Geology and Metallogeny of Archean and Proterozoic Basement Terranes in the Northern Midcontinent, U.S.A.— An Overview

U.S. GEOLOGICAL SURVEY BULLETIN 1815

Prepared in cooperation with the
Missouri Geological Survey and
Minnesota Geological Survey

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By P.K. SIMS, U.S. Geological Survey, and
EVA B. KISVARSANYI, Missouri Geological Survey, and
G.B. MOREY, Minnesota Geological Survey

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Missouri Geological Survey and Minnesota Geological Survey

A description of major known and potential mineral resources

U.S. GEOLOGICAL SURVEY BULLETIN 1815

CONTRIBUTION TO THE GEOLOGY OF THE MIDCONTINENT REGION

DEPARTMENT OF THE INTERIOR
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By P.K. Sims, Eva B. Kisvarsanyi[1], *and* G.B. Morey[2]

Abstract

The exposed and buried basement in the northern midcontinent (lat 36°–46° N., long 88°–100° W.) is a collage of tectono-stratigraphic terranes that range in age from Archean to Middle Proterozoic. Eight major terranes have been identified and delineated. From oldest to youngest, these are (1) Archean gneiss terrane (age, 2.6–3.6 Ga); (2) Late Archean greenstone-granite terrane (age, 2.6–2.7 Ga); (3) Early Proterozoic Wisconsin magmatic terrane (age, 1.83–1.89 Ga) and associated epicratonic rocks (age, ~1.9–2.1 Ga) of the Penokean orogen; (4) Early Proterozoic rhyolite-granite terrane of southern Wisconsin (age, 1.76 Ga); (5) Early Proterozoic metamorphic and granitoid rocks of the Central Plains orogen (age, 1.63–1.8 Ga); (6) Middle Proterozoic St. Francois granite-rhyolite terrane (age, 1.48 Ga); (7) Middle Proterozoic Spavinaw granite-rhyolite terrane (age, 1.35–1.4 Ga); and (8) Middle Proterozoic Midcontinent rift system (age, 1.0–1.2 Ga). Other coherent rock units include quartzite of the Baraboo interval (age, ~1.63–1.76 Ga) and plutons of anorthosite and mesozonal rapakivi granite of the Transcontinental anorogenic province (age, ~1.4–1.5 Ga). Three of the terranes—the Late Archean greenstone-granite terrane, the Wisconsin magmatic terrane, and the rocks of the Central Plains orogen—are entirely or mostly oceanic-arc complexes that were accreted to the North American continent; whereas most other terranes are continental crustal segments that evolved in extensional environments.

The northern midcontinent is traversed by numerous northwest-trending tectonic zones which are interpreted as shears and are characterized by cataclastic zones in the basement, by aligned granite and mafic intrusions of Middle Proterozoic age and, commonly, by faulting and folding in overlying Paleozoic rocks. Movements on the shears are poorly known, but the shears are believed to belong to a family of regional transcurrent dextral faults known from exposed areas in the Lake Superior region and adjacent Canada. They are potential sites for epigenetic ore deposits.

The northern midcontinent has a high potential for undiscovered mineral resources because many of the terranes are favorable for ore generation. Exposed parts of the region—the Lake Superior region in the north and the Southeast Missouri district in the southeast—are major mineral-producing areas that together have yielded ores, mainly of iron and copper, valued at several billion dollars. A further positive factor has been the relatively recent discoveries of as yet unmined deposits containing large zinc-copper and copper-nickel, cobalt-platinum resources in the Lake Superior region. Another positive aspect for exploration is the relatively shallow depth of much of the basement; in about two-thirds of the northern midcontinent area, the basement is less than 3,000 feet (910 meters) below the surface.

Four major geologic terranes known to contain substantial mineral resources extend into the subsurface. The first, the Late Archean greenstone-granite terrane in the buried basement of the Dakotas, could host massive sulfide deposits about 5 million tons in size, stratiform gold deposits, Algoma-type iron-formation deposits, and possibly other types of deposits. Probably, felsic volcanic rocks of tholeiitic affinity would be the most favorable host rocks.

The second, the Wisconsin magmatic terrane, contains at least four volcanic-hosted massive sulfide deposits of future economic importance, the largest of which (Crandon) contains about 60 million tons of copper-zinc ore. Other known deposits are smaller, being about 5 million tons or less. Gold is another potential commodity.

The third, the St. Francois granite-rhyolite terrane, hosts large deposits of iron and copper-iron and apparently smaller deposits of tin, tungsten, silver, lead, and antimony.

The fourth terrane, rocks of the Midcontinent rift system, hosts world-class stratiform volcanic-hosted and sedimentary-hosted copper deposits and the very large, unmined gabbro-hosted copper-nickel deposits of the Middle Proterozoic Duluth Complex. Iron oxide-rich mafic intrusive rocks could host platinum-group metals. In recent years, the sedimentary rocks have been targeted as potential sources of petroleum.

Other terranes, by analogy with similar rocks elsewhere in the world known to contain valuable ore deposits, are potentially ore bearing. The quartzite of the Baraboo interval possibly could host unconformity-type uranium deposits. Also, rocks of the Central Plains orogen could host base-metal sulfide and tungsten deposits. Contrary to current exploration philosophies, the Archean gneiss terrane possibly could host base-metal sulfide and precious metal deposits, inasmuch as it probably has in part a greenstone-belt protolith.

The Middle Proterozoic anorogenic terranes in the southern part of the midcontinent—the St. Francois and Spavinaw granite-rhyolite terranes—provide a broad tectonic environment similar to that of the world-class Olympic Dam deposit in southern Australia, and they deserve consideration for exploration for such a deposit.

[1]Missouri Geological Survey.
[2]Minnesota Geological Survey.

INTRODUCTION

A new Precambrian basement map of the northern midcontinent (lat 36°–46° N., long 88°–100° W.; Sims, 1985, in press) provides a geologic framework within which known and potential mineral resources in the region can be discussed. Within the map area (fig. 1), significant known mineral deposits are confined to a part of Wisconsin within the Lake Superior region and to the St. Francois Mountains in southeastern Missouri.

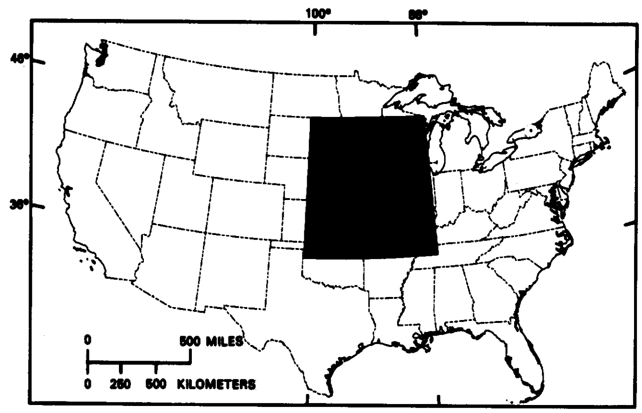


Figure 1. Map showing area covered by new basement map of the northern midcontinent by Sims (1985, in press).

In order to provide a broader base for discussing the metallogeny of the region, we have extended the area of concern northward to the United States-Canada border and westward to about long 105° W. (fig. 2), because this area encompasses nearly all the important past and present metal-mining districts and potential ore deposits in the Lake Superior region and northern midcontinent. Although the map covers the Black Hills uplift in South Dakota—within the Trans-Hudson orogen—this area will not be discussed specifically in this report.

Guild (1971, 1972) has shown that metallogeny (the study of the genesis of ore deposits in their total geologic environment) is a valuable approach to exploration and that a broad-scale relationship exists between types of ore and elements of global plate tectonics, at least in post-Eocene time. Albers (1981) successfully extended this approach to include the older Phanerozoic rocks in California. Sims (1987) attempted to show that metallogeny is a powerful tool also in understanding the distribution of mineral deposits in the Precambrian tectono-stratigraphic terranes of the Great Lakes region, and that it can be applied to other, similar terranes. This report attempts to utilize this method of investigation to estimate the mineral potential of the buried Precambrian basement of the interior platform.

The Precambrian basement map of the northern midcontinent region (scale 1:1,000,000; Sims, 1985, in press) was compiled from 1:500,000-scale maps submitted by the respective state geological surveys showing basement drill holes, lithotypes or preliminary geologic map units, and basement topography, contoured at 200-ft intervals. In compiling the map, available regional aeromagnetic (Zietz, 1982; Zietz and others, 1984; Burchett, 1985) and gravity anomaly (Hildenbrand and others, 1982) maps were utilized to define insofar as possible the extent and outlines of related rock bodies; all available isotopic age data were utilized (Marvin, 1987). The map is a revision of the earlier basement rock map for the northern midcontinent region (Bayley and Muehlberger, 1968).

The term "anorogenic" is used herein for granitoid and volcanic rocks that were generated along rift zones and within stable continental blocks and were emplaced during periods of negligible crustal strain. The granitoid rocks have been termed A-type (Loiselle and Wones, 1979; Collins and others, 1982), because they are somewhat alkaline, anorogenic, and anhydrous, to distinguish them from I- and S-type (Chappell and White, 1974) orogenic granitoids. Anorogenic granitoids have low CaO, Al_2O_3, and MgO, high K_2O/Na_2O, and greater than 60 percent SiO_2. They show definite iron enrichment compared to orogenic rock associations (Martin and Piwinskii, 1972), and they are relatively enriched in the incompatible trace elements. In the region covered by this report, the term anorogenic has been used previously by Kisvarsanyi (1980) to describe the alkali-feldspar-rich rocks of the St. Francois granite-rhyolite terrane, by Anderson (1983) to describe the granitoid rocks in the Transcontinental anorogenic province, and by Smith (1983) to describe the post-Penokean granite and rhyolite from southern Wisconsin.

Throughout this report isotopic ages are generally reported with the abbreviation Ga (Giga-annum; 10^9 years), but precise ages are reported with the abbreviation Ma (Mega-annum; 10^6 years) as for example $3{,}545 \pm 45$ Ma.

Acknowledgments

R.E. Denison provided descriptions of core samples from two wells in Fulton and Randolph Counties in northeastern Arkansas, which were recently obtained by the Arkansas Geological Commission. We benefited from numerous discussions with Geza Kisvarsanyi regarding the geology and mineral resources of Missouri and adjacent areas. Warren Day and Richard Grauch provided constructive reviews that materially improved the manuscript.

TECTONO-STRATIGRAPHIC FRAMEWORK

The tectono-stratigraphic framework of the Precambrian basement rocks in the northern midcontinent

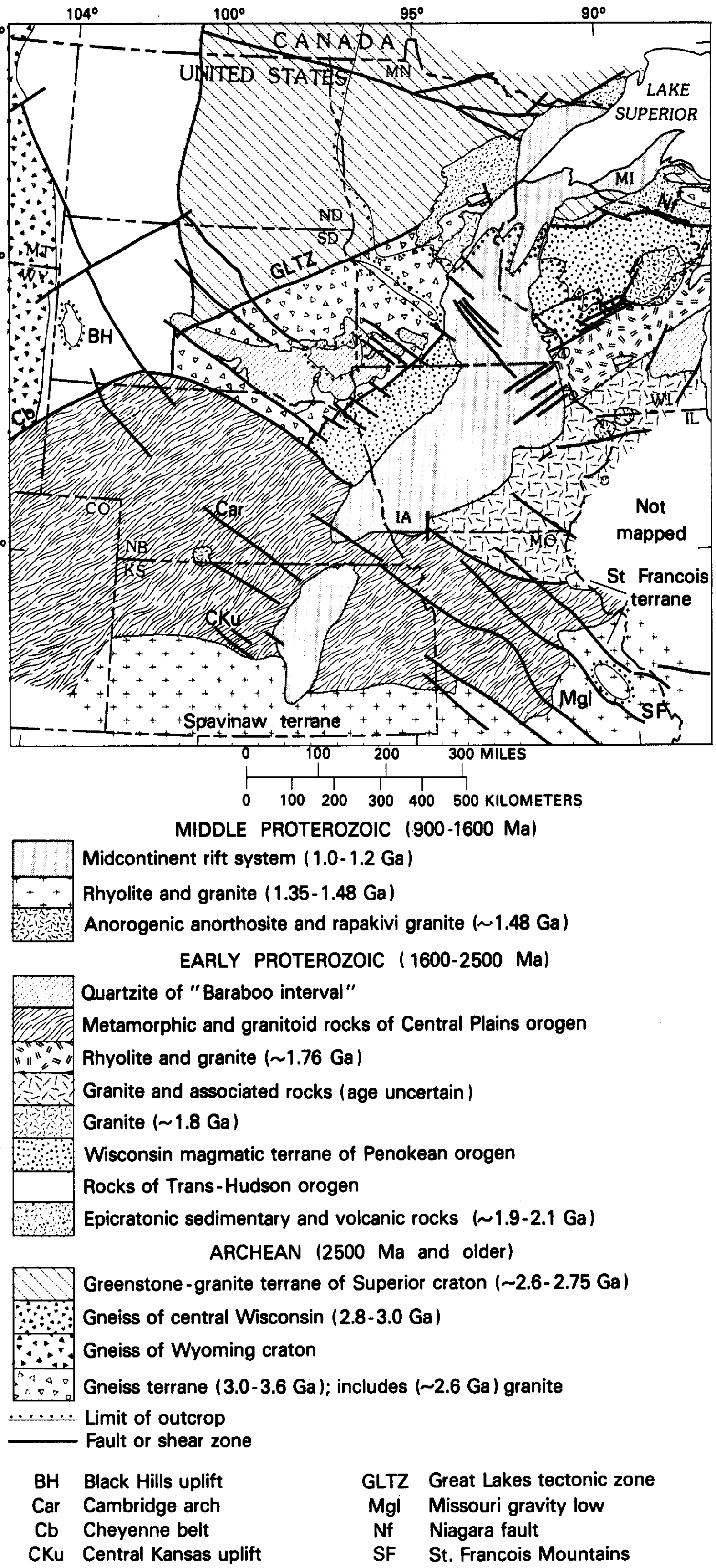


Figure 2. Generalized Precambrian basement map of the northern midcontinent.

can be inferred from the exposed rocks in the Lake Superior region and in the St. Francois Mountains of southeastern Missouri, from extrapolation of exposed terranes into the subsurface, and from basement drill-hole data together with pertinent aeromagnetic and gravity data. U-Pb zircon age data, obtained by M.E. Bickford, W.R. Van Schmus, and students (compiled by Marvin, 1987), provide a necessary time frame for the buried basement rocks.

The combined data show that the exposed and buried rocks in the midcontinent region are a tectonic assemblage of anastomosing Early Proterozoic orogenic belts that border and marginally affect the southern part of the Archean Superior craton, Early Proterozoic intracratonic igneous and sedimentary rocks, Middle Proterozoic anorogenic intrusions and associated volcanic rocks, and a Middle Proterozoic intracratonic rift (fig. 3). The rocks record several major crust-forming events, local reactivation of the Archean gneisses in the Penokean orogen, and the erosion and deposition of epicratonic successions. The major tectono-stratigraphic units for the broader region are shown on figures 2 and 3 and are listed in table 1.

Sequential Development of Terranes

Nine coherent episodes of major crust generation have been distinguished by geochronology in the northern midcontinent. The nominal ages of these events are 3.6–2.6 Ga, 2.7–2.6 Ga, ~2.1–1.9 Ga, 1.89–1.83 Ga, 1.76 Ga, 1.8–1.63 Ga, 1.48 Ga, 1.4–1.35 Ga, and 1.2–1.0 Ga. More local rock-forming events included deposition of quartzite of the Baraboo interval (~1.76–1.63 Ga; Dott, 1983) in the northern part of the region, intrusion of anorthosite and rapakivi granite within the Transcontinental anorogenic province (~1.5–1.4 Ga; Silver and others, 1977), and deposition of local(?) clastic sedimentary rocks in one or more basins in and adjacent to southwestern Missouri in Middle(?) Proterozoic time.

The development of successive crustal segments can be discussed with respect to a series of simplified regional paleogeologic maps. In preparing the maps, the rocks were restored to their approximate position prior to the aborted rifting (Midcontinent rift system) in Keweenawan time (~1.1 Ga) (Sims, 1976b); their geographic positions are based on their present-day orientations and relative positions because their locations on the earth in pre-Keweenawan time are not known.

The oldest crustal segment, the Archean gneiss terrane (2.6–3.6 Ga) is inferred to have extended from the Lake Superior region eastward into the Lake Huron region (fig. 4*A*). Its southern and western extents are not known. The gneiss represents a remnant of a large sialic protocontinent.

