The Great Lakes Tectonic Zone—Revisited

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Chapter S

The Great Lakes Tectonic Zone—Revisited

By P.K. SIMS and W.C. DAY

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
BRUCE BABBITT, Secretary

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

UNITED STATES GOVERNMENT PRINTING OFFICE: 1993

For sale by
USGS Map Distribution
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Sims, P.K. (Paul Kibler), 1918–
Great Lakes tectonic zone—revisited / by P.K. Sims and W.C. Day.
p. cm. — (U.S. Geological Survey bulletin ; 1904–S)
(Contributions to Precambrian geology of Lake Superior region ; ch. S)
Includes bibliographical references.
Supt. of Docs. no.: I 19.3:1904S
1. Geology, Stratigraphic—Archaean. 2. Geology—Middle West. 3. Faults (Geology)—Great Lakes Region. I. Day, Warren C. II. Title.
III. Series. IV. Series: Contributions to Precambrian geology of Lake Superior region ; ch. S.
QE75.B9 no. 1904–S
[QE653.3]
557.3 s—dc20
[551.7'12'0977] 92–42437
CIP

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The Great Lakes Tectonic Zone—Revisited

By P.K. Sims *and* W.C. Day

Abstract

The Great Lakes tectonic zone (GLTZ) is a Late Archean crustal boundary (paleosuture) at least 1,200 kilometers long that juxtaposes a Late Archean greenstone-granite terrane (Wawa subprovince of Superior province) on the north and an Early to Late Archean gneiss terrane (Minnesota River Valley subprovince) on the south. Recent mapping of an exposed segment in the Marquette, Michigan, area provides new data on the vergence of the structure. These data necessitate reexamination of the COCORP seismic-reflection profiling in central Minnesota, which has been the principal basis for past views on the vergence of the GLTZ.

In the Marquette area, the GLTZ is a northwest-striking mylonite zone about 2.3 kilometers wide that is superposed on previously deformed rocks of both Archean terranes. Shear zone walls strike N. 55°–60° W., and foliation in mylonite within the GLTZ strikes (average) N. 70° W. and dips 75° SW. A stretching lineation plunges 42° in a S. 43° E. direction. Hinges of tight to open (sheath?) folds of both Z- and S-symmetries plunge parallel to the lineation. The attitude of the lineation (line of tectonic transport and X finite strain axis), together with asymmetric kinematic indicators, indicates that collision at this locality was oblique; the collision resulted in dextral-thrust shear along the boundary, northwestward vergence, and overriding of the greenstone-granite terrane by the gneiss terrane.

In contrast, the seismic-reflection profiling in central Minnesota has been interpreted by several investigators to indicate that the GLTZ is a shallowly north dipping (≈30°) structure, which implies southward vergence on a north-dipping subduction zone. We suggest, alternatively, that the shallow-dipping reflectors in the seismic profiles indicate lithologic contacts related to recumbent and gently inclined folds (D_1), perhaps enhanced by ductile deformation zones, and that the Morris fault is indeed the GLTZ. The Morris fault strikes about N. 70° E., dips steeply southeastward, is transparent in seismic profiles, appears to be narrow, and coincides with the inferred position of the GLTZ as shown on earlier maps.

The oblique collision along northwest-trending segments of the GLTZ would be expected to produce dextral transpression across a large region north of the GLTZ, and may have produced an early nappe-forming event (D_1) as well as younger upright folds (D_2), and as a later, more brittle event, the numerous dextral faults and conjugate sinistral faults that are widespread in the Wawa and adjacent subprovinces.

INTRODUCTION

The Great Lakes tectonic zone (GLTZ), named in 1980 (Sims and others, 1980), forms the boundary between an Archean gneiss terrane (Minnesota River Valley subprovince of Superior province) on the south and a Late Archean greenstone-granite terrane (Wawa subprovince) on the north. These terranes differ in age, rock assemblages, metamorphic grade, and structural style (Morey and Sims, 1976). The GLTZ has now been traced across the Lake Superior region (Sims, 1991; fig. 1), and is inferred to extend westward to the Trans-Hudson orogen in central South Dakota (Sims and others, 1991) and eastward through the Sudbury structure to the Grenville front (Sims and others, 1980). The postulated length of the GLTZ exceeds 1,200 km; thus, it is a feature of subcontinental length.

This boundary was first recognized in Minnesota from regional geologic relations. Because the boundary is covered by glacial deposits in Minnesota, its position was determined initially from aeromagnetic and gravity data (Morey and Sims, 1976). Later (Sims, 1980), the boundary was approximately located using regional geologic relations 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. More recently it was mapped in the Marquette, Michigan, area (Sims, 1991; 1993), where it is exposed along a strike length of about 10 km.

The purpose of this report is to (1) describe the general geology of each segment of the GLTZ within the Lake Superior region, (2) describe the kinematics determined from the one area where the GLTZ is exposed, (3)

