaces overturned to the northwest and, in the area north of the Watersmeet dome, to the north. The folding was accompanied by development of a steep, southward-dipping, axial-planar foliation in the Early Proterozoic rocks and a similar foliation in the Archean rocks that was superposed on older Late Archean structures. The folding and the development of cleavage decrease in intensity northwestward from the center of the map area (fig. 2) but persist to the northernmost outcrops of the Copps Formation at the east end of the Gogebic Range. Probably this deformation took place under upper greenschist metamorphic conditions. Later, during reactivation of the Archean rocks in the Watersmeet dome, the overlying Early Proterozoic bedded rocks were deformed, producing a rim syncline in the supracrustal rocks about 1.5–2 km outside of the core-mantle boundary. During this uplift, the Archean supracrustal rocks overlying the tonalitic gneiss in the



Geology modified from Sims and others (this volume)

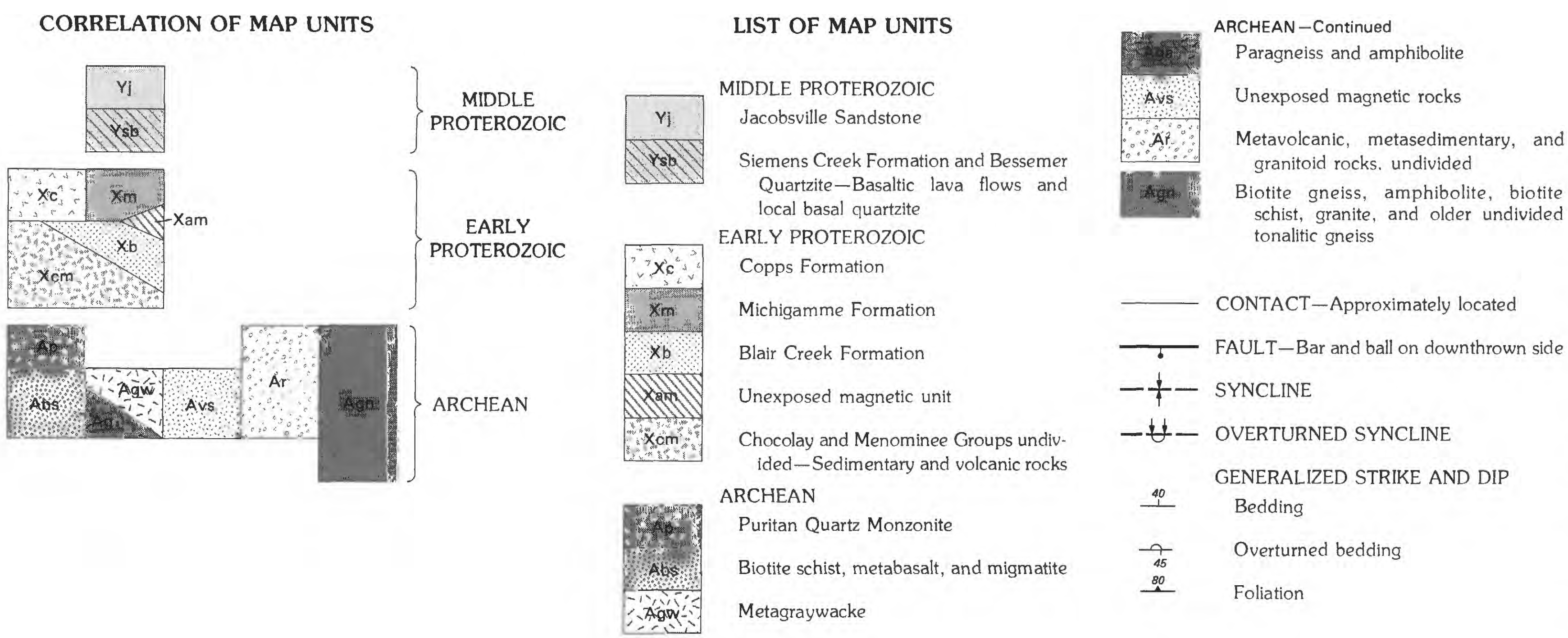


FIGURE 2.—Generalized geology of the Marenisco-Watersmeet area, northern Michigan.

core of the Watersmeet dome were deformed, mainly by recumbent folding and development of a northward-dipping axial-planar foliation. During this tectonism, all the Archean rocks in the dome were cataclastically deformed and recrystallized, and both the Archean rocks and the supracrustal mantling bedded rocks were subjected to amphibolite-grade metamorphism. Radiometric studies indicate that this event took place about 1,800 m.y. ago (Peterman and others, 1980).

Three major fault sets have been recognized in the area: a northwest-trending set, which probably was initiated in the Archean and later rejuvenated, an east-northeast-trending set, and a northeast-trending set (Sims and others, this volume, fig. 19). The main northwest-trending fault is the Banner Lake fault. A major related fault, the Barb Lake fault, has an apparent right-lateral displacement of about 6.5 km, as measured by lateral offset of the Blair Creek Formation (fig. 2). Eastward, the Barb Lake fault appears to truncate the northern margin of the Watersmeet dome; its vertical displacement is not known.

