Great Lakes Tectonic Zone in Marquette Area, Michigan—Implications for Archean Tectonics in North-Central United States

U.S. GEOLOGICAL SURVEY BULLETIN 1904–E

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Chapter E

Great Lakes Tectonic Zone in Marquette Area, Michigan—Implications for Archean Tectonics in North-Central United States

By P.K. SIMS

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

P.K. SIMS and L.M.H. CARTER, Editors

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE: 1991

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Sims, P.K. (Paul Kibler), 1918—
Great Lakes Tectonic Zone in Marquette area, Michigan—implications for Archean tectonics in north-central United States /by P.K. Sims.
p. cm.—(Contributions to Precambrian geology of Lake Superior region ; ch. E) (U.S. Geological Survey bulletin ; 1904–E)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:1904–E
1. Geology, Stratigraphic—Archaean. 2. Geology—Middle West. 3. Faults (Geology)—Michigan—Marquette Region. 4. Faults (Geology)—Great Lakes Region. I. Title. II. Series. III. Series: U.S. Geological Survey bulletin ; 1904–E
QE75.B9 no. 1904–E
[QE653.3]
557.3 s—dc20 90–13956
[551.7'12] CIP

CONTENTS

FIGURES

TABLES

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

Great Lakes Tectonic Zone in Marquette Area, Michigan— Implications for Archean Tectonics in North-Central United States

By P.K. Sims

Abstract

The Great Lakes tectonic zone (GLTZ) is an Archean crustal boundary of subcontinental length that separates a greenstone-granite terrane (southern part of Superior province of Canadian Shield) on the north from a partly older gneiss terrane on the south. It is generally interpreted as a paleosuture resulting from continent-continent collision. The tectonic zone is covered at most places in the Lake Superior region by Proterozoic rocks or Pleistocene glacial deposits, and its position and characteristics previously have been determined mainly by geophysical data. Geologic mapping in the Marquette, Michigan area provides for the first time direct observations of the structure.

In the Marquette area, the GLTZ is characterized by a zone of mylonite (orthomylonite) that has been superposed on previously deformed rocks of both the Archean greenstone-granite terrane and the Archean gneiss terrane. Foliation in the mylonite strikes about N. 60° W. and dips steeply southwest, presumably subparallel to the boundary between the greenstone-granite and gneiss terranes. A pronounced stretching lineation and tight fold hinges plunge about 45° S. 45° E. The attitude of the stretching lineation (line of tectonic transport) together with asymmetric structures indicative of movement sense indicates that collision at this locality was oblique, resulting in dextral-thrust shear along the boundary, northwestward vergence, and probable overriding of the greenstone-granite terrane by the gneiss terrane. Transmittal of the dextral shear stress across a large area of the greenstone-granite crust (Superior province) to the north may have been responsible for the nearly east-west foliation, upright folds, and northwest- to east-west-trending dextral faults and shear zones at least as far north as the Quetico fault, in southern Ontario, a distance of about 250 kilometers.

As a whole, the GLTZ is characterized by systematic angular bends that alternately trend west-northwestward, as in the Marquette area, and northeastward. This zigzag pattern probably reflects original irregularities in the continental margin (Superior province) composed of greenstone-granite crust. Late Archean convergence along this margin resulted in a variable trajectory of stress into the greenstone-granite crust and probably in along-strike diachroneity of orogeny. The major deformation resulted from oblique compression at promontories, which acted as buttresses against which compressive stress was directed into the crust. In addition to the dominant foliation, major brittle-ductile to brittle strike-slip faults, such as the Vermilion fault system in northern Minnesota and the Quetico and Rainy Lake–Seine River faults in southern Ontario, resulted from a more brittle continuum of the transcurrent shear caused by collision along the GLTZ.

INTRODUCTION

The Great Lakes tectonic zone (GLTZ) is an Archean crustal boundary more than 1,000 km long that separates a greenstone-granite terrane (southern part of Superior province) on the north from a gneiss terrane on the south (Sims and others, 1980; Sims and Peterman, 1981; Peterman, 1979). It is covered throughout most of the Great Lakes region by younger Proterozoic rocks or Pleistocene glacial deposits, but recently it has been delineated and studied in outcrop in an area south of Marquette, Mich. (fig. 1).

The boundary was first recognized in Minnesota (Sims and Morey, 1973; Morey and Sims, 1976) from regional geologic relations, which indicated that the two basement terranes had different geologic histories and probably had evolved separately. Regional magnetic and

---

Manuscript approved for publication June 26, 1990.

gravity data were utilized to determine the position of the boundary. Later (Sims, 1980), the boundary was approximately delineated in the western part of Upper Michigan (Sims and others, 1984) and northwestern Wisconsin (Sims and others, 1985), east of the Middle Proterozoic Midcontinent rift system, and it was inferred on indirect evidence to extend eastward through the Sudbury structure, where it is truncated by the Middle Proterozoic Grenville tectonic zone (Sims and others, 1980).

Recent geologic mapping in the Sands 7½-minute quadrangle, Michigan (fig. 1), previously mapped by Gair and Thaden (1968), has delineated this Archean boundary in outcrop for the first time. It is exposed on the south side of the Early Proterozoic Marquette synclinorium (or trough), and its northwestern projection into the trough coincides with a major Early Proterozoic fault, the Richmond fault. The GLTZ here is a mylonite zone about 2.4 km wide that mainly is overprinted on rocks of the greenstone-granite terrane but also affects an approximately 0.4-km-wide zone of the Archean gneiss. In this area, the GLTZ is interpreted as a continent-continent collision zone. The collision was oblique, resulting in dextral wrench shear on the N. 60° W.-trending boundary and northwestward vergence of the gneiss terrane against the greenstone-granite terrane.

The purpose of this report is to describe the exposed GLTZ in the context of the regional geology, to discuss genetic relationships between convergence along the boundary and structural features in the Archean rocks to the north, and to present a refined interpretation of the evolution of the GLTZ throughout the Lake Superior region.

ACKNOWLEDGMENTS

Critical reviews of an early draft by D.L. Southwick, G.B. Morey, and W.C. Day and of a later version by R.L. Bauer and W.C. Day significantly improved the manuscript. W.C. Day helped with the kinematic analysis.

GEOLOGIC SETTING

The Great Lakes tectonic zone is moderately well exposed in the Sands 7½-minute quadrangle in Upper Michigan (see fig. 5). It separates the two distinctive Archean terranes in the area. The northern greenstone-granite terrane is composed largely of Late Archean granitoid rocks and approximately coeval metavolcanic and lesser metasedimentary rocks of greenstone affinity. The layered rocks and most of the granitoid rocks were metamorphosed (mainly to greenschist facies) and deformed during Late Archean orogeny. The southern Archean gneiss terrane is composed mainly of layered gneiss, migmatite, and amphibolite—rocks that are distinctly different from those in the greenstone-granite terrane. Except for late-tectonic to post-tectonic, generally small(?) granitoid bodies, the rocks are metamorphosed mainly to amphibolite facies. The rocks exposed within the two terranes in Upper Michigan are closely similar to those in Minnesota (Morey and Sims, 1976; Sims and others, 1980), thus establishing the identity of the GLTZ in the Marquette area.

The Archean rocks in Michigan are overlain in the Marquette synclinorium, the Republic trough, and the Dead River, Clark Creek, and Baraga basins by shelf deposits of the Early Proterozoic Marquette Range Supergroup (fig. 1; Cannon and Gair, 1970). For the Archean rocks north of the Marquette synclinorium, Van Hise and Bayley (1897) introduced the name "northern complex"; the Archean rocks south of the synclinorium they named "southern complex."

A Late Archean age for the GLTZ is now established by regional geologic relationships in north-central United States. The Archean rocks in the greenstone-granite terrane in northern Minnesota (Hudleston and others, 1988) and northernmost Michigan (fig. 1) are characterized mainly by ductile and brittle structures formed in response to dextral shear, which accords with the deformation pattern observed in mylonite within the exposed GLTZ south of Marquette, Mich. These structures include a generally west trending steep foliation and upright folds, widespread Z-shaped folds, and northwest- to west-trending dextral faults, indicative of dextral shear. In contrast, Early Proterozoic Penokean deformation in the Marquette area had little effect on the Archean basement (Cambray, 1984). Cambray proposed that the Penokean deformation was produced by horizontal compression that was transmitted from the basement to the folded cover rocks by narrow ductile shears in the basement. Readjustment of rigid basement blocks along these shears using old weaknesses resulted in some shortening, but not folding of the basement rocks. For the Early Proterozoic Marquette trough, Cambray proposed a nearly north-south compressional axis, which initially produced reverse dip slip on faults bounding the trough and compressed the Early Proterozoic sedimentary rocks within the trough into west-trending folds. Subsequently, resistance to this movement resulted in a sinistral strike-slip motion and the development of F_2 folds with northwest-trending axial surfaces and variable plunge.

Gair and Thaden (1968) applied the name "Compeau Creek Gneiss" to both the foliated granitoid rocks of the Archean greenstone-granite terrane and the layered gneisses and massive intrusions of the gneiss terrane, and subsequent investigators extended this terminology to the western parts of the southern complex (Cannon and Simmons, 1973). To apply this name to rocks in both Archean terranes, however, is inappropriate, because the two terranes consist of distinctive rock types of different origins. Accordingly, in this report informal lithologic names are used to describe the crystalline rocks in the two diverse terranes.

ARCHEAN GREENSTONE-GRANITE TERRANE

The greenstone-granite terrane in the Marquette area (fig. 1) consists of several thousand meters of subaqueous mafic to felsic flows and pyroclastic rocks and volcanogenic sedimentary rocks in a succession that is intruded by small bodies of gabbro and ultramafic rocks and by large plutons of granitoid rocks (Bornhorst, 1988). The volcanic rocks have been named the Ishpeming greenstone belt (Morgan and DeCristoforo, 1980); they represent the southwestern extension of the Wawa subprovince of the Superior province (Card and Ciesielski, 1986). Felsic volcanic rocks adjacent to an ultramafic body north of Ishpeming host gold deposits of the Ropes mine (Brozdowski and others, 1986; Brozdowski, 1988, 1989), and the ultramafic body hosts additional mineral prospects (Bodwell, 1972). Foliated tonalite from the northern complex (Hammond, 1978) has a U-Pb zircon age of 2,703±16 Ma (recalculated by Zell E. Peterman), and associated rhyolite has a U-Pb zircon age of 2,780±69 Ma (recalculated by Zell E. Peterman). These ages are consistent with more precise U-Pb ages in the Wawa (Shebandowan) subprovince in adjacent Canada (Corfu and Stott, 1986).