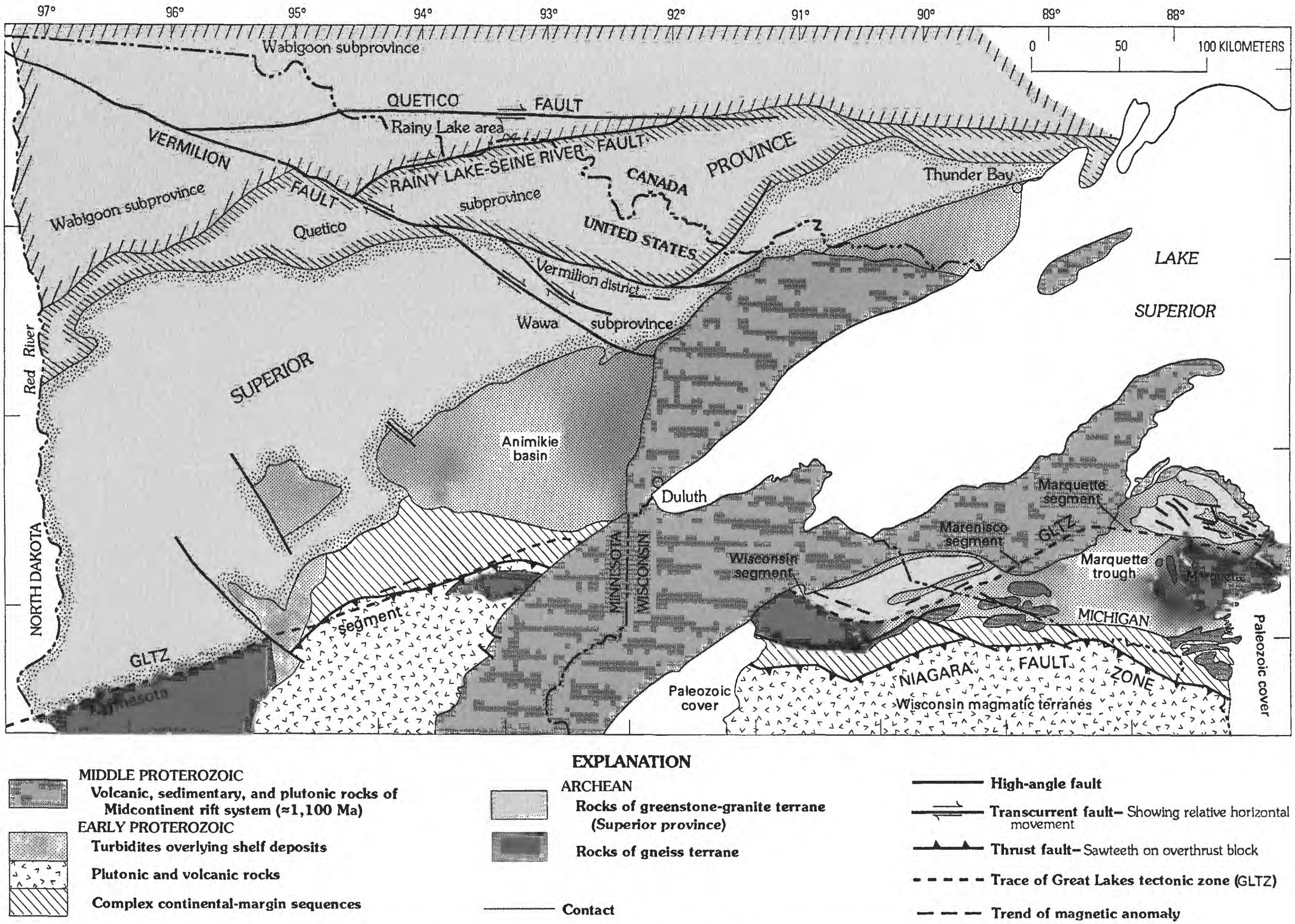


Figure 1. Simplified tectonic map of Lake Superior region showing Great Lakes tectonic zone and adjacent Archean terranes. Modified from Sims (1991).

speculate on the trajectory of stress into the Archean greenstone-granite crust resulting from collision along the GLTZ, and (4) propose an alternative to the prevailing interpretation of vergence based on geophysical data from central Minnesota that is consistent with the kinematics determined in the exposed area.

GREAT LAKES TECTONIC ZONE

Geologic and geophysical data in the Lake Superior region indicate that the GLTZ is characterized by angular bends, so that it alternately trends northeast and west-northwest (fig. 1). The Minnesota and Marenisco segments trend northeast; the Wisconsin and Marquette segments trend west-northwest. Brief descriptions follow for each segment of the GLTZ.

Minnesota Segment

The Minnesota segment of the GLTZ trends about N. 70° E. (fig. 1). It is not exposed, but its position has been delineated rather accurately using aeromagnetic and gravity anomaly maps (Morey and Sims, 1976). It is a conspicuous linear feature in west-central Minnesota on the shaded-relief aeromagnetic maps of the State (Chandler, 1991a) and on the aeromagnetic anomaly map of Minnesota (Chandler, 1991b).

The Archean greenstone-granite terrane (Wawa subprovince), to the north of the GLTZ, as exposed in northern Minnesota and adjacent Ontario, Canada, comprises a metamorphosed succession of volcanic and volcanogenic sedimentary rocks of Late Archean age intruded by several episodes of Late Archean plutonic rocks (Sims, 1976; Day, 1990b). In the Shebandowan greenstone belt of adjacent Ontario, southwest of Thunder Bay (fig. 1), the volcanic succession has a U-Pb zircon age of about 2,730 Ma (Corfu and Stott, 1986). A first deformation (D_1) occurred during or before intrusion of a major (Shebandowan Lake) pluton at 2,696±2 Ma. A second deformation (D_2) caused by regional transpression occurred after 2,689+3−2 Ma and before 2,684+6−3 Ma. New mapping in the Wawa subprovince of northern Minnesota by Boerboom and Jirsa (1992) has identified two main periods of deformation that are correlative with the two deformations in the Vermilion district (Hudleston and others, 1988), and almost certainly also with the two events in the Shebandowan belt. An older (D_1) event associated with recumbent folding is followed by a younger (D_2) transpressive event. Boerboom and Jirsa reported that D_2 ended between 2,685 Ma and 2,674 Ma, apparently slightly later than D_2 deformation in the Shebandowan belt. The D_2 event, clearly demonstrated by several investigators in the Vermilion district, extends into the Quetico subprovince (Bauer, 1985; Bauer and Bidwell, 1990) and the adjacent Wabigoon subprovince (to the north) (Poulsen, 1986; Day, 1990b). The D_2 deformation throughout its known extent was caused by northwest-directed compression.