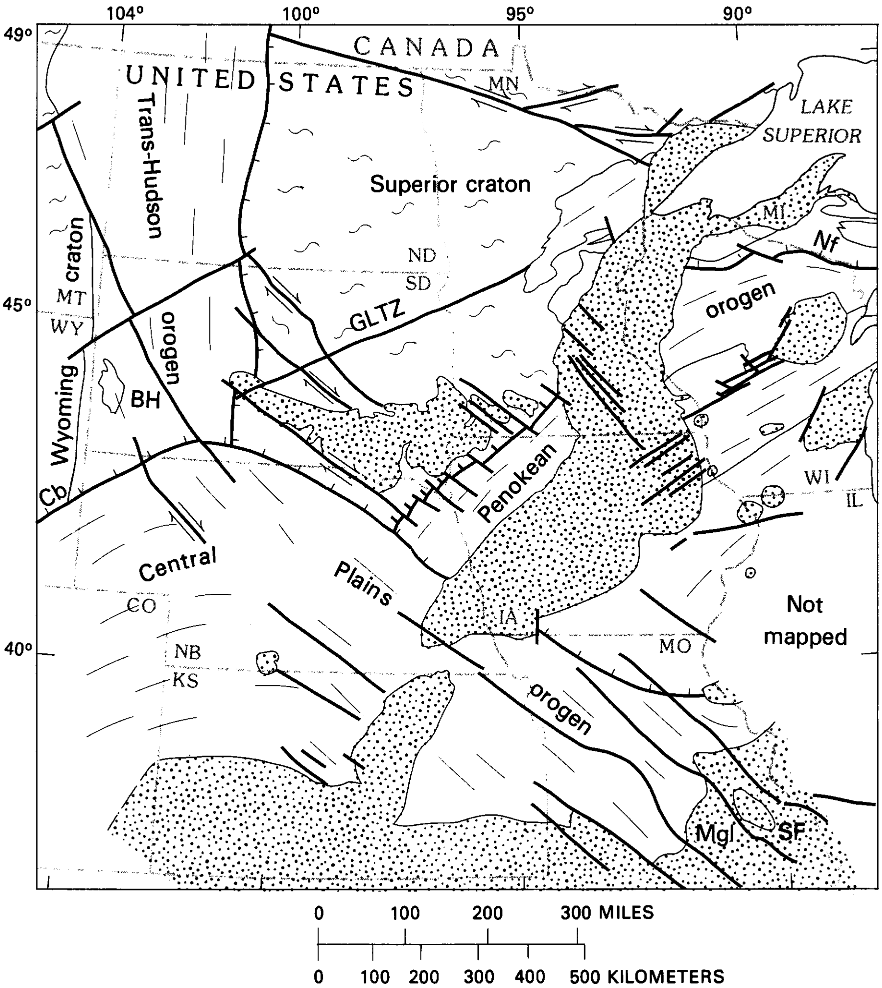
During a major tectonothermal event in the Late Archean (2.6–2.7 Ga), large quantities of subaqueous volcanic rocks, derivative sedimentary rocks, and granitoid bodies were generated to the north of the older Archean protocontinent (fig. 4*B*). This crustal segment (greenstone-granite terrane), which formed within a time span of 50–100 m.y., was sutured to the older gneiss terrane near the end of the Archean.

After stabilization and strengthening of the crust (~2.5 Ga), an asymmetrical sequence of sediments (~1.9–2.1 Ga) accumulated in the Lake Superior region (fig. 5*A*). The rocks were deposited in a large basin (Animikie) over the boundary (GLTZ; Great Lakes tectonic zone) between the two Archean terranes prior to continental breakup (~1.9 Ga). Following breakup of the North American continent—and the development of oceanic crust, the remnants of which have been destroyed—a complex island arc system (Wisconsin magmatic terrane; 1.83–1.89 Ga) was formed on the south (present-day coordinates). Collision of this arc complex with the Archean craton and its partial cover of Early Proterozoic epicratonic rocks, about 1.85 b.y. ago, was responsible for the Penokean orogeny in the Great Lakes region (fig. 5*B*).

Rifting apparently occurred in the northern part of the region shortly after cessation of the Penokean orogeny and was accompanied by the outpouring of subaerial, anorogenic rhyolite and the intrusion of cogenetic epizonal granite (1.76 Ga) in southern Wisconsin and adjacent areas. The basement associated with these rocks probably is mainly older Early Proterozoic rocks of the Wisconsin magmatic terrane. Apparently, deposition of mature quartzite of the Baraboo interval began soon after the 1.76-Ga magmatism in a dominantly fluvial depositional environment. Remnants of quartzite are present today over wide areas in Wisconsin and southern Minnesota and South Dakota and are known to be present, at least locally, in eastern Iowa (Sims, 1985).

The last major orogenic event in north-central United States was breakup of the North American continent along a west-trending axis (fig. 6*A*), which truncated generally north-trending Archean and Early Proterozoic terranes to the north. Breakup was followed by the presumed development and eventual consumption of new oceanic crust and by the formation of ocean arc systems to the south. Collision of this arc complex with the older continent (fig. 6*B*) produced the Central Plains orogen (1.63–1.8 Ga). This orogen is interpreted to be continuous with the metamorphic foldbelts exposed in mountain ranges in Colorado and adjacent states (Sims and Peterman, 1986), and thus is a major segment of dominantly juvenile material that was accreted to the North American continent in the interval 1.6–1.8 Ga.

About 100 m.y. after cessation of the Central Plains orogeny, diachronous rhyolitic volcanism and associated



FAULTS

High-angle, relative movement not known

High-angle reverse fault; bars on downthrown side

Strike-slip, showing relative horizontal movement

STRUCTURAL TREND LINES

Proterozoic rocks

Archean rocks

BH	Black Hills
Cb	Cheyenne belt
GLTZ	Great Lakes tectonic zone
Mgl	Missouri gravity low
Nf	Niagara fault
SF	St. Francois Mountains

Figure 3. Generalized tectonic map of Precambrian basement rocks of the northern midcontinent. Stipple pattern denotes intracratonic igneous and sedimentary rocks.

Table 1. Major crust-forming events and associated metalliferous deposits in the northern midcontinent

Age (Ga)	Terrane	Local rock forming events	Tectonic setting	Description	Known mineral deposits	Probable and speculative resources
2.6-3.6	Archean gneiss terrane	---	Uncertain	Amphibolite-bearing migmatitic gneisses, younger gneisses and schists of greenstone affinity, and 2.6-Ga granite.	---	Volcanic-hosted massive sulfide deposits. Volcanic-hosted gold deposits.
2.6-2.7	Late Archean greenstone-granite terrane.	---	Oceanic arc	Tholeiitic basalt, basalt, komatiite, calc-alkaline basaltic andesite, andesite, and dacite; distinctly bimodal. Tonalite to granite intrusive rocks. Sutured to gneiss terrane in Late Archean.	Algoma-type iron-formation	Volcanic-hosted massive sulfide deposits. Volcanic-hosted gold deposits Gabbro-hosted nickel-copper deposits.
~1.9-2.1	Early Proterozoic epicratonic sedimentary rocks of Penokean orogen.	---	Rift to shelf to deep-water environment on passive margin.	Bimodal basalt-rhyolite volcanic rocks and intercalated clastic and chemical sedimentary rocks.	Lake Superior-type iron-formation. Carbonate-hosted stratiform copper deposits.	---
1.83-1.89	Early Proterozoic Wisconsin magmatic terrane of Penokean orogen.	---	Oceanic arc	Tholeiitic basalt and calc-alkaline andesite to rhyolite extrusive rocks and calc-alkaline gneiss and tonalite to granite. Sutured to continental margin ~1.85 Ga.	Volcanic-hosted massive sulfide deposits.	Volcanic-hosted gold deposits.
1.76	Early Proterozoic rhyolite-granite terrane of southern Wisconsin.	Quartzite of Baraboo interval (~1.63-1.76 Ga).	Extension	Anorogenic rhyolite and cogenetic epizonal granite; locally overlain by fluvial quartzite of the Baraboo interval.	---	Olympic-Dam-type iron-copper-uranium-gold deposits.
1.63-1.8	Early Proterozoic metamorphic and granitoid rocks of Central Plains orogen.		Oceanic arc	Gneisses and schists and synkinematic granitoids extensively intruded by younger (1.35-1.48 Ga) granite.	Massive and disseminated zinc-copper deposits. Disseminated tungsten-copper deposits.	Gabbro-hosted iron-nickel-copper-cobalt deposits. Gabbro-ultramafic-hosted platinum-chromium-titanium deposits.
1.48	Middle Proterozoic St. Francois granite-rhyolite terrane.	Intrusive rocks of Transcontinental anorogenic province (~1.4-1.5 Ga).	Extension	Ash-flow tuff of rhyolite composition and lesser trachyte and associated granitic rocks related to cauldrons and calderas.	Volcanic- and intrusion-hosted iron and copper-iron deposits. Volcanic-hosted manganese deposits. Vein deposits of tin, tungsten, silver, lead, and antimony.	Olympic Dam-type iron-copper-uranium-gold deposits.
1.35-1.4	Middle Proterozoic Spavinaw granite-rhyolite terrane.	---	Extension	Rhyolite and associated granite	---	Gabbro-hosted iron-nickel-copper-cobalt deposits. Olympic Dam-type iron-copper-uranium-gold deposits.
?	---	Clastic sedimentary rocks.	Wrench basin(?)	Conglomerate and iron-rich clastic rocks	---	Olympic Dam-type iron-copper-uranium-gold deposits.
1.0-1.2	Middle Proterozoic Midcontinent rift system.	---	Extension (intracontinental rift).	Aluminum-rich olivine tholeiite, high-iron tholeiite and rhyolite; tholeiitic intrusions.	Volcanic- and sedimentary-hosted copper deposits. Gabbro-hosted copper-nickel-cobalt deposits.	Redbed copper deposits

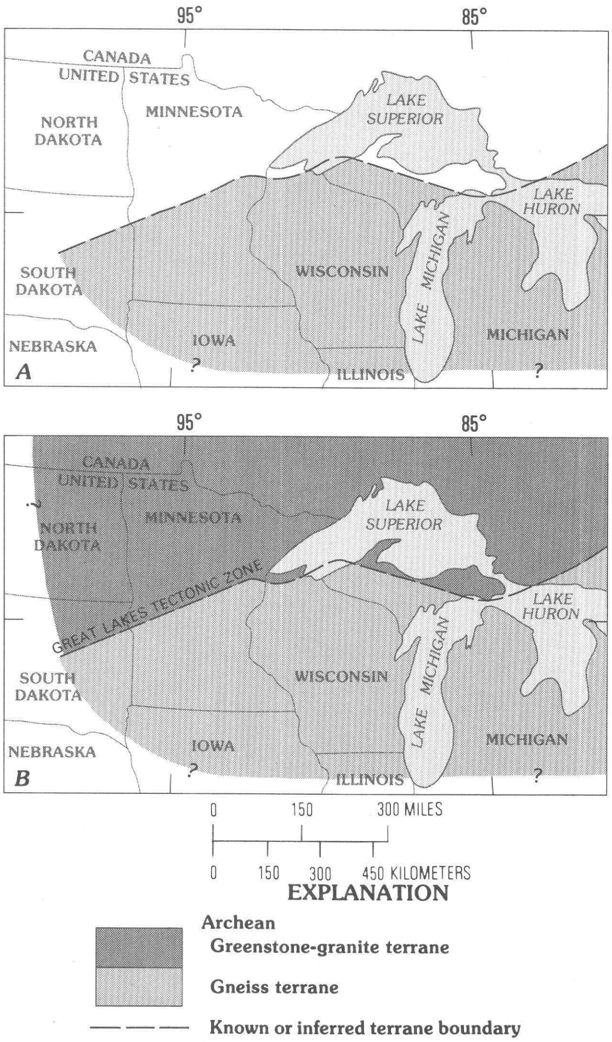


Figure 4. Paleogeographic maps of Archean terranes in the Great Lakes region. Modified from Sims (1987). *A*, Archean gneiss protocontinent (2.6–3.6 Ga). *B*, Archean craton formed by suturing of Late Archean greenstone-granite (2.6–2.7 Ga) and Middle and Late Archean gneiss terranes.

cogenetic plutonism occurred in the southern part of the metamorphic-granitoid terrane of the Central Plains orogen, apparently as a consequence of rifting on a large scale. Magmatism in the St. Francois granite-rhyolite terrane (1.48 Ga) was followed by magmatism in the Spavinaw granite-rhyolite terrane (1.35–1.4 Ga). Small to large intrusions of alkali feldspar-rich granitic rocks (~1.4–1.5 Ga) were emplaced at about the same time in a wide belt that transects the northern midcontinent and which has been termed the Transcontinental anorogenic province (Silver and others, 1977; Anderson, 1983). The rhyolite and associated granite in the St. Francois and Spavinaw terranes have chemical and mineralogic compositions similar to the plutonic rocks of the Transcontinental anorogenic province and perhaps are related petrogenetically.

Subsequent to, or perhaps partly contemporaneous with, the later stages of the granite-rhyolite magmatism, clastic sedimentary rocks were deposited within and adjacent to a northwest-trending basin (or basins) floored by anorogenic granite. The extent of these rocks is not known, but remnants of them have been penetrated by drilling in southwestern Missouri and adjacent parts of Kansas and Arkansas (fig. 17).

The youngest crust-forming event in the northern midcontinent was the magmatism and subsequent sedimentation within the Midcontinent rift system (fig. 5*C*), which aborted before achieving significant crustal separation. Dominantly mafic volcanic rocks and related hypabyssal intrusions of apparent mantle derivation are intercalated with lesser clastic sedimentary rocks within the rift system. Local uplifts, such as the Goodman swell (~1.1 Ga; Peterman and Sims, 1986), accompanied the rifting, as indicated by Rb-Sr isotopic ages of biotite in rocks of Archean and Early Proterozoic ages.

Archean Gneiss Terrane

Rocks of the Archean gneiss terrane are exposed in the Minnesota River Valley in southwestern and east-central Minnesota and northern Wisconsin and Michigan. In Wisconsin and Michigan they mainly compose the cores of mantled gneiss domes or uplifted fault blocks (Morey and others, 1982) that formed as a result of reactivation during the Early Proterozoic Penokean orogeny. The gneiss terrane has been encountered by drilling in southwestern Minnesota, and it apparently extends beneath the Early Proterozoic Sioux Quartzite of the Baraboo interval (Sims, 1985). It appears to be terminated southward in northeastern Nebraska and southeastern South Dakota by the crosscutting Central Plains orogen (fig. 2).

The gneiss terrane in the Minnesota River Valley composes a grossly conformable sequence of interlayered migmatitic gneisses that is a few thousand meters thick (Grant, 1972). It is intruded by younger granitic and pegmatitic rocks. The gneisses are folded on east-trending, gently plunging axes and have mineral assemblages characteristic of upper amphibolite- and granulite-facies metamorphism.

In the central part of the valley, the gneisses are metamorphosed to granulite grade and are assigned to the Early and Middle Archean Montevideo Gneiss of Lund (1956). The Montevideo Gneiss consists of a gray, foliated, granodioritic to locally tonalitic paleosome that is cut both concordantly and discordantly by layers and veins of a red granitic neosome. The gray granodioritic paleosome yields a Rb-Sr whole-rock age of 3,680±70 Ma, whereas the red granitic neosome yields an age of 3,045±32 Ma (Goldich and others, 1980).