Granitoid Rocks

The Late Archean granitoid rocks in the greenstone-granite terrane (fig. 1) are dominantly pink to grayish-pink, generally medium grained, porphyritic, foliated, homogeneous tonalite or granodiorite (Gair and Thaden, 1968, p. 18–23). They contain xenoliths and schlieren of biotite schist and amphibolite. In the Sands quadrangle (fig. 1), weakly foliated granite also is a common rock type (table 1; fig. 2), but its age relation to the tonalite-granodiorite was not determined. The bimodal composition of the granitoid rocks (fig. 2) suggests, however, that the granite represents a discrete magmatic event.

The granitoid rocks of the greenstone-granite terrane in the Marquette area exposed on both sides of the Marquette trough are strongly altered (table 1). Plagioclase (oligoclase) is saussuritized and albite twinning is largely obscured, and biotite is largely changed to chlorite and opaque oxides (locally rutile). The rocks are highly fractured, and fracture surfaces are coated by chlorite and other propylitic minerals. Along the south margin of the Marquette trough, the granitoid rocks are exceptionally rich in quartz (table 1; fig. 2). The granitoid rocks in the Sands quadrangle also are mylonitic. The protomylonite is characterized by recrystallization of quartz to fine grain sizes and localized shear-induced recrystallization of plagioclase and potassium feldspar to fine-grained polycrystalline aggregates (type 1P, 11P, 1M, and 11M structures of Hanmer, 1982). The protomylonite grades into orthomylonite at a distance of about 2 km north of the GLTZ. (See fig. 5.)

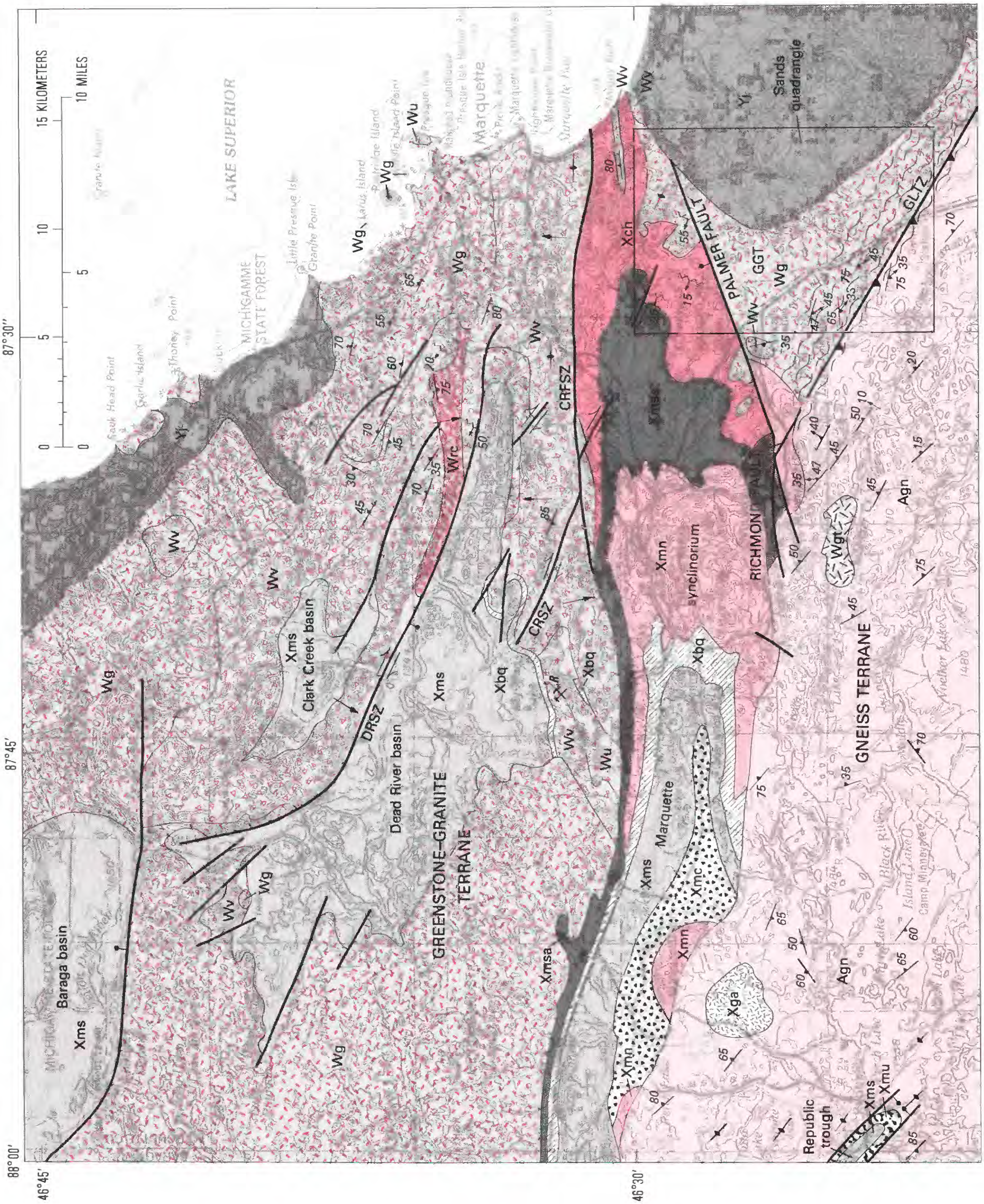
The relative homogeneity of the granitoid rocks, the occurrence of sharp-walled xenoliths, and the general absence of a lithologic layering that could represent original sedimentary or volcanic layering suggest that the granitoid rocks of the greenstone-granite terrane are of magmatic origin. Their pervasive foliation is attributed to deformation subsequent to primary crystallization, as discussed following.

Structure

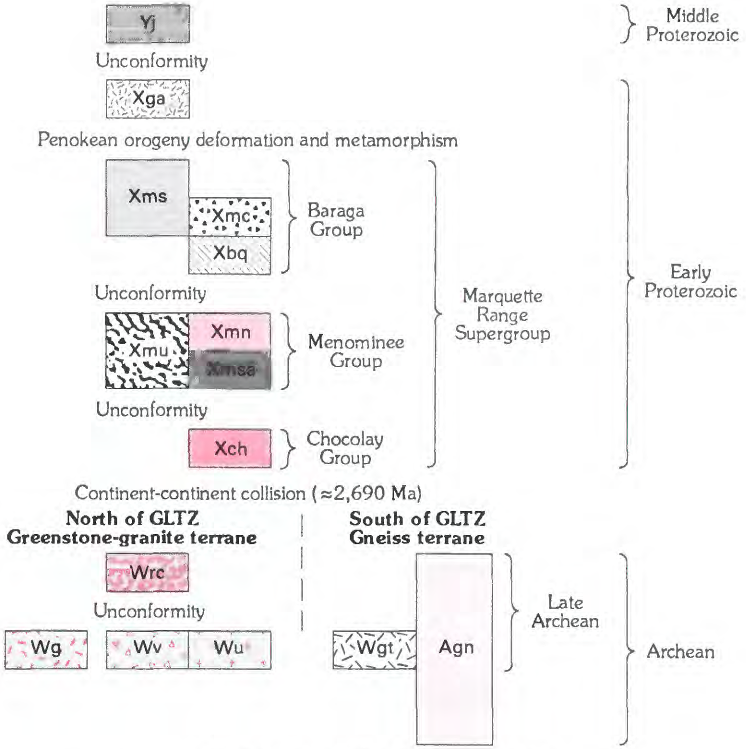
The rocks in the greenstone-granite terrane, on the north side of the GLTZ (fig. 1), record early recumbent folding (F_1) of metavolcanic rocks of the Ishpeming greenstone belt. Superposed deformation (D_2) produced northwest- to west-trending upright, upward- and downward-facing folds (F_2) that are Z-shaped in plan view (Rodney Johnson, written commun., 1989). An axial plane foliation was developed during F_2. The Z-symmetry of the F_2 folds is consistent with their development in a deformation regime with a dextral shear component. Associated granitoid rocks also were deformed by D_2. Younger, northwest- to west-trending faults, some of which have demonstrable dextral movement, transect and offset the folded rocks. Commonly, these faults separate volcanic rock domains having opposite stratigraphic facing directions, as shown in figure 1.

Foliation and lithologic layering in the vicinity of the Ropes mine (R, fig. 1) are puzzling with respect to the dominant regional structure. Here, foliation and lithologic layering strike about N. 70° E. and are nearly vertical (Brozdowski, 1988, p. A–44). The published geologic map that includes the Ropes mine area (Negaunee SW quadrangle; Clark and others, 1975) also shows a steep (stretch?) lineation that plunges southeastward in unit Wkf of the Kitchi Schist. Possibly, the northeast foliation in the Ropes mine area represents the east-northeast-trending limb of a large-scale D_2 Z-fold.

The steep, northwest- to west-trending shear zones and faults in the greenstone-granite terrane are tens of meters to a few hundred meters wide. They are highly schistose zones characterized by an intense, close-spaced foliation, a steep stretching(?) lineation, and strong retrograde alteration. The faults are of both ductile and brittle-ductile types. Major structures include the Dead River shear zone (fig. 1, DRSZ) (Puffett, 1974), which forms the northern boundary of the Dead River basin; the Carp River shear zone (CRSZ), northeast of the Ropes mine, which separates two different blocks of Archean volcanic rocks; and the Carp River Falls shear zone (CRFSZ), which forms the north margin of the Marquette trough in this area. The Carp River Falls shear zone is


15 KILOMETERS
10 MILES
0
5
10
15
LAKE SUPERIOR
MICHIGAMME STATE FOREST
Marquette
Sands quadrangle
87°30′
87°45′
88°00′
46°45′
46°30′
GREENSTONE-GRANITE TERRANE
GNEISS TERRANE
Dead River basin
Clark Creek basin
Baraga basin
Marquette
synclinorium
Republic trough
PALMER FAULT
RICHMOND FAULT
GLTZ
DRSZ
CRSZ
CRFSZ
GGT
Wg
Wv
Wu
Wrc
Wgt
Yi
Xms
Xmsa
Xmn
Xmc
Xmu
Xch
Xbq
Xga
Agn

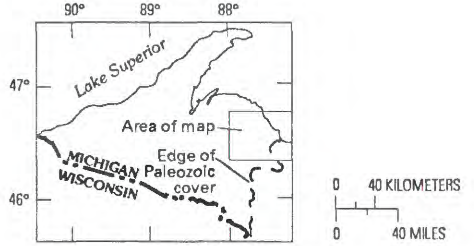
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