The east-northeast-trending fault set had an important effect on the distribution of the Keweenawan or Middle Proterozoic basaltic lavas and the structure of rocks in the Gogebic Range. The northernmost known fault in this set, the Presque Isle fault, separates steeply north-dipping rocks of the east Gogebic Range and the overlying Keweenawan lavas from Archean rocks on the south. The fault appears to have been mainly responsible for the tilting, which occurred after extrusion of the Keweenawan lavas and before deposition of the Middle Proterozoic Jacobsville Sandstone.

The north-northeast-trending fault set also is late Keweenawan in age; it is inferred to be younger than the east-northeast set and, unlike the east-northeast set, had little effect on the distribution of rock units, for it mainly displaced the Keweenawan lavas, probably by dominantly dip-slip movements. One fault in this set, however—the Slate River fault—repeated the Blair Creek Formation in the vicinity of U.S. Highway 2, south of Lake Gogebic (fig. 2).

A minor set of faults in the eastern part of the map area trends northwest and appears to displace the Keweenawan lavas. Probably the faults are late Keweenawan in age.

GRAVITY MAP

The Bouguer gravity anomaly map prepared for this study (fig. 3) was compiled from approximately 310 gravity stations. Data for about 180 of these stations were obtained during an earlier regional gravity survey of the Upper Peninsula of Michigan (Bacon, 1957); the remainder were obtained recently by the U.S. Geological Survey to fill gaps in the coverage and to construct profiles across the geologic structure of this area. Stations are spaced about 3 km apart on the average, but are as much as 6.5 km apart in some areas of poor accessibility. Most of the new regional gravity data were obtained as part of a regional gravity survey of the Iron River 1°×2° quadrangle (Klasner and Jones, 1979). About 85 additional gravity readings were taken at 300-m intervals along roads. The stations were located by chaining, and altitudes were determined by multiple-loop altimeter surveys from U.S. Geological Survey bench marks. The altitude readings have an estimated accuracy of 5 feet or better. The gravity data were tied to or recalculated to conform to the 1971 International Gravity Standardization Net (Morelli, 1974). Data were reduced to sea level datum using the 1967 Geodetic Reference System (International Association of Geodesy, 1971) and using a density of 2.67 g/cm^3 for rock between the ground surface and datum. The estimated accuracy of the gravity data is ± 0.3 milligal according to a code developed by Robbins and others (1974) for land-based gravity data in California.

GEOLOGIC INTERPRETATION OF GRAVITY ANOMALIES

Comparison of the Bouguer gravity anomaly map with the geologic map (fig. 2) shows a close correspondence of gravity anomalies and surface geology. A gravity low deeper than -50 milligals at A (fig. 3) lies above a basin in which the low-density Jacobsville Sandstone is probably thicker than that in other areas within figure 3. In contrast, moderately high gravity values at B (fig. 3) are associated with dense lower Keweenawan lavas in the northwest corner of the area where, according to a gravity model by Klasner and Jones (1979), the Jacobsville Sandstone is thin and the underlying lavas have moderately steep northward dips. A gravity plateau (-30 milligals) at C overlies exposed lower Keweenawan lavas; elsewhere in the northeast part of the map area these lavas may be too thin and discontinuous to provide positive gravity anomalies, or perhaps the gravity stations are too widely spaced to recognize them. A pronounced elongate gravity low of nearly -50 milligals (D, fig. 3) coincides closely with the Puritan batholith, which is composed mainly of granite; the width and amplitude of this anomaly suggest that the batholith is deep-rooted, a characteristic of many of the larger linear granitic plutons in the Archean greenstone terrane of Minnesota (Sims, 1972). A lesser gravity low (E) overlies Archean granitic gneisses and associated pegmatite, which is cogenetic with the Puritan batholith. Another gravity low (F)