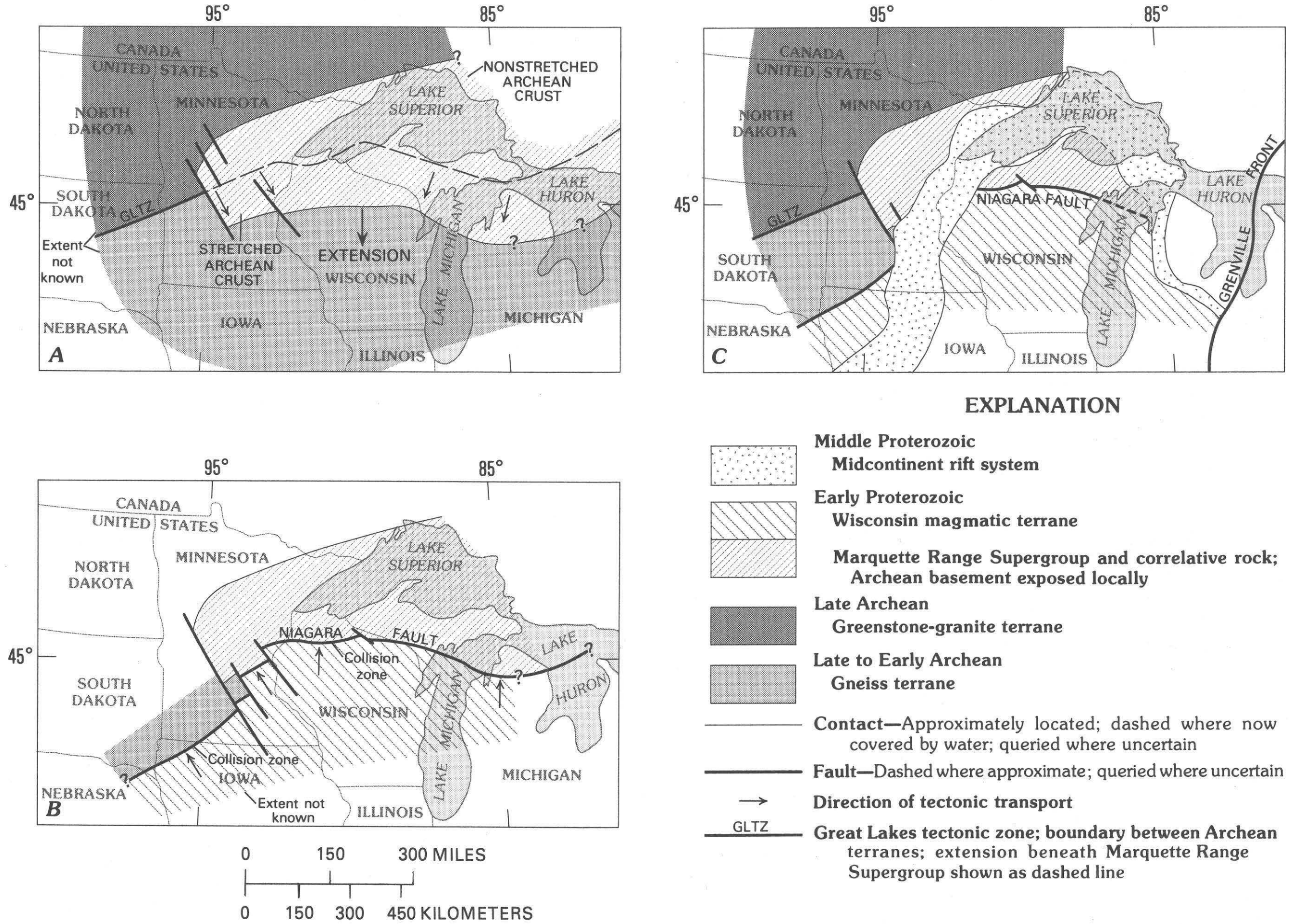


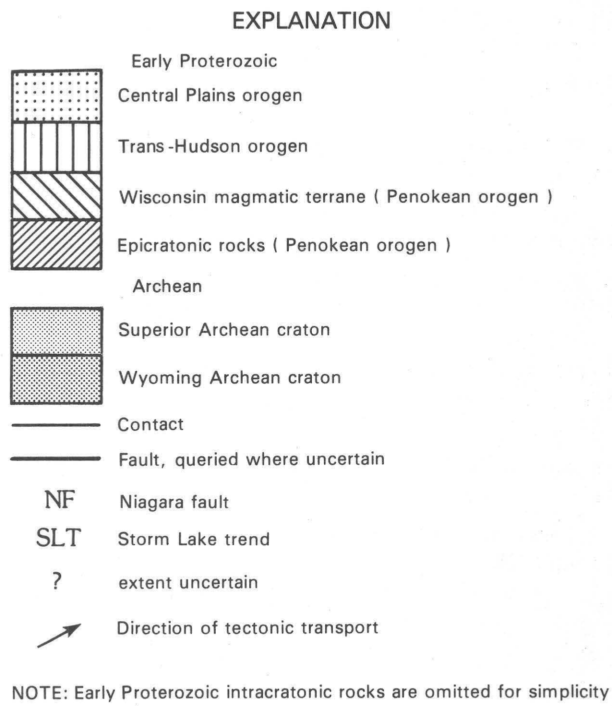
Figure 5. Paleogeologic maps showing successive stages of development of Early Proterozoic Penokean orogen. Modified from Sims (1987). *A*, Early Proterozoic epicratonic sequence (~1.9–2.1 Ga), showing inferred outline of depositional basin. *B*, Arc-continent collision (~1.85 Ga) which resulted in Penokean orogeny. *C*, Midcontinent rift system (1.0–1.2 Ga).

In the southern part of the valley the gneisses are metamorphosed to the amphibolite grade. Three quasi-stratigraphic units that have been delineated are characterized from bottom to top by abundant, common, and rare rafts of amphibolite, respectively. The middle unit in this succession is assigned to the Archean Morton Gneiss of Lund (1956). As in the central part of the valley, the quartzofeldspathic gneisses are migmatized. However, the paleosome is compositionally layered and dominantly consists of tonalitic gneiss with lesser but locally significant quantities of granodioritic material. Rb-Sr and U-Pb isotopic data suggest that the tonalitic and granodioritic gneisses and the associated amphibolite lenses are 3.5 Ga or more old (Goldich and Wooden, 1980). Zircon dating by ion microprobe methods similarly indicates an age of 3,535±45 Ma (Williams and others, 1984). The neosome, which is granite and locally pegmatite, formed during two later episodes. A deformed granite was emplaced 3,043±26 Ma, and a younger, largely undeformed granite was emplaced 2,555±55 Ma (Goldich and Wooden, 1980).

Various rock units of supracrustal origin structurally overlie the amphibolite-bearing migmatitic gneisses. Although the supracrustal sequences contain discontinuous layers, lenses, and boudins of amphibolite, they lack any evidence of migmatization. The unmigmatized rocks include hornblende-pyroxene gneiss and garnet-biotite gneiss in the central part of the valley and several kinds of biotite gneiss that contain garnet, anthophyllite and cordierite or sillimanite and K-feldspar in the southern part. A metagabbro intrudes the hornblende-pyroxene and garnet-biotite gneisses in the central part of the valley. The supracrustal sequences and the metagabbro record a metamorphic event or events in the interval between 2,600 and 2,900 m.y. ago (Wilson and Murthy, 1976), but presumably are themselves much older.

The gneissic rocks are intruded by several granitic units of batholitic dimensions, including the Late

Archean Sacred Heart Granite, which is a medium-grained, generally homogeneous to weakly foliated rock that yields a Pb-Pb age of 2,605±6 Ma, which Doe and Delevaux (1980) interpret as the time of emplacement. The Sacred Heart Granite is thus late tectonic or possibly posttectonic.



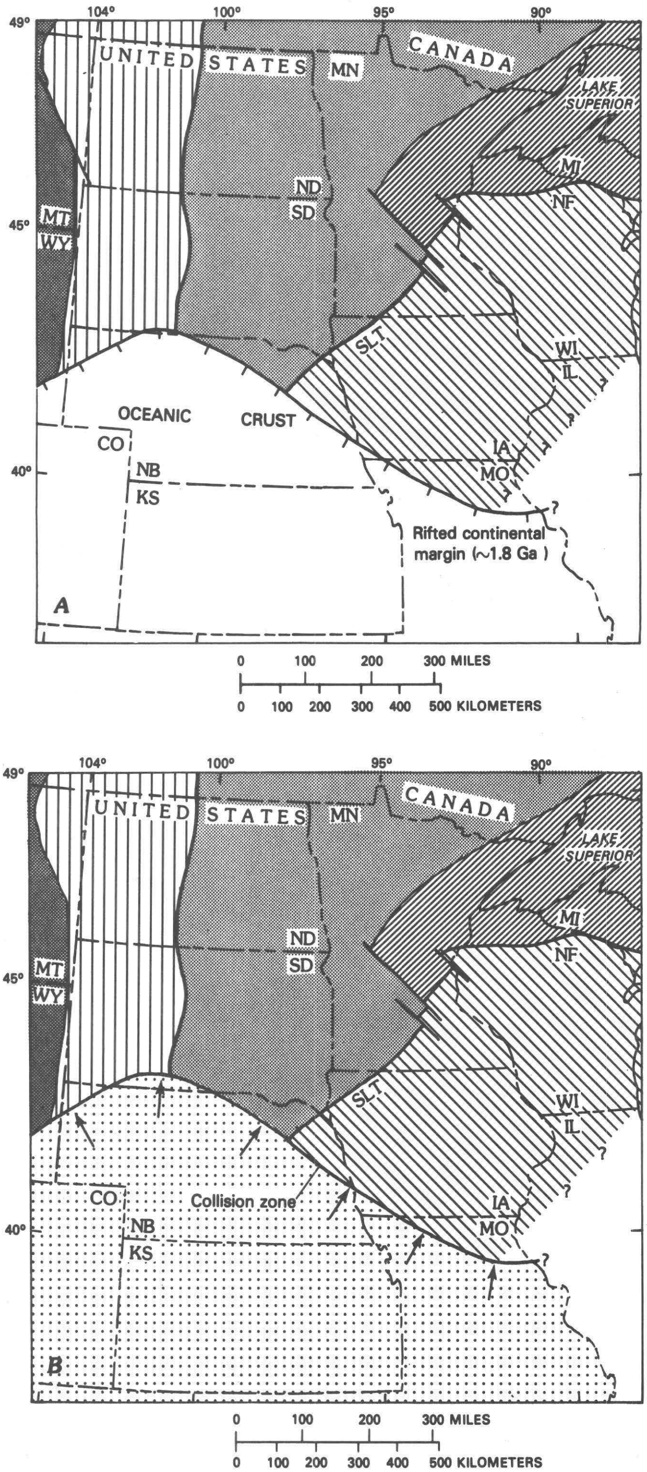


Figure 6. Paleogeologic maps showing inferred development of the Early Proterozoic Central Plains orogen (present-day coordinates). *A*, Postbreakup stage, resulting from rifting of the continental margin (~1.8 Ga). *B*, Arc-continent collision (~1.65 Ga).

Gneisses of comparable age and complexity are exposed (Watersmeet dome; Sims and others, 1984) in northern Michigan. Approximately 3.56 Ga in age, they are locally overlain by younger (2.64 Ga) metavolcanic rocks and are intruded by 2.6-Ga leucogranite (Peterman and others, 1985). In contrast to the Archean gneisses in the Minnesota River Valley, these gneisses were partly reactivated during the Penokean orogeny, and Rb-Sr whole-rock and mineral systems in the Watersmeet dome were reset 1,800–1,750 m.y. ago.

Late Archean Greenstone-Granite Terrane

The next younger crustal entity, the greenstone-granite terrane (Morey and Sims, 1976; Sims, 1976a), forms the southernmost part of the Superior province of Canada and the United States. This segment of the crust stabilized by the end of the Archean (2.5 Ga). It is separated from the Archean gneiss terrane to the south by a discontinuity termed the Great Lakes tectonic zone (Sims and others, 1980), which has been interpreted by Gibbs and others (1984) as a paleosuture. The greenstone-granite terrane can be traced by its characteristic east-northeast-trending magnetic (Zietz, 1982) and gravity (Hildenbrand and others, 1982) anomalies from outcrops in northern Minnesota westward to central North Dakota and South Dakota, where it is truncated by a north-trending belt of anomalies colinear with the Superior-Churchill province boundary in Canada (Green and others, 1985). The Churchill province in this region has been termed the Trans-Hudson orogen by Hoffman (1981).

The greenstone-granite terrane generally consists of low-grade volcanogenic rocks and intrusive plutonic rocks, but it can be subdivided further into volcanic and metasedimentary gneiss units (subprovinces; Goodwin, 1978). Typically, the volcanic subprovinces are made up of several individual greenstone belts. In the United States, no evidence has been found of older continental crust on which the supracrustal rocks of the greenstone belt association have been deposited (Sims and Peterman, 1981), and the geochemically "primitive" nature of the rocks has been interpreted as indicating direct additions of mantle-derived material to the crust (Jahn and Murthy, 1975; Arth and Hanson, 1975). The mafic rocks are dominantly tholeiitic basalt but include komatiite (Schulz, 1980). The less common felsic volcanic rocks, at least locally, have both tholeiitic and calc-alkaline affinities (Campbell and others, 1982). The granitoid rocks are mainly calc-alkaline, but relatively late tectonic and post-tectonic rocks typically are alkaline (Arth and Hanson, 1975; Day and Weiblen, 1986).

Early Proterozoic Wisconsin Magmatic Terrane and Associated Epicratonic Rocks of the Penokean Orogen

The Early Proterozoic Penokean orogen, as defined in the Lake Superior region (Cannon, 1973; Sims and Peterman, 1983), has a distinct tectono-stratigraphic zonation. Early Proterozoic epicratonic sedimentary and volcanic rocks, which overlie Archean basement on the north, are separated from a volcanic-plutonic (Wisconsin magmatic) terrane (Van Schmus, 1980) on the south by a major ductile shear zone (Niagara fault; Sims and others, 1985; Sedlock and Larue, 1985). The shear zone is interpreted as a suture formed at ~1.85 Ga when the magmatic (island) arc collided with the continental margin and its superjacent cover. This collision triggered the Penokean orogeny.

The magmatic arc (Wisconsin magmatic terrane) is inferred from sparse drill-hole data and aeromagnetic and gravity signatures to extend in the subsurface into southern Minnesota, then through northwestern Iowa into northeastern Nebraska, where it is truncated by the Central Plains orogen (Sims, 1985). The epicratonic succession, on the other hand, probably terminates westward in central Minnesota (Southwick and Chandler, 1983; (fig. 5), apparently because of a northwest-trending, transformlike fault (Sims, 1987), although remnants of volcanic-sedimentary rocks of possible Early Proterozoic age extend discontinuously into southern Minnesota (Sims, 1985).

The epicratonic rocks are a southward-thickening sequence of clastic and chemical sedimentary rocks as well as bimodal volcanic rocks and are assigned to the Early Proterozoic Marquette Range Supergroup in Michigan (Cannon and Gair, 1970) and the Early Proterozoic Mille Lacs and Animikie Groups in Minnesota (Morey, 1983a). The sequence includes the vast Lake Superior-type iron-formations of the region. In Minnesota, Morey has divided the Mille Lacs and Animikie Groups into five depositional phases. The first two phases constitute an early rift to miogeoclinal succession of predominantly quartz rich rocks and lesser iron-formation and interlayered volcanic rocks. The third phase was a shelf sequence, including the major Lake Superior-type iron-formations, whereas the fourth phase forms a transitional succession marked by rapid subsidence of the shelf and deposition of black carbonaceous muds. The fifth phase is a southward-thickening eugeoclinal succession of epiclastic sediments and bimodal volcanic rocks; the sediments are primarily graywacke deposited by southward-flowing turbidity currents. The bimodal volcanic rocks have chemical affinities with continental tholeiites, such as the volcanics in the Midcontinent rift system. It is now generally agreed that the Early Proterozoic epicratonic rocks were deposited in a basin (Animikie) on the passive rifted margin of the Superior Archean craton (Schulz and others, in press).

The Wisconsin magmatic terrane is lithologically distinct from the Early Proterozoic margin accumulation in that it consists mainly of volcanic rocks—basalt and lesser rhyolite and andesite—and plutonic rocks, which range in composition from quartz diorite to granite (Schulz, 1984). An Archean basement is present in central Wisconsin but apparently is lacking in other parts of the terrane, although isotopic lead data (Afifi and others, 1984) and Nd-Sm model age data (Nelson and DePaolo, 1985) suggest a possible Archean component in the crust in the northern part of the magmatic terrane.

At any particular locality in the magmatic terrane two or more volcanic successions commonly are present (Sims and others, 1985; LaBerge and Myers, 1984), but regional correlations have not been made. In the northern part (Ladysmith-Pembine belt), an Early Proterozoic migmatitic gneiss underlies dominant basalt, andesite, and rhyolite successions (Sims and others, 1985). Both the gneiss and the volcanic rocks are intruded by bodies of quartz diorite to granite. In the northeastern part of this terrane, an older succession of volcanic rocks that are composed of tholeiitic basalt and basaltic andesite is overlain by a calc-alkaline suite which ranges in composition from andesite to rhyolite (Sims and others, 1987). In the Monico area, near the Pelican River massive sulfide deposit, the volcanic rocks compose a bimodal suite of high-aluminum basalt to low-silica andesite pillowed flows and dacite to rhyolite tuffs and porphyries. Detailed U-Pb zircon isotopic dates from rocks in the northeastern part of the magmatic terrane indicate that accumulation of the gneisses and volcanic rocks, deformation and metamorphism, and emplacement of the granitoid plutons spanned a relatively short time interval, 1,865–1,835 Ma (Sims and others, 1985).