	Middle Proterozoic
Yj	**Jacobsville Sandstone**
	Early Proterozoic
Xga	**Alkali granite (1,733 ±25 Ma)**
	Marquette Range Supergroup
Xms	**Michigamme Formation**—Dominantly slaty rocks in lower part
Xmc	**Clarksburg Volcanics Member of Michigamme Formation**
Xbq	**Goodrich Quartzite**
Xmu	**Menominee Group, undivided, in Republic trough**
Xmn	**Negaunee Iron-formation**
Xmsa	**Siamo Slate and Ajibik Quartzite, undivided**
Xch	**Chocolay Group, undivided**
	Archean
	Greenstone-granite terrane
Wrc	**Reany Creek Formation**
Wg	**Granitoid rocks**—Dominantly granodiorite and tonalite but including granite; generally foliated
Wv	**Mafic to felsic flows and pyroclastic rocks and volcanogenic sedimentary rocks**
Wu	**Ultramafic rocks**
	Gneiss terrane
Wgt	**Granite near Tilden (Hammond, 1978)**
Agn	**Gneiss, migmatite, and amphibolite**—Includes foliated and massive granite

—	**Contact**
	High-angle fault—Bar and ball on downthrown side
	Transcurrent fault—Showing relative horizontal movement
	Thrust fault—Sawteeth on upthrown side
	Strike and dip of foliation
50	**Inclined**
	Vertical
→15	**Bearing and plunge of lineation**—May be combined with foliation symbol
→	**Direction of stratigraphic tops**
→15	**Bearing and plunge of minor fold**
〰	**Mylonite**—Dominantly orthomylonite
CRSZ	**Carp River shear zone**
CRFSZ	**Carp River Falls shear zone**
DRSZ	**Dead River shear zone**
GLTZ	**Great Lakes tectonic zone**
GGT	**Greenstone-granite terrane**
⚒R	**Ropes mine**



INDEX MAP

Figure 1. Geologic map of part of the Marquette 1°×2° quadrangle. Compiled by P.K. Sims, 1989, from various sources.

Table 1. Approximate modes of granitoid rocks, in volume percent, in Archean greenstone-granite terrane

[Tr., trace; blank, absent]

Sample No.	136R	177A	177B	179A	179B	182A	182B	183A	186A	199	200	202	208	211A	136–1	203	1	2	3
Plagioclase	37	35	60	66	54.5	48	52.5	38	54.5	36	56.5	60	39	41	27.5	33	61.2	58.5	50.6
Quartz	30	32.5	24	21.5	28.5	45	36	34	24	27.5	37.5	28	30	27	39	28	26	22.2	37.5
Potassium feldspar	30	31	10	5.5	2.5	0	0.5	24.5	14.5	31	3	1	30	24	32	37.5	3.8	12.8	1.4
Biotite	Tr.	Tr.	Tr.	Tr.	10	Tr.	Tr.	2.5	7	5	Tr.	10	0	Tr.	Tr.	Tr.	0.2	Tr.	1
Chlorite	3	1.3	6	7	Tr.	6	6.5	Tr.	Tr.	Tr.	3	Tr.	Tr.	8	1.5	0.5	3.6	2.5	1.8
Epidote					4	Tr.		Tr.	Tr.								0.6	Tr.	Tr.
Sphene					Tr.												0	0	
Opaque oxides	Tr.	Tr.	Tr.	Tr.		Tr.	Tr.	Tr.		Tr.		Tr.		Tr.	Tr.	Tr.	0.2	Tr.	Tr.
Accessory minerals	Tr.	0.2	Tr.	Tr.	0.5		0.5	1	Tr.	0.5	Tr.	1	1	Tr.	Tr.	1	Tr.	Tr.	Tr.
Muscovite							4			Tr.	Tr.						2.5	1.3	7

SAMPLE DESCRIPTIONS

136R. Pink, fine- to medium-grained, slightly porphyritic altered granite; contains wispy inclusions of biotite schist. Sands quadrangle, 1,800 ft W., 675 ft N., SE. cor. sec. 3, T. 47 N., R. 25 W.
177A. Pink, medium-grained, porphyritic massive altered granite; cut by chlorite-coated fractures. Sands quadrangle, 775 ft S., 2,150 ft E., NW. cor. sec. 16, T. 47 N., R. 25 W.
177B. Pink, fine-grained, porphyritic massive altered granite. Sands quadrangle. Same locality as 177A.
179A. Pinkish-gray, medium-grained, porphyritic altered tonalite; contains oriented layers of biotite schist. Palmer quadrangle, 650 ft S., 250 ft W., NE. cor. sec. 26, T. 47 N., R. 26 W.
179B. Gray, medium-grained, foliated altered tonalite. Biotite is fresh. Palmer quadrangle. Same locality as 179A.

182A. Pinkish-gray, medium-grained altered tonalite gneiss. Sands quadrangle, 1,350 ft E., 100 ft N., SW. cor. sec. 31, T. 47 N., R. 25 W.
182B. Pinkish-gray to medium-gray altered tonalite gneiss. Sands quadrangle. Same location as 182A.
183A. Pinkish-gray, fine- to medium-grained granite gneiss. Sands quadrangle, 675 ft N., 300 ft E., SW. cor. sec. 31, T. 47 N., R. 25 W.
186A. Pinkish-gray, medium-grained altered granodiorite gneiss. Palmer quadrangle, 2,500 ft N., 2,200 ft E., SW. cor. sec. 36, T. 47 N., R. 26 W.
199. Pinkish-gray, medium-grained granite gneiss. Sands quadrangle, 1,000 ft S., 2,000 ft W., NE. cor. sec. 16, T. 46 N., R. 25 W.

200. Pinkish-gray, fine- to medium-grained altered tonalite gneiss. Sands quadrangle, 775 ft N., 2,075 ft E., SW. cor. sec. 9, T. 46 N., R. 25 W.
202. Gray, fine-grained biotite tonalite gneiss cut by chlorite-coated fractures. Sands quadrangle, 850 ft N., 2,350 E., SW. cor. sec. 5, T. 46 N., R. 25 W.
208. Pink, medium-grained leucocratic granite gneiss. Sands quadrangle, 2,150 ft N., 2,000 ft W., SE. cor. sec. 8, T. 46 N., R. 25 W.
211A. Pink, medium-grained altered granite gneiss. Sands quadrangle, 2,550 ft S., 150 ft W., SE. cor. sec. 7, T. 46 N., R. 25 W.
136–1. Pink, medium- to coarse-grained foliated granite gneiss. Fractures coated by chlorite. Sands quadrangle. Same location as 136R.

203. Pink, medium-grained leucocratic granite gneiss. Sands quadrangle, 200 ft N., 2,300 ft W., SE. cor. sec. 5, T. 46 N., R. 25 W.
1. Average of 14 samples of foliated tonalite. Marquette quadrangle, north of Marquette synclinorium (Gair and Thaden, 1968, table 6, no. 1).
2. Average of five samples of foliated granodiorite. Marquette quadrangle, north of Marquette synclinorium (Gair and Thaden, 1968, table 6, no. 9).
3. Average of 11 samples of quartz-rich foliated tonalite. Sands quadrangle, south of Marquette synclinorium (Gair and Thaden, 1968, table 6, no. 6).

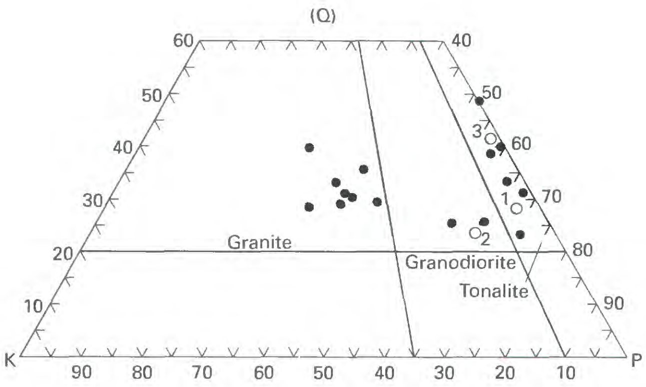


Figure 2. Quartz–alkali feldspar–plagioclase diagram for granitoid rocks of Archean greenstone-granite terrane, Marquette area. Rock classification modified from Streckeisen (1976). Modes determined by 600 to 1,000 point counts on standard thin sections, and given in table 1. Open circles 1, 2, and 3, average compositions reported by Gair and Thaden (1968).

reported to be cut by relatively undeformed mafic dikes of presumed Late Archean age, indicating a probable Archean age for the shear zone (Baxter and Bornhorst, 1988).

In the area north of the Palmer fault (fig. 1), foliated and fractured Late Archean granitoid rocks form partly fault bounded domes surrounded by Early Proterozoic rocks of the Marquette Range Supergroup. The large Archean granitoid body in the Sugarloaf Mountain area, north of Marquette, also is a dome; foliation in adjacent metavolcanic rocks (Puffett, 1974) dips gently to moderately away from the granite contact.

Late-Tectonic Conglomerate

The youngest Archean unit in the greenstone-granite terrane is the Reany Creek Formation (Puffett, 1969; 1974). On the basis of the reinterpretation of age and structural relationships, the Reany Creek Formation is no longer included as part of the Chocolay Group or the Marquette Range Supergroup. It is a heterogeneous body of conglomerate, arkose, chloritic slate, graywacke, and boulder-bearing slate. It transects structures in the older volcanic rocks, is less deformed than the volcanic rocks, and is bounded along its south margin by the northwest-trending Dead River shear zone (fig. 1). Its age has been uncertain (see Puffett, 1974), but its penetrative foliation, asymmetry of basin fill, and relationship to the Dead River shear zone strongly suggest that it developed concurrently with dextral shear along the Dead River shear zone. It is similar to "Timiskaming-type" sequences, such as the Seine Group, in northern Ontario, now commonly interpreted as forming in Archean analogs to modern pull-apart basins (Poulsen, 1986; Thurston and Chivers, 1990).

ARCHEAN GNEISS TERRANE

The Archean gneiss terrane in the Marquette area (fig. 1) constitutes the greater part of the southern complex, as defined by Van Hise and Bayley (1897). It consists of gneiss, migmatite, and amphibolite, substantial amounts of deformed and undeformed granite pegmatite, and massive to weakly foliated granite plutons. Cannon and Simmons (1973) have described the general rock types in much of the southern complex. One rock has been dated as Late Archean. A sample of gray gneiss (called Compeau Creek Gneiss by Gair, 1975) collected in SE¼SW¼ sec. 36, T. 47 N., R. 27 W. (Hammond, 1978) has a U-Pb zircon age of 2,779±21 Ma and a lower intercept age of 802±76 Ma (recalculated by Zell E. Peterman).