The Archean gneiss terrane exposed in the Minnesota River Valley south of the GLTZ consists of complexly folded migmatitic felsic gneisses of presumed volcanic affinity, local amphibolite units, and lesser amounts of metagabbro and metasedimentary rocks (Grant, 1972). The rocks have been metamorphosed to upper amphibolite and (or) granulite facies (Himmelberg and Phinney, 1967). Protoliths of the older gneisses date from ≈3,500 Ma; high-grade metamorphism occurred at ≈3,050 Ma and was followed by emplacement of the late-tectonic Sacred Heart Granite at ≈2,600 Ma (Goldich and others, 1980; Goldich and Wooden, 1980; Doe and Delevaux, 1980). Tonalitic gneiss recovered in a drill core from a covered block south of the Minnesota River Valley was recently dated at 2,642±57 Ma (U-Pb zircon method; D.L. Southwick, written commun., 1992). This isotopic age indicates that at least some rocks of Late Archean age are present in the Minnesota River Valley subprovince in southwestern Minnesota.

The Minnesota segment of the GLTZ is the type area for the feature and has been extensively studied. In the initial report on the structure, Morey and Sims (1976, figs. 1, 8) visualized the GLTZ as a narrow zone, at most a few kilometers wide, that separates a major greenstone-granite terrane to the north from a gneiss terrane of mini-continental dimensions to the south. Because the boundary along the Marenisco segment, Upper Michigan (fig. 1), coincides with a broad belt of distinctive tectonism in the overlying Early Proterozoic supracrustal rocks (Sims, 1980), the use of the term GLTZ was later modified to include the Early Proterozoic (Penokean) deformation as well as the Archean (Sims and others, 1980). In central Minnesota, the zone within which deformation of Early Proterozoic age was superposed on the Late Archean structure was estimated to be ≈50 km wide (Morey and others, 1982). This broader usage was continued in a later report on seismic-reflection profiling across the GLTZ (Gibbs and others, 1984). Shallow drilling and potential-field geophysics to aid in interpreting the seismic profiles (Southwick and Chandler, 1983; Southwick and others, 1986) have indicated that the GLTZ in central Minnesota is indeed narrow; the rocks within the "wide" tectonic zone are typical of volcanic subprovinces within the Archean greenstone-granite terrane. Because of their low magnetization (Chandler, 1991b), the rocks in this zone have been called the "quiet zone" (Chandler and Southwick, 1990).

In addition to the seismic-reflection profiling acquired by COCORP (Consortium for Continental Reflection Profiling) (Gibbs and others, 1984), the GLTZ in central