Early Proterozoic Rhyolite-Granite Terrane of Southern Wisconsin

An extensive terrane of ~1.76-Ga rhyolite and coeval epizonal granite is known in south-central Wisconsin from exposures in river valleys and from drill holes (Smith, 1983). The terrane is characterized magnetically by conspicuous northeast-trending, linear, positive anomalies, which reflect the substantial accessory magnetite content of the rocks. The northern edge of the terrane is marked by prominent east-northeast-trending magnetic lineaments (faults?), which separate it from Archean rocks to the north (Sims, 1985). The terrane is inferred to extend westward from known areas in Wisconsin to the Midcontinent rift system, where it is truncated. Probably, similar rocks extend southward into northernmost Illinois (Sims, 1985), although these rocks have a different geophysical expression, which includes a conspicuous positive gravity anomaly, than the known 1.76-Ga rhyolite-granite terrane (Hildenbrand and others, 1982). The positive gravity anomaly suggests that dense rocks such as basalt exist at shallow crustal depths.

The rhyolite-granite terrane represents the oldest Proterozoic anorogenic magmatic activity in the Great Lakes area and probably is related to extensional tectonism. These rocks consist mainly of two mineralogically and chemically distinct rock suites (Smith, 1983): (1) a peraluminous suite of texturally variable ash-flow tuffs and related two-mica granites, and (2) a metaluminous suite containing quartz- and orthoclase-bearing rhyolites and related biotite-hornblende to biotite granites. The granitoid rocks are granophyric and apparently were intruded into their own volcanic cover. Younger, but undated intrusions form two additional suites: (1) the Baxter Hollow intrusive suite, which includes low silica, high strontium, and REE (rare-earth element)-depleted granites and chemically similar rhyolite dikes, and (2) the Denzer intrusive suite, which consists of a diorite intrusion and numerous tholeiitic basalt to andesite dikes.

Rocks within the rhyolite-granite terrane are mildly metamorphosed (greenschist facies) and deformed along northeast-trending fold axes (Smith, 1978). Cataclastic textures are widespread. The folding occurred after deposition of the overlying quartzite of the "Baraboo interval" and has been documented most thoroughly at Baraboo, Wis. (Dott and Dalziel, 1972). Rb-Sr whole-rock isochron ages of about 1.615–1.64 Ga on the quartzite are thought to record the tectonothermal event that was responsible for the folding and metamorphism of the rhyolite and quartzite (Smith, 1983).

Coeval (1.76 Ga) granitic rocks intrude the older Early Proterozoic rocks of the Wisconsin magmatic terrane to the north in northern Wisconsin (Anderson and others, 1980; Sims, 1987).

Quartzite of Baraboo Interval

Dott (1983) proposed that the red quartzites south of Lake Superior be referred to as the "Baraboo interval" to distinguish them from younger quartz-rich rocks associated spatially with the Midcontinent rift system (Ojakangas and Morey, 1982), and this terminology is used here.

The quartzites of the Early Proterozoic Baraboo interval include six major exposed units scattered over an area of 75,000 mi^2 (194,000 km^2) south of the Great Lakes tectonic zone (Sims, 1985). In addition, buried quartzite has been penetrated by drilling in southeastern Wisconsin (Smith, 1978) and eastern Iowa (Anderson and Ludvigson, 1986). The major exposed bodies are the Sioux Quartzite, which composes the Sioux ridge in southeastern South Dakota and adjacent areas; the Baraboo Quartzite near Baraboo in southern Wisconsin; and the Barron Quartzite in Barron and adjacent counties, northwestern Wisconsin. All these quartzite bodies are presumed to be approximately the same age, that is, in the range of 1,600–1,700 Ma (Morey and Van Schmus, in press).

The quartzites of the Baraboo interval mainly consist of tightly cemented, very mature quartz arenite that typically is red or pink to purple because of the presence of disseminated hematite. The interval also contains scattered beds of conglomerate, conglomeratic quartzite and, locally, red mudstone (pipestone). A kaolinitic regolith about 50 ft (15 m) thick underlies parts of the Sioux Quartzite (Southwick and Mossler, 1984), whereas volcanic rocks of rhyolitic composition underlie the Baraboo Quartzite. Mature basal conglomerates are known from several localities in the Sioux and a quartzite at McCaslin Mountains, in Oconto County, Wis. (Olson, 1984). The Baraboo Quartzite is overlain by a unique sequence, from bottom to top, of slate, dolomite, banded iron-formation, quartzite, and slate (Dalziel and Dott, 1970; Geiger, 1986). Except for the Waterloo Quartzite in southern Wisconsin, which contains intercalated beds of an aluminous pelitic schist having amphibolite-facies metamorphic mineral assemblages (Geiger and others, 1982), the quartzites have regional greenschist-facies mineral assemblages. Both the Waterloo and Baraboo Quartzites are moderately to strongly deformed on approximately east-trending fold axes, whereas the Sioux and Barron Quartzites are only mildly deformed.

The volcanic rocks beneath the Baraboo Quartzite have been dated at 1,760 ± 10 Ma (Van Schmus, 1978), which provides a maximum age for deposition. The upper age limit is not known directly, but is inferred to be approximately 1.63 Ga, which is the time of widespread Rb-Sr whole-rock and mineral resetting in much of Wisconsin and adjacent areas (see Peterman and others, 1985, for summary).

Facies and paleocurrent analyses as summarized by Ojakangas (in press) indicate that the quartz-rich detritus of the Baraboo interval was deposited dominantly by fluvial processes in a braided stream environment. Dott (1983) and Ojakangas and Weber (1984) suggested that the fluvial deposits of the Baraboo and Sioux were succeeded, at least locally, by a tidally influenced marine environment. Most of the detritus was probably of first-cycle origin, and was derived mainly from a hinterland to the north—a stable, intensively weathered and leached, peneplaned landmass.

The quartzites of the Baraboo interval have been attributed to deposition along an east-trending passive continental margin which was later deformed by subduction (Dott, 1983; Anderson and Ludvigson, 1986); alternatively, Greenberg and Brown (1984) proposed sedimentation in an intracratonic setting with deformation due to anorogenic igneous activity and orogenic doming. Southwick and others (1986) have argued that there is no clear-cut evidence for marine sedimentation in the Sioux Quartzite. Because of this and because the sedimentation was associated with rhyolitic ignimbritic volcanism, Southwick and others (1986) have suggested that the Sioux was deposited in an intracratonic setting. Deposition probably occurred within a series of fault-bounded en-echelon basins that were oblique to the east-west passive continental margin proposed by Dott (1983) but more or less parallel to the trend of the Central Plains orogen. Therefore, the basins may have formed in response to tectonic activity along a plate margin which lay well to the south.

Early Proterozoic Metamorphic and Granitoid Rocks of the Central Plains Orogen

A northwest-trending belt of metamorphic and granitoid rocks that crosses Nebraska, northern Kansas, and Missouri was delineated during preparation of the basement map and named the Central Plains orogen (Sims, 1985). Later, Sims and Peterman (1986) suggested that the orogen correlates with the Early Proterozoic foldbelt exposed in the basement uplifts of Colorado and southern Wyoming, and accordingly that it is part of a wide, continuous foldbelt extending through northern Arizona and New Mexico into California (Silver and others, 1977).

In the northern midcontinent, the Central Plains orogen is an arcuate belt at least 250 mi (400 km) wide (fig. 2) that is reflected by conspicuous linear magnetic (Zietz, 1982) and gravity (Hildenbrand and others, 1982; Guinness and others, 1982) anomalies. In Missouri, east of the Midcontinent rift system, northwest-trending magnetic (Zietz and others, 1984) and gravity (Hildenbrand and others, 1982; Arvidson and others, 1984) anomalies are pronounced. These anomalies reflect known or inferred lithologic and structural trends in the basement rocks (Kisvarsanyi, 1984). The dominant gravity feature, the Missouri gravity low (fig. 3, Mgl), has a maximum amplitude of ~40 mGal and has been modeled as a 4–6-km crustal excess at the Mohorovicić discontinuity (Arvidson and others, 1984). To the west of the Midcontinent rift system, in Kansas and Nebraska, the magnetic and gravity anomalies are somewhat more subdued but clearly indicate a sharp westward bend in the orogen at the Nebraska-South Dakota State line (fig. 7).

The northern margin of the orogen, as shown on figure 7, is subparallel to anomalies to the south within the orogen. The northeast to east trend of the anomalies in eastern Colorado is subparallel to the structural trends of the buried basement rocks (Tweto, 1987).

The ages of the rocks within the orogen were poorly constrained until recently because the only ages available were from highly disturbed Rb-Sr whole-rock and K–Ar mineral systems (Van Schmus and Bickford, 1981). More recent U-Pb zircon determinations on the metamorphic rocks and mesozonal granitoid rocks indicate a range in age from 1.63 to 1.8 Ga (Bickford, Harrower, and others, 1981; Bickford and others, 1986). The older (>1.7 Ga) ages are from gneisses and granite in Kansas and Nebraska, whereas the younger ages are from granite and metarhyolite from Missouri. The ages are grossly equivalent to those on Early Proterozoic metamorphic and granitoid rocks exposed in the basement uplifts of Colorado and adjacent areas (Hedge and others, 1967; Peterman and others, 1968; Silver and Barker, 1968; Stern and others, 1971; Bickford and Boardman, 1984).

Extensive petrographic data on drill-hole samples show that metavolcanic and metasedimentary rocks as well as gneissic granitoid rocks characterize the Central Plains orogen in Nebraska (Lidiak, 1972), Kansas (Bickford, Harrower, and others, 1981), and Missouri (Kisvarsanyi, 1974, 1984). The metamorphic rocks are mainly amphibolite facies but include greenschist- and granulite-facies assemblages as well as retrogressive assemblages. Textures range from granoblastic to cataclastic and mylonitic. The principal metamorphic

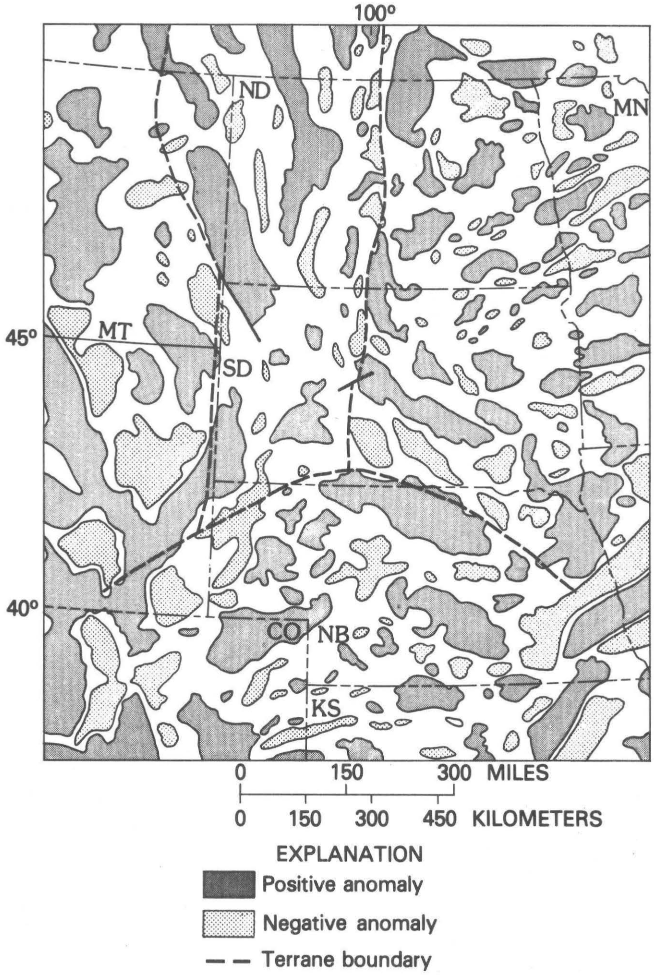


Figure 7. Gravity anomaly map of part of north-central United States. After Hildenbrand and others (1982).

rocks are quartz-feldspar gneiss, biotite-, hornblende-, and quartz-muscovite schist, amphibolite, metarhyolite, marble, micaceous quartzite, and phyllite. The granitoid rocks range from quartz diorite through granodiorite to granite (Lidiak, 1972). Treves and Low (1985) stated that quartzite in western Nebraska contains sillimanite and muscovite and apparently lies on older granitic and metamorphic rocks.

In central and western Missouri, where about 35 holes have been cored in Precambrian rocks, several rock types of the orogen are associated with the northwest-trending Central Missouri topographic high (Kisvarsanyi, 1974). The orogenic suite includes garnet-bearing quartz-microcline gneiss, biotite schist, muscovite-talc schist, quartzite, forsterite marble, sillimanite-bearing quartz-microcline gneiss, kyanite-bearing granite gneiss, metarhyolite, and amphibolite.

The orogenic suite is intruded locally by layered mafic complexes of gabbro-norite composition, which are commonly associated with pronounced positive magnetic anomalies and appear to have been emplaced along northwest-striking structural zones (Kisvarsanyi, 1984). Some are metamorphosed to metagabbro; most are pervasively intruded by 1.47–Ga granite (Bickford, Harrower, and others, 1981), which has resulted in strongly hybridized phases (epidiorite and migmatite). Sylvester (1984) suggested that some of the mafic complexes were formed under granulite-facies conditions in deep crustal levels and were tectonically uplifted to their present levels where they underwent retrograde metamorphism to produce the amphibolite-facies mineral assemblage that now exists.

The rocks of the Central Plains orogen closely resemble the Early and Middle Proterozoic rocks in Colorado (Tweto, 1979) that include a diverse gneiss complex—rocks metamorphosed from a pre-1.7–Ga assemblage of volcanic, sedimentary, and intrusive igneous rocks—and granitoid rocks of the Routt and Berthoud Plutonic Suites (Tweto, 1977; Taylor and others, 1984). The Early Proterozoic Routt Plutonic Suite is composed of 1.65–1.76–Ga igneous rocks, which are mainly calc-alkaline granodiorite and quartz monzonite; the Middle Proterozoic Berthoud Plutonic Suite includes 1.35–1.48–Ga granitic rocks (Peterman and others, 1968; Thomas and others, 1984), which mainly are peraluminous two-mica granites. The rocks of the Routt Plutonic Suite were emplaced late in the principal period of regional metamorphism and are generally foliated to intensely deformed, whereas the rocks of the Berthoud Plutonic Suite were emplaced after the main regional metamorphism and have a dominant primary flow structure.

In Missouri, Kisvarsanyi (1984) has identified five principal northwest-trending tectonic zones on the basis of surface and subsurface geology and magnetic lineaments (Zietz and others, 1984; Sims, 1985). The tectonic zones are mainly basement faults (fig. 9); they coincide with major structures in the overlying Paleozoic strata. For example, the Bolivar-Mansfield tectonic zone is named after the Bolivar-Mansfield fault system, a zone of faults and folds mapped in the Paleozoic sedimentary rocks (McCracken, 1971). Basement tectonic zones similar to those in Missouri have been delineated in Kansas and Nebraska (Sims, 1985). These coincide with the Central Kansas uplift and the Cambridge and Chadron arches. Clearly, reactivation of the basement structures in the Paleozoic produced folds and faults in the overlying sedimentary rocks.

A possible extension of the Central Plains orogen on the southern side of the Middle Proterozoic St. Francois granite-rhyolite terrane is suggested by core recently acquired by the Arkansas Geological Commission from a drill hole in Randolph County, northeastern Arkansas. About 6.5 ft (2 m) of muscovite-biotite quartzofeldspathic gneiss—probably a metamorphosed argillaceous sandstone—was cored; the upper part is highly weathered (R.E. Denison, Mobil Research and Development Corp., written commun., 1986).

Middle Proterozoic Anorthosite and Rapakivi Granite of Transcontinental Anorogenic Province

A moderately well defined belt of anorogenic granitoid rocks (~1.4–1.5 Ga) that extends across North America from Labrador to southern California has been delineated in recent years (Silver and others, 1977; Denison and others, 1984). The rock types range from anorthosite, mangerite, and associated rapakivi granite, as in the Wolf River batholith in Wisconsin (Van Schmus and others, 1975), to two-mica granite, such as the Middle Proterozoic Graniteville Granite in southeastern Missouri (Kisvarsanyi, 1980) and the Middle Proterozoic Silver Plume Granite (Berthoud Plutonic Suite) and other similar granites in Colorado and elsewhere in the southwest (Anderson, 1983). The former are marginally metaluminous and generally contain biotite and (or) hornblende; the latter are marginally peraluminous and contain topaz as an accessory mineral.

In the northern midcontinent, this group of anorogenic granitoid rocks is represented by the Wolf River batholith (Anderson, 1980; Anderson and Cullers, 1978), the Red Willow batholith of southern Nebraska (Van Schmus and Bickford, 1981), and unnamed plutons in northern Illinois (Hoppe and others, 1983) and adjacent Iowa. These rocks are similar petrochemically to epizonal granites in the region that have granophyric textures; the epizonal granites are coeval and cogenetic with rhyolites of the Middle Proterozoic St. Francois terrane (age, 1.48 Ga; Bickford, Harrower, and others, 1981) and Spavinaw terrane (age, 1.35–1.40 Ga; Thomas and others, 1984).