Gneiss and Associated Granitoid Rocks

Compositionally layered, medium-grained gneiss and migmatite are the dominant rock types in the gneiss terrane in the Marquette area. Layered felsic gneisses ranging in composition from tonalite to granite predominate. Smaller amounts of massive to layered amphibolite are intercalated with the felsic gneiss, but amphibolite constitutes layers several tens of meters thick at places, as can be seen on the geologic map of the Palmer 7½-minute quadrangle (Gair, 1975, pl. 1), which is immediately west of the Sands quadrangle. The felsic gneisses are gray to pinkish gray; typically, compositional layering is expressed by different proportions of the major silicate minerals, as for example, (1) plagioclase-quartz-biotite-microperthite, (2) microperthite-quartz-plagioclase-biotite, and (3) biotite-quartz-plagioclase-microperthite. Textural differences at places emphasize the compositional layering. Pink aplitic granite and granite pegmatite commonly transect the gneiss and amphibolite and locally form migmatite. Metasedimentary rocks such as iron-formation, which forms layers in the felsic gneisses in the vicinity of the Republic trough (Cannon and Simmons, 1973), were not observed in the Marquette area.

Pinkish-gray to pink, medium-grained, massive to weakly foliated, homogeneous granite (table 2; fig. 3) intrudes the gneisses at places. Hammond (1978) delineated a body of massive granite about 4 km^2 in areal extent south of Ishpeming, Mich. (unit Wgt, fig. 1), which he informally called the "Tilden granite." It is a gray to pink, medium-grained, locally porphyritic massive granite that locally contains oriented xenoliths of mafic gneiss. It is cut by pink pegmatite and is highly fractured. The fractures have slickensided surfaces and a thin coating of chlorite and other propylitic alteration minerals. Isotopic data on samples of the granite near Tilden of Hammond (1978) indicate that both the Rb-Sr and U-Th-Pb systems are highly disturbed. Four zircon fractions from one sample of a red phase of the

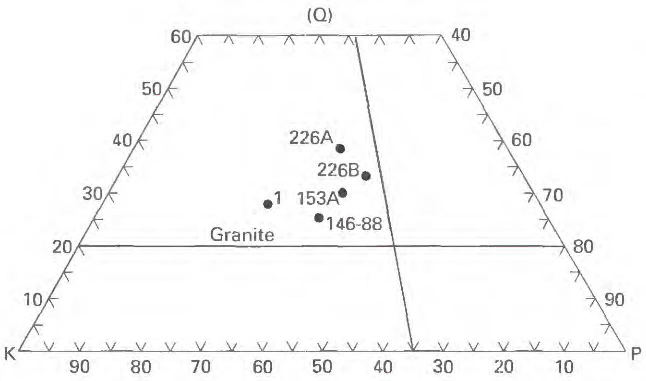


Figure 3. Quartz–alkali feldspar–plagioclase diagram for granitoid rocks of Archean gneiss terrane, Marquette area. Modes given in table 2.

granite yield an age of 2,545±71 Ma, but when combined with two zircon fractions from another red phase yield an age of 2,633±100 Ma (Hammond, 1978, p. 38). Six zircon fractions from two samples of the gray phase, however, yield an age of 2,345±20 Ma, which is comparable to a 2,330 Ma Rb-Sr whole-rock age on the same rock body. Hammond (1978) concluded that the granite near Tilden probably dates at about 2,350 Ma. I suggest, however, that the granite is Late Archean in age and that the ≈2,350 Ma age records highly disturbed Rb-Sr and U-Pb systems.

A nearly circular body of alkali granite (unit Xga, fig. 1) about 2 km in diameter occurs about 3 km south of Humboldt, Mich. (Schulz and others, 1988). The granite is light red to brick red, generally massive, fine to medium grained, and equigranular to hypidiomorphic granular. The granite is similar compositionally to Sn-W mineralized alkali feldspar granites of the Arabian Shield (Jackson and Ramsay, 1986) and the Nigerian younger granite province (Kinnaird and others, 1985). The granite has a Rb-Sr whole-rock age of 1,733±25 Ma, which is interpreted as a crystallization age (Zell E. Peterman, written commun., 1988); it is a post-tectonic intrusion.

Structure

Archean gneisses in the southern complex form a northwest-trending antiformal structure that closes to the west and is overlapped by Paleozoic rocks to the east (Sims, 1991). An infolded belt of Early Proterozoic (Marquette Range Supergroup) rocks indents the Archean fold nose in the Republic trough (fig. 1). In the area west of the Republic trough, Taylor (1967) determined two principal phases of deformation: (1) early, probably flat lying folds with axial planes trending northeastward, and (2) younger upright folds with steep northwest-trending axial surfaces. The latter phase mainly controls the distribution of the rock units.

Table 2. Approximate modes of granitoid rocks, in volume percent, in Archean gneiss terrane

[Tr., trace; blank, absent]

Sample No.	153A	146–88	1	226A	226B
Plagioclase	34.7	33.5	25	26.3	39.3
Quartz	28	23.8	25	38.2	32.7
Potassium feldspar	28	34.2	40	33.0	25.0
Biotite	9	8.0	3	2.2	3
Chlorite		Tr.	Tr.	Tr.	Tr.
Muscovite	Tr.	Tr.	2		Tr.
Epidote		Tr.			
Sphene			Tr.		
Opaque oxides	Tr.		Tr.		
Accessory minerals	0.3	0.5	Tr.	0.3	Tr.

SAMPLE DESCRIPTIONS

153A.	Pinkish-gray, medium-grained, foliated granite, SE¼NE¼ sec. 7, T. 46 N., R. 26 W. Biotite is weakly altered.
146–88.	"Tilden granite" of Hammond (1978). Quartz and biotite are recrystallized in shears; biotite slightly altered to chlorite.
1.	"Tilden granite" of Hammond (1978, p. 63). Potassium feldspar is microperthite. Plagioclase has concentric zoning. Highly fractured.
226A.	Light-gray, medium-grained, foliated granite. Cut by fractures. Biotite highly altered to chlorite. Quarry, SE¼SW¼ sec. 21, T. 46 N., R. 26 W.
226B.	Pale-reddish-brown, medium-grained foliated granite. Cut by shears, some with mylonite. Biotite highly altered to chlorite and calcite. SE¼SW¼ sec. 21, T. 46 N., R. 26 W. Same locality as 226A.

In the Marquette area, early gently inclined to recumbent folds that trend northwestward and plunge gently northward (fig. 4) are the dominant structure in the gneisses. These folds deform an older foliation (S_1). Boudinage accompanied the folding; the boudins plunge subparallel to gently inclined fold hinges. The flat foliation is overprinted at a distance of about 0.4 km from the GLTZ by the mylonite foliation in the GLTZ. Discernible remnants of the older, gently dipping foliation remain, however, in the mylonite zone.

A narrow ductile shear zone trending N. 45° W. and dipping 75° NE. was delineated in the eastern part of sec. 31, T. 47 N., R. 26 W., 1.5 km south of Palmer (fig. 1). A mineral lineation and mullions in the shear zone plunge 70° N. 10° E. The rocks within this shear zone are fine grained (mylonite) and extensively sericitized. The shearing obliterates the older, gently dipping foliation.

GREAT LAKES TECTONIC ZONE

The GLTZ is characterized in the Marquette area (figs. 1, 5, and 6) by a mylonite zone about 2.4 km wide that

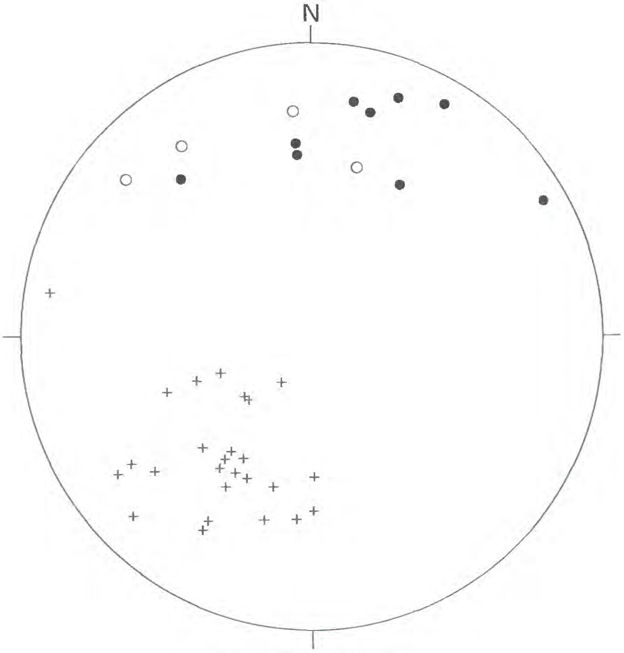


Figure 4. Equal-area projection of poles to foliation (cross, *n*=26), lineations (dot, *n*=9), and fold hinges (open circle, *n*=4) in gneisses of Archean gneiss terrane.

has been superposed on dominantly massive granitoid rocks and schists of the Archean greenstone-granite terrane and previously deformed rocks of the Archean gneiss terrane. As mapped (fig. 5), the mylonite zone is about 2 km wide in the greenstone-granite terrane and 0.4 km wide in the gneiss terrane. The great width of this shear zone distinguishes it from the other, much narrower shear zones and faults in the region. The mylonite grades northward into protomylonite and highly fractured and altered rocks (fig. 5).

Foliation in the mylonite zone strikes west-northwest and dips steeply southwest (fig. 7), presumably subparallel to the N. 60°–65° W.-trending boundary between the greenstone-granite and gneiss terranes. A pronounced rodding (stretching) lineation in the mylonite, expressed mainly by comminuted and recrystallized quartz and quartz-feldspar aggregates, plunges about 45° S. 45° E. Hinges of tight folds are subparallel to the plunge of the stretching lineation (fig. 7). Locally, slickensides and tectonic grooves are also parallel to the lineation.

Mylonite

The mylonite is mainly orthomylonite, as defined by Wise and others (1984), inasmuch as surviving megacrysts compose 10–20 percent of the rock. In the terminology of Hanmer (1987), the mylonites are mainly "heteroclastic" because the porphyroclasts have variable size ranges, but include "homoclastic" mylonite having more uniform textural characteristics. Ultramylonite is absent except on a scale of a few centimeters.

Mylonite on the north side of the boundary between the greenstone-granite terrane and the gneiss terrane shows progressive sequential textural development from protomylonite to orthomylonite. In the zone of protomylonite, quartz in granitoid rocks is strained, sutured, and recrystallized into lensoid aggregates. In the northern part of the mylonite zone, as defined in figure 5, quartz typically is recrystallized into "ribbon quartz," yielding a pronounced rodding (stretch) lineation. Amphibolite xenoliths in the granitoid rocks in this part of the zone are virtually undeformed but are somewhat retrograded, as indicated by the presence of some actinolite and chlorite, indicating deformation under upper greenschist metamorphic conditions. Inward, the relatively stiff minerals, plagioclase and potassium feldspar, are progressively recrystallized to finer grain sizes, with the development of core-mantle structures (White, 1976) or type 1P and 1M structures (Hanmer, 1982); these structures yielded oriented aggregates of quartz and of quartz-and-feldspar that produce a prominent stretching lineation. Accompanying biotite is mainly recrystallized in planar or irregular shears.