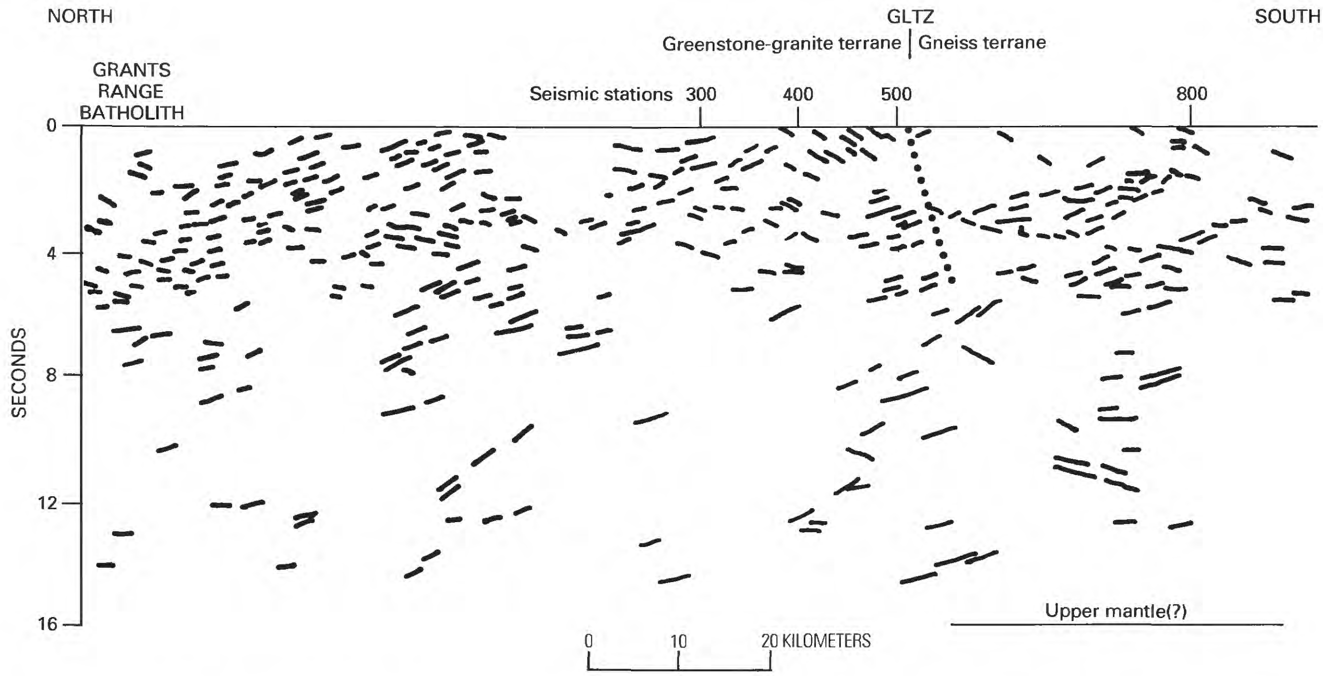


Figure 2. Migrated composite section of COCORP north-south seismic-reflection profiles, Minnesota. Dashed lines, seismic surfaces; dotted line, Morris fault. Modified from Gibbs and others, 1984, fig. 6. Great Lakes tectonic zone (GLTZ) is reinterpreted as the Morris fault.

Minnesota has been investigated by a detailed aeromagnetic survey (Chandler, 1991b). These data have been interpreted using various computer-generated graphical enhancement techniques, computer-generated mapping of the second vertical derivative of the gravity field, and shallow test-drilling (Southwick and Chandler, 1983; Southwick and others, 1986).

The seismic-reflection profiling in central Minnesota (fig. 2) has defined abundant shallowly dipping seismic surfaces in the upper 30 km of greenstone crust. One particularly conspicuous zone of north-dipping reflectors projects to the surface near station 400 (fig. 2). The moderate dip of this zone of reflectors, their continuity over tens of kilometers, and their extension to midcrustal depths led Gibbs and others (1984) and other investigators to infer that the reflectors correspond to a zone of imbricate thrust faults (GLTZ) that displaced rocks of the greenstone-granite terrane (Wawa subprovince) southward over rocks of the gneiss terrane (Minnesota River Valley subprovince). This interpretation implies southward vergence for the GLTZ on a shallowly north dipping subduction zone.

Wisconsin Segment

The Wisconsin segment of the GLTZ strikes northwest, as indicated by trends of gravity and aeromagnetic anomalies and by available geologic data. Some aspects of the geologic relations in the area are not definitive, however, because the Archean rocks are poorly exposed. Also, the Archean rocks were tilted by movements on the Middle Precambrian (Keweenawan) Pelton Creek fault (fig. 3), a southward-directed, listric thrust fault (Cannon and others, in press). At the time of the initial geologic mapping, Sims and others (1985) recognized textures in the Archean rocks indicative of a nearly pervasive brittle-ductile deformation that formed at about 1,050 Ma, and which is superposed on Archean structures, but the cause of the deformation was not known. We now know from more recent mapping that all but the southernmost rock exposures in the area shown in figure 3 were rotated at least 35° northward during the tilting along the Pelton Creek fault. Interestingly, evidence for Penokean deformation is lacking along the Wisconsin segment of the GLTZ (Sims and others, 1985).

Despite the sparse exposures and the tilting caused by the Pelton Creek fault, the position of the GLTZ in northwestern Wisconsin (fig. 2) is believed to be accurate within a few kilometers. The rocks to the north of the tectonic zone comprise a bimodal Late Archean volcanic succession (interlayered felsic gneiss and amphibolite) that correlates with the succession (greenstone-granite terrane) exposed between Marenisco and the Watersmeet dome to the northeast. These bimodal rocks are similar chemically to bimodal volcanic rocks in the Rainy Lake area (Day, 1990a) of the Wabigoon subprovince, along the Minnesota-Ontario border. Small granite to tonalite bodies