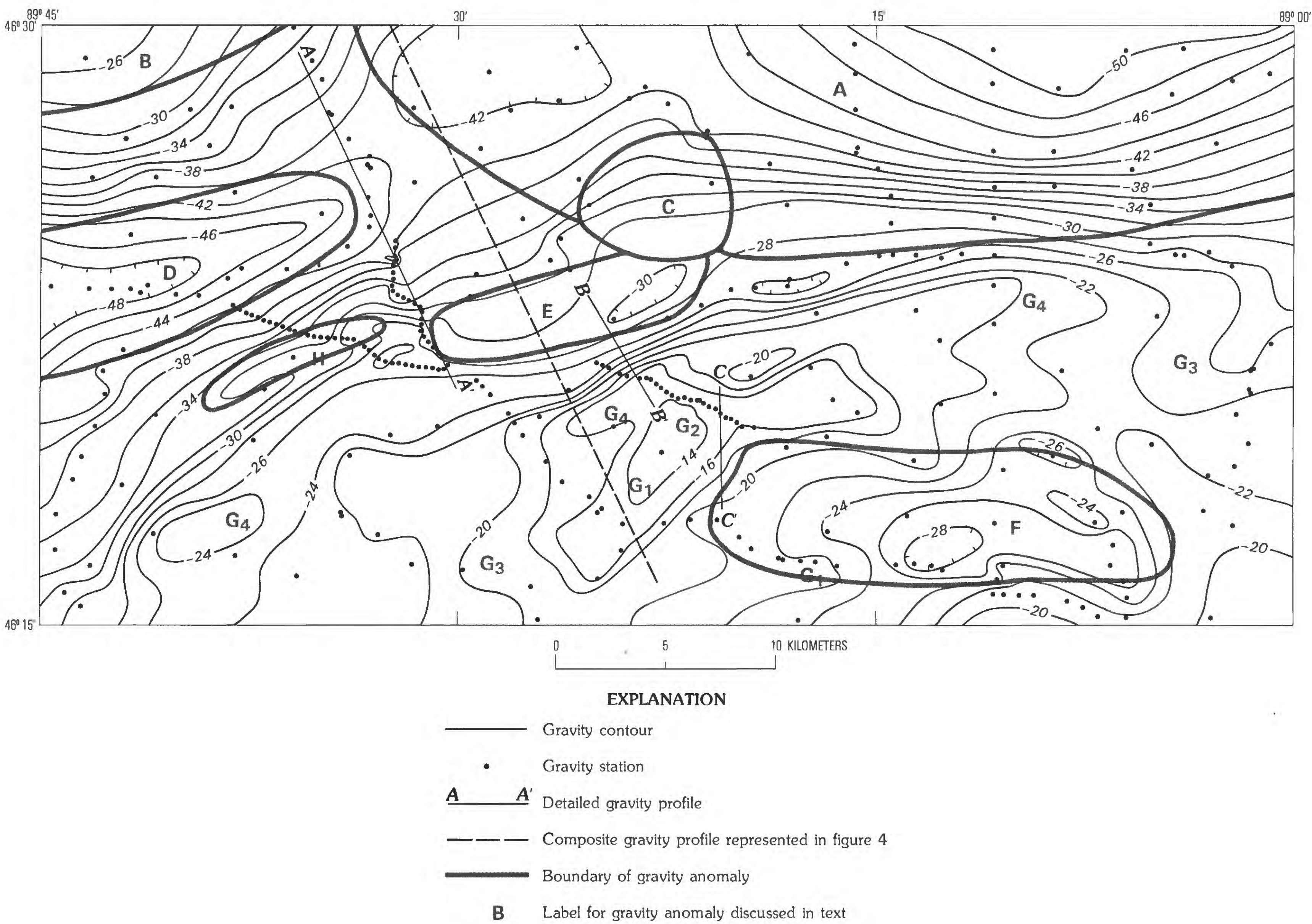
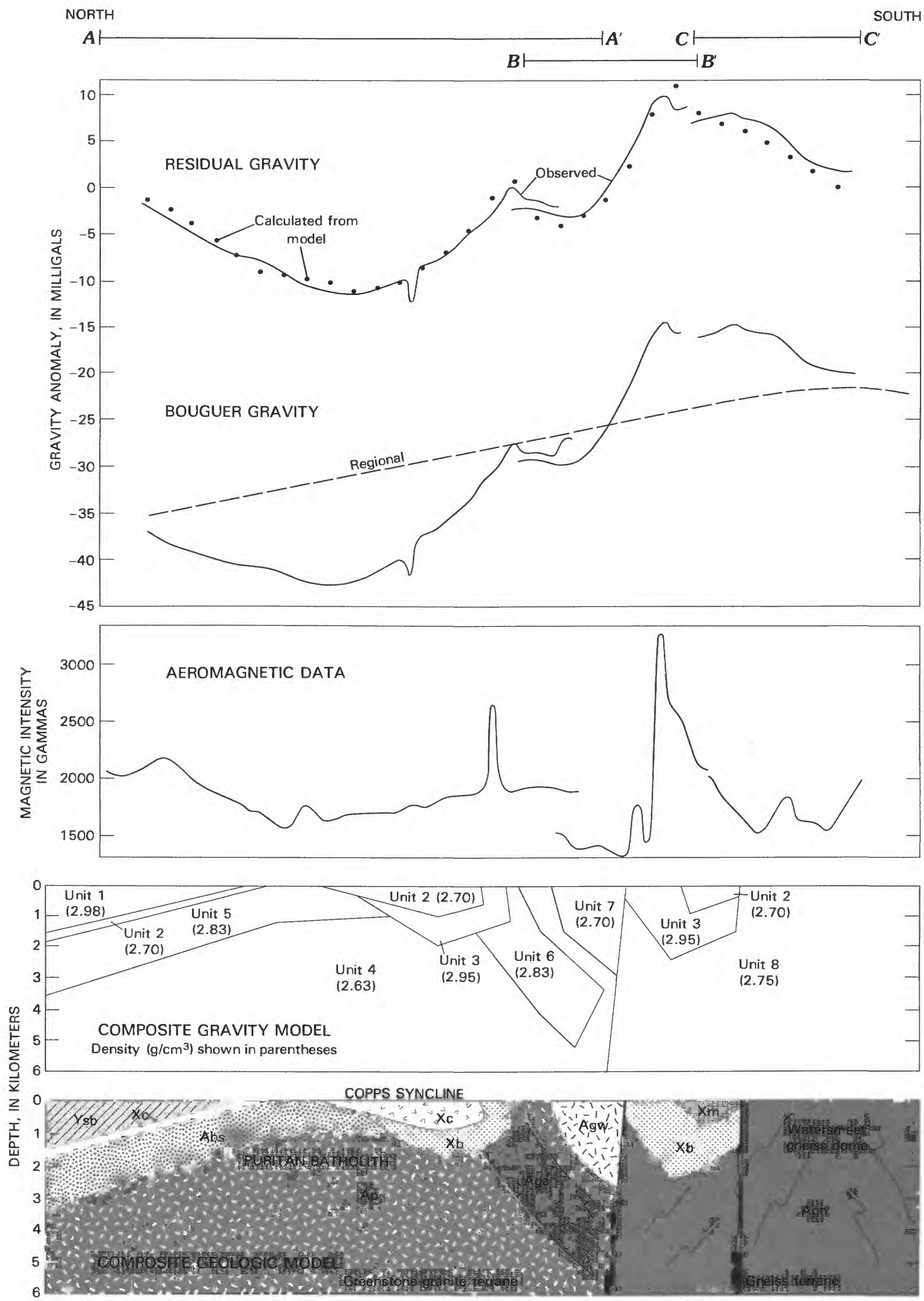