Interpretation

The Great Lakes tectonic zone has been interpreted (Gibbs and others, 1984; Southwick and Sims, in press) as a paleosuture resulting from continent-continent collision that juxtaposed the Archean gneiss and greenstone-granite terranes. In the Marquette area, the stretching lineation, which represents the line of tectonic transport (Schackleton and Ries, 1984), indicates that collision was oblique, resulting in dextral shear along the N. 60°–65° W.-trending boundary (paleosuture). The parallelism of the fold axes with the extension direction (X finite strain axis), which is common in many ductile shear zones (Bryant and Reed, 1969), can be accounted for by rotation of fold axes as a result of shear strain perpendicular to the displacement direction (Ridley, 1986; Ridley and Casey, 1989). The deformation resulted from a combination of thrust shear and wrench shear.

The oblique collision would be expected to produce dextral shear across a large region north of the GLTZ (fig. 8). The extent of the area affected by this dextral transcurrent shear is not definitely known, however, because dextral shear was the dominant mechanism of deformation throughout most of the Superior province (Card, 1990). Card has proposed that the Superior craton was constructed from the oblique subduction of a succession of arcs, seamounts, and microcontinents or cratonized islands (modern analogs such as Borneo or New Guinea) that progressed temporally from north (oldest) to south (youngest). This hypothesis is supported by existing

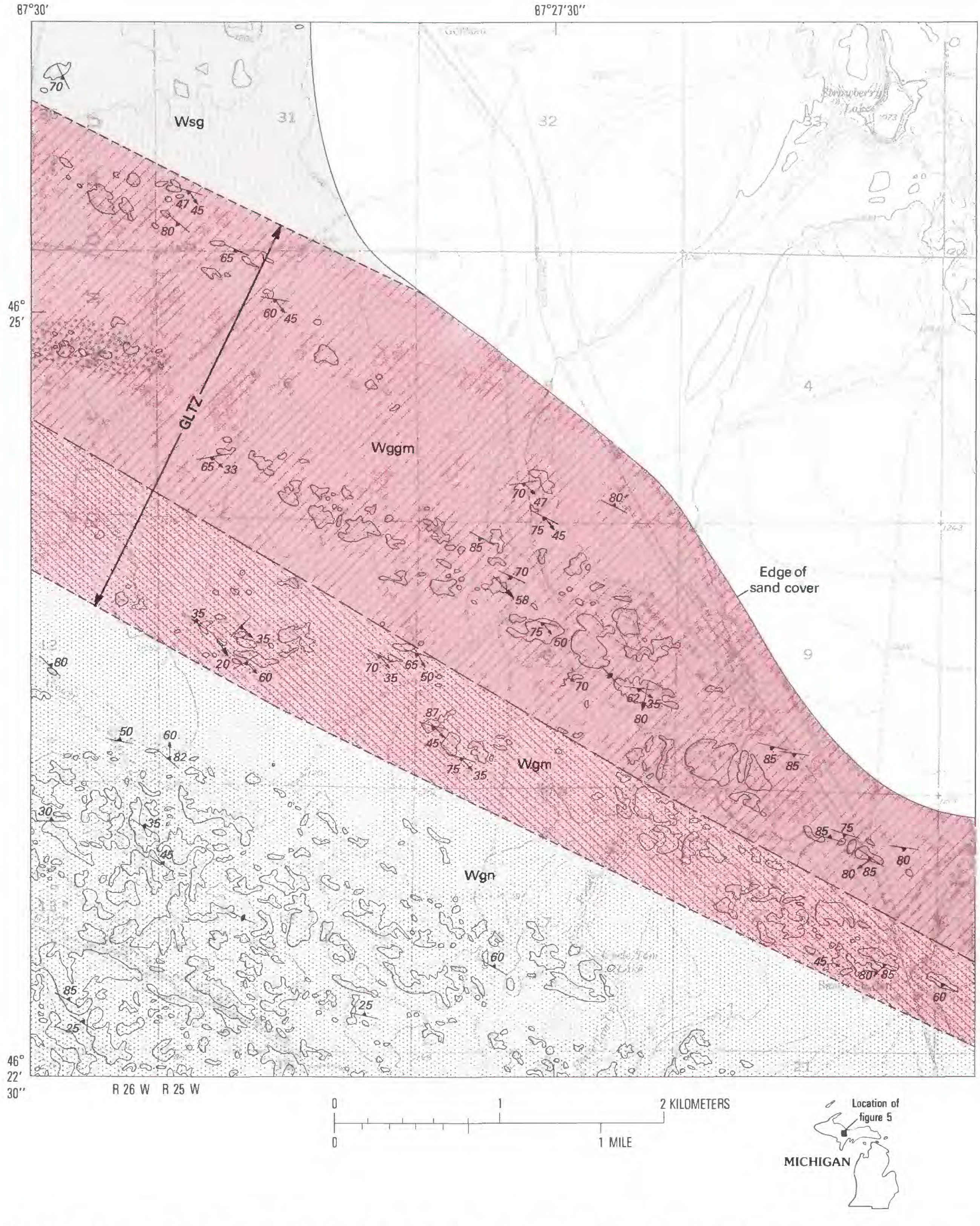


Figure 5 (above and facing page). Structure map of southwestern part of Sands 7½-minute quadrangle showing Great Lakes tectonic zone (modified from Gair and Thaden, 1968, with 1989 additions by Sims). Surficial materials above Archean not shown; outlines of outcrops are from plate 2 of Gair and Thaden (1968).

EXPLANATION

Archean

Greenstone-granite terrane

Wsg	**Biotite schist and granitoid rocks**
Wggm	**Mylonite**—Protolith dominantly granitoid rocks but includes biotite schist and amphibolite

Gneiss terrane

Wgn	**Gneiss, migmatite, and amphibolite**—Includes foliated and massive granite
Wgm	**Mylonite**—Dominantly mylonitic quartzofeldspathic gneiss
⁘	**Silicified rocks**
— — —	**Boundary between rocks of greenstone-granite terrane and gneiss terrane within the Great Lakes tectonic zone** (GLTZ)
- - - - - -	**Approximate outer limit of orthomylonite in Great Lakes tectonic zone**
25	**Strike and dip of foliation** **Inclined**
┼	**Vertical**
45	**Bearing and plunge of minor fold**
→ 20	**Bearing and plunge of lineation**—May be combined with foliation symbols

geochronological data, particularly the southward-younging ages of the terminal granitoid plutons in the various subprovinces of the Superior province (Hoffman, 1989).

The absence of any known suture in the Wawa subprovince (fig. 8) suggests that it is a single structural terrane. Structures in the greenstone-granite rocks of northern Minnesota (Wawa subprovince) are remarkably similar to those in northern Michigan. In northern Minnesota, deformed and metamorphosed volcanic and sedimentary rocks of the Vermilion district (Sims, 1976; Sims and Southwick, 1985) compose an east-trending belt between higher grade rocks of the Late Archean Vermilion Granitic Complex (Quetico subprovince, fig. 8) (Southwick, 1972) and the Giants Range batholith to the south. The measured strain, a cleavage, upright folds, and a mineral lineation in this belt have been attributed to the "main" phase of deformation (D_2) that followed an early nappe-forming event (D_1) (Bauer, 1985). The nappes show little evidence of a penetrative fabric (Hudleston, 1976). Hudleston and others (1988) attributed the (D_2) deformation to regional dextral transpression, as the strain pattern requires a northeast-southwest component of shortening in addition to shear. They further proposed that major dextral faults, such as the Vermilion fault (fig. 8), are later more brittle expressions of this shear regime. They concluded that the D_2 transpressive deformation resulted from oblique compression between the two more rigid crustal blocks to the north (Quetico subprovince) and south (Giants Range batholith). A similar tectonic regime has been recognized in the Rainy Lake area (Poulsen and others, 1980; Day and Sims, 1984; Wood, 1980), where early recumbent folding was followed by upright folding and dextral strike-slip faulting.

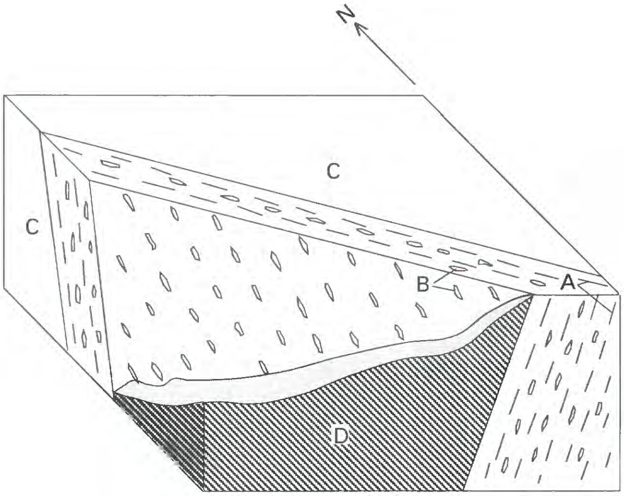


Figure 6. Isometric diagram (not to scale) illustrating geometry and deformational elements of Great Lakes tectonic zone. A, mylonitic foliation; B, quartz and quartz-feldspar aggregates that define a moderately plunging stretch lineation; C, dominantly granite-tonalite rocks of Archean greenstone-granite terrane; D, gneiss of Archean gneiss terrane.

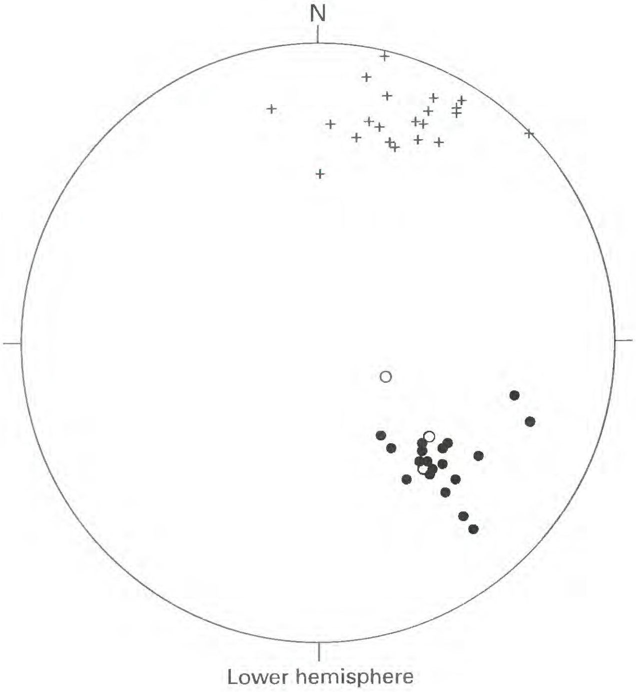


Figure 7. Equal-area projection of poles to foliation (cross, n=21), stretching lineation (dot, n=19), and fold hinges (open circle, n=3) in mylonite of Great Lakes tectonic zone, Sands and Palmer 7½-minute quadrangles, Marquette area, Michigan.

