A Regional Structural Model for Gold Mineralization in the Southern Part of the Archean Superior Province, United States

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Chapter M

A Regional Structural Model for Gold Mineralization in the Southern Part of the Archean Superior Province, United States

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

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A Regional Structural Model for Gold Mineralization in the Southern Part of the Archean Superior Province, United States

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

Abstract

The Canadian segment of the Archean Superior province is a major world source of lode gold. The gold deposits occur in or near regional transcurrent and oblique slip-shear deformation zones that comprise a conjugate set to a northwest-directed compression of the Superior province. These structures provided permeable pathways for the flow of large volumes of auriferous fluid derived from an external source.

Historic gold production from the United States segment of the Superior province is modest, but the close similarity in the geologic environment of the United States and Canadian segments suggests that large gold deposits should be present in the U.S.A.

An occurrence model largely based on known parameters of gold mineralization in Canada suggests that the greenstone-granite terranes of the Wawa and Wabigoon subprovinces in the United States are favorable for important gold deposits. The deposits should be hosted at a regional, district, and deposit scale in or adjacent to transcurrent faults, such as the Vermilion fault system in northeastern Minnesota and its smaller splays. These structures are sites of high strain that are commonly discordant to the boundaries of rock units on a regional scale and extend to great depths. The model suggests that gold mineralization took place during or later than the transcurrent faulting and that it took place contemporaneously with emplacement of silica-undersaturated intrusions. The faulting occurred late in the igneous-tectonic history of the Superior province, about 2,690 Ma. Extensive, intense alteration comprising carbonitization, silicification, and sulfidization accompanied the gold mineralization. The relationships between alteration minerals and mineralized veins suggest a close temporal relationship between the alteration and gold mineralization processes.

The proposed occurrence model for gold mineralization and the available data suggest that two broad regions of greenstone in the Archean Superior province in north-central United States are particularly favorable for gold deposits: (1) the Upper Peninsula of Michigan, and (2) northeastern Minnesota. The Ishpeming greenstone belt of the Wawa subprovince in Michigan contains the important Ropes deposit and several other known gold occurrences, and the Vermilion district (Wawa subprovince) in northeastern Minnesota contains highly anomalous gold in soils and minor known bedrock occurrences. Transcurrent faults in both areas should be favorable sites for gold mineralization.

INTRODUCTION

A consensus obtains that the numerous gold deposits in the Superior province of Canada are spatially associated with regional transcurrent and oblique slip-shear deformation zones formed in Late Archean time (Colvine, 1989; Card and others, 1989; Hodgson, 1989). The deformation zones comprise a conjugate set to a northwest-directed compression of the Archean Superior province.

The United States segment of the Archean Superior province in northern Minnesota, northern Michigan, and Wisconsin lacks large *known* gold deposits, but it contains regional transcurrent structures and other geologic characteristics very similar to those in the Canadian part, where large deposits are known and exploited. Because of the similar tectonostratigraphic setting, significant gold deposits should exist in Archean rocks in north-central United States. Exploration for gold deposits in this region is hampered, however, by a generally thin, discontinuous mantle of Pleistocene glacial deposits.

Manuscript approved for publication August 5, 1991.

ACKNOWLEDGMENTS

Development of an occurrence model for gold mineralization in the United States part of the Archean Superior province is possible because of the many excellent published geologic maps in north-central United States and adjacent Canada and the thoughtful syntheses of Canadian Archean lode gold deposits by Colvine and others (1988), Colvine (1989), Card and others (1989), and Roberts (1987). Constructive reviews by T.J. Bornhorst and G.B. Morey significantly improved the manuscript.

GEOLOGIC FRAMEWORK OF SUPERIOR PROVINCE

The Superior province is the world's largest relatively undisturbed Archean craton; it has been tectonically stable since 2.5 Ga. It comprises the core of the Canadian Shield and extends southward into north-central United States. The south half of the province consists dominantly of alternating belts of volcano-plutonic (greenstone-granite) terranes and metasedimentary rock terranes that have been designated as subprovinces (fig. 1). The Superior province is surrounded by Proterozoic orogenic belts, which marginally affect the Archean craton, and is covered to the west and north by Phanerozoic rocks. The geology of the Superior province has been described elegantly by Card (1990) and Hoffman (1989).

The subprovinces of the Superior province have contrasting lithologic assemblages, metamorphic and structural styles, geophysical characteristics, and ages, and are largely fault bounded. They are comparable to Phanerozoic tectonostratigraphic (or suspect) terranes in the North American cordillera (Jones and others, 1977). The greenstone-granite terranes, which host the gold deposits known in Canada and are the most favorable hosts for deposits in the United States, are characterized by dominantly greenschist-facies volcano-sedimentary sequences that are mainly 2.75 Ga to 2.70 Ga. Volcanism was accompanied by mafic to trondhjemitic plutonism. Late Archean orogenesis, accompanied and followed by calc-alkalic to alkalic plutons, occurred in the interval 2.70–2.68 Ga in the southern part (Wawa and Quetico subprovinces) of the Superior province. The deformation resulted from general north-south compression and dextral transpression (Poulsen, 1986; Hudleston and others, 1988), which was caused in part at least by oblique collision of the southern Archean gneiss terrane (in part 3.5 Ga) with the Superior province along the Great Lakes tectonic zone (Sims, 1991).

NATURE AND DISTRIBUTION OF CANADIAN GOLD DEPOSITS IN SUPERIOR PROVINCE

The Superior province of the Canadian Shield has yielded more than 4,500 t (metric tons) of gold—more than any other Archean craton in the Western Hemisphere. One hundred twenty deposits exceed 3,000 kg (kilograms) of production each, plus reserves. About 60 percent of the production has come from the Abitibi subprovince, in eastern Ontario and western Quebec (fig. 1); substantial production has also come from the Uchi and Wabigoon subprovinces. More than 80 percent of the gold has been recovered from about 30 lode gold deposits, each with a production of more than 30 t (Card and others, 1989; Colvine, 1989).

Card and others (1989) have distinguished two types of gold deposits in the Superior province of Canada: (1) sulfide schist deposits, and (2) epigenetic vein deposits. The sulfide schist deposits are paraconcordant and consist dominantly of disseminated and vein pyrite and (or) pyrrhotite in sericitic schist; quartz veins are subordinate. The wall rocks are altered to aluminous mineral assemblages, including combinations of aluminosilicate species, chloritoid, staurolite, and garnet. This deposit type, which many believe is that of the large Hemlo, Ontario, deposit (Muir and Elliot, 1987; Corfu and Muir, 1988), is sited in wide zones of ductile transcurrent shear. Sulfide schist deposits are less common and less productive than epigenetic vein deposits.

Epigenetic vein deposits comprise veins, disseminations, and replacements in steeply dipping reverse to reverse-oblique, ductile to brittle shear zones, with subordinate veins in extensional fractures and stockworks. The gold deposits are spatially associated with major fault or shear zones tens to hundreds of kilometers long within or along the margins of greenstone belts. The mineralized structures transect all rock types. Lode gold deposits occur in every rock type within greenstone belts (or greenstone-granite terranes) but are spatially and temporally associated with small, late-tectonic to post-tectonic intermediate to felsic intrusions, including syenite and lamprophyre (Colvine and others, 1984; Wyman and Kerrich, 1988). The veins contain quartz and carbonate minerals with subordinate pyrite, arsenopyrite, tourmaline, chlorite, and scheelite. They are surrounded by zoned alteration envelopes dominated by carbonate, including ferroan dolomite and ankerite, and are a few meters to a few tens of meters thick; hydrothermal minerals overprint metamorphic minerals, and a correlation exists between alteration mineralogy and regional metamorphic grade, presumably because alteration within the shear zones was approximately synchronous with subprovince-wide regional metamorphism (Colvine, 1989, table 1). The alteration is characterized overall by carbonitization, potassium metasomatism (generally sericite), and