FIGURE 3.—Simple Bouguer gravity anomaly map of the Marenisco, Thayer, and Watersmeet 15-minute quadrangles, Michigan. Contour interval 2 milligals.


NORTH
SOUTH
A
A′
B
B′
C
C′
GRAVITY ANOMALY, IN MILLIGALS
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
RESIDUAL GRAVITY
Observed
Calculated from model
BOUGUER GRAVITY
Regional
MAGNETIC INTENSITY IN GAMMAS
3000
2500
2000
1500
AEROMAGNETIC DATA
DEPTH, IN KILOMETERS
0
1
2
3
4
5
6
Unit 1 (2.98)
Unit 2 (2.70)
Unit 5 (2.83)
Unit 2 (2.70)
Unit 4 (2.63)
Unit 3 (2.95)
Unit 6 (2.83)
Unit 7 (2.70)
Unit 3 (2.95)
Unit 2 (2.70)
Unit 8 (2.75)
COMPOSITE GRAVITY MODEL
Density (g/cm3) shown in parentheses
COPPS SYNCLINE
Ysb
Xc
Abs
Xc
Xb
PURITAN BATHOLITH
Ap
Agw
Ags
Xm
Xb
Watersmeet gneiss dome
Agn
COMPOSITE GEOLOGIC MODEL
Greenstone-granite terrane
Gneiss terrane

coincides with the Watersmeet gneiss dome, in the southestern part of the map area.

Most positive gravity anomalies in the area underlain by pre-Keweenawan rocks are associated with exposed Early Proterozoic rocks of the Marquette Range Supergroup. The broad gravity high at the west end of the Watersmeet dome (G_1, fig. 3) corresponds in part with a sharp, positive magnetic anomaly that encircles the western and southern margins of the dome (U.S. Geological Survey, 1972a). This unit is mapped on figure 2 as an unexposed magnetic unit; a drill hole on the anomaly south of Watersmeet penetrated biotite schist (C. E. Dutton, oral commun., 1976). The extension of anomaly G_1 to the northeast (designated G_2, fig. 3) overlies the Michigamme Formation, but undoubtedly reflects underlying denser Proterozoic rocks—probably the Blair Creek Formation, which has a density of about 0.25 g/cm^3 greater than the Michigamme. Dense dolomite of Early Proterozoic age (Xcm, fig. 2), which is exposed at one place along the county highway about a kilometer east of Beatons Lake and is known to contain some sulfide minerals, could also be associated with this positive anomaly. The gravity high extends both to the east and west (G_3) but is more subdued in these areas, probably because of deeper burial of the relatively dense rocks or because of thinning of these rocks. The positive gravity anomaly designated as G_4 coincides with volcanic rocks and lean iron-formation of the Blair Creek Formation (Xb, fig. 2) along the northwest and north margins of outcrops of the Michigamme Formation. A slight gravity high (H, fig. 3) occurs above the volcanic rocks of the Blair Creek Formation along the southwest, overturned limb of the Copps syncline. This anomaly is widest along U.S. Highway 2, about 12 km east of Marenisco, where the Blair Creek is repeated by a north-northeast-trending fault. The amplitude of the anomaly suggests that dense Archean amphibolite, which underlies the Blair Creek at this locality, contributes to the positive anomaly.

EXPLANATION FOR COMPOSITE GEOLOGIC MODEL

MIDDLE PROTEROZOIC

Ysb — Siemens Creek Formation and Bessemer Quartzite—Basaltic lava flows and local basal quartzite

EARLY PROTEROZOIC

Xc — Copps Formation

Xm — Michigamme Formation

Xb — Blair Creek Formation

ARCHEAN

Ap — Puritan Quartz Monzonite

Abs — Biotite schist, metabasalt, and migmatite

Agw — Metagraywacke

Aga — Paragneiss and amphibolite

Agn — Tonalitic gneiss and younger amphibolite, biotite gneiss, biotite schist, and granite, undivided

CONTACT

FAULT

0 5 KILOMETERS

FIGURE 4.—Two-dimensional gravity model and interpretive geologic section along a composite gravity profile constructed from profiles *A–A'*, *B–B'*, and *C–C'*. (See fig. 3.) Note the projections onto the line shown on figure 3. The model has the same vertical and horizontal scales.