Recent precise isotopic analyses of zircon, titanite, and rutile from the Rainy Lake area, Canada (Davis and others, 1989), which lies between the Quetico and Wabigoon subprovinces, have provided time constraints on these

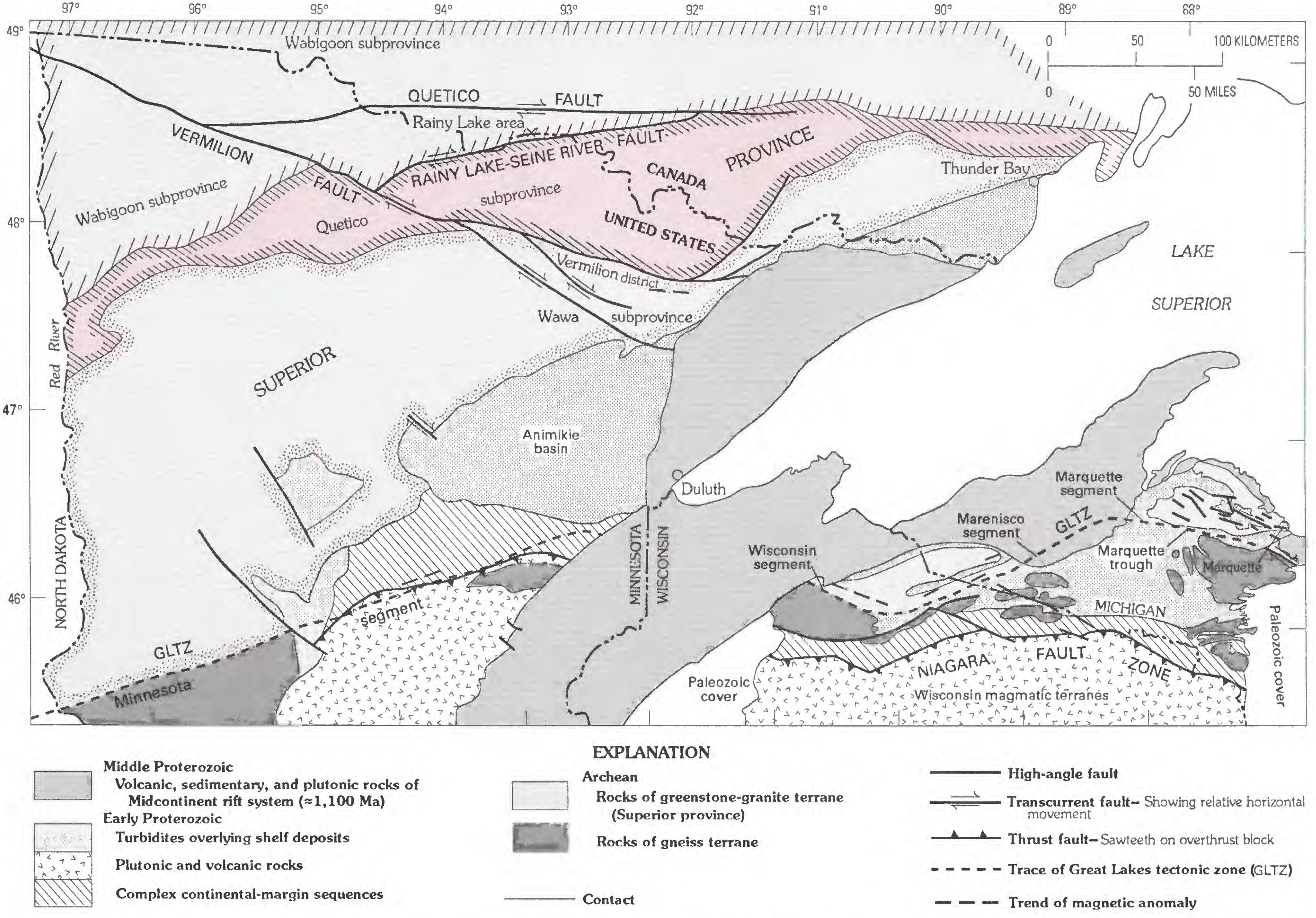


Figure 8. Simplified tectonic map of Lake Superior region showing Great Lakes tectonic zone and adjacent Archean terranes. Geology modified from Morey and others (1982), Southwick and Morey (in press), Sims (1991), and W.C. Day (written commun., 1990). Terminology of Early Proterozoic rocks modified from Southwick and Morey (in press).

structural events. The major deformation, including nappe emplacement, thrusting, and local doming, took place between 2,696 Ma and 2,692 Ma; this deformation was followed shortly by wrench faulting and simultaneous deposition of conglomerate/arenite (Seine Group), which occurred in the interval 2,692–2,686 Ma. Late (Algoman) granitic plutons were emplaced about 2,686 Ma, although some are older. In the Wawa subprovince, west of Thunder Bay, Ont. (fig. 8), Corfu and Stott (1986) found that the D_1 deformation occurred during or before the intrusion of the Shebandowan Lake pluton at 2,696±2 Ma. Deformation D_2 in this area occurred between 2,689+3/–2 Ma and 2,684+6/–3 Ma, similar to the age suggested by Davis and others (1989) for D_2 in the Rainy Lake wrench zone. These ages are compatible with the less precise isotopic ages on rocks in northern Minnesota and Michigan (Peterman, 1979), and it seems probable that the rocks and structures throughout the Wawa and Quetico subprovinces are approximately coeval (Percival, 1989). Although convergence along the GLTZ undoubtedly was diachronous, collision probably occurred in the approximate interval 2,692–2,686 Ma (Davis and others, 1989).

Kinematic Analysis

The attitude of the stretching lineation (line of tectonic transport) in the mylonite exposed south of Marquette together with asymmetric meso- and micro-structures revealing sense of movement indicates that the oblique collision resulted in dextral-thrust shear along the GLTZ and northwestward vergence and probable overriding of the Archean greenstone-granite terrane by the Archean gneiss terrane. Kinematic indicators—rotated mica grains within narrow compositional layers, asymmetric porphyroclasts with tails (σ type; Simpson, 1986), and asymmetric microfolds in mylonitic layering—indicate northwestward vergence. This information implies southward subduction of the Archean greenstone-granite terrane (Wawa subprovince) beneath the Archean gneiss terrane.

Evolution

The northwest direction of tectonic transport during suturing of the Archean terranes ascertained from the Marquette area provides a means for determining the evolution of the GLTZ and the variable trajectory of stress into the Superior province crust.

The GLTZ in the Lake Superior region is characterized by systematic angular bends that alternately trend northeastward and west-northwestward (fig. 8). Presumably this zigzag pattern reflects original irregularities in the margin of the Archean greenstone-granite terrane (or Superior province) crust, which was a continental margin before convergence and collision with the southern Archean gneiss terrane.

The northeast-trending and west-northwest-trending segments of the GLTZ have different structural styles. As discussed earlier, deformation along the northwest-trending segments of the GLTZ, as particularly shown by data from the Marquette segment, was principally caused by dextral transpression resulting from oblique collision. Transmittal of this transcurrent shear into rocks north of the GLTZ yielded a widespread, pervasive west-northwest- to west-striking foliation, subparallel upright folds, and northwest- to west-trending dextral faults and shear zones in the Archean greenstone-granite terrane.

The similarly oriented northwest-trending segment of the GLTZ in northwestern Wisconsin has many structural features in common with the Marquette segment. Foliation and upright folds in low amphibolite-facies rocks of the Archean greenstone-granite terrane (unit **Wga**, fig. 4, Sims and others, 1985) strike west-northwest, and mineral lineations and fold hinges mainly plunge gently southeast. The boundary between the two terranes is not exposed because of a glacial cover, but is presumed to lie along the south edge of unit **Wga**. Numerous northwest-trending dextral faults, some of which reactivated in Early Proterozoic time, have been mapped in the area (Sims and others, 1985; fig. 1).

Collision along the northeast-trending segments of the GLTZ, on the other hand, produced northeast-trending structures of apparently more restricted areal extent. In the northeast-trending Marenisco segment (fig. 8; Sims and others, 1984), the boundary is covered by Early Proterozoic sedimentary and volcanic rocks, but lithologic layering and foliation in rocks of the adjacent Archean greenstone-granite terrane near the boundary trend northeastward and are deformed into upright, moderately tight northeast-trending folds that plunge 45°–50° SW. These structures are presumably subparallel to the covered Archean boundary. Archean metamorphism has been overprinted by Early Proterozoic Penokean nodal metamorphism centered on the Watersmeet dome (Sims and others, 1985; Sims, 1990); the presence of relict garnet at a few places in the Archean rocks of the greenstone-granite terrane near the boundary suggests that these rocks were metamorphosed to at least upper greenschist facies in Archean time. In the same way, north-verging Penokean deformation in the boundary zone overprinted Archean structures (Sims and others, 1984). An axial plane S_2 (Penokean) penetrative cleavage that strikes northeast and dips 45°–70° SE. was superposed on the previously folded rocks. Apparently the Archean rocks were not refolded, however, as a result of the Penokean deformation.

In the northeast-trending Minnesota segment of the GLTZ, neither the terrane boundary nor the Archean rocks on either side are exposed. They are covered in west-central Minnesota by thick Quaternary glacial deposits and in central Minnesota by Early Proterozoic sedimentary and volcanic rocks of the Animikie basin (Southwick and others, 1988). The GLTZ has been investigated, however, by a detailed aeromagnetic survey, by computer-generated mapping of the second vertical derivative of the gravity field, and by shallow test-drilling (see Southwick and Sims, in press); the boundary has been located rather accurately on the basis of these data. The drilling has shown that the rocks on the northwest side are volcanogenic sedimentary and mafic to intermediate volcanic rocks, metamorphosed to upper greenschist facies, which are intruded by Archean tonalite (Southwick and Chandler, 1983). These rocks are typical of the Archean greenstone-granite terrane in exposed parts of the Lake Superior region. A seismic reflection profile in central Minnesota acquired by COCORP (Consortium for Continental Reflection Profiling) has been interpreted to indicate that the GLTZ in this area is a shallow (≈30°) north-dipping tectonic feature (Gibbs and others, 1984). In east-central Minnesota, the GLTZ is covered by Proterozoic rocks of the Animikie basin. The structural style in the Proterozoic cover indicates north-verging tectonism (Southwick and others, 1988), and as in the Marenisco segment, the Archean crustal boundary had a role in defining Penokean deformation.