The anorogenic granites of the Transcontinental anorogenic province have distinctive mineralogies reflecting strongly differentiated potassic and iron-enriched compositions (Anderson, 1983). Alkali feldspars are predominant over plagioclase; mafic silicates are iron rich; and the accessory mineral suite includes ubiquitous fluorite as well as topaz, spinel, allanite, sphene, and cassiterite (Kisvarsanyi, 1980). These characteristics clearly distinguish the anorogenic rocks from the older synorogenic, calc-alkaline plutons. Except for the Wolf River batholith, which is ilmenite-bearing, the anorogenic bodies are magnetite-bearing, and hence belong to the magnetite series of Ishihari (1977). Chemically, the anorogenic granites differ from other granitic suites in having high K_2O, K_2O/Na_2O, iron/magnesium, and fluorine and low CaO, MgO, and Al_2O_3 (Anderson, 1983). The same major element chemistry is typical of the anorogenic plutons and associated rhyolite of the St. Francois terrane (Kisvarsanyi, 1972). Also, the anorogenic plutons of the Transcontinental anorogenic province are enriched in many LILE (large-ion lithophile elements), including rubidium, barium, gallium, yttrium, REE (except europium), zirconium, thorium, niobium, tin, beryllium, lithium, and uranium. In Missouri, many of these granites have been described as "tin granites" (Kisvarsanyi, 1980).

Cullers and others (1981) have presented convincing arguments that most of the granite bodies of the Transcontinental anorogenic province have been derived from nonradiogenic crustal sources of Early Proterozoic age. For the Wolf River batholith, they have suggested that the anorthosite and (or) mangerite likely provided at least part of the heat source necessary for generation of the granitic melt.

Because of the mineralogical, major element, and trace element similarities between rocks of the Transcontinental anorogenic province and rocks of the Middle Proterozoic epizonal terranes of the southern midcontinent, the former may merely correspond to deeper levels, now exposed by erosion, of the latter. In the epizonal terranes of the southern part of the area (fig. 2), unmetamorphosed volcanic rocks are associated with cogenetic granites. The chemically and mineralogically similar plutons of the Transcontinental anorogenic province, on the other hand, generally perforate older crust and are surrounded by older rocks; they appear to be "isolated" or circumscribed plutons, and their textural features reflect their emplacement at deeper crustal levels. We suggest that these mesozonal granitoids, which are coeval with Middle Proterozoic epizonal terranes, are possibly feeders or conduits for epizonal rocks that were removed by erosion before the onset of the Phanerozoic. Thus, the Transcontinental anorogenic province is possibly not a distinct tectonic and magmatic unit but merely a mesozonal equivalent of the epizonal terranes.

Middle Proterozoic St. Francois Granite-Rhyolite Terrane

The St. Francois terrane is one of two Middle Proterozoic epizonal granite-rhyolite terranes in the midcontinent, the other being the Spavinaw. About 900 km^2 (350 mi^2) of the terrane are exposed in the St. Francois Mountains, at the crest of the Ozark dome in southeastern Missouri (Tolman and Robertson, 1969; Anderson, 1970; Berry and Bickford, 1972; Kisvarsanyi, 1972; Pratt and others, 1979; Sides and others, 1981). Data from more than 500 drill holes indicate that the terrane extends outward from outcrop areas, below a cover of Paleozoic rocks; the terrane underlies most of southeastern Missouri (Kisvarsanyi, 1981) and has an inferred areal extent of at least 35,000 mi^2 (90,000 km^2). Its outer boundaries are not well defined because drill-hole data are sparse to the east toward the Illinois basin and to the south into the Mississippi embayment. However, Hoppe and others (1983) suggest that a similar granite-rhyolite terrane underlies most of Illinois, Indiana, and western Kentucky, as far east as the Grenville boundary, as shown on the regional map of Bickford and others (1986). U-Pb ages on zircons indicate a 1.48-Ga crystallization age for the rocks in the St. Francois terrane, but it does contain some younger (1.38 Ga) plutons (Bickford and Mose, 1975; Bickford, Harrower, and others, 1981). The terrane could extend as far west as the Decaturville cryptoexplosion structure (Offield and Pohn, 1979) and the Orla mafic complex (Kisvarsanyi, 1985), in central Missouri, as suggested by 1.47-Ga plutons which intrude the older metamorphic rocks in that area.

The correlation of surface and subsurface geologic data and analysis of aeromagnetic maps in southeastern Missouri have shown that the St. Francois terrane apparently consists of more than a dozen overlapping ring complexes, cauldron subsidence structures with ring volcanoes and ring plutons, and resurgent calderas with central plutons (fig. 8; Sides and others, 1981; Kisvarsanyi, 1980, 1981). These volcano-tectonic features are comparable to some of the classic ring complexes of the world, such as the "younger" granites in Nigeria and Glen Coe in Scotland. Although the volcanic superstructure of the St. Francois terrane has been largely removed by pre-Paleozoic erosion, as much as 5,500 ft (1,680 m) of rhyolite ash-flow tuff are preserved locally. These rocks are thickest in the area of the Taum Sauk volcano-tectonic depression (Anderson, 1970; Cordell, 1979) or caldera (Berry and Bickford, 1972) in the St. Francois Mountains.

Most of the volcanic rocks are confined to a northwest-trending (fig. 8) topographic high that forms a buried ridge of knobs extending as far northwest as the Missouri River (see figure 3 in Denison and others, 1984; also refer to Kisvarsanyi, 1974). The fact that the volcanic rocks are constrained by two major tectonic zones associated with the Early Proterozoic Central Plains orogen, the Grand River and Northeast Missouri tectonic zones (represented by faults of the same name on fig. 9), as defined by Kisvarsanyi (1984), suggests that their emplacement and distribution are controlled mainly by structures in the older terrane. Mesozonal granite of the same age as the St. Francois terrane (Bickford, Harrower, and others, 1981), which is part of the Transcontinental anorogenic province, has been identified along the northwestward extension of the St. Francois volcanic terrane, in north-central Missouri.

The volcanic rocks of the St. Francois terrane are predominantly rhyolite ash-flow tuffs containing very high SiO_2, K_2O/Na_2O, iron/magnesium, and fluorine, and low CaO, MgO, and Al_2O_3 (Kisvarsanyi, 1972; Bickford, Sides, and Cullers, 1981). They are characterized by perthitic alkali feldspar phenocrysts and iron-rich mafic minerals, including fayalite, ferrosilite, and ferrohastingsite. The mineralogy of the silicic volcanic rocks indicates that they have silica-oversaturated alkaline to peralkaline chemistry. Although some of the rocks are transitional to comendites, their agpaitic index (molecular ratio sodium + potassium/aluminum) is always less than one (Kisvarsanyi, 1981). Although the volcanic suite is bimodal because of the presence of minor basaltic flows interlayered with rhyolite in the Taum Sauk area (Blades and Bickford, 1976), intermediate and mafic rocks are rare. The intermediate rocks are chiefly trachyte and trachyandesite (Anderson, 1970; Kisvarsanyi, 1981). The volcanic suite is distinguished from those of calc-alkaline petrogenetic provinces by the absence of andesites.

The granitic rocks of the St. Francois terrane have been classified into three distinct types based on composition and mode of occurrence (Kisvarsanyi, 1980, 1981): (1) subvolcanic massifs, (2) ring intrusions, and (3) central plutons. The subvolcanic massifs, which are the intrusive equivalents of the comagmatic rhyolites, are typical epizonal rocks having granophyric texture and perthitic alkali feldspar; biotite is the characteristic mafic mineral and magnetite is ubiquitous. Near the contact with the intruded rhyolites, the subvolcanic massifs consist almost entirely of fine-grained granophyre; at depth, they grade into medium- to coarse-grained rapakivi granite and thus form one part of the "anorogenic trinity" of Anderson (1983). The subvolcanic massifs are inferred to be the most widespread component of the St. Francois epizonal terrane (fig. 8). Wherever they are identified in drill holes, they are assumed to have once been covered by rhyolite that subsequently was stripped off.

The ring intrusions are intermediate- to high-silica rocks whose emplacement is inferred to have been controlled by ring fractures related to caldera collapse and cauldron subsidence (fig. 8). The suite of rocks associated with the ring structures ranges from trachyandesite through trachyte and syenite to amphibole-biotite granite; porphyritic textures are common. Trace element data indicate that the ring intrusions crystallized from magmas derived through partial melting of older crustal rocks (Cullers and others, 1981).

The central plutons of the terrane are typically high-silica, evolved LILE two-mica granites having distinctive accessory minerals and trace element suites (Kisvarsanyi, 1980, 1981). The accessory minerals include abundant fluorite, topaz, apatite, spinel, allanite, sphene, and cassiterite. Because of the granites' relative enrichment in tin, lithium, beryllium, rubidium, barium, yttrium, niobium, uranium, thorium, and fluorine, they have been described as "tin granites" (Kisvarsanyi, 1981). They are inferred to have been emplaced in resurgent cauldrons and are circular to oval in plan; they have distinctive associated negative magnetic anomalies.

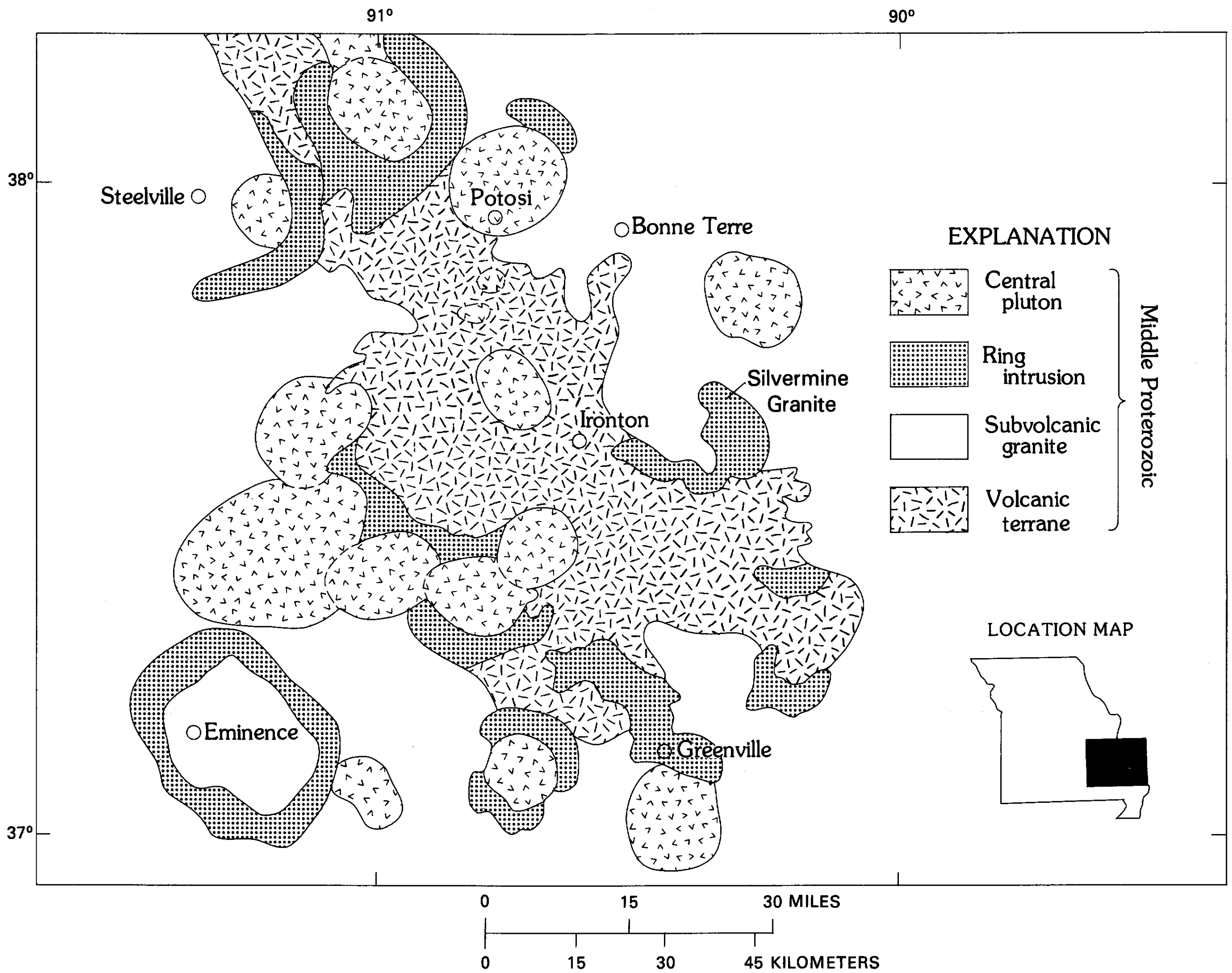


Figure 8. Integrated surface and subsurface geologic map of the St. Francois terrane, southeastern Missouri. Modified from Kisvarsanyi (1981).

As discussed in the section on the Transcontinental anorogenic province, at least some of the 1.45–1.48-Ga granitoid plutons outside of the St. Francois Mountains possibly are deeper analogues of the epizonal St. Francois terrane. Both rapakivi massifs and "tin granite" plutons, which intruded and partly assimilated rocks of the older crustal terrane, have been identified in the buried basement. That unmetamorphosed volcanic rocks of Middle Proterozoic age are preserved at all in southeastern Missouri is fortuitous; these rocks must have been protected in low-lying depressions. The older crustal terrane, the Central Plains orogen, is inferred to underlie the younger epizonal terranes to the south. Neodymium-samarium isotope data of Nelson and DePaolo (1985) imply a 1.8–2.0-Ga crustal source from which the epizonal rocks in the southern midcontinent were derived by partial melting. This is consistent with the earlier conclusion of Cullers and others (1981) that some of the rocks of the St. Francois terrane crystallized from primary crustal melts, and that most of the high-silica rocks crystallized from highly evolved magmas that were derived through differentiation of the primary magmas.

The rocks and associated ore deposits of the St. Francois terrane have features indicative of an extensional tectonic regime. A rift-related genesis for the terrane has been proposed by G. Kisvarsanyi (1975), an idea that was further developed by E.B. Kisvarsanyi (1980) as supportive trace element data (Viets and others, 1978) became available. The terrane has many of the petrological and geochemical attributes of Proterozoic rifts proposed for North America (Emslie, 1978; Anderson, 1983) and lacks only anorthosite massifs, which have not been encountered in drill holes. In contrast to the younger Keweenawan rift system, the 1.48-Ga tensional event(s) did not lead to extensive crustal separation and the emplacement of large volumes of basaltic magma in the rift(s).

Middle Proterozoic Spavinaw Granite-Rhyolite Terrane

The rock association identified as the Spavinaw terrane is similar in composition and tectonic setting to the St. Francois terrane but is approximately 100 m.y. younger. Zircons from granite and rhyolite in Missouri, Kansas, and Oklahoma yield U–Pb ages between 1.35 and 1.40 Ga (Thomas and others, 1984).

The Spavinaw terrane is represented in surface exposures by a few small outcrops of micrographic granite porphyry near Spavinaw, in Mayes County, northeastern Oklahoma. More than 300 drill holes, however, indicate that this terrane underlies most of northeastern Oklahoma, eastern Kansas, southwestern Missouri, and northern Arkansas (Denison, 1981, 1984; Kisvarsanyi, 1984; Thomas and others, 1984; Sims, 1985) and, thus, is an extensive Middle Proterozoic epizonal terrane. As used in this report, the Spavinaw terrane includes all the rocks of the Northeastern Oklahoma province (Washington County Volcanic Group, Spavinaw Granite Group, Osage County Microgranite), and the informal Central Oklahoma granite group mapped in the subsurface by Denison (1981).

The volcanic rocks of the terrane (Washington County Volcanic Group of Denison, 1981) are dominantly rhyolite (locally metamorphosed to hornfels) and minor dacite, trachyte, and andesite. Data from northeastern Oklahoma (Denison, 1981) suggest that rocks of intermediate composition are more widespread and (or) volumetrically more abundant than in the St. Francois terrane, although this observation may be more apparent than real due to sampling bias. The mineralogical and chemical composition of rhyolites and ash-flow tuffs in the Spavinaw terrane are virtually identical to those in the St. Francois terrane (Bickford, Harrower, and others, 1981).