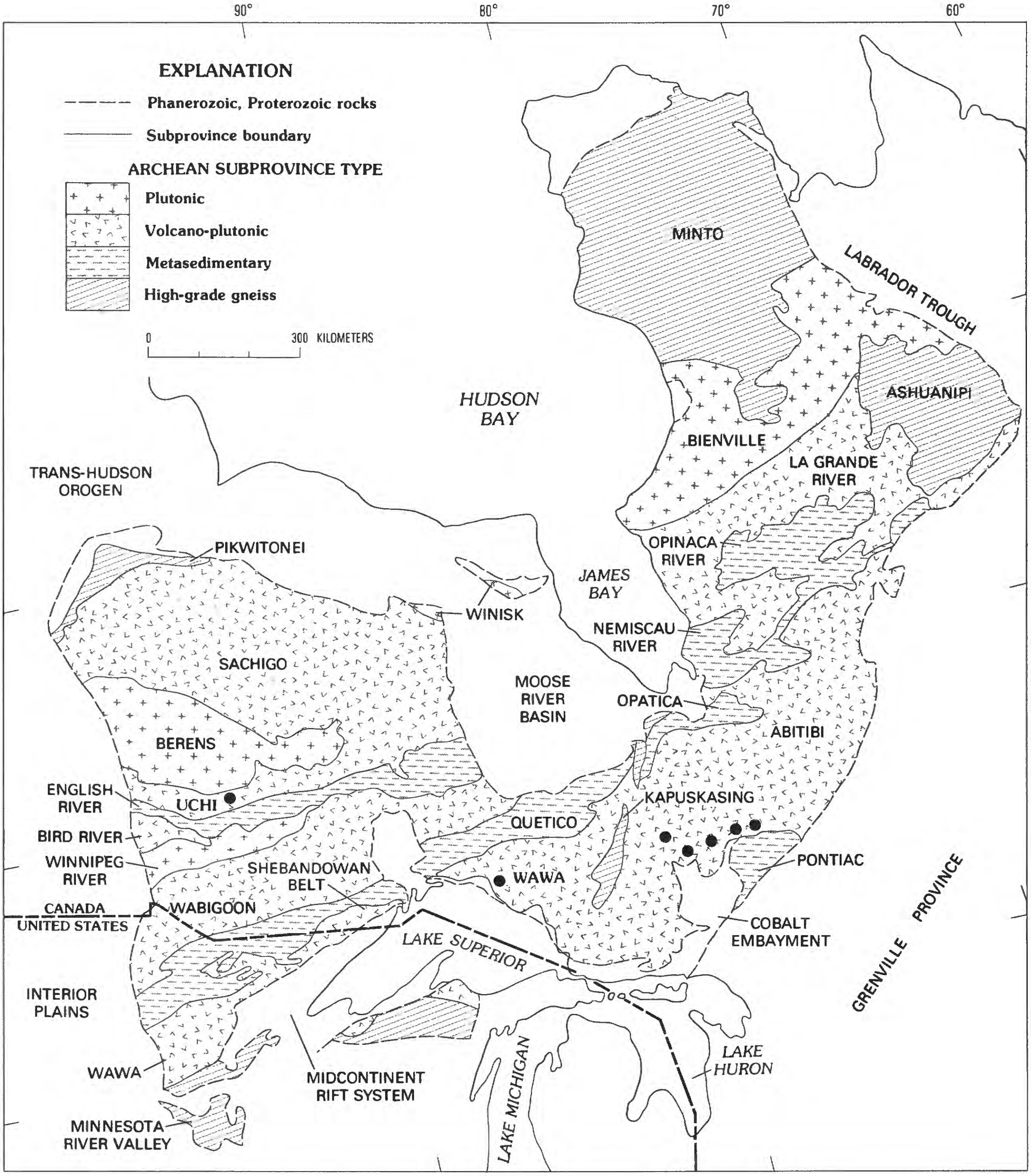


Figure 1. Generalized geology of Superior province showing subprovinces and Canadian gold camps. Modified from Card and Ciesielski (1986). Gneiss in Minnesota River Valley and in northern Michigan is not part of Superior province. Dot, major gold camp.

sulfidization of adjacent wall rocks and is accompanied by the addition of CO_2, K, S, and H_2O, as well as Au, As, Bi, and W (Roberts, 1987; Kerrich, 1983).

The fundamental regional control on gold deposits in the Superior province is transcurrent and oblique slip-shear deformation zones that formed in Late Archean time (Colvine and others, 1988, Colvine, 1989; Card and others, 1989; Roberts, 1987; Hodgson, 1989). The deformation zones form a conjugate set to a northwest-directed compression. The major structures are east-trending, dextral transcurrent shear zones, many of which are subprovince boundaries, and northeast-trending, sinistral faults that branch from and occur between the dextral shears. The known distribution of gold deposits can be seen to be controlled by the complex structures, but it is also influenced by and closely associated spatially and temporally with late tectonic syenite and lamprophyre dikes (Wyman and Kerrich, 1988), which were emplaced preferentially along the regional shear zones. Wyman and Kerrich (1988) contended that volatile-rich lamprophyre magmas from deep sources were emplaced along major deep-seated structures that also hosted gold mineralization. They did not suggest, however, that gold mineralization in the Superior province is directly related to lamprophyre emplacement; they suggested instead that both gold mineralization and lamprophyre genesis are related to a common tectonic environment; both were emplaced under localized tensional conditions along structures that extend to the mantle, but each is derived from a different source region. In a far-reaching study, Rock and others (1989) further emphasized the close space-time association between gold deposits and calc-alkaline (shoshonitic) lamprophyres. They also demonstrated that many lamprophyric rocks are enriched in gold relative to other igneous rocks, and suggested that lamprophyres may contribute at least some gold directly to gold-bearing systems.

The time of gold mineralization in the southern part of the Superior province has been approximately determined by precise isotopic analyses of zircon, titanite, and rutile from the Rainy Lake area, Ontario (Davis and others, 1989), which lies astride the Quetico-Wabigoon subprovince boundary (figs. 1 and 9). The major ductile deformation took place between 2,696 Ma and 2,692 Ma; this deformation was followed shortly by transcurrent (wrench) faulting and simultaneous deposition of conglomerate and arenite of Timiskaming type (Thurston and Chivers, 1990), which can be constrained in the interval 2,692–2,686 Ma. Late (Algoman) granitic plutons were emplaced about 2,686 Ma. Gold was deposited at about 2,690 Ma in structures related to transcurrent faulting. In the Shebandowan belt of the Wawa subprovince, west of Lake Superior, in Canada (fig. 1), transcurrent faulting occurred between 2,689+3/–2 Ma and 2,684+6/–3 Ma (Corfu and Stott, 1986), thus approximately dating the gold mineralization in this area. In the Abitibi subprovince, gold deposits in the Timmins and Matheson areas are somewhat younger, having formed in the interval 2,678–2,673 Ma; deposits in the Detour Lake mine are 2,722+3/–2 Ma (Marmont and Corfu, 1989).

SUPERIOR PROVINCE IN NORTH-CENTRAL UNITED STATES

The United States segment of the Archean Superior province, in northern Minnesota, northern Michigan, and northwestern Wisconsin, contains regional transcurrent structures and other geologic characteristics similar to those in the southern part of the Superior province in Canada. Although major known gold deposits currently are lacking, the transcurrent structures should be favorable for the occurrence of such deposits.

Archean Tectonic Framework

Three subprovinces of the southern part of the Superior province extend from Canada into the United States (fig. 1). From north to south, these are the Wabigoon, Quetico, and Wawa subprovinces. The Wawa subprovince is the southwestern extension of the Abitibi subprovince, on the west side of the Kapuskasing structure, which is a discontinuous, partly fault bounded, north-northeast-trending zone of high-grade gneiss that cuts across the east-west trends of the lower grade, supracrustal rocks of the central Superior province (Percival and Card, 1983). The Wawa subprovince comprises volcano-plutonic rocks typical of greenstone-granite terranes in the Superior province, such as that exposed in the Vermilion district of northeastern Minnesota (Sims, 1976) and the Ishpeming greenstone belt in northern Michigan (Johnson and Bornhorst, 1991). The Vermilion district consists mainly of a central belt of metavolcanic and metasedimentary rocks that is bounded on the south by the Giants Range batholith. It is separated from the Quetico metasedimentary-granitoid subprovince to the north by the Haley and Burntside Lake normal faults and locally by the Vermilion dextral transcurrent fault (fig. 2). The dominant structures in the region compose the Vermilion fault system, which consists of several east-trending anastomosing fault strands, each of which shows dextral movement; the aggregate horizontal displacement on the fault system within the area of figure 2 is 17–19 km (Sims, 1976). Subsidiary complementary faults having sinistral movement trend northeast and show lateral offsets of as much as 7 km (Waasa fault, fig. 2). Details of the conjugate fault system are shown on the geologic maps of the Vermilion district (Sims and Southwick, 1985; Sims, 1985).

The Ishpeming greenstone belt consists dominantly of mafic metavolcanic rocks (Johnson and Bornhorst, 1991) but includes felsic metavolcanic and metasedimentary rocks. These rocks are bounded by gneissic plutons of tonalite-granite (Archean) and are locally overlain by sedimentary rocks of the Early Proterozoic Marquette Range Supergroup (fig. 3). Several dextral transcurrent faults or shear zones, the largest of which are assigned names in figure 3, cut the Archean rocks.

In the Vermilion district, Minnesota, the deformed and metamorphosed volcanic and sedimentary rocks compose an east-trending belt between more competent rocks of the Late Archean Vermilion Granitic Complex (Southwick and Sims, 1980) (Quetico subprovince) and the Giants Range batholith to the south (fig. 2). Hudleston and others