GRAVITY MODEL

A two-dimensional gravity model (fig. 4) was constructed from a composite gravity profile to aid in determining shallow crustal structure across the Great Lakes tectonic zone. The composite gravity profile was constructed by projecting segments *A–A'*, *B–B'*, and *C–C'* roughly along gravitational strike onto the line shown on figure 3. The three segments were positioned to take advantage of detailed gravity measurements along roads and are located in areas where the surface geology is moderately well known. The principal uncertainties in knowledge of the geology occur in segments *B–B'* and *C–C'*, for the structure in the basement rocks and the exact nature of the discontinuity between the Archean gneiss in the Watersmeet dome and the rocks in the Archean greenstone block to the northwest are not known. The geology of this area is further complicated by the fault along the north margin of the Watersmeet dome.

Regional gravity on figure 4 was estimated by a graphical cross-profile interpretation of the Bouguer gravity map. The residual, obtained by subtracting regional from Bouguer gravity values, has an abrupt increase of about 20 milligals from north to south, with the lowest values (D, fig. 3) being above the Puritan batholith and the highest being above exposed Blair Creek Formation (G_4, fig. 3). As mentioned above, a lesser gravity high (H) also overlies Early Proterozoic rocks in the south, overturned limb of the Copps syncline.

Aeromagnetic data (U.S. Geological Survey, 1972a, b) are plotted on the gravity profile and were useful in constructing the gravity model. Sharp magnetic highs correspond with gravity highs over some parts of areas underlain by Proterozoic metavolcanic and metasedimentary rocks, apparently indicating the positions of iron-formation. Magnetic lows occur above the

Puritan batholith and the Watersmeet dome. Small-amplitude highs within the magnetic low over the dome probably mark the position of Late Archean metavolcanic and metasedimentary supracrustal rocks that overlie the older tonalite gneiss in the core of the dome (Sims and others, this volume).

Density measurements were made on rocks that crop out along or near the position of the composite gravity profile (table 1). These 26 determinations and some additional values taken from the literature for certain rock types provide a reasonably accurate estimate of the range in the densities of the rock units at the surface. Densities used in the model for units 4 and 7 correspond closely with the median density of these units (table 1).

Unit 1—Although the north end of the gravity profile represents an area underlain by Jacobsville Sandstone, as shown on the geologic map (fig. 2), earlier gravity studies in this area (Klasner and Jones, 1979) indicated that the Jacobsville is thin and is underlain by Keweenawan lavas at shallow depths. For this reason, the Jacobsville Sandstone was not included in the model.

Unit 2—Four samples of the Copps and Michigamme Formations have a median density of 2.72 g/cm^3. However, measurement of many more samples of the Michigamme Formation from the western Marquette district, about 100 km to the east, indicate that a density of 2.70 g/cm^3 is a more appropriate figure (Cannon and Klasner, 1976), and this figure is used in the model.

Unit 3—Although the Blair Creek Formation consists mainly of mafic volcanic rocks having densities in the range 2.92 to 2.99 g/cm^3, the formation also contains lenses of other rock types, such as iron-formation, metaconglomerate, metagraywacke, and felsic volcanic rocks, whose distributions are poorly known, especially at depth. A density of 2.95 g/cm^3 was used in the model.

Unit 5—Geologic mapping shows that this unit is composed of biotitic schist and gneiss, migmatite, and lesser amphibolite, but the proportions of these rock types in the segment along the composite gravity profile are uncertain. The 2.83 g/cm^3 density used in the calculations is based on an estimate that the rock contains 85 percent tonalite or equivalent rocks having a density of 2.8 g/cm^3 and 15 percent amphibolite having a density of 2.98 g/cm^3.

Unit 6—The Archean paragneiss and amphibolite unit is a mixed unit containing felsic gneisses, amphibolite, and a few small bodies of granite; accordingly, it is difficult to accurately estimate its density. The 2.83 g/cm^3 density (table 1) is based on an estimate that the unit contains 40 percent amphibolite having a density of 3.00 g/cm^3 and 60 percent intermediate volcanic rocks with a density of 2.72 g/cm^3.

Unit 8—The rocks in the core of the Watersmeet dome are poorly exposed, but judged from geologic mapping (Sims and others, this volume) and aeromagnetic data they consist of Early Archean tonalitic gneiss (density approximately 2.70 g/cm^3) overlain by supracrustal biotite gneiss, biotite schist, and amphibolite that are intruded locally by Late Archean granite. The selected density of 2.75 in the model is an estimate that falls well within the range of measured densities in table 1.