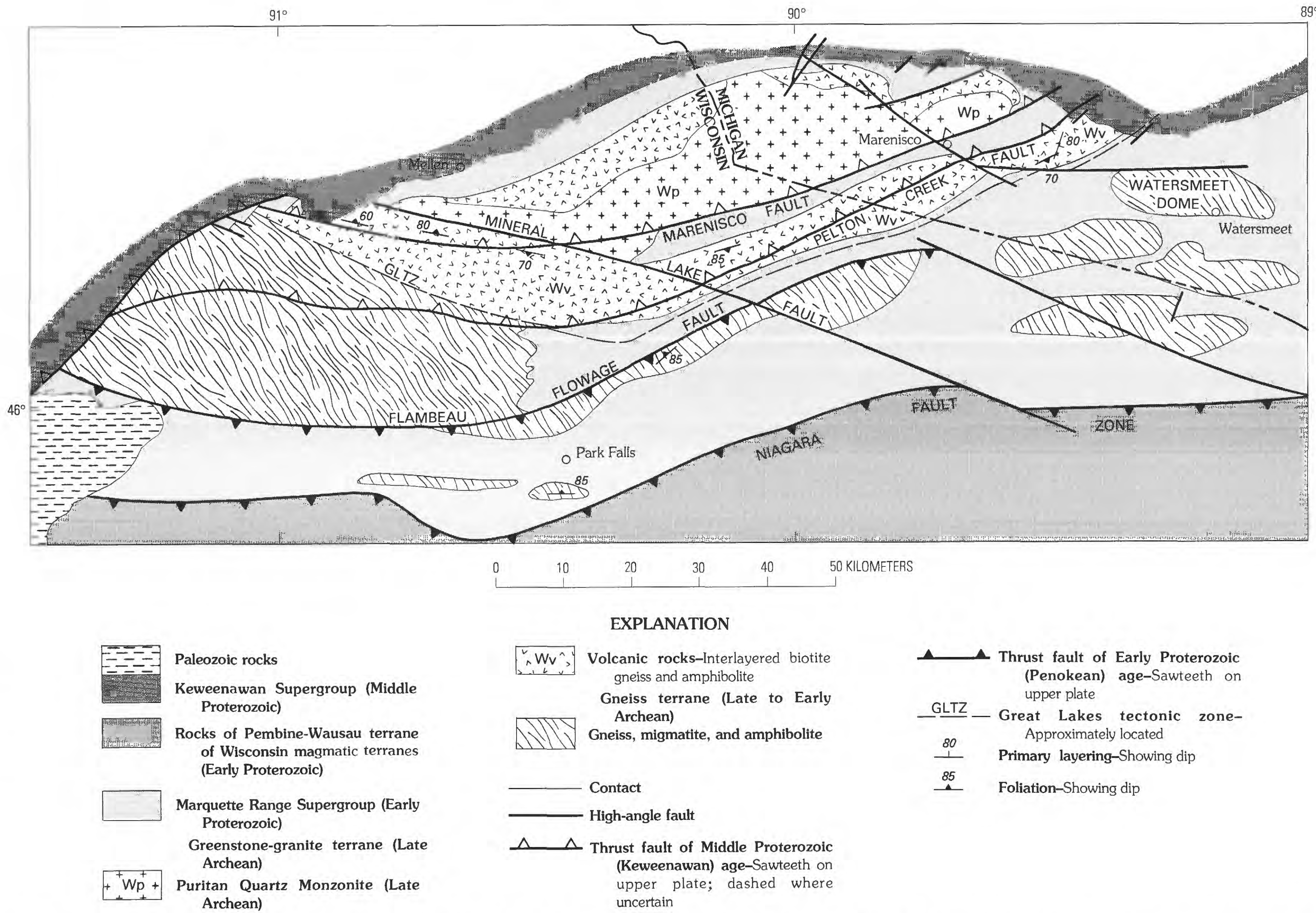


Figure 3. Generalized geologic map of northwestern Michigan and Wisconsin, showing approximate trace of the Great Lakes tectonic zone. Modified from Sims (1992).

cut the interlayered succession, and the Late Archean Puritan Quartz Monzonite batholith is exposed north of the Mineral Lake fault (fig. 3). The interlayered biotite gneiss and amphibolite unit has a U-Pb zircon upper intercept age of 2,735±16 Ma and a lower intercept age of 1,052±70 Ma (Sims and others, 1985); the lower intercept age is nearly identical to Rb-Sr and K-Ar biotite ages from the gneisses and is interpreted as the result of Keweenawan disturbance. The 2,735±16 Ma age is virtually identical to that determined from the same unit in the Marenisco area. The rocks in the interlayered unit (unit Wv, fig. 3) strike northwest and dip nearly vertical. Before Middle Proterozoic rotation on the Pelton Creek fault, the general dip of rocks in the unit would have been steep to the south. This rotation did not appreciably change the strike of the rocks.

Sparse data from drilling (Sims and others, 1985, and references therein) and from outcrops indicate that the Archean gneiss terrane to the south of the GLTZ in this area consists mainly of quartzo-feldspathic gneisses. Aeromagnetic and gravity trends indicate a predominant east-west strike for the gneisses. Gneisses from the linear northeast-trending Archean block south of the Flambeau Flowage thrust fault (fig. 3) have a Rb-Sr whole-rock age of ≈2,700 Ma (Sims and others, 1985, fig. 3), and gneiss from the small body exposed south of Park Falls has a U-Pb zircon upper intercept age of 2,984±51 Ma (W.R. Van Schmus, written commun., 1988).

Marenisco Segment

The Marenisco segment of the GLTZ (fig. 1) trends northeast and is covered by mafic volcanic rocks of the Early Proterozoic Blair Creek Formation of the Marquette Range Supergroup (not shown separately in fig. 3; Sims and others, 1984; Sims, 1990). In the area east of Marenisco the boundary lies between exposures of Archean metagraywacke (included in unit Wv, fig. 3) of the greenstone-granite terrane and Archean gneiss in the Watersmeet dome (Sims, 1990); the position of the boundary is constrained within a distance of 6 km.

The rocks immediately northwest of the GLTZ in the greenstone-granite terrane are the same bimodal volcanic rocks (unit Wv, fig. 3) that occur in northwest Wisconsin (fig. 3). These volcanic rocks are intruded by granitic rocks of the Puritan batholith (unit Wp, fig. 3; Sims and others, 1977) and by associated granite pegmatite. One sample of biotite gneiss from the bimodal volcanic unit has a U-Pb zircon concordia-intercept age of about 2,750 Ma (Sims and others, 1984, fig. 12). The Puritan Quartz Monzonite has a Rb-Sr whole-rock isochron age of 2,650±140 Ma (Sims and others, 1977). The bimodal volcanic and graywacke units were deformed during a Late Archean event into upright, moderately tight north-northeast-trending folds. The axial surfaces of these folds are commonly marked by lenses of quartz. A foliation that strikes northeast and dips steeply southeast (Sims and others, 1984, fig. 19) that formed during the Early Proterozoic Penokean orogeny is superposed on these folds. The exposed width of the zone of superposed Penokean foliation is about 6 km. This zone is terminated to the west by the Pelton Creek fault (Sims, 1990).