Deformation along both of the northeast-trending segments of the GLTZ resulted mainly from northwest-southeast shortening, probably dominantly by flattening strain. The direction of tectonic transport during convergence was virtually perpendicular to the juncture of the two terranes at these localities.

The origin of the zigzag pattern of the south edge of the Superior province, now marked by the GLTZ, is uncertain. The prevailing thought is that the Wawa subprovince is one of a sequence of stacked island arcs that formed progressively from north to south above north-dipping subduction zones as the continental mass to the south of the GLTZ (that is, the Archean gneiss terrane) migrated to the north (Card, 1990). With this interpretation, possible modern analogs of the Superior province are the convergent-plate boundaries of the western Pacific, as for example those of the Indonesian region (Hamilton, 1979).

The physical resemblance of the south margin of the Superior province to the Appalachian-Ouachita Paleozoic orogenic belt (Thomas, 1977), however, suggests a possible alternative interpretation for the origin of the Superior margin. In this interpretation, the Superior margin was a rifted continental margin. Two interpretations have been made for the origin of the Paleozoic continental margin: (1) rift segments offset by transform faults, as suggested by Thomas (1977, 1983), or (2) intersections between active rift arms at triple junctions (Rankin, 1976). Of these two suggestions, the rift-transform mechanism seems the more likely, with the Minnesota and Marenisco segments being the rifted segments (fig. 8) and the northwestern Wisconsin and Marquette segments being highly modified transform faults. Regardless of the mechanism by which the zigzag Archean continental margin originated, the subsequent trace of the orogenic belt probably was inherited from the shape of the earlier margin.

CONCLUDING REMARKS

Convergence along the irregularly shaped margin of the Archean greenstone-granite terrane (GLTZ) resulted in a variable trajectory of stress into the continental crust and probably in along-strike diachroneity of orogeny. Structural data from the Marquette area, in particular, as well as elsewhere along the GLTZ, suggest that the major direction of tectonic transport was northwestward. Accordingly, promontories such as those along the concave part of the Marquette and Wisconsin segments of the GLTZ (fig. 8) must have projected as buttresses against which compressive stress was directed into the continental crust. Oblique compression at these points produced dextral shear across the region north of the suture, probably at least as far northward as the Quetico fault, a distance of about 250 km. This shear imposed a roughly east west, steep structural fabric on the rocks and, as a late, more brittle expression of the shear regime (Hudleston and others, 1988), the northwest- to west-trending dextral transcurrent faults.

Along the Marenisco and Minnesota segments of the GLTZ, where convergence was more nearly perpendicular to the ancient continental margin, a northeast-trending structural fabric was imposed on the rocks immediately cratonward from the suture.

I suggest that the main structural fabric (D_2) in rocks of the Archean greenstone-granite terrane in the north-central United States (Wawa and Quetico subprovinces; fig. 8) resulted from the collision along the GLTZ. The predominance of orthomylonite rather than ultramylonite and the nearly pervasive retrogressive alteration (greenschist facies) in rocks of the greenstone-granite terrane suggest that the exposed collision zone was developed at a moderately shallow crustal level. As discussed in a previous report (Sims and others, 1980), the Archean structures in this regime played a strong role also in subsequent tectonism, especially in the Early Proterozoic north-verging deformation.

I further suggest that the late-tectonic granite bodies in the Archean gneiss terrane are possibly related to the collision along the GLTZ and presumed southward subduction. The available age data on these granites are compatible with a presumed 2.69 Ga age for the collision. The "Tilden granite" of Hammond (1978) in Michigan has a probable Late Archean age, although both the U-Pb and Rb-Sr systems are disturbed. In the Minnesota River valley, in southwestern Minnesota, a large pluton of late-tectonic granite (Sacred Heart Granite) has a Pb-Pb age of about 2,605 Ma (Doe and Delevaux, 1980) and a Rb-Sr age of about 2.7 Ga (Goldich and others, 1970). Doe and Delevaux

(1980) have shown that ^{207}Pb-^{204}Pb values in the Sacred Heart Granite are characteristic of ensialic environments, as contrasted with the ensimatic (arc) granitoid bodies in the Superior province (greenstone-granite terrane). The ensialic environment indicates that the Archean gneiss terrane had been cratonized prior to emplacement of the Sacred Heart Granite. Precise ages are required to test the hypothesis that the Late Archean granites south of the GLTZ were indeed formed during continent-continent collision.

Cumulative data on the Archean Superior province (see Hoffman, 1989, for review) indicate that it consists of generally east trending belts of island arc and related rocks that were assembled progressively from north to south (Card, 1990), before finally colliding with the Archean gneiss terrane (continent) on the south at about 2,690 Ma. This pattern of accretion as well as the tectonic style is not unlike that in modern plate-tectonic regimes, indicating that plate-tectonic mechanisms existed in the Archean as well as in the Proterozoic and Phanerozoic.

REFERENCES CITED

Bauer, R.L., 1985, Correlation of early recumbent and younger upright folding across the boundary between an Archean gneiss belt and greenstone terrane, northeastern Minnesota: Geology, v. 13, p. 657–660.

Baxter, D.A., and Bornhorst, T.J., 1988, Multiple discrete mafic intrusions of Archean to Keweenawan age, western Upper Peninsula, Michigan: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Proceedings and Abstracts, p. 6–8.

Bodwell, W.A., 1972, Geologic compilation and non-ferrous metal potential, Precambrian section, northern Michigan: Houghton, Mich., Michigan Technological University M.S. thesis, 106 p.

Bornhorst, T.J., 1988, Geological overview of the Marquette greenstone belt, Michigan: Institute on Lake Superior Geology Field Trip Guidebook, v. 34, pt. 2, p. A1–A18.

Brozdowski, R.A., 1988, Geology of the Ropes gold mine: Institute on Lake Superior Geology Field Trip Guidebook, v. 34, pt. 2, p. A32–A53.

______ 1989, Geology of the Ropes gold deposit, *in* Margeson, G.B., ed., Precambrian geology and metal occurrences, Michigan's Upper Peninsula, Field Conference: Society of Economic Geologists, p. 38–75.

Brozdowski, R.A., Gleason, R.J., and Scott, G.W., 1986, The Ropes mine—A pyritic gold deposit in Archean volcaniclastic rock, Ishpeming, Michigan, U.S.A., *in* MacDonald, A.J., ed., Proceedings of Gold 86, an International Symposium on the Geology of Gold, Toronto: p. 228–242.

Bryant, Bruce, and Reed, J.C., Jr., 1969, Significance of lineation and minor folds near major thrust faults in the southern Appalachians and the British and Norwegian Caledonides: Geological Magazine, v. 106, p. 412–429.

Cambray, F.W., 1984, Proterozoic geology, Lake Superior, south shore: Geological Association of Canada–Mineralogical Association of Canada, London, Ontario, Field trip 5, 55 p.

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

Cannon, W.F., and Simmons, G.C., 1973, Geology of part of the southern complex, Marquette district, Michigan: U.S. Geological Survey Journal of Research, v. 1, no. 2, p. 165–172.

Card, K.D., 1990, A review of the Superior province of the Canadian Shield, a product of Archean accretion: Precambrian Research, v. 48, p. 99–156.

Card, K.D., and Ciesielski, Andre, 1986, DNAG No. 1 Subdivision of the Superior Province of the Canadian Shield: Geoscience Canada, v. 13, no. 1, p. 5–13.

Clark, L.D., Cannon, W.R., and Klasner, J.S., 1975, Bedrock geologic map of the Negaunee SW quadrangle, Marquette County, Michigan: U.S. Geological Survey Geologic Quadrangle Map GQ–1226, scale 1:24,000.

Corfu, F., and Stott, G.M., 1986, U-Pb ages for late magmatism and regional deformation in the Shebandowan belt, Superior province, Canada: Canadian Journal of Earth Sciences, v. 23, p. 1075–1082.

Davis, D.W., Poulsen, K.H., and Kamb, S.L., 1989, New insights into Archean crustal development from geochronology in the Rainy Lake area, Superior Province, Canada: Journal of Geology, v. 97, p. 379–398.

Day, W.C., and Sims, P.K., 1984, Tectonic evolution of the Rainy Lake area, northern Minnesota: Geological Association of Canada, the Mineralogical Association of Canada, London, Ontario, Canada, Program with Abstracts, v. 9, p. 57.

Doe, B.R., and Delevaux, M.H., 1980, Lead-isotope investigations in the Minnesota River Valley—Late-tectonic and post-tectonic granites, *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. 105–112.

Gair, J.E., 1975, Bedrock geology and ore deposits of the Palmer quadrangle, Marquette County, Michigan: U.S. Geological Survey Professional Paper 769, 159 p., scale 1:24,000.

Gair, J.E., and Thaden, R.E., 1968, Geology of the Marquette and Sands quadrangles, Marquette County, Michigan: U.S. Geological Survey Professional Paper 397, 77 p., scale 1:24,000.

Gibbs, A.K., Payne, B., Setzer, T., Brown, L.D., Oliver, J.E., and Kaufman, S., 1984, Seismic-reflection study of the Precambrian crust of central Minnesota: Geological Society of America Bulletin, v. 95, p. 280–294.

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.

Hamilton, W.B., 1979, Tectonics of the Indonesian region: U.S. Geological Survey Professional Paper 1078, 345 p.

Hammond, R.D., 1978, Geochronology and origin of Archean rocks in Marquette County, Upper Michigan: Lawrence, Kans., University of Kansas M.S. thesis, 108 p.

Hanmer, Simon, 1982, Microstructure and geochemistry of plagioclase and microcline in naturally deformed granite: Journal of Structural Geology, v. 4, p. 197–213.

_____ 1987, Textural map units in quartzo-feldspathic mylonitic rocks: Canadian Journal of Earth Sciences, v. 24, p. 2065–2073.

Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A.W., and Palmer, A.R., eds., The geology of North America—An overview: Boulder, Colo., Geological Society of America, The Geology of North America, v. A, p. 447–512.

Hudleston, P.J., 1976, Early deformational history of Archean rocks in the Vermilion district, northeastern Minnesota: Canadian Journal of Earth Sciences, v. 13, p. 579–592.

Hudleston, P.J., Schultz-Ela, D., and Southwick, D.L., 1988, Transpression in an Archean greenstone belt, northern Minnesota: Canadian Journal of Earth Sciences, v. 25, p. 1060–1068.

Jackson, N.J., and Ramsay, C.R., 1986, Post-orogenic felsic plutonism, mineralization, and chemical specialization in the Arabian Shield: Transactions of the Institute of Mining and Metallurgy (Sec. B, Applied Earth Sciences), v. 95, p. B83–B93.