An additional uncertainty, perhaps of greater significance to gravity modeling than uncertainties in the mean density of separate rock units, is the distribution

TABLE 1.—*Measured densities for selected rock units of the Marenisco-Watersmeet area, northern Michigan*

Unit No.	Unit name and (or) rock type	Map symbol (fig. 2)	Number of measurements	Density range (g/cm^3)	Median density (g/cm^3)
1	Keweenawan lavas; basalt lava flows[1]	Ysb	([1])	2.88-3.1	2.98
2	Copps and Michigamme Formations: metagraywacke	Xc, Xm	4	2.71-2.74	2.72
3	Blair Creek Formation; basaltic lava, graywacke, and conglomerate	Xb	4	2.92-2.99	2.95
4	Puritan Quartz Monzonite in batholith; granite and lesser granodiorite	Ap	3	2.60-2.69	2.63
5	Biotite schist, amphibolite, and tonalite[2]	Abs	([2])	([2])	2.83
6	Tonalitic gneiss, amphibolite, and sparse granite	Aga	8	2.60-3.07	2.83
7	Metagraywacke and lesser tuff	Agw	4	2.65-2.75	2.70
8	Tonalite gneiss, biotite gneiss and schist, amphibolite, and granite	Agn	3	2.70-2.81	2.76

[1]From Klasner and Jones (1979); number of measurements not reported.
[2]From Daly and others (1966); number of measurements and density range not reported.

of the rock units in the subsurface. In contrast to the stratiform nature of the Proterozoic bedded rocks, the Archean rocks are composite bodies composed of lenticular rock units having a complex internal structure. In the same way, the nature and attitude of the boundary between rocks of the Archean greenstone terrane and those of the Archean gneiss terrane, represented at the surface by the Watersmeet dome (fig. 2), is uncertain. In this area, the boundary is further complicated by the presence of high-angle faults. Thus, gravity modeling of the boundary zone is subjective, and the model presented here represents just one of several possible models.

Despite the uncertainties imposed by limitations in our knowledge of mean densities of rock bodies and of the detailed subsurface structure, the gravity data provide useful information about the gross stucture of the upper crust in the vicinity of the Archean basement boundary, and they support earlier contentions that this juncture is an important crustal feature in the Lake Superior region (Morey and Sims, 1976; Sims, 1976; Sims and others, 1980).

First, the gravity model suggests that the density of the crust in the gneiss terrane is higher than that of the greenstone-granite terrane, on the north. A density difference of approximately 0.1 g/cm^3 is necessary to explain the 20–milligal increase in gravity from the strongly negative anomaly (D, fig. 3) over the Puritan batholith to the positive anomaly (G_2) over Proterozoic rocks on the north flank of the Watersmeet dome. This model involves only the upper 6 km of the crust. There is an additional north-sloping regional gravity gradient that also spans the boundary zone; this regional gradient has been interpreted by Klasner and Bomke (1977) as resulting from density variations in the deeper crust.

Secondly, the gravity data suggest that the Proterozoic structural basins in the area are somewhat deeper over Archean gneiss basement rocks than over Archean greenstone-granite complexes. As shown in the geologic model (fig. 4), the Copps syncline is interpreted as being about 2 km deep, whereas the Michigamme basin (G_2, fig. 3) is at least half a kilometer deeper. The Michigamme basin widens eastward, and the Michigamme Formation covers a vast region to the east of the map area.

Finally, the gravity data and the model support a sharp discontinuity between the two juxtaposed Archean crustal segments. However, seismic studies such as that carried out recently by COCORP (the Consortium for Continental Reflection Profiling) across this tectonic zone in Minnesota are needed to determine more precisely the attitude and nature of the juncture between the two basement crustal blocks.

RELATION OF TECTONIC ZONE TO REGIONAL GRAVITY

East of the midcontinent rift system, the Great Lakes tectonic zone lies along the northern edge of a generally east-trending gravity high that has a wavelength of about 80 km. In northern Michigan (Klasner and others, 1979) and northern Wisconsin (Ervin and Hammer, 1974) the gravity high is a gradual, convex northward arc that extends from the eastern end of the Upper Peninsula of Michigan to northwestern Wisconsin. Near the west end of Lake Superior, the gravity high is offset across the midcontinent rift system by a northwest-trending fault (Sims and others, 1980), and west of the rift system it occurs in central Minnesota. Thus, the gravity expression across the Great Lakes tectonic zone is comparable throughout the Lake Superior region.

To further show the regional gravity expression of the Great Lakes tectonic zone, we have constructed a profile (fig. 5), taken from regional gravity maps, that extends from just north of the Minnesota–Canada border across western Lake Superior, along the detailed gravity profile of this study, into north-central Wisconsin. The smoothed regional profile approximates the gravity field if the effects of the Keweenawan volcanic and gabbroic rocks are removed. Regional gravity on the north end of the profile approximates the –60-mGal gravity field over Archean rocks near the Canadian border; the regional gravity in Michigan and Wisconsin is closely controlled by observed gravity. The high-frequency anomalies about the gravity field in Michigan and Wisconsin reflect near-surface geology, such as Early Proterozoic basins and reactivated gneiss domes.