The volcanic rocks of the Spavinaw terrane are on the northern and southern flanks of the broad, presediment Spavinaw arch (Denison, 1966), which extends from central Oklahoma east-northeastward 240 km (150 mi) into southwestern Missouri. The arch is underlain by micrographic granite porphyry and fine-grained granophyre of the Spavinaw Granite Group of Denison (1981). These granites are petrographically similar to the subvolcanic granite massifs of the St. Francois terrane and, by analogy with the St. Francois terrane, are interpreted here as the comagmatic, intrusive phase of the volcanic rocks. Several 1.35–1.40–Ga rapakivi plutons (Thomas and others, 1984) that perforate the older metamorphic terrane of the Central Plains orogen in eastern Kansas and western Missouri probably correspond to deeper levels of the subvolcanic granites. Some of the rapakivi granites in Missouri contain as much as 20 ppm tin, 30 ppm niobium, and 5 ppm beryllium (E.L. Mosier, written commun., 1985) and have geochemical signatures similar to the "tin granites" identified in the St. Francois terrane (Kisvarsanyi, 1980).

The rocks of the Spavinaw terrane are assumed to have formed in a tectonic regime similar to those of the St. Francois terrane. If a prerift, mantle-arching, crustal-melting, tensional tectonic environment applies to the St. Francois terrane, similar conditions and processes are likely to have produced the Spavinaw terrane. This implies that thermal anomalies in the mantle and attendant magma generation shifted southwestward with time. Although the 1.35–1.40–Ga Spavinaw rocks form a fairly well defined, apparently continuous terrane in the four-state area of Kansas, Missouri, Oklahoma, and Arkansas, at least one 1.38–Ga pluton has been identified near the center of the exposed St. Francois terrane in southeastern Missouri (Bickford and Mose, 1975; Thomas and others, 1984). Other "exceptions" are likely to be present. They may signify that thermal activity was nearly continuous in the central midcontinent during the Middle Proterozoic, but that it culminated in different areas at different times.

Middle(?) Proterozoic Sedimentary Rocks

Clastic sedimentary rocks of low metamorphic grade have been penetrated by drilling at three localities in southwestern Missouri and adjacent parts of Kansas and Arkansas (fig. 17): (1) Vernon County, Mo., and adjacent Bourbon County, Kans., (2) Cedar County, Mo., and (3) Fulton County, Ark. The rocks apparently mainly occupy a graben between the Chesapeake and Bolivar-Mansfield tectonic zones. The rocks at the first two localities were assigned to the X^3m unit (Metamorphic rocks, undivided) on the open-file map (Sims, 1985), but they were designated Ys (Clastic sedimentary rocks) on the colored geologic map (Sims, in press) because of their distinctive lithology and low metamorphic grade. Subsequent to compilation of the basement map, the Arkansas Geological Commission obtained core from a drill hole in Fulton County, Ark., that penetrated sedimentary rocks (R.E. Denison, Mobil Research and Development Corp., written commun., 1986); the location of this hole is shown on figure 17. The rocks from the three localities appear to be parts of a distinctive sedimentary assemblage of presumed Middle Proterozoic age.

In Vernon County, southwestern Missouri, a 300-m-thick (984-ft-thick) succession of red clastics was described by Skillman (1948) as pre-Upper Cambrian. The rocks include feldspathic quartzite, argillite, and metaconglomerate containing rhyolite and granite clasts. The rocks are variably altered; albite and epidote are characteristic of the most intensely altered rocks, at deeper levels, whereas quartz and magnetite are characteristic of the less intensely altered zones. Pyrite is conspicuous in argillite layers. Other alteration minerals are chlorite, sericite, calcite, and muscovite. The alteration minerals replace primary constituents, both as disseminations and as veinlets. Skillman (1948) recognized two stages of alteration: (1) extensive albitization resulting in almost complete local replacement of clastic sediments; and (2) later introduction of quartz, epidote, chlorite, muscovite, magnetite, calcite, and associated minerals. The sedimentary rocks lie on epizonal volcanic rocks of the Spavinaw terrane (Denison, 1966), which in turn appear to overlie rocks of the Central Plains orogen—indicated by a U-Pb zircon age of 1.65 Ga from a mylonitized granite core drilled within the graben (W.R. Van Schmus, University of Kansas, oral commun., 1986).

In Cedar County, Mo., 80 ft (24 m) of low rank argillite, meta-arkose, and metaconglomerate were penetrated in a drill hole near Stockton (Kisvarsanyi, 1985). The fine-grained rocks are laminated and contain finely contorted layers of sericite and abundant granoblastic magnetite and ilmenite. The metaconglomerate contains clasts of quartzite. The sedimentary rocks appear to overlie mesozonal granite of the Spavinaw terrane (age, 1.35–1.4 Ga).

In Fulton County, Ark., 10 ft (3 m) of hornfelsic conglomerate were cored (R.E. Denison, Mobil Research and Development Corp., written commun., 1986). Clasts of both igneous (rhyolite, granite, and micrographic granite) and low-rank metasedimentary rocks occur in a sandy argillaceous matrix. The basement on which the rocks were deposited is unknown. These clastic rocks appear to represent remnants of a succession of pre-Late Cambrian age of unknown areal extent in the midcontinent region; other sedimentary rocks of Late Proterozoic age have been penetrated sporadically in southern Illinois, western Tennessee, and Kentucky (Denison and others, 1984), but their relationship to those described here is uncertain.

The lithologies of the clastic rocks suggest that they were formed in local basins, possibly as a result of differential uplift caused by Middle Proterozoic reactivation of the Chesapeake and Bolivar-Mansfield basement tectonic (shear) zones (fig. 17). The tectonic instability probably occurred during or subsequent to the volcanism in the Spavinaw terrane (1.35–1.4 Ga). Pull-apart basins, comparable to the much younger Ridge basin in the San Andreas fault system in California (Crowell, 1974), are possible sites for deposition of the sediments.

The alteration minerals that record the mild metamorphism of the sedimentary rocks probably formed from low-temperature, alkaline hydrothermal solutions that circulated through the clastic accumulation. The shear zones might be deeply penetrating structures that tapped warm alkaline waters. A regional metamorphism is not feasible as an explanation for the replacement minerals inasmuch as the rocks of the subjacent St. Francois and Spavinaw terranes are virtually unmetamorphosed.

Middle Proterozoic Midcontinent Rift System

The "Midcontinent rift system" is an informal term referring to the geological and geophysical record of intracontinental rifting in the North American continent during Middle Proterozoic time, about 1,200–1,000 Ma (Van Schmus and Hinze, 1985). Rifting was accompanied by the massive upwelling of mantle-derived magmas with the solidification of mafic plutonic rocks at depth and widespread volcanism and clastic sedimentation at the surface (fig. 2).

Rift-related rocks are well developed in the Lake Superior region where a wide variety of mafic plutonic rocks, their coeval volcanic rocks, and derivative sedimentary rocks are exposed along both shores of Lake Superior. These rocks disappear beneath Paleozoic strata 100 mi (160 km) south of the western end of Lake Superior, but they continue southward in the subsurface for more than 600 mi (1,000 km) as a belt of volcanic and sedimentary rocks some 25–50 mi (40–85 km) wide (King and Zietz, 1971). The mafic rocks yield the so-called "Midcontinent gravity high," one of the largest positive gravity anomalies in the United States. A related arm of the rift system has been identified by geophysical data at the eastern end of Lake Superior (Hinze and others, 1975). This arm extends southeastward beneath Paleozoic strata of the Michigan basin to a point where it is apparently truncated by the Grenville front.

The rift consists grossly of a medial horst of basaltic and lesser rhyolitic volcanic rocks. The horst is partly covered by epiclastic rocks, bounded by high-angle faults, and flanked by half-graben basins filled with epiclastic rocks. Two layered gabbroic bodies, the Duluth Complex in northeastern Minnesota and the Mellen Intrusive Complex in northwestern Wisconsin, flank the main rift in the exposed area. Other gabbroic bodies have been mapped in the subsurface of southeastern Minnesota and northeastern Iowa (Sims, 1985) from geophysical anomalies and a few drill-hole penetrations.

The Keweenawan lavas exposed in the Lake Superior region constitute one of the world's major plateau or flood basalt provinces. The lavas and associated intrusions are typically tholeiitic in composition, as are other major plateau lavas, but they have a wide range of compositions (Green, 1982, 1983). Although dominated by olivine tholeiites and transitional basalts, the lavas also include large volumes of tholeiitic basaltic andesites and locally abundant rhyolites and icelandites. Green (1983, p. 419) stated that "The initial flows * * * are slightly more alkaline than succeeding eruptions, yet high in nickel and chromium as well as incompatible elements, but the most abundant types are (a) high-Al olivine tholeiites with variable iron/magnesium ratios and undepleted light rare-earth elements that show strong resemblance to some mid-ocean ridge basalts, and (b) high-iron transitional basalts or iron-titanium tholeiites which resemble the bulk of younger major continental tholeiitic provinces." Green (1983) prefers a mantle-derivation for the rocks; they could have resulted from about 30 percent melting of mantle spinel lherzolite. Lead, strontium, and neodymium isotopic studies show the mantle source to be as old as 4 Ga (Leeman, 1977). The large relative volume of rhyolite seems too great to be accounted for by fractional crystallization of mantle melts (Green, 1983), but isotopic data imply little crustal contamination (Van Schmus and others, 1982).

The epiclastic rocks in the Lake Superior region are of alluvial-fluvial and locally lacustrine origin. An older suite, which locally is intercalated with lava flows, consists of red shale and sandstone of lithic composition. These rocks were derived from sources within the rift and were deposited in several fault-bounded basins along the axis of the rift. In Wisconsin this sequence is called the Oronto Group (Middle Proterozoic); it is notable for a medial, dark, carbonaceous and pyritic shale and siltstone unit called the Nonesuch Formation (Daniels, 1982; Elmore, 1984). A younger suite, called the Bayfield Group (Middle Proterozoic) in Wisconsin, also is of alluvial-fluvial and locally lacustrine origin. It consists of red shale and sandstone of arkosic, feldspathic, and quartzose affinity. These rocks were derived from sources outside the rift and were deposited in large, half-graben basins along the flanks of the rift.

In the Lake Superior region, the stratified rocks of volcanic and sedimentary origin have been assigned to the Keweenawan Supergroup, and this name also has been applied to similar rocks in other parts of the rift system. Because sedimentary rocks of both Oronto and Bayfield affinity have been recognized, these names also have been used in buried parts of the rift system, even though the various subsurface units are not continuous or necessarily correlative with those exposed in the Lake Superior region.

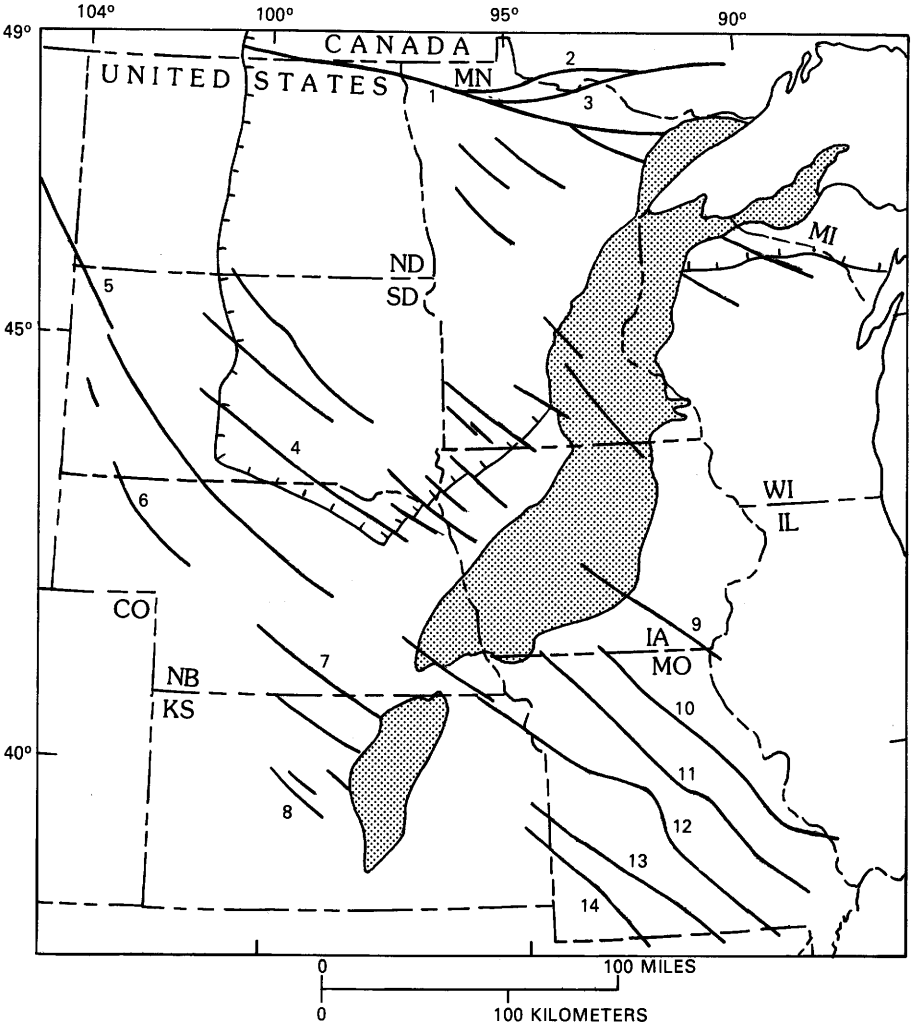
Although an aborted intracratonic rift model is generally accepted for the rift system, structural details concerning the geometry of the rift and its consequent effect on volcanism and sedimentation are debatable (see Weiblen and Morey, 1980; Green, 1983, for discussion). Furthermore, although several attempts have been made to produce integrated models of relationships between the Midcontinent rift and deformation associated with the Grenville front (Gordon and Hempton, 1986), many details remain to be established.

Recent modeling of gravity and aeromagnetic data in Minnesota and adjoining parts of Wisconsin (McSwiggen and others, 1986) has shown that the basic structure of the rift is more complex than the simple horst-graben relationship envisioned in many previous structural analyses (for example, Craddock and others, 1963; Mooney and others, 1970). Mafic volcanic rocks in the central part of the horst are as much as 9.3–12.5 mi (15–20 km) thick, whereas the sedimentary rocks in the flanking basins are only about 2.5 mi (4 km) thick. Thus, this part of the Midcontinent rift system has a gross structural geometry similar to that observed in the Rio Grande rift in the southwestern United States (Cape and others, 1983). Furthermore, modeling of seismic data from the southern (Kansas) part of the Midcontinent rift (Serpa and others, 1984) indicates that structural details in the upper part of the rift are markedly similar to those observed in the upper part of the Rio Grande rift. The seismic model takes into account the probable difference in the response of the upper and lower crust to extensional stresses, a factor that was not considered in earlier models of the rift system.

ORIGIN AND AGE OF TRANSCURRENT FAULTS

Northwest-trending faults are abundant in the basement rocks of north-central United States (fig. 9), and they appear to be part of a family of faults of this trend in the Superior craton and flanking Proterozoic terranes in Canada and the United States. The faults transect rocks ranging in age from Archean to Middle Proterozoic; those in Archean terranes have been shown to be dextral transcurrent faults (Sims, 1976a) that formed initially in Late Archean time and were reactivated at least in part in Proterozoic time.

A classic example of a dextral transcurrent fault in an Archean terrane is the Vermilion fault system in northern Minnesota (fig. 10). This fault system consists of anastomosing fault strands, each of which shows dextral movement; the aggregate horizontal displacement on the fault system is 10.5–11.8 mi (17–19 km) (Sims, 1976a). Subsidiary complementary faults have sinistral movement, showing lateral offsets of as much as 4.3 mi (7 km) (Waasa fault). Faults of both sets are ductile shear zones characterized by mylonitization and locally by silicification. Hudleston and Southwick (1984) have suggested a mechanism for the origin of the dextral faults; they proposed that the Vermilion fault was formed during Late Archean time as part of a continuum of dextral shear of regional extent. Regional folding that produced east-trending structures was followed by later faulting, which was simply a more brittle expression of the shear regime. They attributed the deformation to transpression: oblique compression between two more rigid crustal blocks to the north and south. A similar structural regime occurred along the United States-Canada border (Day and Sims, 1984; Poulson, 1983) and in areas northward to Hudson Bay (Card and Ciesielski, 1986).



EXPLANATION

Midcontinent rift system

Outline of Archean Superior craton

FAULTS

1 Vermilion	8 Central Kansas
2 Quetico	9 Des Moines River
3 Rainy Lake-Seine River	10 Northeast Missouri
4 Reservation	11 Grand River
5 Cedar Creek	12 Central Missouri
6 Chadron	13 Bolivar-Mansfield
7 Cambridge	14 Chesapeake

Figure 9. Major known and inferred transcurrent faults in north-central United States.