Kinnaird, J.A., Batchelor, R.A., Whitley, J.E., and MacKenzie, A.B., 1985, Geochemistry, mineralization, and hydrothermal alteration of the Nigerian high heat producing granites, *in* High heat production granites, hydrothermal circulation and ore genesis: Institute of Mining and Metallurgy, p. 169–195.

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.

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

Morgan, J.P., and DeCristoforo, D.T., 1980, Geological evolution of the Ishpeming Greenstone Belt, Michigan, U.S.A.: Precambrian Research, v. 11, p. 23–41.

Percival, J.A., 1989, A regional perspective of the Quetico metasedimentary belt, Superior Province, Canada: Canadian Journal of Earth Sciences, v. 26, p. 677–693.

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

Poulsen, K.H., 1986, Rainy Lake wrench zone—An example of an Archean subprovince boundary in northwestern Ontario, *in* deWit, M.J., and Ashwal, L.D., eds., Tectonic evolution of greenstone belts: Lunar and Planetary Institute, Houston, Texas, Technical Report 86–10, p. 177–179.

Poulsen, K.H., Borradaile, G.J., and Kehlenbeck, M.M., 1980, An inverted succession at Rainy Lake, Ontario: Canadian Journal of Earth Sciences, v. 17, p. 1358–1369.

Puffett, W.P., 1969, The Reany Creek Formation, Marquette County, Michigan: U.S. Geological Survey Bulletin 1274–F, 25 p.

_____ 1974, Geology of the Negaunee quadrangle, Marquette County, Michigan: U.S. Geological Survey Professional Paper 788, 53 p., scale 1:24,000.

Rankin, D.W., 1976, Appalachian salients and recesses—Late Precambrian continental breakup and opening of the Iapetus Ocean: Journal of Geophysical Research, v. 81, p. 5605–5619.

Ridley, John, 1986, Parallel stretching lineations and fold axes oblique to a shear displacement direction—A model and observations: Journal of Structural Geology, v. 8, p. 647–653.

Ridley, John, and Casey, M., 1989, Numerical modeling of folding in rotational strain histories—Strain regimes expected in thrust belts and shear zones: Geology, v. 17, p. 875–878.

Schackleton, R.M., and Ries, A.C., 1984, The relation between regionally consistent stretching lineations and plate motions: Journal of Structural Geology, v. 6, p. 111–117.

Schulz, K.J., Sims, P.K., and Peterman, Z.E., 1988, A post-tectonic rare-metal-rich granite in the southern complex, Upper Peninsula, Michigan: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, Proceedings and Abstracts, p. 95–96.

Simpson, Carol, 1986, Determination of movement sense in mylonites: Journal of Geological Education, v. 34, p. 246–261.

Sims, P.K., 1976, Early Precambrian tectonic-igneous evolution in the Vermilion district, northeastern Minnesota: Geological Society of America Bulletin, v. 87, p. 379–389.

_____ 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 gneisses and lower Proterozoic rocks, southern Canadian Shield: Geological Society of America Special Paper 182, p. 113–124.

_____ 1990, Geologic map of Precambrian rocks, Marenisco, Thayer, and Watersmeet 15-minute quadrangles, Gogebic and Ontonagon Counties, Michigan, and Vilas County, Wisconsin: U.S. Geological Survey Miscellaneous Investigations Series Map I–2093, scale 1:62,500.

_____ 1991, Geologic map of Precambrian rocks, southern Lake Superior region, Wisconsin and northern Michigan: U.S. Geological Survey Miscellaneous Investigations Series Map I–2185, scale 1:500,000.

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. 1, p. 690–698.

Sims, P.K., and Morey, G.B., 1973, A geologic model for the development of early Precambrian crust in Minnesota: Geological Society of America Abstracts with Programs, v. 5, p. 812.

Sims, P.K., and Peterman, Z.E., 1981, Archean rocks in the southern part of the Canadian Shield—A review: Geological Society of Australia Special Publication 7, p. 85–98.

Sims, P.K., Peterman, Z.E., Prinz, W.C., and Benedict, F.C., 1984, Geology, geochemistry, and age of Archean and Early Proterozoic rocks in the Marenisco-Watersmeet area, northern Michigan: U.S. Geological Survey Professional Paper 1292–A, 42 p.

Sims, P.K., Peterman, Z.E., Zartman, R.E., and Benedict, F.C., 1985, Geology and geochronology of granitoid and metamorphic rocks of Late Archean age in northwestern Wisconsin: U.S. Geological Survey Professional Paper 1292–C, 17 p.

Sims, P.K., and Southwick, D.L., 1985, Geologic map of Archean rocks, western Vermilion district, northern Minnesota: U.S. Geological Survey Miscellaneous Investigations Series Map I–1527, scale 1:48,000.

Southwick, D.L., 1972, Vermilion granite-migmatite massif, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 108–119.

Southwick, D.L., and Chandler, V.W., 1983, Subsurface investigations of the Great Lakes tectonic zone, west-central Minnesota: Geological Society of America Abstracts with Programs, v. 15, p. 692.

Southwick, D.L., and Morey, G.B., in press, Tectonic imbrication and foredeep development in the Penokean orogen, east-central Minnesota—An interpretation based on regional geophysics and the results of test-drilling: U.S. Geological Survey Bulletin 1904–C, 17 p.

Southwick, D.L., Morey, G.B., and McSwiggen, P.L., 1988, Geologic map of the Penokean orogen, central and eastern Minnesota, and accompanying text: Minnesota Geological Survey Report of Investigations 37, 25 p., scale 1:250,000.

Southwick, D.L., and Sims, P.K., in press, The Great Lakes tectonic zone, *in* Reed, J.C., Jr., and others, eds., Precambrian—Conterminous United States: Boulder, Colo., Geological Society of America, The Geology of North America, v. C–2.

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

Taylor, W.E.G., 1967, The geology of the lower Precambrian rocks of the Champion-Republic area of Upper Michigan: Evanston, Illinois, Northwestern University Report 13, 33 p.

Thomas, W.A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233–1278.

______ 1983, Continental margins, orogenic belts, and intracratonic structures: Geology, v. 11, p. 270–272.

Thurston, P.C., and Chivers, K.M., 1990, Secular variation in greenstone sequence development, emphasizing Superior Province, Canada: Precambrian Research.

Van Hise, C.R., and Bayley, W.S., 1897, The Marquette iron-bearing district of Michigan: U.S. Geological Survey Monograph 28, 608 p.

White, S.H., 1976, The effects of strain on the microstructures, fabrics, and deformation mechanisms in quartzites: Royal Society of London Philosophical Transactions, ser. A283, p. 69–86.

Wise, D.U., and seven others, 1984, Fault-related rocks—Suggestions for terminology: Geology, v. 12, p. 391–394.

Wood, John, 1980, Geology of the Hewitt Lake area, District of Kenora, Patricia portion: Ontario Geological Survey, Report 186, 122 p.

☆U.S. GOVERNMENT PRINTING OFFICE: 1991-573-049/46001

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

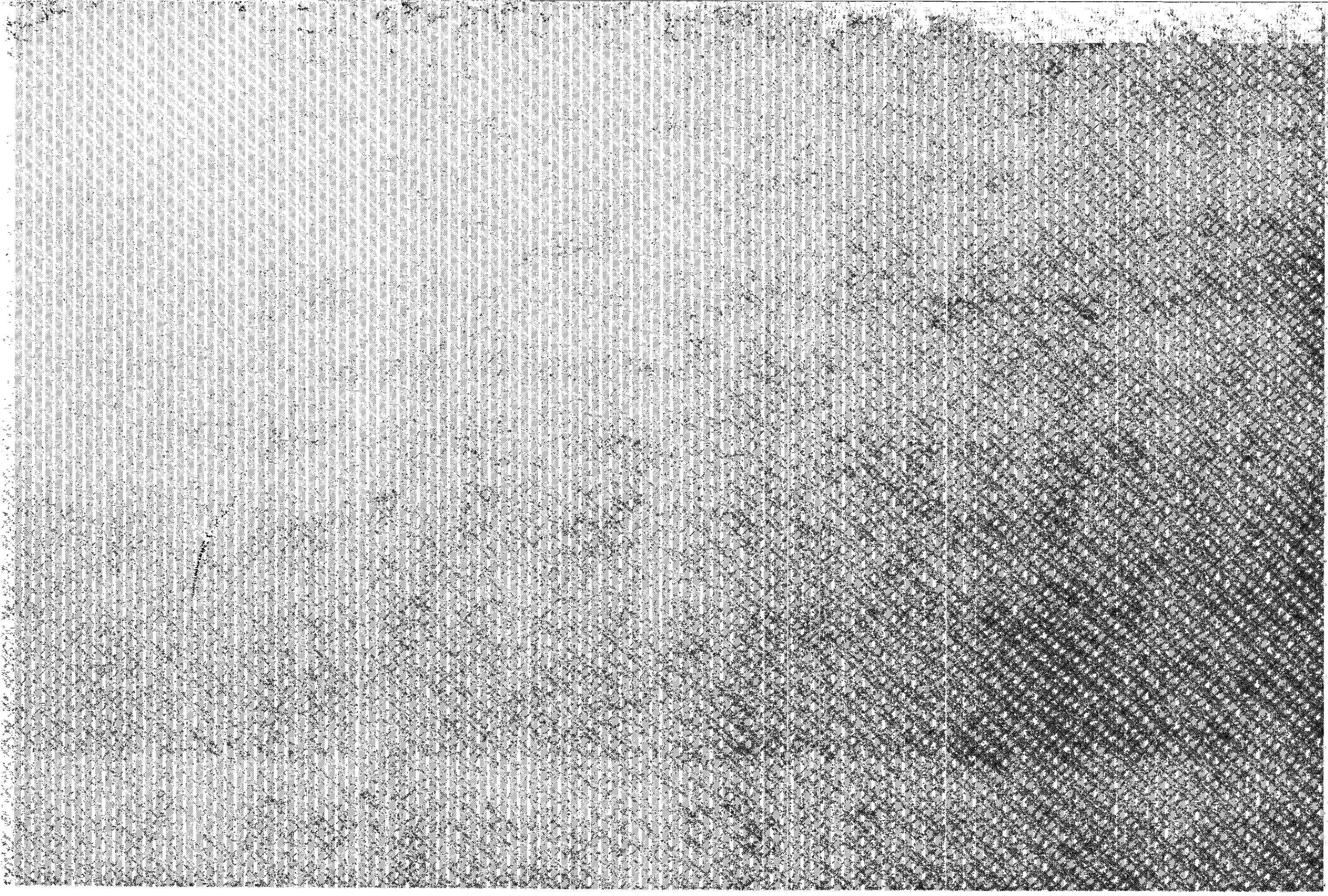
Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.



[illegible]