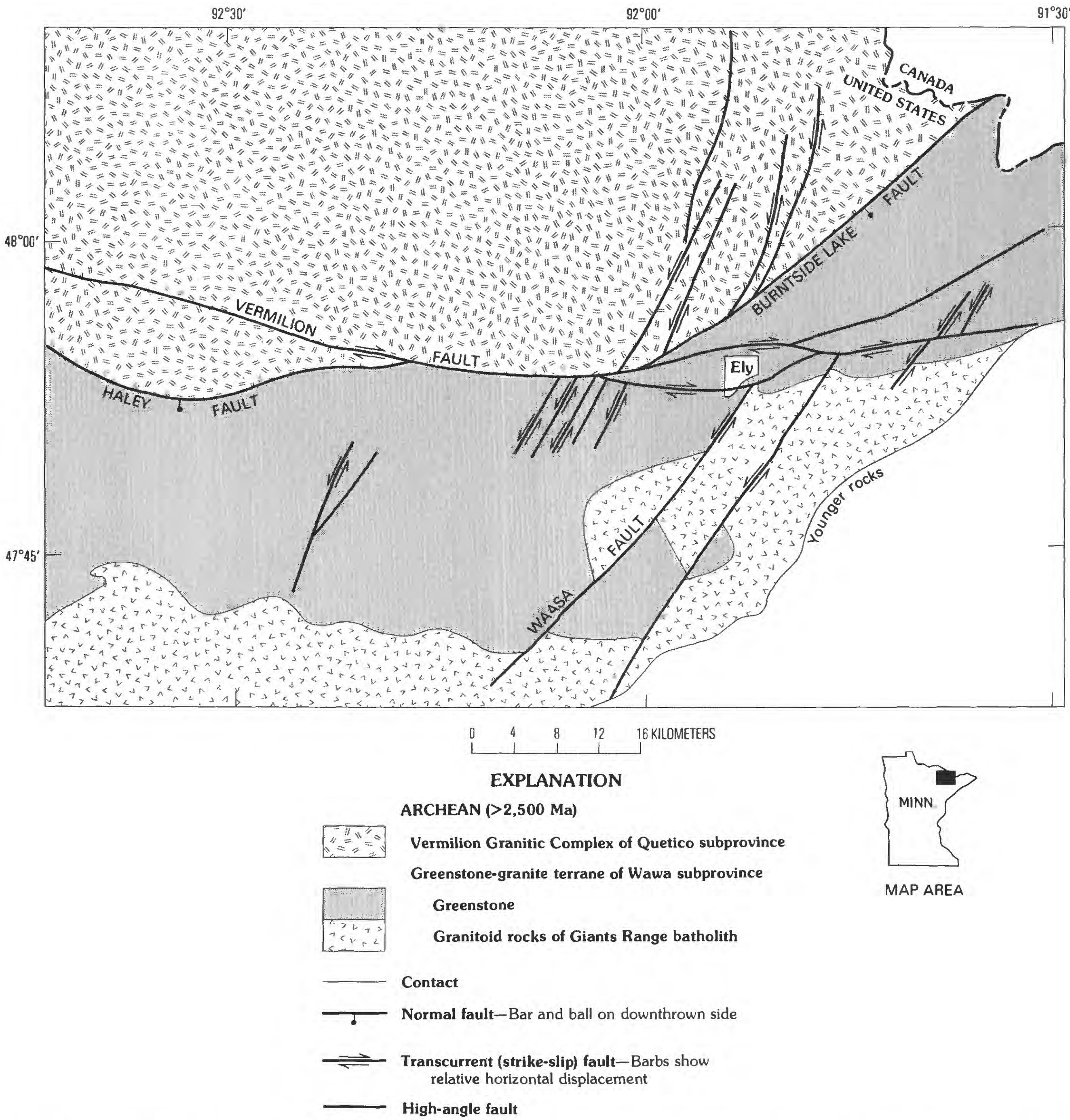


Figure 2. The Vermilion fault system of dextral transcurrent faults and complementary sinistral faults, Vermilion district, northern Minnesota. The faults comprise a conjugate system. Modified from Sims and others (1987).

(1988) attributed the measured strain, a steep cleavage, upright folds, and a mineral lineation in this belt to the "main" phase of deformation (D_2) that followed an early nappe-forming event (D_1) (Bauer, 1985). The nappes in the Vermilion district show little evidence of a penetrative fabric (Hudleston, 1976). Hudleston and others (1988) attributed the D_2 deformation to a regional dextral transpression, as the strain pattern requires a northeast-southwest component of shortening in addition to shear. They concluded that major dextral faults, such as the Vermilion fault (fig. 2), are later more brittle expressions of this shear regime. They postulated that the D_2 transpressive deformation resulted from oblique compression of the greenstone 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

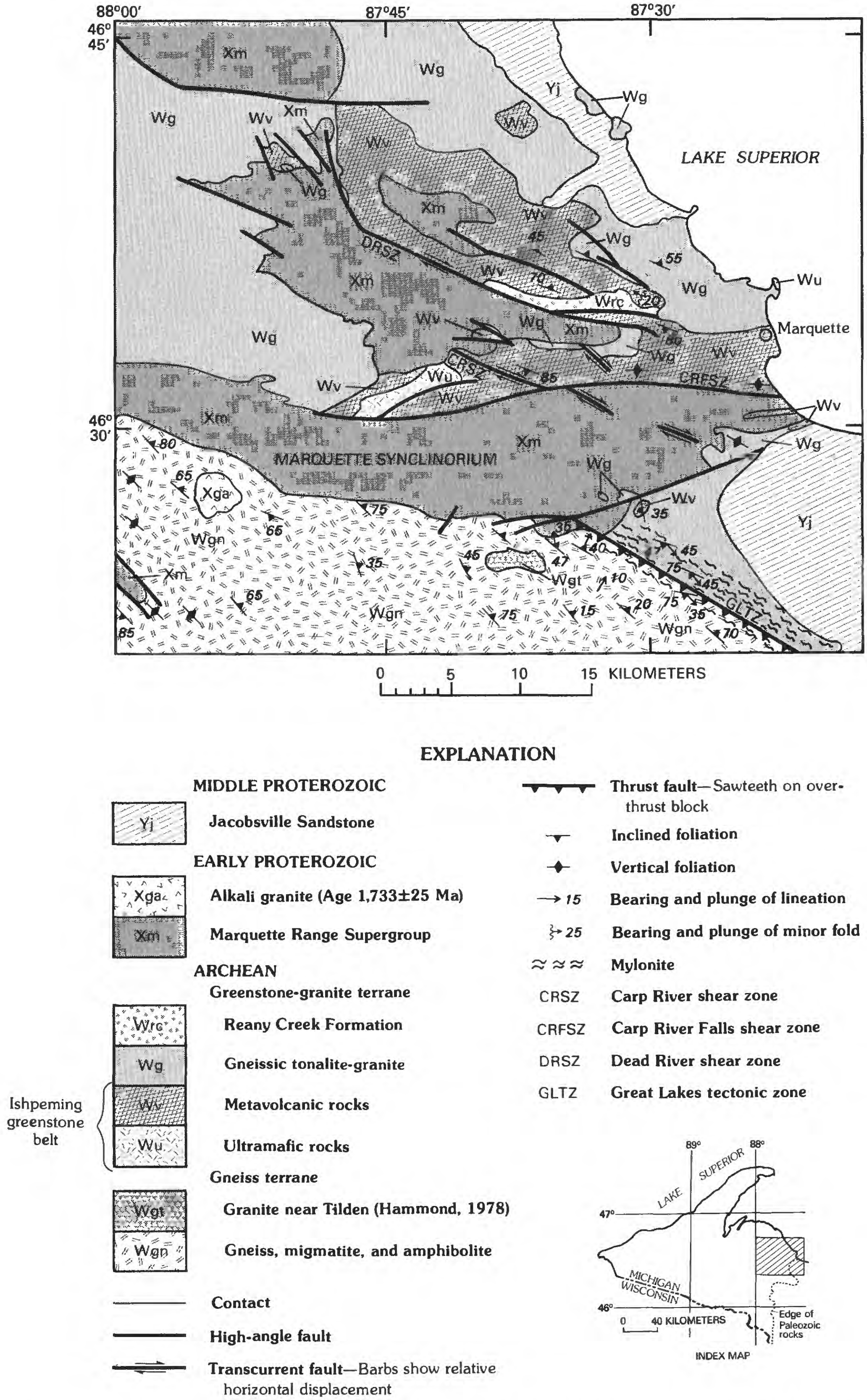


Figure 3. Geology of part of Marquette 1°×2° quadrangle, northern Michigan. Compiled by P.K. Sims, 1990.

the Rainy Lake area, astride the International border (Poulsen and others, 1980; Day and Sims, 1984; Day and others, 1990; Day, 1990), where early recumbent folding was followed by upright folding and dextral strike-slip faulting. The same general tectonic regime has been recognized in the Ishpeming greenstone belt in northern Michigan, north of the Marquette trough (fig. 3) (Johnson and Bornhorst, 1991). In this region, early recumbent folds (F_1) are deformed by upright, predominantly Z-shaped folds and by younger dextral faults.

Sims (1991) has proposed that the transcurrent faulting and earlier upright folding (D_2) in the Wawa subprovince, and possibly also the Wabigoon subprovince, in north-central United States, resulted mainly from oblique collision along the Great Lakes tectonic zone (GLTZ), which is the paleosuture between Superior province rocks (Wawa subprovince) and the Archean gneiss terrane to the south (fig. 4). Based on data from the Marquette, Mich., area, the collision resulted in dextral thrust shear along the GLTZ and northward vergence and probable overriding of the south margin of the Superior province by the Archean gneiss terrane (Sims, 1991). This implies southward subduction of the Superior province rocks beneath the gneiss terrane, or northward obduction of the gneiss terrane over the Wawa subprovince. Age dating in the Rainy Lake area (Davis and others, 1989) indicates that the collision along the GLTZ occurred about 2,690 Ma, approximately concurrent with gold mineralization.