The rocks that comprise the Archean gneiss terrane exposed in the Watersmeet dome (fig. 3) consist of older, Early Archean tonalitic augen gneiss and biotite gneiss overlain by a supracrustal succession of interlayered gneiss and amphibolite of bimodal composition. The older gneisses have a U-Pb zircon age of 3.56±0.04 Ga, comparable in age to gneisses in the Minnesota River Valley; the supracrustal rocks have a U-Pb zircon age of about 2.64 Ga (Peterman and others, 1986). Small bodies of leucogranite (≈2.59 Ga) intrude the layered rocks (Sims and others, 1984, fig. 9). The Watersmeet dome (fig. 3) is mantled by Early Proterozoic rocks. A strong, east-trending moderately northward dipping foliation was imposed on gneisses in the dome during the Penokean deformation, as indicated by the deformation of Early Proterozoic metagabbro dikes that cut the Archean rocks in the dome. 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, 1,800–1,750 m.y. ago (Sims and others, 1984). This event followed collision along the Niagara fault zone, dated at ≈1,852 Ma (Sims and others, 1989), by 50 to 100 m.y.

Marquette Segment

The Marquette segment of the GLTZ is a 2.3-km-wide mylonite zone that trends northwest and dips steeply southwest (Sims, 1991). It is exposed along strike for a distance of ≈10 km and extends northwestward beneath Early Proterozoic rocks of the Marquette syncline. The mylonite zone is superposed on previously deformed rocks of the greenstone-granite terrane on the north and the gneiss terrane on the south.

Rocks of the greenstone-granite terrane exposed on the south side of the Marquette syncline (but north of the GLTZ) consist predominantly of foliated tonalite-granite but include small masses of biotite and hornblende schists, similar to those rocks exposed to the north of the syncline (Johnson and Bornhorst, 1991). Foliated tonalite from the northern complex (north side of the Marquette syncline) (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). The rocks south of the Marquette syncline in the greenstone-granite terrane have variable strikes because of folding, generally moderate to gentle dips, and shallow plunging fold axes and mineral lineations (Sims, 1993). In the Ishpeming greenstone belt on the north side of the Marquette syncline, the rocks in this terrane record early recumbent folds (F_1) and younger (D_2) west-trending upright, upward- and downward-facing folds formed by transpression that are mainly Z-shaped in plan view (Johnson and Bornhorst, 1991). These rocks are cut by younger northwest- to west-trending faults (or shear zones), some of which have demonstrable dextral movement. Commonly, these faults in the northern complex, which belong to the same family of transcurrent faults deciphered in northern Minnesota (Hudleston and others, 1988), separate volcanic rock domains having opposite stratigraphic facings (Johnson and Bornhorst, 1991). The granitoid rocks that surround and intrude the greenstone bodies are mostly strongly foliated as a result of regional deformation D_2.

Rocks that compose the gneiss terrane to the south of the GLTZ along the Marquette segment are compositionally layered, medium-grained gneiss, migmatite, and amphibolite cut by pink aplitic granite and granite pegmatite (Sims, 1993). A sample of gray gneiss 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). A post-tectonic intrusion about 4 km in areal extent (granite near Tilden of Hammond (1978)) has a U-Pb zircon age of 2,585±15 Ma (Sims and Peterman, 1992). The dominant structures in the Archean gneiss to the south of the GLTZ are gently inclined to recumbent folds oriented northwestward and plunging gently to moderately northward (Sims, 1991, fig. 4). A younger steep, northwest-oriented foliation occurs locally. This younger foliation is subparallel to the northwest-trending antiformal structure of the southern complex of the Marquette district, and presumably is related to the deformation that produced the antiform. Both the recumbent folds and the younger foliation predate the GLTZ.

In the exposed part of the Marquette segment (Sims, 1991; 1993), the shear zone walls of the GLTZ are subparallel and strike N. 60° W. Foliation in mylonite within the GLTZ strikes (average) N. 70° W. and dips 75° SW. A stretching lineation in the mylonite foliation plunges 42° in a S. 43° E. direction. Hinges of tight to open sheath(?) folds of both Z- and S-symmetries plunge parallel to the lineation. The attitude of the lineation (line of tectonic transport and X finite strain axis), together with asymmetric kinematic indicators, indicates that collision along this segment of the GLTZ was oblique; the collision resulted in dextral-thrust shear along the boundary, northwestward vergence, and overriding of the greenstone-granite terrane by the gneiss terrane.

VERGENCE

Two interpretations have been proposed for the vergence on the GLTZ: (1) the interpretation based on geophysical data in Minnesota regards the GLTZ as characterized by southward vergence on a shallowly northward dipping subduction zone (Gibbs and others, 1984; Chandler and Morey, 1989), and (2) the interpretation based on geologic data using kinematics in outcrops in the Marquette, Michigan, area (Sims, 1991) characterizes the GLTZ as a northward-verging, high-angle, south-dipping structure on which the gneiss terrane was displaced northward over the greenstone-granite terrane. We have proposed from the kinematic data along the Marquette segment that vergence along each of the segments was northward, and have suggested an alternative interpretation of the north-dipping seismic reflectors in the Minnesota profiles (Sims and Day, 1992). The alternative interpretation is consistent with data from the exposed area.