On the profile (fig. 5), the Great Lakes tectonic zone lies at the north edge of a broad gravity high; the gravity gradient slopes gently northward from the tectonic zone over the greenstone-granite terrane (Superior province). The gravity model of the detailed profile (fig. 4) suggests that the steep north-sloping gradient results from an increase from north to south in the density of near-surface rocks. It is also likely that the broad regional high is caused by southward density increases in the upper crust, but as mentioned above, previous regional models (Klasner and Bomke, 1977) suggested that the broad gravity high results from changes in density of the deep crust, perhaps at a depth of about 16 km. Thus, it is reasonable to conclude that the broad high results from the combined effect of changes in density of near-surface rocks and the deeper crust, thereby indicating that the discontinuity between the two Archean basement segments is a fundamental crustal feature.

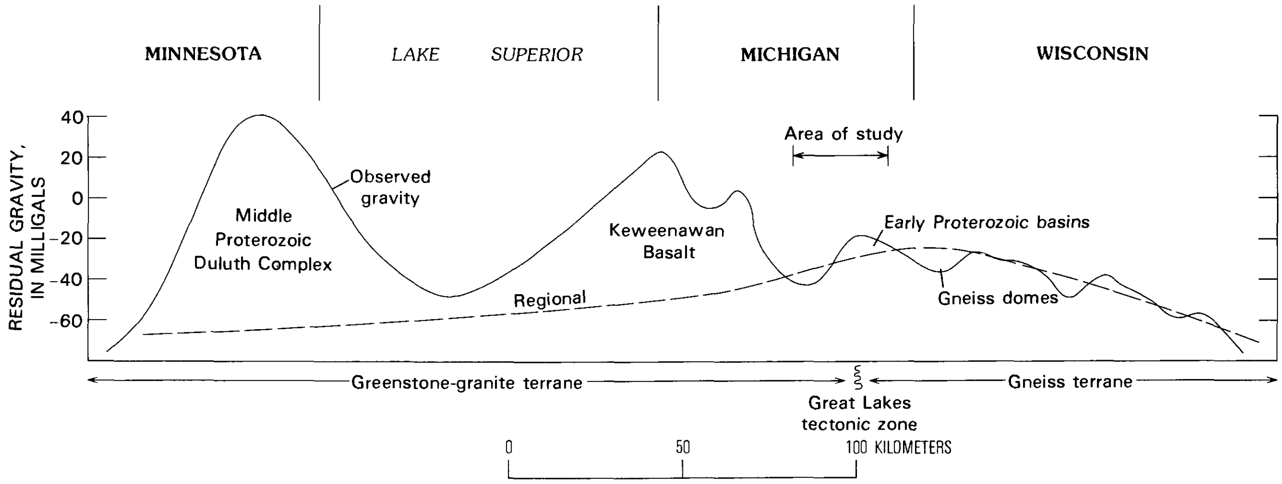


FIGURE 5.—Regional gravity profile, Lake Superior region, showing relation to Archean basement terranes.

TECTONIC ENVIRONMENT

The boundary between the two Archean basement terranes in the Lake Superior region has been interpreted as resulting from the joining together of two ancient crustal segments of contrasting lithologies and ages in Late Archean time (Sims and others, 1980). Geologic data strongly indicate that the two terranes were tightly juxtaposed in Early Proterozoic time, when the sedimentary-volcanic sequence of the Marquette Range Supergroup accumulated, but that extensive movement of both extensional and compressional regimes took place along the boundary during this time interval. The contrasting tectonic behavior of the two basement terranes in Early Proterozoic time has been attributed primarily to differences in heat flux (Sims and others, 1981). The greenstone-granite terrane stabilized near the end of the Archean, probably as a result of depletion of lithophile elements during the extensive igneous episodes 2,700 m.y. ago; whereas the gneiss terrane retained much of its lithophile element content and remained somewhat mobile until about 1,600 m.y. ago.

The gravity data as interpreted above support the earlier interpretation that the boundary between the two Archean crustal segments was an intracratonic feature during the Early Proterozoic (Sims and others, 1981). The residual gravity increases rather abruptly across the boundary from north to south. Some of the increase results from lateral changes in the density of Archean rocks in the upper crust, indicating that crustal rocks in the gneiss segment are denser than those in the greenstone segment. Much of it can be accounted for by dense Early Proterozoic rocks that clearly lie unconformably on the basement gneises. Some of these supracrustal rocks span the boundary and thus overlie both basement segments. The absence of a major positive anomaly over the boundary zone shows clearly that extension across the boundary was not sufficient to cause separation and formation of oceanic crust.

REFERENCES CITED

Bacon, L. O., 1957, Relationship of gravity to geological structure in Michigan's Upper Peninsula, *in* Snelgrove, A. K., ed., Geological exploration—Institute on Lake Superior Geology: Houghton, Mich., Michigan College of Mining and Technology, p. 54–58.

Cannon, W. F., 1973, The Penokean orogeny in northern Michigan, *in* Young, G. M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada Special Paper 12, p. 251–271.