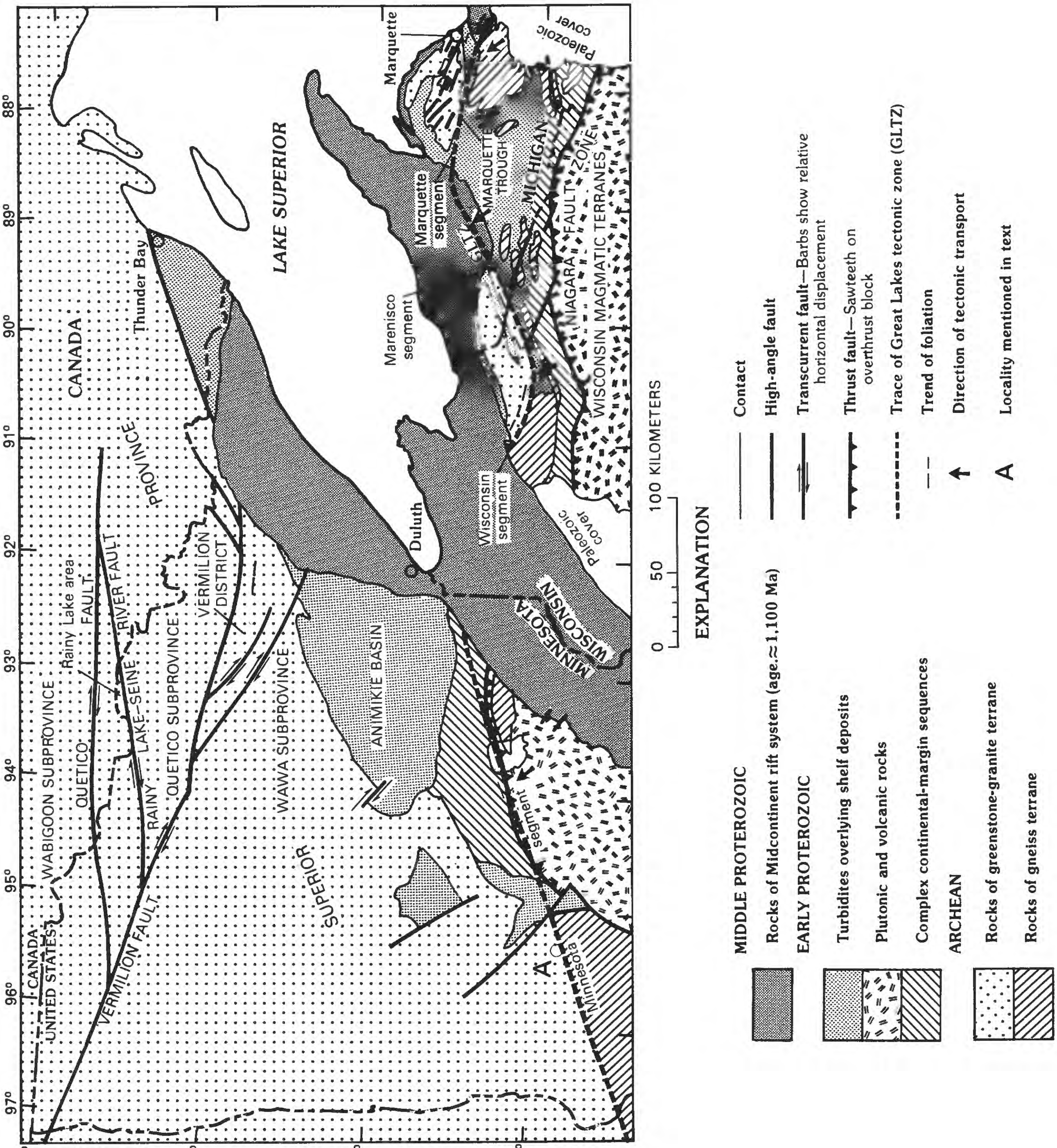
In east-central Minnesota, the nature of the GLTZ and its vergence is controversial. Shallowly dipping seismic reflectors throughout the upper 30–35 km of greenstone-granite crust have been interpreted as indicating faults, probably thrusts, that dominantly dip gently (≈30°) northward (Gibbs and others, 1984). A particularly conspicuous zone of reflectors of this attitude projects to the surface about 45 km north of the position of the GLTZ as delineated previously from discontinuities in gravity and magnetic anomalies (Morey and Sims, 1976, fig. 8), and this zone has been interpreted by Gibbs and others (1984) as the GLTZ. Other shallow-dipping reflectors both above and below the zone interpreted as the GLTZ presumably represent imbricate thrust structures related to the GLTZ. With this interpretation, the northward dip implies southward vergence and southward overriding of the gneiss terrane by the greenstone-granite terrane. However, by analogy with seismic reflection profiles in the greenstone-granite terrane of the Abitibi subprovince (Jackson and others, 1990), along strike to the northwest in Ontario and Quebec, we propose an alternative interpretation of the Minnesota seismic data. In the Abitibi belt, relatively flat seismic reflectors characterize the upper 12 km of greenstone crust. These reflectors resemble those in the greenstone crust of Minnesota in being discontinuous and having variable shallow dips. These 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 in seismic profiles. The shallow-dipping reflectors in the Abitibi subprovince are interpreted by Jackson and others (1990) as layering and (or) tectonic high-strain zones, perhaps low-angle faults that produced an "out of sequence" stratigraphy revealed by U-Pb geochronology (Corfu and others, 1989). We propose that the shallow-dipping seismic reflectors in the greenstone crust of central Minnesota represent recumbent folds and perhaps related faults, rather than structures related to the GLTZ. Such recumbent folds have been demonstrated in outcropping areas in northern Minnesota (Hudleston and others, 1988) as preceding upright folding and transpressive dextral shear (D_2).

We also propose that the steep southeast-dipping fault shown by Gibbs and others (1984) near station 500 on line 3 is the GLTZ. This structure, locally called the Morris fault (Gibbs and others, 1984, fig. 2), is 5 km south of Alexandria, in Douglas County, Minn. This position (locality A) is shown along the trace of the GLTZ in Minnesota in figure 4 of this report. The Morris fault has been determined from surface-wave focal-plane determinations of a recent earthquake near Morris to have a steep southerly dip (≈70°) (Herrmann, 1979). A steep southerly dip for the GLTZ in Minnesota would be consistent with structural observations in the tectonic zone near Marquette, Mich. (Sims, 1991), as well as with northward vergence on the structure. Also, the apparent narrowness of the tectonic zone in Minnesota is consistent with the 2.4-km-wide mylonite zone in the GLTZ exposed in Michigan.

Lamprophyre and Syenite in Vermilion District, Minnesota

Lamprophyre and syenite bodies of Late Archean age are common in the Vermilion district (Wawa subprovince) and adjacent parts of the Vermilion Granitic Complex (Quetico subprovince) (fig. 5). They are concentrated along and near the boundary of the Wawa subprovince and the Vermilion transcurrent fault, but are not confined to this zone, and are late- to post-tectonic, having been emplaced after the main regional deformation (D_2) (Hudleston and others, 1988).

The lamprophyre bodies are dominantly metaspessartite that contains euhedral ferromagnesian phenocrysts in a microgranular groundmass (Sims and Mudrey, 1972; Geldon, 1972). Hornblende and clinopyroxene are the dominant phenocrysts; plagioclase and potassium feldspar, in varying proportions and amounts, and ferromagnesian minerals occur in the groundmass. The intrusions are silica-undersaturated and volatile rich; they have high Fe_2O_3:FeO ratios and relatively high lime and total alkali contents. Lamprophyres within the Vermilion Granitic Complex (Quetico subprovince) are associated with and locally cut by appinites and hornblende diorites, their plutonic



CANADA
UNITED STATES
WABIGOON SUBPROVINCE
QUETICO
Rainy Lake area
FAULT
RIVER FAULT
LAKE-SEINE
RAINY
QUETICO SUBPROVINCE
PROVINCE
VERMILION FAULT
VERMILION DISTRICT
WAWA SUBPROVINCE
SUPERIOR
CANADA
Thunder Bay
LAKE SUPERIOR
ANIMIKIE BASIN
Duluth
Minnesota segment
A
Wisconsin segment
Paleozoic cover
MINNESOTA
WISCONSIN
Marenisco segment
Marquette segment
GLTZ
MARQUETTE TROUGH
MICHIGAN
NIAGARA FAULT ZONE
WISCONSIN MAGMATIC TERRANES
Marquette
Paleozoic cover
97°
96°
95°
94°
93°
92°
91°
90°
89°
88°
49°
48°
47°
46°
0
50
100 KILOMETERS
EXPLANATION
MIDDLE PROTEROZOIC
Rocks of Midcontinent rift system (age ≈ 1,100 Ma)
EARLY PROTEROZOIC
Turbidites overlying shelf deposits
Plutonic and volcanic rocks
Complex continental-margin sequences
ARCHEAN
Rocks of greenstone-granite terrane
Rocks of gneiss terrane
Contact
High-angle fault
Transcurrent fault—Barbs show relative horizontal displacement
Thrust fault—Sawteeth on overthrust block
Trace of Great Lakes tectonic zone (GLTZ)
Trend of foliation
Direction of tectonic transport
Locality mentioned in text

Figure 4 (facing page). Simplified tectonic map of Lake Superior region, showing Great Lakes tectonic zone and adjacent Archean terranes. Fault pattern is simplified from figure 2. Modified from Sims (1991). Terminology of Early Proterozoic rocks modified from Southwick and Morey (1991).

equivalents. McCall and others (1990) have shown that these lamprophyres range from olivine-normative to quartz-normative and are associated with cumulate hornblenditic rocks and pyroxenites. Values for εNd indicate derivation from a depleted mantle source. Lamprophyres along or adjacent to faults are foliated and metamorphosed, suggesting emplacement during the faulting. The lamprophyres and associated syenitic rocks in the western Vermilion district are clustered about a magnetic anomaly that presumably indicates a buried, cogenetic magnetite series (Ishihara, 1981) pluton (fig. 5). This interpretation is based on outcrops of syenite and lamprophyre along the margins of the buried anomaly.

Gold Deposits, Occurrences, and Anomalies

Ropes Gold Mine, Northern Michigan

The Ropes gold mine, in northern Michigan (location, fig. 6), has been the only substantial gold producer in the United States segment of the Archean Superior province. From 1882 to 1897 it produced 1,250 kg of gold and 6,200 kg of silver (Broderick, 1945), and from 1985 to closing in 1989 it produced 5,219 kg of gold (R.A. Brozdowski, written commun., 1990).