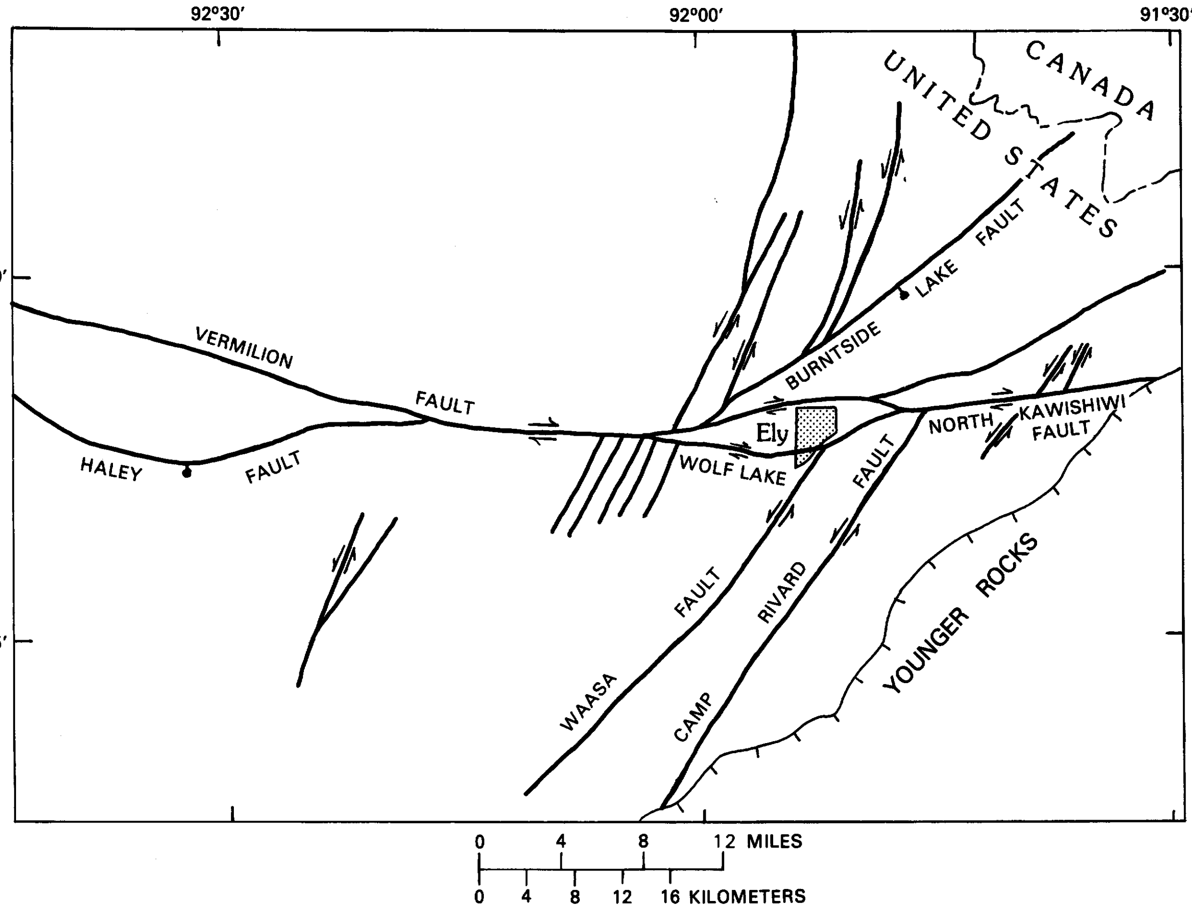


Figure 10. Map showing the Vermilion fault system of dextral transcurrent faults and related sinistral faults, Vermilion district, northern Minnesota. Country rocks are Archean metamorphic and granitoid rocks, except as noted. Modified from Sims (1976a, fig. 4) with additions from Sims and Southwick (1985).

Northwest-trending dextral faults also transect the Archean greenstone-granite terrane in northern Michigan and Wisconsin (Morey and others, 1982), the Archean gneiss terrane in southern Minnesota (Sims, 1985), and the Early Proterozoic Wisconsin magmatic terrane.

Several faults of Archean age in southwestern Minnesota and adjacent areas were reactivated in the Proterozoic. Southwick and Mossler (1984) have postulated that northwest-trending faults that border basins of Sioux Quartzite were active during sedimentation, as indicated by alternating thick coarsening- and fining-upward sequences. In northeastern Nebraska, Houser (in Houser and Gray, 1980) has shown that reactivation of a major northwest-trending fault (Reservation fault, fig. 9) continued, or was renewed, in the Paleozoic. This fault borders the Sioux Quartzite body on the southwest (Sims, 1985); the Sioux is about 3,800 ft (1,150 m) thick immediately northeast of it. Southwest of this fault, the basement is Precambrian crystalline rocks overlain directly by Ordovician strata, which indicates that the northeastern side was downdropped during or shortly after deposition of the Sioux. Stratigraphic patterns within the Paleozoic strata indicate that the fault acted as a hinge line (southwestern side down) that controlled the position of Paleozoic shorelines. Paleozoic rocks are absent immediately northeast of the fault, whereas they thicken southwestward from it. Fault movement had ceased by Cretaceous time because there is no apparent vertical displacement of the base of Cretaceous strata on opposite sides of the fault. Today, the fault is the locus of abnormally high temperature ground water in the Upper Cretaceous Dakota Formation, the principal aquifer in the area.

The kinematics of the faults to the south of those in outcrop areas, known only from the subsurface, is equivocal. However, the faults are tentatively included in the family of transcurrent faults, although they transect Proterozoic rocks and show no evidence of an Archean ancestry. These structures have been referred to, in Iowa, as "structural zones" (R.R. Anderson, Iowa Geological Survey, written commun., 1985) and, in Missouri, as "tectonic zones" (Kisvarsanyi, 1974, 1984). Although their origin is obscure, they have two things in common: they coincide with known structures in overlying

Paleozoic rocks and they clearly were reactivated in Paleozoic time.

A major northwest-trending fault in Montana and adjacent South Dakota (Peterman and Sims, in press), here termed the Cedar Creek fault (fig. 9), underlies the Cedar Creek or Glendive-Baker anticline (Gilles, 1952). This structure is expressed at the surface in Upper Cretaceous rocks as an asymmetrical anticline trending N. 30° W. and having a steeper southwestern limb. An isopach of the Phanerozoic rocks (Jensen and Mitchell, 1972) indicates as much as 1,100 ft (330 m) of vertical displacement of the basement surface across the anticline; the northeastern side moved upward. Gravity values decrease as much as 50–70 mGal across a steep gradient coincident with the axis of the anticline (Simpson and others, 1986), and magnetic values are markedly higher on the downthrown side as compared to the upthrown side (Zietz, 1982). The fault is interpreted (Peterman and Sims, in press) as the western boundary of the Trans-Hudson orogen in Montana, with Archean rocks of the Wyoming craton on the western side. The fault is projected southeastward into Nebraska (fig. 9) on the basis of magnetic and gravity data. A subparallel fault, here termed the Chadron fault, coincides with the Chadron arch; the southwestern side of this fault also moved downward (Bayley and Muehlberger, 1968). A possible northwestern extension of this fault is the set of northwest-trending transcurrent faults in the Black Hills uplift (Redden and Norton, 1975). Faults that coincide with the Cambridge arch and the Central Kansas uplift, both Paleozoic structures, are present in Kansas to the southeast (Sims, 1985). The northwest-trending tectonic zones that have been recognized in Missouri (Kisvarsanyi, 1984; Zietz and others, 1984) are characterized along their trends by faulting and folding in the Paleozoic rocks, Proterozoic igneous intrusions of both felsic and mafic rocks, and cataclastic granulation of the basement rocks. In central Missouri, two of the structures approximately bound the pronounced Missouri gravity low (Guinness and others, 1982; fig. 3).

Although the age and origin of the faults in the central part of the midcontinent region are uncertain, it seems reasonable to interpret them as transcurrent structures kinematically related to those on the Superior craton and immediately adjacent Early Proterozoic terranes, as proposed earlier by Sims (1985). Some of the southern group of structures could be rift-related faults, however, as suggested by Guinness and others (1982). Regardless of their origin, the northwest-trending faults are fundamental crustal structures in the north-central United States that have profoundly affected the evolution of the Precambrian terranes and apparently also the overlying Paleozoic rocks. Within the Superior Archean craton (fig. 9), they originated in Archean time and, at least in part, were reactivated during Proterozoic time. In the Early Proterozoic terranes that partly surround the Superior craton, the faults necessarily are post-Archean inasmuch as none of these terranes are thought to have an Archean basement. This could be interpreted as indicating that dextral shear of subcontinental extent persisted intermittently in the Superior craton and flanking Early Proterozoic mobile belts from the Late Archean (~2.6 Ga) to about 1.6 Ga. Possibly, these structures were utilized still later as transform faults during the Keweenawan rifting event, as suggested by the large lateral displacement of the central horst of the Midcontinent rift system in southern Minnesota (Sims, 1985). Finally, many of the northwest-trending basement structures were the sites of dominantly vertical movements in the Paleozoic, which produced mainly asymmetrical folds in the Paleozoic strata, such as the Cedar Creek anticline.

SUMMARY OF TECTONIC EVOLUTION

The early geologic history of the northern midcontinent spans an interval of more than 2,000 m.y. and records the fragmentation and reassembly of Archean and Early Proterozoic terranes of the North American continent and several Proterozoic anorogenic magmatic events. Much of the record is restricted to rocks in the buried basement—a record that is just beginning to be deciphered.

The earliest event significant to the northern midcontinent was suturing of the two Archean crustal segments in the Lake Superior region—the gneiss terrane on the south and the greenstone-granite terrane on the north (fig. 4). The suture, termed the Great Lakes tectonic zone (GLTZ), trends generally northeastward across Minnesota and adjacent states in the Lake Superior region (Sims and others, 1980). Gibbs and others (1984) concluded that the suturing resulted from thrusting of the northern greenstone-granite terrane over the gneiss terrane, apparently in Late Archean time.

Following stabilization of the Archean crust, Early Proterozoic epicratonic rocks were deposited in the Animikie basin (Minnesota and northern Michigan and Wisconsin; Morey, 1983a) during a period of extensional tectonism localized over and along the profound structural break (GLTZ) between the two Archean basement terranes (fig. 5*A*). These rocks are interpreted as recording the formation and evolution of a rifted continental margin (Schulz and others, 1987) along the southern edge of the Superior craton. Deposition began with sedimentation in elongate troughs and intervening platform areas (Larue and Sloss, 1980), then gave way to a broad shelf phase and finally to a flysch phase (Morey, 1983a). The flysch sequence is interpreted as deposits formed during rapid subsidence of the rifted margin following crustal breakup. The breakup of the continent led to ocean spreading, formation of volcanic-arc systems from about 1.89 to 1.83 Ga (Wisconsin magmatic terrane), subduction along the southern rifted margin and, eventually, collision of the oceanic arcs with the passive margin (~1.85 Ga; Penokean orogeny; fig. 5*B*). The juncture between the two contrasting terranes in Wisconsin is the Niagara fault, which is probably a high-angle thrust. A relatively small block of Archean gneissic crust that crops out in central Wisconsin (Sims, 1985) accompanied docking of the Early Proterozoic arc systems (Sims, 1985).

At about the same time as the events that culminated in the Penokean orogeny, rifting of the western margin of the Superior craton occurred and resulted in new north-trending volcanic crust and eventual collision of volcanic arc systems with the continent at about 1.85 Ga (Lewry, 1981; figs. 2 and 3), to produce the Trans-Hudson orogen (Churchill province). Whether the Wyoming Archean craton was rifted from the Superior craton and subsequently returned or whether it is part of an exotic continental mass is not known.

The Penokean orogeny and its predominantly calc-alkalic magmatism was followed in the Lake Superior region by a 1.76-Ga episode of anorogenic activity. Rhyolite ash-flow tuffs and cogenetic epizonal granite of metaluminous and peraluminous affinities that formed on older orogenic rocks in southern Wisconsin and adjacent areas (Smith, 1983) were derived by partial melting of older calc-alkaline rocks. The metaluminous and peraluminous affinity of these rocks is typical of the rhyolites and granites that form shortly after a major orogenic event (Rogers and Greenberg, 1981).

In the Lake Superior region and apparently in areas at least as far south as Iowa (Sims, 1985), the 1.76-Ga anorogenic magmatism was succeeded shortly(?) by deposition of mature quartzite that locally has thicknesses of as much as 5,000 ft (1,500 m). Apparently, the quartz sands were transported in generally southward flowing, braided river-alluvial plain environments and deposited in fault-bounded (rift?) basins, as proposed by Southwick and Mossler (1984) for the Sioux Quartzite in an intracratonic setting in southwestern Minnesota and adjacent areas.

Both the 1.76-Ga rhyolite-granite and the younger quartzite were mildly deformed and metamorphosed in southern Wisconsin at ~1.63 Ga (Van Schmus and Bickford, 1981; Peterman and others, 1985), whereas the Sioux Quartzite in the Sioux ridge area was virtually undeformed and unmetamorphosed. The cause of the 1.63-Ga event, which has now been recognized over much of Wisconsin and Michigan, is not confidently known, but Dott (1983) has suggested that it might have been caused by continent-arc collision to the south of Wisconsin.

Major orogenic activity, resulting in formation of the Central Plains orogen, took place virtually contemporaneously with the 1.76-Ga anorogenic event and deposition of the succeeding quartzite. Judged from available U-Pb zircon data (Bickford and others, 1986), the orogenic activity spanned the interval from about 1.8 to 1.63 Ga. By analogy with the presumed correlative Early Proterozoic foldbelt exposed in the basement uplifts of Colorado and adjacent states (Karlstrom and Houston, 1984; Condie, 1982), we infer that the Central Plains orogen probably resulted from continent-arc collision. The volcanic rocks in the orogen that have been studied are dominantly calc-alkaline, and they have geochemical characteristics similar to those of modern convergent-margin volcanics (Condie and Shadel, 1984). We tentatively suggest that collision in the Central Plains orogen occurred in the interval 1.63–1.70 Ga, but it could have been a more complex event that involved successive accretion of volcanic arcs. In any case, this episode of magmatic activity, which presumably involved much of southwestern United States, represented a major episode of addition of new crust to the North American continent (see Bickford and others, 1986, for discussion).

After a relatively quiescent interval of more than 100 m.y. of which there is no known geologic record in the region, anorogenic magmatism occurred once again. Discrete, widely separated plutons, mainly of batholithic dimensions, were emplaced within the Transcontinental anorogenic province (Anderson, 1983). Anderson (1983) attributed the magmatism to local thermal doming in the mantle in a regional extensional setting.

Approximately contemporaneously with, and possibly related to, the Transcontinental anorogenic magmatism, rhyolite and cogenetic epizonal granite (~1.48 Ga) were formed in the St. Francois Mountains and vicinity in southeastern Missouri (Kisvarsanyi, 1981; Sims, 1985), in a postulated tensional tectonic regime. The rocks accumulated on and within an older crust, presumably mainly rocks of the Central Plains orogen, and like other anorogenic Precambrian rocks in the midcontinent, are interpreted to be the products of partial melting of the lower crust (Van Schmus and Bickford, 1981; Nelson and DePaolo, 1985). This episode of anorogenic activity was followed by renewed granite-rhyolite magmatism (1.35–1.4 Ga) in the Spavinaw terrane of Oklahoma, Kansas, and Missouri and areas to the south (Thomas and others, 1984).

The nature and significance of the tectonic event responsible for accumulation of the Middle(?) Proterozoic sedimentary rocks in southwestern Missouri and adjacent areas in Kansas and Arkansas is speculative. Apparently, the sedimentary rocks reflect rather local tectonism—reactivation of major tectonic (shear) zones—although they could be part of a larger event that has not been recognized on a regional scale because of inadequate drill-hole coverage.

The youngest major tectonic event in the region was development of the Midcontinent rift system and its coeval igneous and sedimentary rocks (~1.1 Ga). The rift transects and interrupts several older tectono-stratigraphic terranes, and it is widely recognized as a rift that aborted before an ocean basin was formed. The magmatic rocks have chemical characteristics of mantle-derived sources (Green, 1983; Naldrett, 1981). The rifting was accompanied by differential uplift that reset Rb-Sr biotite ages (~1.14 Ga) over a large area, and which was greatest in northern Wisconsin (Peterman and others, 1985). The rapid uplift was accompanied by erosion, and detritus from the uplift presumably was shed into nearby tectonic basins, which have not been identified, if indeed they have survived. The uplift event may have affected areas south of Wisconsin also, because K–Ar biotite ages of ~1.2 are common in Iowa and adjacent areas (Goldich and others, 1966).

Subsequent crustal movements in the northern midcontinent have been largely epeirogenic and mainly have involved basin development in the Paleozoic. During this tectonism, basement faults were commonly reactivated, with concomitant folding and faulting of the Paleozoic strata and the local movement of fluids, including ore-forming fluids.