Seismic reflection zones such as those in the greenstone (Wawa subprovince) crust in Minnesota can be attributed to (1) lithologic contacts of units of contrasting composition, which can provide velocity contrast, (2) igneous layering, and (3) fluid-rich zones, as well as (4) brittle-ductile deformation zones. That the Minnesota seismic planes could be lithologic contacts perhaps enhanced by shallow-dipping faults or shear zones is suggested by the informative seismic-reflection profiles in the southern Abitibi greenstone belt, Canada (Jackson and others, 1990), which is along strike to the northeast from Minnesota. The seismic profiles in the Abitibi belt reveal abundant subhorizontal reflection zones of regional extent in the upper 15 km of crust. These reflectors resemble those in the greenstone crust of Minnesota in generally being discontinuous and having variable shallow dips. The shallow-dipping reflectors in the Abitibi belt are interpreted by Jackson and others (1990) as layering and (or) tectonic high-strain zones, possibly like the low-angle faults that produced the "out of sequence" stratigraphy demonstrated by U-Pb geochronology (Corfu and others, 1989). The shallow-dipping reflectors are truncated and in part offset by regional, steeply dipping, ductile-brittle shear zones such as the Dexter-Porcupine and Cadillac-Larder Lake fault zones, which are transparent and cannot be identified directly in the seismic profiles. Some of these faults penetrate to depths of 15–18 km.

We suggest that the GLTZ would not be identifiable on the COCORP profiles in Minnesota because of its steep dip; we also suggest that the steep southeast-dipping fault shown by Gibbs and others (1984) near station 500 on line 3 (fig. 2) is the GLTZ. This structure has the local name Morris fault. At the time of the COCORP investigation, the Morris fault was considered as the southeast margin of a "wide" GLTZ (Gibbs and others, 1984, fig. 2). That the Morris fault could indeed be an expression of the GLTZ is suggested by drilling by the Minnesota Geological Survey (Southwick and others, 1986). A hole (1985–11) located on the approximate trace of the Morris fault in Todd County and near station 500 on COCORP line 3 (Gibbs and others, 1984) penetrated 11 ft of mylonite at depths of 333–344 ft (1 ft=0.328 m). The hole bottomed in mylonite. Previously, Herrmann (1979) determined from surface-wave focal plane data of a recent earthquake near Morris that the fault probably trends northeast and has a steep (≈70°) southeast dip. A steep southward dip of this structure is consistent with the observed southward dip of the GLTZ in the Marquette, Michigan, area, as well as with northward vergence on the structure. The apparent narrowness of the tectonic zone in Minnesota also is consistent with the observed ≈2-km-wide mylonite zone that comprises the GLTZ in the outcrop area in Michigan.

Structural data from northern Minnesota and Michigan support our suggestion that the shallowly dipping seismic reflectors are predominantly lithologic contacts rather than faults or ductile shear zones. Early (D_1) recumbent or gently inclined folds, some of large areal extent, have been recognized over wide areas of the Wawa subprovince (Hudleston and others, 1988; Day and Sims, 1984; Johnson and Bornhorst, 1991). Such large structures could produce the strong seismic reflections shown in the COCORP profiles. Also, no evidence has been recognized in exposed areas of the Wawa subprovince in northern Minnesota for imbricate shallow-dipping ductile-brittle deformation zones, such as postulated for the entire upper crust from the COCORP profiles (Gibbs and others, 1984). The faults and shear zones in the region north of the GLTZ, such as the Vermilion fault in northern Minnesota (Sims, 1976), are nearly vertical, and formed from regional transpression (Hudleston and others, 1988).

The COCORP seismic profiles in central Minnesota show shallow-dipping reflection zones in the gneiss crust south of the GLTZ that extend to depths of about 36 km. These reflectors accord with the generally shallow dipping gneissic foliation and open folds in gneiss exposed at the surface in the Minnesota River Valley, about 100 km to the south (Bauer, 1980). Gibbs and others (1984, p. 291) noted that because of differences in stacking velocity this crust differs in seismic character from the greenstone crust north of the GLTZ.

EVOLUTION AND SIGNIFICANCE

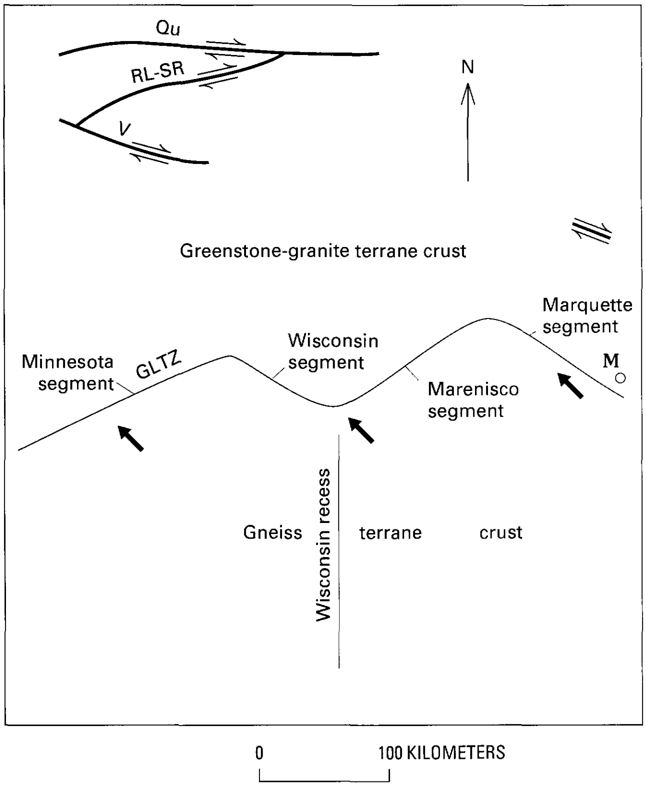
The Great Lakes tectonic zone was formed by the final collision in the assembly of the Superior province of the Canadian Shield. According to our model, the collision resulted from northwest-directed tectonic transport of the gneiss terrane (micro-continent) against the previously assembled, predominantly island-arc terranes that comprise most of the Superior province. Collision was oblique along the northwest-trending segments, resulting in dextral-thrust shear along the boundary and probable overriding of the island arc terrane by the gneiss terrane. Southward subduction may have resulted in emplacement of the large ≈2,600-Ma batholithic Sacred Heart Granite into the gneisses in southwestern Minnesota.