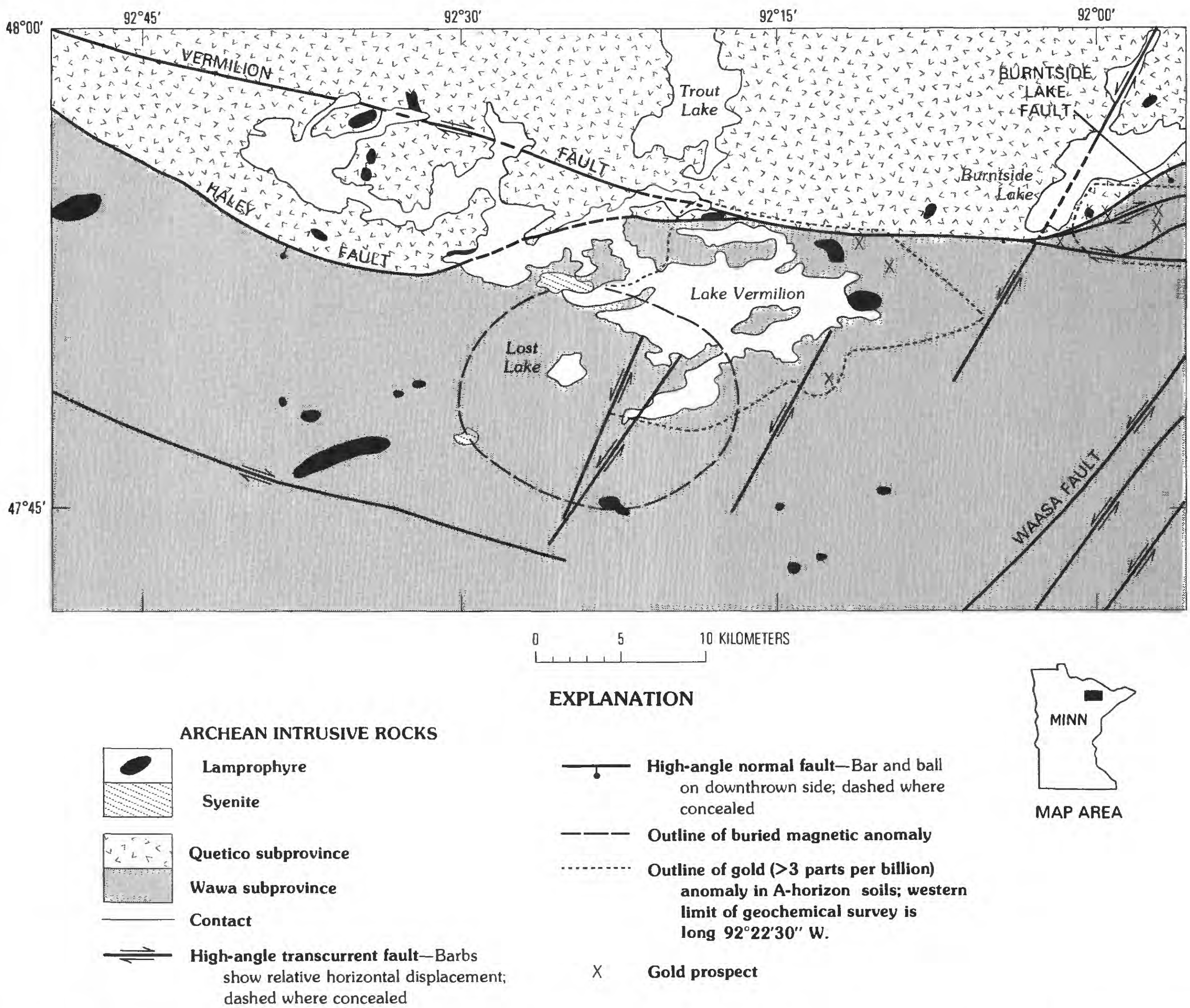


Figure 5. Simplified geology of western Vermilion district, Minnesota, showing distribution of gold prospects and area of anomalous gold in A-horizon soils relative to faults, lamprophyre and syenite bodies, and buried magnetic anomaly at Lost Lake. Sinistral faults are highly generalized. Modified from Sims and Mudrey (1972), with additions from Sims and Southwick (1985).

The Ropes deposit contains 2.8 million t (metric tons) of ore assaying 3.24 g Au/t and minor silver (R.A. Brozdowski, written commun., 1989). It occurs in quartz-sericite-chlorite rock within serpentinized peridotite (fig. 7). The protolith of the quartz-sericite-chlorite rock is altered dacite tuff, tuff breccia, and flows. The quartz in the altered rock shows undulose extinction and subgrain textures indicative of grain size reduction (Hanmer, 1982) during ductile deformation. The deposit has been described by Bornhorst and others (1986), Brozdowski and others (1986), and Brozdowski (1988; 1989); and earlier by Broderick (1945).

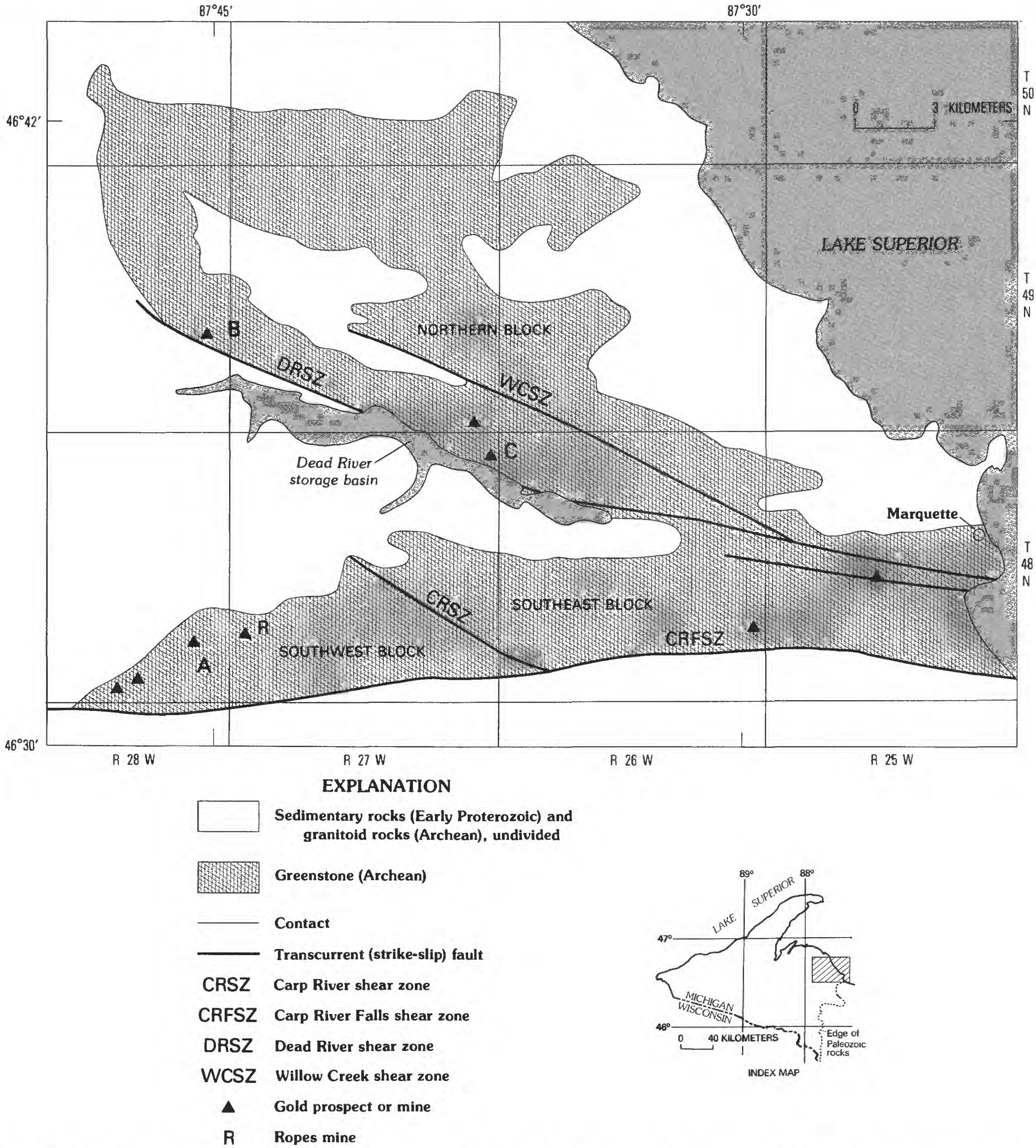


Figure 6. Simplified geology of Ishpeming greenstone belt, northern Michigan, showing major faults and gold prospects and mines. Geology modified from Brozdowski (1989) and Johnson and Bornhorst (1991). A, B, and C mark concentrations of gold occurrences (Brozdowski, 1989, fig. 8).