Cannon, W. F., and Klasner, J. S., 1976, Geologic map and geophysical interpretation of the Witch Lake quadrangle, Marquette, Iron, and Baraga Counties, Michigan: U.S. Geological Survey Miscellaneous Investigations Map I–987, scale 1:62,500.

Daly, R. A., Manger, G. E., and Clark, S. P., Jr., 1966, Density of rocks, *in* Clark, S. P., Jr., ed., Handbook of physical constants: Geological Society of America Memoir 97, p. 19–26.

Ervin, C. P., and Hammer, S. H., 1974, Bouguer anomaly gravity map of Wisconsin: Madison, Wis., Wisconsin Geological and Natural History Survey, scale 1:500,000.

International Association of Geodesy, 1971, Geodetic reference system, 1967: Special Publication 3, 115 p.

Klasner, J. S., and Bomke, D., 1977, A regional gravity anomaly in northern Michigan and Wisconsin, possible extension around the Superior province, associated foldbelts [abs.]: EOS (American Geophysical Union Transactions), v. 59, no. 4, p. 226.

Klasner, J. S., and Jones, W. J., 1979, Simple Bouguer gravity anomaly map and geologic interpretation, Iron River 1°×2° quadrangle, northern Michigan and Wisconsin: U.S. Geological Survey Open-File Report 79–1564, 22 p., 1 pl.

Klasner, J. S., Wold, R. J., Hinze, W. J., Bacon, L. O., O'Hara, N. W., and Berkson, J. M., 1979, Bouguer gravity anomaly map of the northern Michigan–Lake Superior region: U.S. Geological Survey Geophysical Investigations Map GP–310, scale 1:1,000,000.

Morelli, Carlo, 1974, The international gravity standardization net, 1971: International Association of Geodesy Special Publication 4, 194 p.

Morey, G. B., and Sims, P. K., 1976, Boundary between two Precambrian W terranes in Minnesota and its geologic significance: Geological Society of America Bulletin, v. 87, p. 141–152.

Peterman, Z. E., Zartman, R. E., and Sims, P. K., 1980, Early Archean tonalitic gneiss from northern Michigan, U.S.A., *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 125–134.

Robbins, S. L., Oliver, H. W., Holden, K. D., and Farewell, R. C., 1974, Principal facts, accuracies, and sources for 3,046 gravity stations on the San Jose $1° \times 2°$ quadrangle, California: Springfield, Va., U.S. Department of Commerce, National Technical Information Service, Report PB–232 729/As, 106 p.

Schmidt, R. G., 1976, Geology of the Precambrian W (lower Precambrian) rocks in western Gogebic County, Michigan: U.S. Geological Survey Bulletin 1407, 40 p.

———1980, The Marquette Range Supergroup in the Gogebic iron district, Michigan and Wisconsin: U.S. Geological Survey Bulletin 1460, 96 p.

Schwerdtner, W. M., Stone, D., Osadetz, K., Morgan, J., and Stott, G. M., 1979, Granitoid complexes and the Archean tectonic record in the southern part of northwestern Ontario: Canadian Journal of Earth Sciences, v. 16, p. 1965–1977.

Sims, P. K., 1972, Regional gravity field, *in* Sims, P. K., and Morey, G. B., eds., Geology of Minnesota, A centennial volume: Minneapolis, Minn., Minnesota Geological Survey, p. 581–584.

———1976, Precambrian tectonics and mineral deposits, Lake Superior region: Economic Geology, v. 71, p. 1092–1118.

———1980, Boundary between Archean greenstone and gneiss terranes in northern Wisconsin and Michigan, *in* Morey, G. B., and Hanson, G. N., eds., Selected studies of Archean and lower Proterozoic rock, southern Canadian Shield: Geological Society of America Special Paper 182, p. 113–124.

Sims, P. K., Card, K. D., and Lumbers, S. B., 1981, Evolution of early Proterozoic basins of the Great Lakes region, *in* Campbell, F. H. A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81–10, p. 379–397.

Sims, P. K., Card, K. D., Morey, G. B., and Peterman, Z. E., 1980, The Great Lakes tectonic zone—A major crustal structure in central North America: Geological Society of America Bulletin, pt. I, v. 91, p. 690–698.

Sims, P. K., and Peterman, Z. E., 1976, Geology and Rb-Sr ages of reactivated Precambrian gneisses and granite in the Marenisco-Watersmeet area, northern Michigan: U.S. Geological Survey Journal of Research, v. 4, no. 4, p. 405–414.

Sims, P. K., Peterman, Z. E., and Prinz, W. C., 1977, Geology and Rb-Sr age of Precambrian W Puritan Quartz Monzonite, northern Michigan: U.S. Geological Survey Journal of Research, v. 5, no. 2, p. 185–192.

Streckeisen, A. L., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1–33.

U.S. Geological Survey, 1972a, Aeromagnetic map of the Watersmeet region, Ontonogan and Gogebic Counties, Michigan, and Vilas County, Wisconsin: U.S. Geological Survey Geophysical Map GP–831, scale 1:62,500.

———1972b, Aeromagnetic map of central Gogebic County, Michigan, and northern Vilas County, Wisconsin: U.S. Geological Survey Geophysical Map GP–828, scale 1:62,500.

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