The deformation along the GLTZ took place under ductile conditions, but near the brittle-ductile transition. These conditions are indicated by the presence of dominant orthomylonite rather than ultramylonite and a slight retrogressive alteration in the zone. Under typical crustal conditions, and assuming a geotherm of 30 °C km^{-1}, the brittle-ductile transition occurs at a depth of 8–12 km, corresponding to vertical stresses of 2–3 kbar and temperatures of 240–360 °C (Kerrich and Feng, 1992).

The northwest-directed tectonic transport during suturing of the Archean terranes, determined from the Marquette, Michigan, area, provides a means for establishing the evolution of the GLTZ and the trajectory of stress into the Archean greenstone-granite crust. The systematic angular bends in the GLTZ that shape segments alternately trending northeastward and west-northwestward (fig. 1) may well reflect original irregularities in the margin of the greenstone-granite terrane, which was a continental margin before convergence and collision with the southern Archean gneiss terrane. This zigzag-shaped Archean continental margin is similar in broad outline to the Appalachian-Ouachita Paleozoic orogenic belt (Thomas, 1983). The Archean continental margin could have resulted from rifting, as proposed for the Paleozoic continental margin. If so, the Minnesota and Marenisco segments probably represent rifted margins, and the Wisconsin and Marquette segments represent former transform faults.

Collision along the Archean continental margin can be discussed with respect to figure 4, a diagrammatic sketch map showing the approximate configuration of the continental margin in Late Archean time. In the reconstruction, the Middle Proterozoic Midcontinent rift system has been removed, thus bringing the Minnesota segment in juxtaposition with the Wisconsin segment.

We presume that the oblique collision determined along the Marquette segment is indicative of convergence along this irregularly shaped continental margin. Thus, the tectonic transport direction of the converging plates was about N. 45° W. (fig. 4), with upthrusting toward the northwest. In this scenario, collision would have been diachronous along the Archean continental margin. The Wisconsin recess (a concave curve toward the continental margin; terminology of Thomas, 1983) would have acted as a buttress against which compressive stress was directed into the greenstone-granite crust to the north.



EXPLANATION

High-angle dextral fault—Barbs show direction of relative movement: Qu, Quetico fault; RL-SR, Rainy Lake–Seine River fault; V, Vermilion fault

Direction of tectonic transport

Marquette, Michigan

Figure 4. Diagrammatic sketch map showing approximate configuration of the continental margin in Late Archean time. The Middle Proterozoic Midcontinent rift system has been removed, thus juxtaposing the Minnesota and Wisconsin segments. Scale is approximate. Refer to figure 1 for geographic positions of segments of Great Lakes tectonic zone.

Transmittal of dextral-thrust shear into the crust to the north can account for the transpressional structures so elegantly described by Hudleston and others (1988) and Day (1990b) from northern Minnesota, and Poulsen (1986) from adjacent Canada. In addition to early recumbent folds (D_1) and younger upright east-west folds, the generally northwest to west trending dextral transcurrent faults and conjugate sinistral faults in the region developed as a later more brittle expression of the shear regime. These faults include the Vermilion, Rainy Lake–Seine River, and Quetico faults, which form the margins of or transect the major Archean subprovinces in northern Minnesota and adjacent Ontario. Recent precise isotopic analyses of zircon, titanite, and rutile of rocks from the Rainy Lake (Davis and others, 1989) and Shebandowan (Corfu and Stott, 1986) areas, Canada, indicate that these faults formed in the approximate interval 2,692–2,686 Ma. Inasmuch as these faults are attributed to collision along the GLTZ, these ages date the approximate time of collision along the GLTZ.

The northwest-directed compression was nearly perpendicular to the northeast-trending segments of the GLTZ, and accordingly the rocks in the foreland deformed zone adjacent to these segments were folded on northeast-trending axes during the collision. This structural fabric is particularly evident along the Marenisco segment (Sims and others, 1984; Sims, 1990, 1992).

CONCLUSIONS

We have suggested a reinterpretation of the COCORP seismic-reflection profiles in central Minnesota (Gibbs and others, 1984) that is consistent with kinematic data from the 10-km-long exposed segment of the GLTZ near Marquette, Michigan. We propose that the GLTZ in Minnesota is a north-verging steep southeast-dipping structure, locally called the Morris fault. We also propose that north vergence characterizes each segment of the tectonic zone. Such vergence on the structure can account for the early recumbent folds (D_1), younger upright folds (D_2), and major transcurrent faults formed by regional dextral transpression in rocks in northern Minnesota (Hudleston and others, 1988) and adjacent areas in Ontario and Michigan. The relatively young age (≈2,600 Ma; Doe and Delevaux, 1980) of the Sacred Heart Granite in the gneiss terrane in southwestern Minnesota and its volcanic-arc granite affinity (Sims, 1992) strongly support an origin for the GLTZ suture through southward subduction prior to continent-continent collision, at about 2,690 Ma.

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Manuscript approved for publication November 2, 1992
Published in the Central Region, Denver, Colorado
Photocomposition by Shelly A. Fields
Graphics by Dennis L. Welp and Springfield & Springfield
Edited by Lorna Carter

☆U.S. GOVERNMENT PRINTING OFFICE: 1993-774-049/66062

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