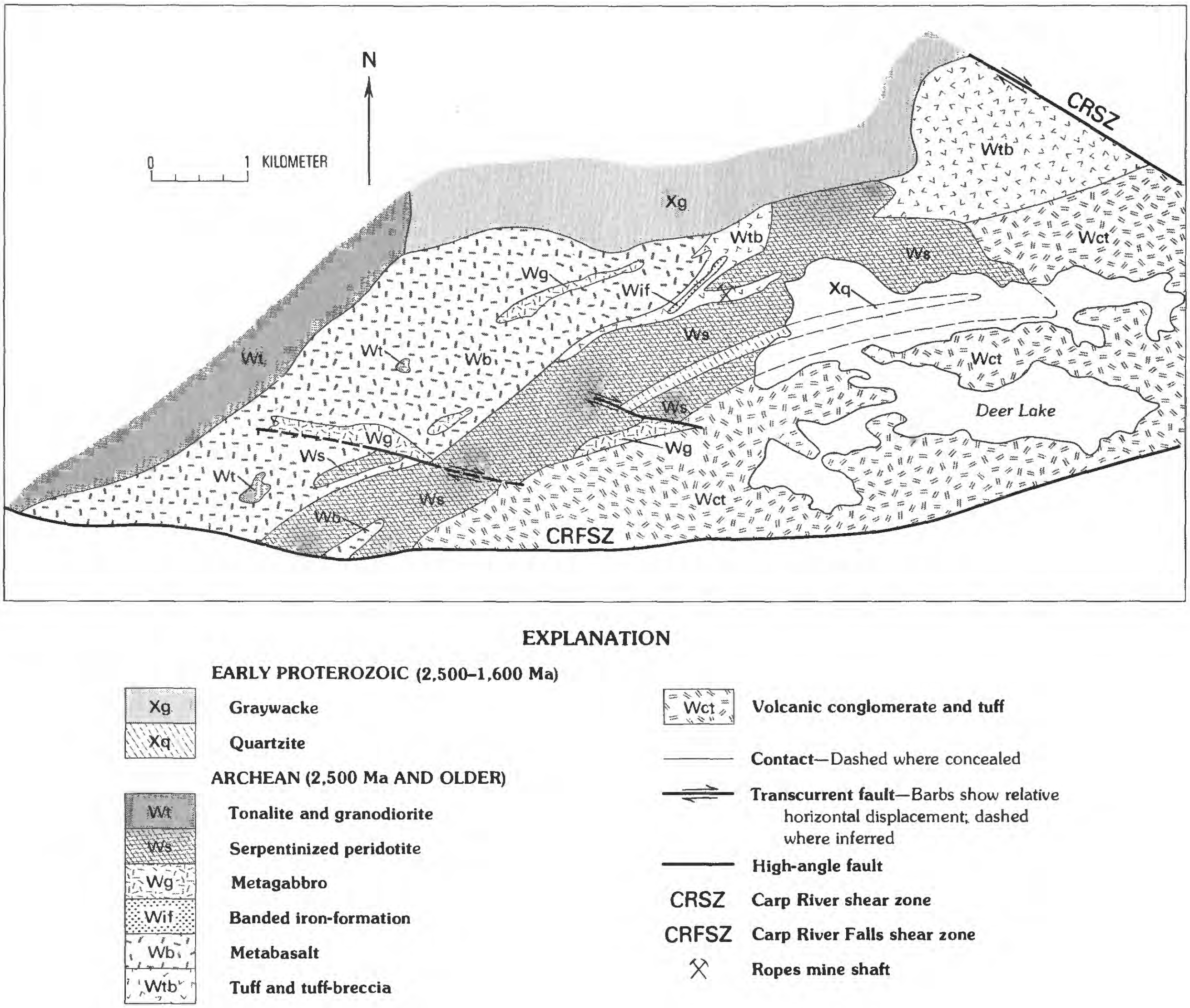


Figure 7. Geology of Ropes mine area, Michigan. Modified from Brozdowski (1989).

The ore is of two types: (1) finely disseminated gold with disseminated pyrite in quartz-sericite-chlorite rock (altered dacite), which comprises about 75 percent of the ore, and (2) gold-bearing quartz-tetrahedrite veins. The main ore zone trends N. 80° E., subparallel to the foliation, dips steeply, and has a strike length of about 335 m, an average width of 12 m, and a down-dip extent of more than 600 m (Brozdowski, 1989).

Ore shoots within the N. 80° E.-trending main ore zone strike N. 55°–65° E. and form en-echelon sigmoidal zones of gold and dispersed pyrite (fig. 8). Brozdowski (1989) determined that the sigmoidal zones of gold concentration follow an S fabric (Lister and Snoke, 1984), interpreted as a largely compressive, ductile feature. The orientation of the S fabric relative to the C direction (fig. 8) indicates a dextral component of shear when viewed in the horizontal plane.

The auriferous quartz veins occur on the south margin of the deposit as en-echelon ore shoots that strike N. 55°–65° E. within the N. 80° E. trend of the host rock, plunge steeply west, and occur progressively farther east in successively deeper mine levels. As in the main ore zone, the quartz has undulatory extinction, subgrain development, and mortar texture along grain boundaries. The maximum stretch direction (X axis of strain ellipse) determined by connecting the midpoints of these extension veins is oriented at an angle of about 45° S. 45° E. These ore shoots plunge subparallel to the stretch lineation in the GLTZ (Sims, 1991).

Prospects in Northern Michigan

Gold occurrences are widely distributed in the Ishpeming greenstone belt but are concentrated in three main

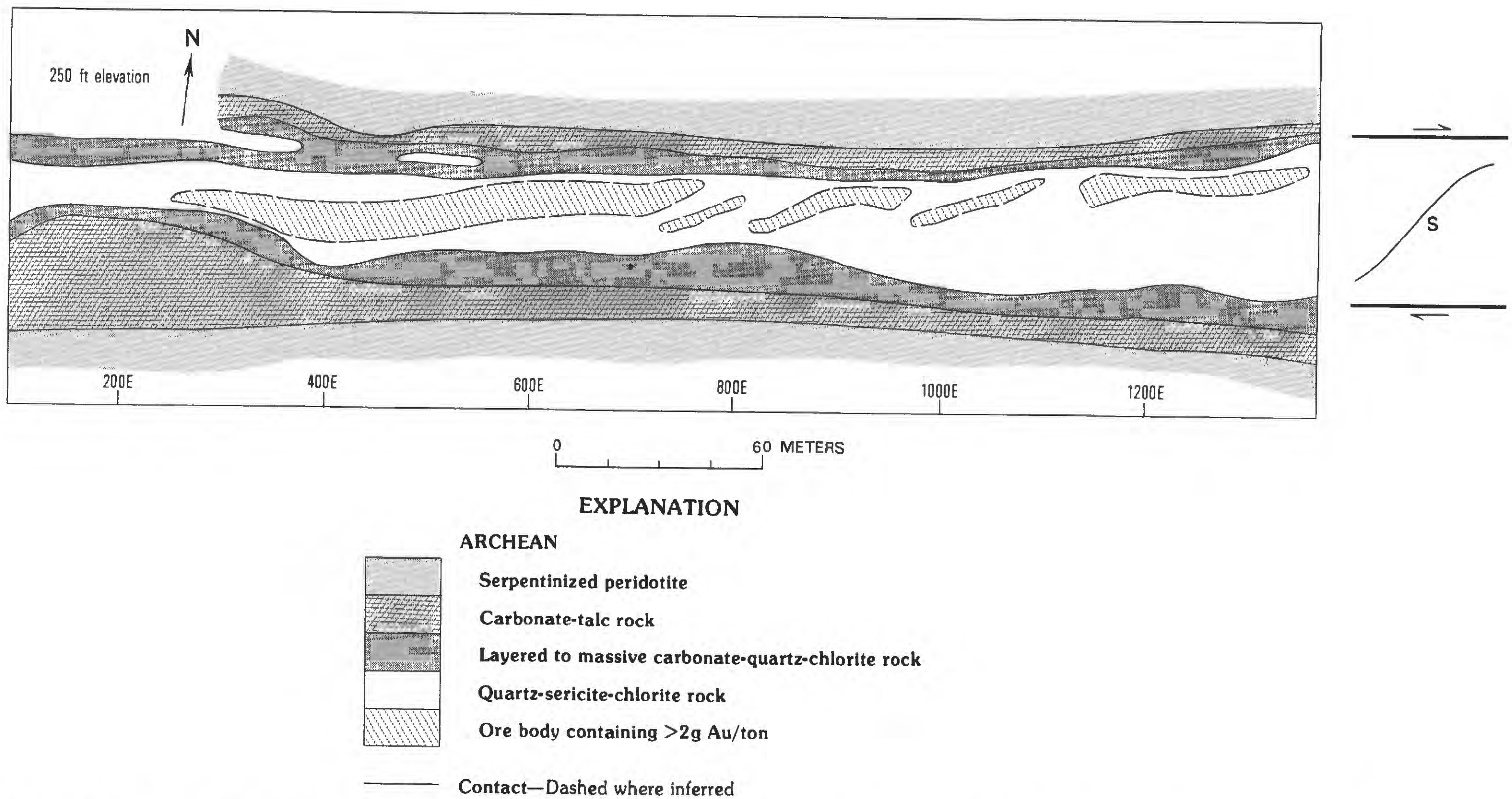


Figure 8. Geology of 1,152-foot level, Ropes mine, Michigan. Modified from Brozdowski (1988). Sketch at right shows S-C fabric with dextral sense of shear.

areas (Brozdowski, 1989, fig. 8), designated A, B, and C in figure 6. In area A, several small deposits and prospects occur within a kilometer-wide belt trending southwestward from the Ropes mine. The deposits strike in diverse directions and lack a common structural control. In area B, known as the Silver Creek area (Brozdowski, 1989), several small occurrences occur in a chlorite-rich altered rock in and adjacent to the Dead River shear zone. In area C, gold occurrences are along sheared rhyolite sills that strike subparallel to the Dead River shear zone.

Rainy Lake Area, Minnesota

Scattered occurrences of gold were discovered in northern Minnesota during the latter part of the 19th century, but these deposits have yielded negligible amounts of gold (Sims, 1972, and references therein). The Little American mine, on Little American Island, near the south shore of Rainy Lake (fig. 9; Day, 1990) yielded a small amount of gold in 1894 and 1895. The gold was extracted from a 4- to 6-ft composite quartz vein zone in sheared chloritic and biotitic schist. The deposit lies within the Rainy Lake–Seine River fault zone, a major dextral transcurrent fault (Day, 1990) that in this area separates the Quetico subprovince from the Wabigoon subprovince to the north (figs. 1 and 9). The gold-bearing quartz vein or veins have associated arsenopyrite and pyrite and ankerite alteration. The veins form concordant and locally discordant pods, boudins, and stringers within the host schist, indicating that mineralization was during or slightly later than shearing associated with the Rainy Lake–Seine River fault. Other prospects were opened intermittently along the east-northeast extension of the vein zone in the Little American mine and in the Vermilion district, to the south.

Poulsen (1983) has reported that the numerous small gold-quartz veins in the Mine Centre–Fort Frances area, between the Rainy Lake–Seine River fault and the Quetico fault to the north (fig. 9), occur in ductile shear zones and associated dilation zones. The shears between the two major dextral transcurrent faults that host the gold deposits are mainly secondary sinistral faults, which are conjugate to the longer east-trending major dextral faults. Stott and Schnieders (1983) reported a similar structural control for Archean lode gold occurrences in the Shebandowan belt (Wawa subprovince) in Canada.

Anomalies in Vermilion District, Minnesota

High-angle faults and shear zones form the subprovince boundary between the migmatitic and granitic Vermilion Granitic Complex (Quetico subprovince) to the north and the greenstone-granite terrane of the Vermilion

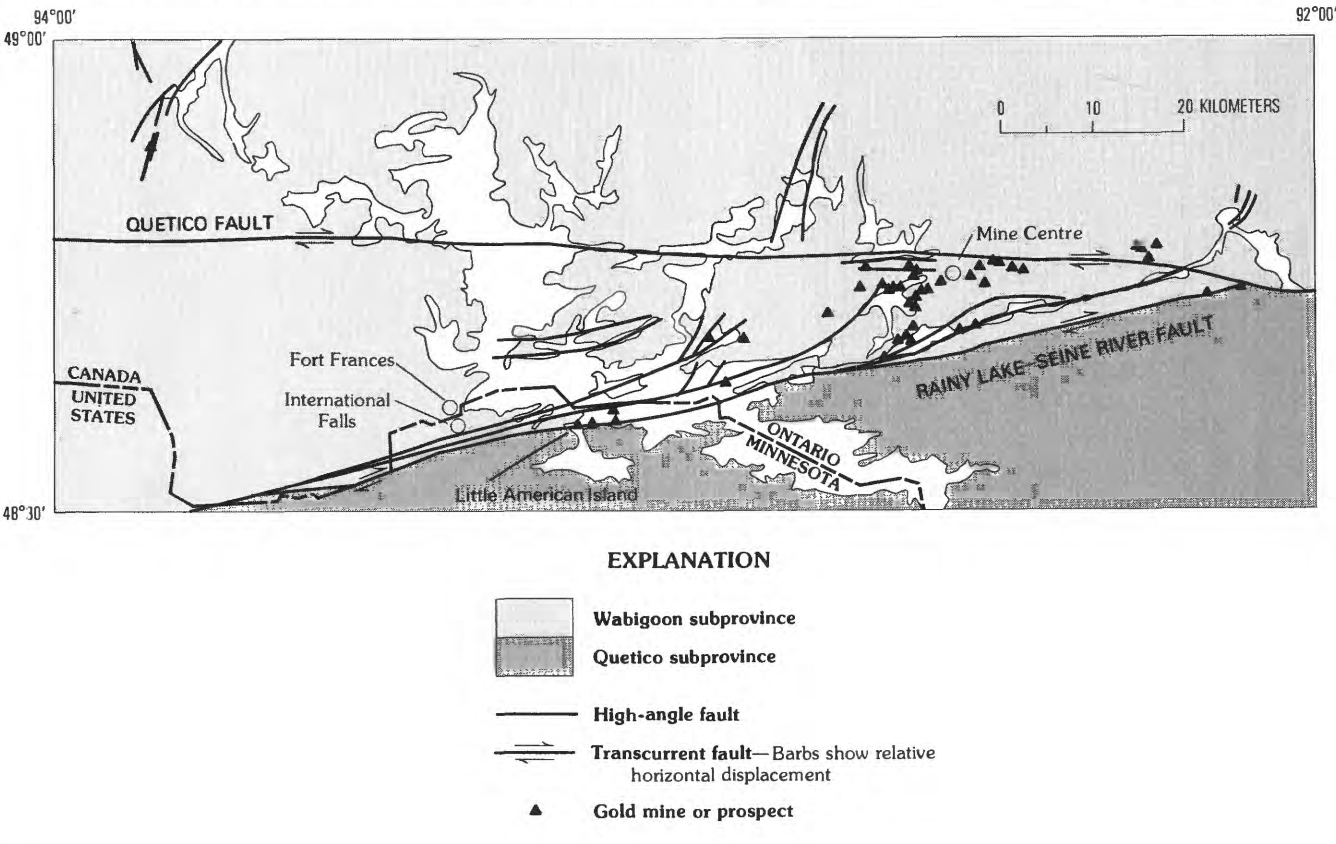


Figure 9. Structure of Rainy Lake area, Minnesota and Ontario, showing relationship of gold deposits to transcurrent faults (modified from Klein, 1989).

district (Wawa subprovince) to the south (fig. 5). The subprovince boundary is delimited in the Vermilion district by the Vermilion, Haley, and Burntside Lake faults. As in the Rainy Lake area, several gold prospects occur within a 2-km-wide belt in adjacent shear zones associated with the subprovince bounding fault zones (fig. 5). The gold-bearing shear zones are typically chlorite schists or phyllonitic schists with notable carbonate and quartz alteration and variable amounts of talc, fuchsite, and tourmaline (A. Koyner, written commun., 1989).

A-horizon soils in the west-central Vermilion district, northern Minnesota, contain anomalous amounts of gold as well as base metals (Alminas and others, 1992). The principal anomalous area, centered on Lake Vermilion (fig. 5), comprises about 90 km^2. In this area, the gold contents of the soils are as high as 1.1 ppm (parts per million); the gold is associated with Ag, Cu, Pb, Zn, Ti, Cr, Co, Ni, La, V, and Y. The original mineralization was nearly restricted to areas underlain by Late Archean volcaniclastic rocks of greenschist facies (Sims, 1985), and took place within an area coincident with a pronounced positive aeromagnetic anomaly that represents a buried pluton probably having affinities with syenite and lamprophyre (fig. 5).

The second anomalous gold area, about 77 km^2 in areal extent, lies about 30 km east-northeast of the east end of Lake Vermilion, and is east of the area of figure 5. Here, the gold is associated with Cu, Ti, Mn, Ag, Co, Mo, Ni, Sc, Zn, and V. The mineralization took place in areas underlain by metavolcanic rocks and metagraywacke bedrock of greenschist facies (Sims, 1985). Lamprophyre and syenite bodies are present in the core of the anomalous area. Alminas and others (1992) have stated that a pronounced positive aeromagnetic anomaly is virtually coextensive with the gold anomaly.

The two areas of anomalous gold and base metals in A-horizon soils are within bedrock, in greenschist-facies volcanic-related rocks that are intensely faulted (Sims, 1985). The east-trending Vermilion and related dextral transcurrent faults and abundant northeast-trending sinistral faults transect the area. Also, as noted previously, epizonal lamprophyre and syenite bodies are uncommonly abundant. Alminas and others (1992) suggested that the gold and base-metal mineralization was spatially related to these magmatic intrusions.

AN OCCURRENCE MODEL FOR GOLD MINERALIZATION IN THE UNITED STATES SEGMENT OF SUPERIOR PROVINCE

The voluminous literature on Archean lode gold deposits in the Canadian segment of the Superior province and the definitive syntheses of Colvine and others (1988), Colvine (1989), and Card and others (1989), together with numerous detailed geologic maps, provide a firm basis for formulating an occurrence model for gold mineralization in the United States part of the Superior province, inasmuch as the geologic setting of the two regions is remarkably similar.

The widely held consensus that Archean lode gold deposits in the Superior province in Canada resulted from the flow of large volumes of fluid, derived from an external source, through structurally formed permeable zones (Colvine and others, 1984; Colvine, 1989; Card and others, 1989) points up the important role of structure in localizing those Archean gold deposits. On a regional scale the deposits are within or near major transcurrent faults or shear zones that are sites of high strain and which form a conjugate system: (1) east-trending dextral faults, some of which are of subcontinental length, and (2) northeast-trending sinistral faults. These faults cover a wide range in style of deformation, from ductile shear zones through brittle-ductile zones to brittle shear zones and faults (Ramsay, 1980; Hodgson, 1989). The faults are a late phase of the regional deformation (D_2). The conjugate systems require compression oriented northwest-southeast. This tectonic environment is similar to that in the Golden Mile area of the Kalgoorlie mining district, Western Australia (Mueller and Harris, 1987; Mueller and others, 1988, and references therein); in Australia, gold deposits are localized in structures subsidiary to large-scale transcurrent shear zones; they postdate regional folding and metamorphism.

Structures related to the regional transcurrent conjugate fault system in the Superior province (figs. 2 and 4) provide the plumbing system for the fluids that deposited the gold. At a deposit scale, enhanced permeability in dilational areas is the main locus of mineralization, relative to the compressional segments of a transcurrent shear system (Sibson, 1987; Hodgson, 1989).

Deformation zones are commonly discordant to the boundaries of rock units on a regional scale. Therefore, they contain the deformed equivalents of many rock types that characterize Superior province greenstone-granite terranes. Deformation zones commonly consist of several separate shears that anastomose and bifurcate in both horizontal and vertical dimensions. Planar fabrics in the shear zones, which may be superposed on one another, include S-C structures, extensional crenulation cleavages, stretch lineations, and lineations caused by the intersection of C and S fabrics (Hodgson, 1989). Grain-size reduction, resulting from syntectonic recrystallization associated with ductile strain or crystal-plastic processes (Wise and others, 1984), and grain fracturing are characteristic of deformation zones. The resulting rocks are mylonite or cataclasite. Colvine and others (1988) have shown that gold-bearing vein systems show systematic vertical and lateral changes in mineralization style: breccia-bearing veins occur mainly within zones of brittle deformation and replacement veins typify ductile deformation zones. Extensive, intense wallrock alteration is associated with most of the lode gold deposits in both mineralizing environments (Roberts, 1987).

With few exceptions, the Canadian gold deposits are restricted to the greenstone belts and immediately adjacent areas. Thus, in the United States, the greenstone-granite terranes of the Wawa and Wabigoon subprovinces should be most favorable areas for the occurrence of gold deposits. Rocks of the Wabigoon subprovince are exposed in extreme northern Minnesota (fig. 10), in the vicinity of International Falls and areas to the west (Day, 1990; Day and others, 1990). Rocks of the other favorable greenstone-granite terrane, the Wawa subprovince (fig. 10) are exposed in northeastern Minnesota, as exemplified by the Vermilion district (Sims and Southwick, 1985; Sims, 1985), and in the Upper Peninsula of Michigan, within the Ishpeming greenstone belt (figs. 3 and 6) (Johnson and Bornhorst, 1991). Potentially favorable host rocks would include ultramafic, mafic, and felsic metavolcanic rocks; clastic metasedimentary rocks, generally of volcanogenic affinity; iron-formation; and mafic to felsic plutons. The most favorable metamorphic grade of the supracrustal host rocks is greenschist facies.

A close spatial and temporal association of silica-undersaturated plutons with gold deposits (Colvine and others, 1988) is observed in many gold-bearing areas, but the role of this suite of alkalic intrusions in gold mineralization is uncertain. Commonly, these intrusions were emplaced within or near the deformation zones with which the gold-mineralized material is associated. As suggested by Wyman and Kerrich (1988), both the gold and the intrusions were emplaced under tensional conditions along structures that extend to mantle depths, but each could have been derived from separate source regions. Alternatively, the mineralization and magmatic activity could be genetically related, as suggested by Rock and others (1989) for at least some deposits; this possible relationship deserves further study.

The nature of the ore-forming fluid is known moderately well for Canadian deposits, as determined from several mining districts in the Abitibi, Wawa, and Wabigoon subprovinces (Colvine and others, 1988, and references therein; Foster, 1990). In brief, the Archean auriferous fluids appear to be characterized by high fluid pressure, low salinity, moderate temperature, and the presence of CO_2. From the striking similarities between data from Canadian and Australian Archean gold deposits, Colvine and others (1989) have suggested that a compositionally uniform fluid of either magmatic or metamorphic derivation was involved in the gold-related alteration and gold precipitation event in both regions. The fluid was derived from a large reservoir, which was external to the immediate depositional environment.

EXPLORATION IMPLICATIONS IN THE UNITED STATES

The occurrence model described previously suggests that two regions in north-central United States are particularly favorable for gold mineralization: (1) northern Michigan and (2) northeastern Minnesota. Both areas contain moderately good bedrock outcrops and have a generally thin cover of Pleistocene glacial deposits and colluvium.

Archean rocks in the Ishpeming greenstone belt in northern Michigan are favorable host rocks for potential gold deposits because of the known valuable deposit at the Ropes mine, minor gold occurrences elsewhere (Bodwell, 1972; Brozdowski, 1989), and the existence of several major dextral transcurrent faults (figs. 3 and 6). Exploration in this region is difficult, however, because of extremely complex folding, including large Z-shaped folds, that preceded development of the dextral transcurrent faults (Johnson and Bornhorst, 1991).

Northern Minnesota has been explored sporadically for gold (Morey, 1989), mainly using a fault model. It deserves further exploration because of the known gold occurrences, the exceptionally anomalous soils in the Lake Vermilion area and vicinity, the numerous lamprophyre and syenite plutons, and the abundant transcurrent faults (figs. 2 and 9). The anomalous gold values in soils in the two areas in the west-central Vermilion district (Alminas and others, 1992) particularly deserve attention, as does the possible relationship between gold mineralization and the late alkalic intrusions.

DISCUSSION

The major transcurrent faults that host gold mineralization in the Superior province of north-central United States and adjacent Canada resulted at least in part from convergent tectonics along the GLTZ. Sims (1991) has shown that the major dextral transcurrent faults in northern Minnesota and Michigan can be accounted for by oblique collision along the GLTZ. This collision caused dextral transpression, resulting in a northwest-southeast component of shortening in addition to shear, followed by dextral faulting, a more brittle expression of the shear regime. A conjugate, northeast-trending sinistral fault system formed essentially concurrently with dextral shear. The northern extent of this shear regime is equivocal, however, because structures resulting from dextral transpression characterize the whole of the Superior province (Card and others, 1989, fig. 6). The shearing provided permeable zones extending at least to the crust-mantle boundary into which lamprophyre and related late- to post-tectonic syenitic rocks were emplaced. Gold deposits are localized in these zones.

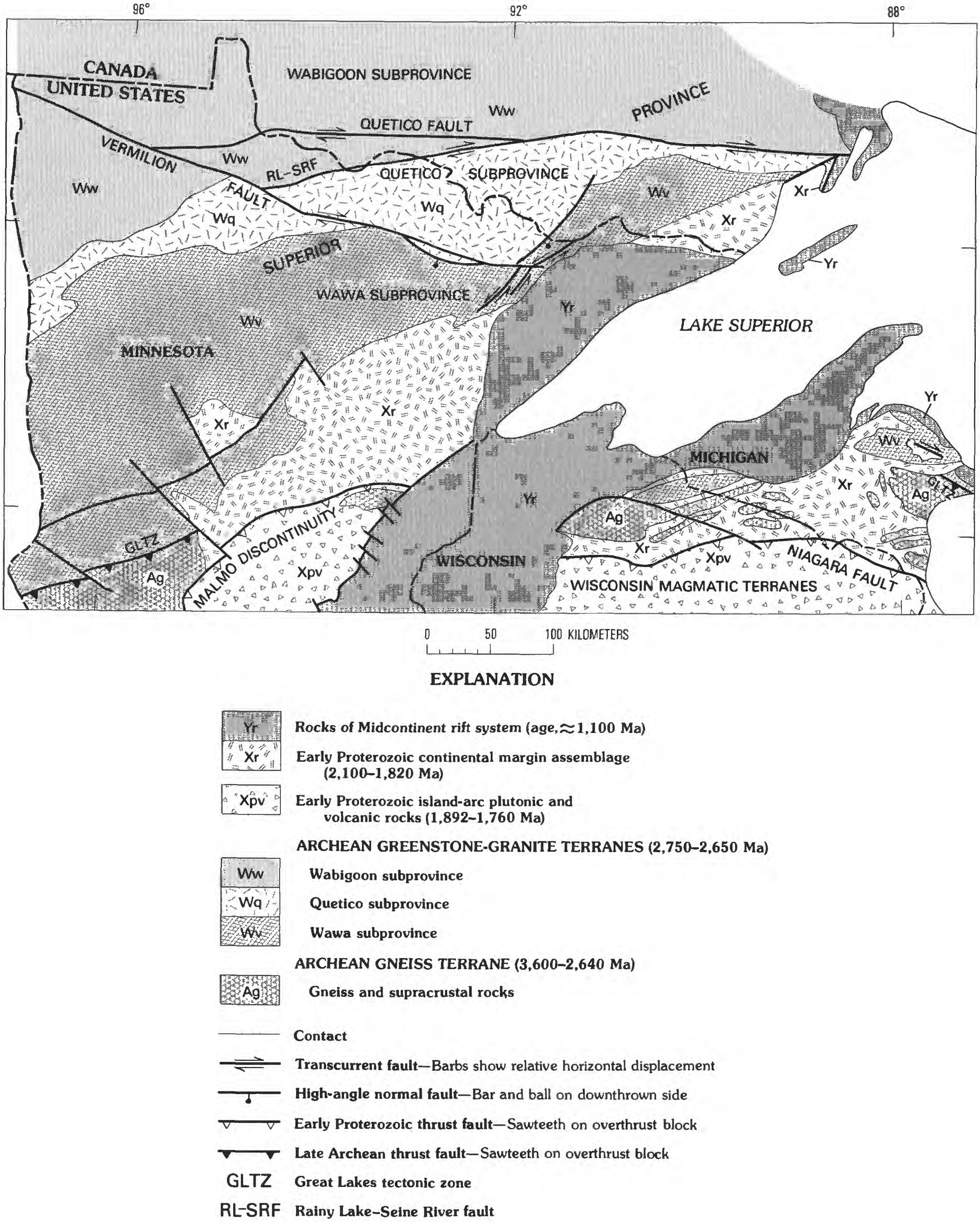


Figure 10. Simplified tectonic map of Lake Superior region, showing outline of subprovinces within the Archean Superior province.

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