METALLOGENY

The Precambrian basement in the northern midcontinent represents a major frontier of future mineral exploration because of its high potential for suitable exploration targets. The Precambrian rocks exposed along the northern margin, in the Lake Superior region, have been one of the Nation's most important mineral-producing areas, especially of ores of iron and copper, and the Southeast Missouri district has been a large source of iron and a lesser source of other metals. The recent discovery of large resources of unmined material in the Lake Superior region (Sims, 1987) adds to the attractiveness of the midcontinent as a potential source of large mineral resources.

Any synthesis of the metallogeny of the buried Precambrian basement in the midcontinent requires some assumptions, including (1) that lithologic associations of ore metals in specific exposed terranes also exist in the subsurface; and (2) that certain types of deposits known to be associated with specific tectonic environments can reasonably be inferred, by analogy, to exist in the buried basement.

Several geologic terranes known to contain valuable mineral resources can confidently be extrapolated in the subsurface. Most notably, these include the Early Proterozoic Wisconsin magmatic terrane, the Middle Proterozoic St. Francois granite-rhyolite terrane, and the Middle Proterozoic Midcontinent rift system. Each of these crustal entities could contain substantial resources in concealed areas. The possible metallogeny of other exposed terranes not known to contain significant mineral deposits, such as the Middle Proterozoic quartzite of the Baraboo interval, can be inferred by analogy with terranes having comparable lithologies and tectonic settings elsewhere in the world.

Because the broad tectonic environment of the anorogenic magmatic terranes in the southern part of the region is similar to that of the world-class Olympic Dam copper-uranium-gold deposit at Roxby Downs, South Australia, consideration is given to the possibilities of such a deposit in the midcontinent.

The Precambrian basement in the midcontinent (lat 36°–46° N., long 88°–100° W.) is largely covered by Phanerozoic platform sedimentary rocks, but in about two-thirds of the region it is easily within the range of the diamond drill and the depth at which mining can be carried out. As shown on figure 11, much of the basement surface is above an altitude of –2,000 ft (–610 m), relative to mean sea level, and thus is within depth limits of about two-thirds of a kilometer below the land surface.

Archean Gneiss Terrane

Exploration geologists have tended to shun high-grade metamorphic terranes in the region, and mineral deposits of economic size have not been found in the Archean gneiss terrane of the Lake Superior region. Elsewhere, however, huge sulfide deposits occur within strongly metamorphosed and deformed Precambrian gneisses, including the lead-zinc ores at Broken Hill, New South Wales (Johnson and Klingner, 1975), and the massive sulfide ores in the Namaqualand Metamorphic Complex, South Africa (Tankard and others, 1982). Sawkins (1984) has suggested that these deposits are highly metamorphosed equivalents of rift-related massive sulfide deposits.

Reconstructions of various lithic and tectonic environments of the Archean gneiss terrane are conjectural because of the pervasive tectonic and metamorphic overprint. However, Goldich and others (1970) have emphasized that the gneisses are not protocrust but rather are rocks that evolved through processes similar to those recognized in many other gneisses of younger age. The garnet-biotite, sillimanite, and garnet-anthophyllite-cordierite gneisses exposed in the Minnesota River Valley were interpreted by Grant (1972) as having been derived from sedimentary rocks, possibly graywacke and shale. Rare beds of intercalated quartzite (chert) and amphibole-rich iron-formation further support this interpretation (Himmelberg and Phinney, 1967; Grant and Weiblen, 1971; Grant, 1972). The amphibolite and hornblende-pyroxene gneisses occur as layers or rafts in the

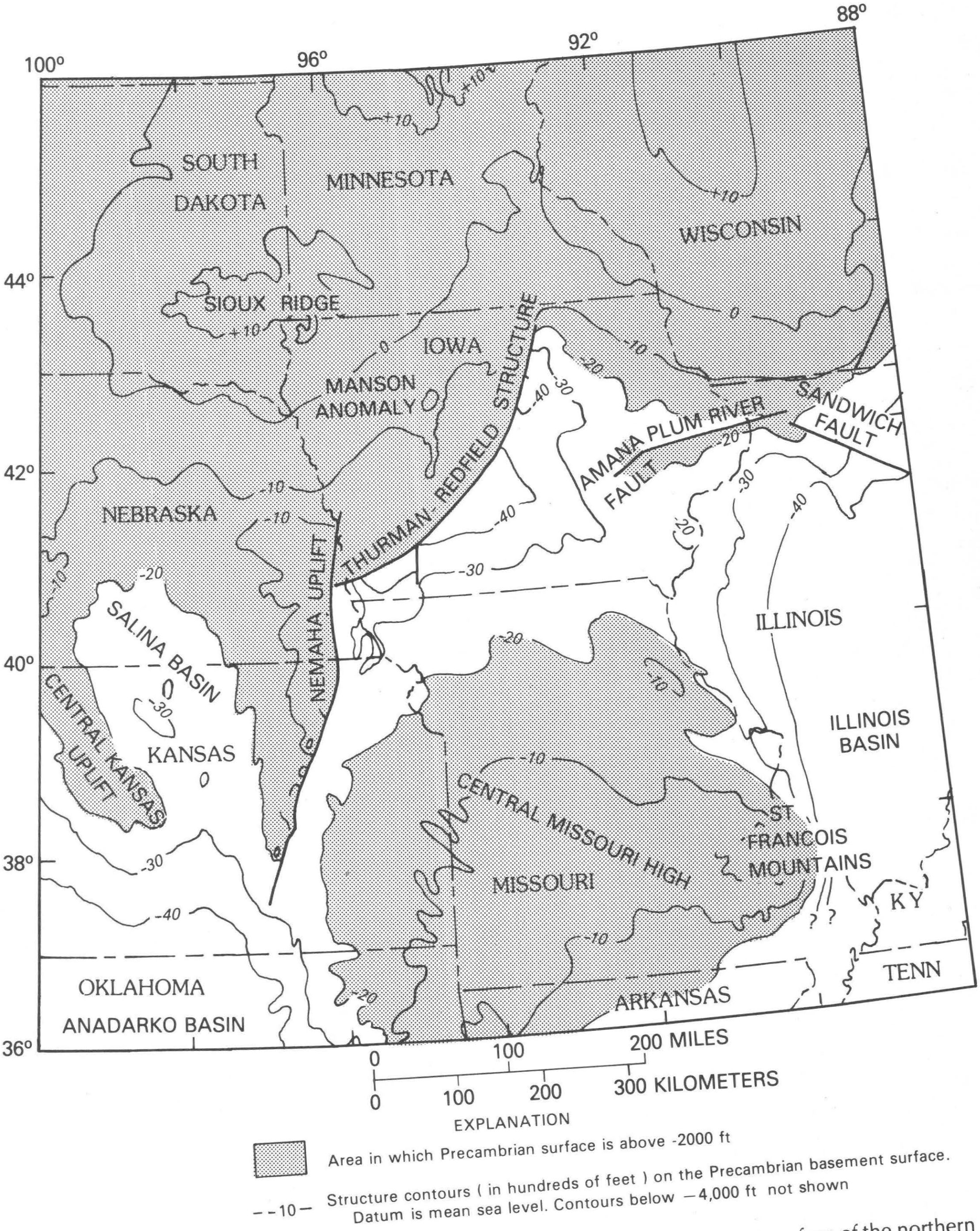


Figure 11. Generalized structure contour map of the Precambrian basement surface of the northern midcontinent. Modified from Sims (1985).

quartzofeldspathic gneisses, implying that they too were originally layered rocks. Thus, Grant (1972) postulated an igneous origin for them, either as mafic volcanic rocks or as their hypabyssal equivalents. Evidence for formation of the mafic rocks during several different geologic episodes is indicated by amphibolites of both tholeiitic and komatiitic affinity (Wooden and others, 1980).

The origin of the stratigraphically older migmatite gneisses is more equivocal, but from field relationships and geochemical criteria, Goldich and Wooden (1980) have concluded that these gneisses formed by the intrusion of coarse-grained tonalite into a volcanic pile of andesitic to dacitic flows and (or) pyroclastic material, which contained units of intercalated basalt.

If the younger successions of the gneiss terrane in the Minnesota River Valley represent the metamorphosed derivatives of supracrustal sequences that include graywacke, shale, iron-formation, and mafic volcanic hypabyssal rocks—rocks typical of Late Archean greenstone-granite terranes—they deserve consideration as exploration targets because greenstone-granite terranes typically contain major mineral deposits.

Late Archean Greenstone-Granite Terrane

The counterpart of the Late Archean greenstone-granite terrane—the Superior province in Canada—records the most varied and richest mineral production of any Archean terrane in the world (Franklin and Thorpe, 1982). The principal types of ore deposits are volcanic-hosted massive sulfide deposits, volcanic- and intrusion-hosted gold deposits, ultramafic- and gabbro-hosted nickel-copper deposits, and iron-formations of Algoma type. Of these several deposit types, only iron-formation has been mined extensively in the United States (Marsden, 1968; Sims, 1972). However, the potential for the existence of economic massive sulfide and gold deposits is excellent, although exploration for such deposits in most of the northern midcontinent region is hindered by the cover of Paleozoic rocks and Pleistocene glacial deposits.

Massive Sulfide Deposits

Zinc-copper massive sulfide deposits of primitive type (Hutchinson, 1980) can be expected to be present in the volcanic subprovinces of the Late Archean greenstone-granite terrane. The most favorable host rocks are tholeiitic and calc-alkaline volcanic and volcaniclastic rocks (Hutchinson and others, 1971). Preliminary studies of REE data from Canada has suggested that rhyolitic rocks of tholeiitic affinity, which form the felsic members of bimodal volcanic sequences, are perhaps the prime hosts for zinc-copper-type massive sulfide deposits (Lesher and others, 1986). However, such felsic rocks have been reported in the United States only in the Rainy Lake area in Minnesota (Day, 1985).

Past exploration in northern Minnesota has not encountered sulfide concentrations of probable economic significance, but thick zones of massive, submassive, and disseminated pyrite and (or) pyrrhotite have been penetrated, and thin, apparently discontinuous zones of zinc and copper sulfides have been encountered locally (Ojakangas and others, 1977). Several of the drilled iron sulfide bodies are thick sulfide-facies iron-formation; most other occurrences are in tuffaceous rocks of general dacitic composition.

Gold Deposits

Gold deposits in the Superior province of Canada occur in a wide variety of habitats (Franklin and Thorpe, 1982), but most of the larger deposits are hosted by volcanic rocks in greenstone belts. These deposits are typically stratiform and are variously interpreted as being either syngenetic or epigenetic in origin, depending upon the convictions of the specific scientist. Geologists of the Ontario Geological Survey, for example, generally favor a structural control for gold deposits (see Colvine, 1983, for summary), including the large, recently discovered Hemlo deposit (Muir, 1983), whereas Cameron and Hattori (1985) have suggested that syngenetic processes were responsible for gold concentration at Hemlo. Cameron and Hattori stated that gold was deposited contemporaneously with pyrite and barite but recognized that some components of the ore were recrystallized and remobilized as a result of deformation and metamorphism. The role of syngenetic versus epigenetic processes in the formation of stratiform gold deposits has not been adequately defined and much further research remains to be done.

In the United States, two gold deposits in the greenstone-granite terrane have been mined. The principal one, the Ropes mine in northern Michigan (Bornhorst and others, 1986), is active and has reported reserves of 20 million metric tons of ore containing 3.3 grams per ton gold and 22 grams per ton silver to the 900-ft level (Mudrey and Kalliokoski, in press). A second, minor deposit, the Little American mine at Rainy Lake, Minn., yielded a small amount of gold at about the turn of the century (Sims, 1972). Poulson (1983) has concluded from studies in the Wabigoon subprovince in an adjacent area in Canada, that gold-bearing quartz veins in the general Rainy Lake area occur in ductile shear zones and as dilations of regionally developed cleavage. These structures are related kinematically to the large, dextral, transcurrent faults in the region (Day and Sims, 1984), such as the Vermilion fault which was discussed in a preceding section of this report. Thus, recognition of the spatial relationship between gold and large dextral faults should be one objective of an exploration strategy for gold in this region.

Early Proterozoic Penokean Orogen

In the Lake Superior region, the Penokean orogen consists of the Early Proterozoic Wisconsin magmatic terrane, interpreted as an island-arc volcanic-plutonic complex (Sims and others, in press), and an Early Proterozoic epicratonic sedimentary-volcanic sequence, interpreted as a passive continental margin sequence (Schulz and others, in press). Inasmuch as the epicratonic sequence, which contains the large, valuable iron-formations of Minnesota, Michigan, and Wisconsin (Marsden, 1968), apparently effectively terminates to the south in central Minnesota (figs. 2, 5), the metallogeny of the epicratonic rocks is not discussed here. It should be mentioned, however, that in addition to the vast iron deposits a large, potentially valuable stratiform copper deposit in the Kona Dolomite (Chocolay Group of the Marquette Range Supergroup; Cannon and Gair, 1970) has been partly delineated by drilling. A resource in this deposit of at least 100 million tons containing more than 0.5 percent copper and modest silver values has been reasonably proved (Brown, 1986). The copper occurs as disseminated chalcocite, bornite, and chalcopyrite, which show well-defined lateral zoning within originally pyritic sediments in quartzite and argillite units in the lower part of the Kona. Taylor (1972) interpreted the deposit as having formed in a sabkha environment.

Massive Sulfide Deposits

The Wisconsin magmatic terrane contains at least four known massive sulfide deposits of future economic significance (Mudrey and others, in press), which are scattered within an east-trending volcanic belt more than 155 mi (250 km) long and less than 30 mi (50 km) wide (Sims, 1987). The actual length of the belt is not known because it passes under Paleozoic strata both to the east and west. The deposits belong to the primitive type of zinc-copper sulfide deposits of Hutchinson (1980), and accordingly they are grossly similar to the massive sulfide deposits in Archean greenstone belts within the Canadian Superior province (Franklin and Thorpe, 1982). The deposits were discovered by airborne electromagnetic methods and have been outlined by drilling (Mudrey and others, in press).

The largest known massive sulfide body, near Crandon, Wis. (May and Schmidt, 1982), contains about 61 million tons of ore, which contains 1 percent copper, 5.6 percent zinc, 0.5 percent lead, 36.8 grams per metric ton of silver, and 1 gram per metric ton of gold. It consists of not only a steeply dipping tabular body, which is hosted by felsic to intermediate pyroclastic rocks, but also the underlying epigenetic stringer or feeder-pipe mineralization. Other known massive sulfide bodies are much smaller, being on the order of 5 million tons or less.

Available chemical data are inadequate to characterize the volcanic rocks within the ore-bearing belt as a whole, but the volcanic rocks near Monico, Wis., in approximately the center of the ore-bearing belt, compose a bimodal suite whose end members are high-alumina basalt and rhyolite (Sims and others, in press). This suite is compositionally similar to the bimodal calc-alkaline volcanic rocks that host the Kuroko massive sulfide deposits of Japan (Dudás and others, 1983). Cathles and others (1983) have suggested that the Kuroko-type deposits were formed in a failed rift, and, by analogy, the Early Proterozoic deposits in Wisconsin also could have formed in an aborted island-arc rift. Such a setting would be compatible with the general linear alignment of the known Wisconsin deposits.

Sims (1985) interpreted the Wisconsin magmatic terrane as extending in the subsurface into southernmost Minnesota, northwestern Iowa, and northeastern Nebraska, on the western side of the Midcontinent rift system, as did Anderson and Black (1983). Accordingly, buried parts of the terrane could contain massive sulfide deposits of approximately the same tonnage and grade as those known in Wisconsin. The top of the basement in the terrane in Iowa and Minnesota is less than 0.35 mi (0.5 km) deep.

Other Deposits

A volcanic-hosted stratiform gold deposit of possible economic interest has been explored in central Wisconsin, east of Wausau, and anomalous gold values have been obtained elsewhere in this region from cherty rocks (G.L. LaBerge, oral commun., 1985).

The Archean crustal block associated with the Early Proterozoic Wisconsin magmatic terrane, which is presumed to have been rafted in with the arc volcanics, contains an Algoma-type iron-formation (Jackson County iron mine) that has yielded a substantial amount of taconite ore (Sims, 1987).

Early Proterozoic Rhyolite-Granite Terrane of Southern Wisconsin

The rhyolite-granite terrane of southern Wisconsin has no reported metallic mineral occurrences, possibly in part because of its sparse exposure. Because of its similarity to the younger St. Francois granite-rhyolite terrane, however, it could contain the same types of mineral deposits as are known to occur in that terrane.

Early Proterozoic Central Plains Orogen

Inasmuch as rocks of the Central Plains orogen are not exposed anywhere in the midcontinent and drill cores apparently have not penetrated ore-bearing material, discussion of the metallogeny necessarily must be based mainly on analogy with the presumed correlative rocks exposed in the basement uplifts in Colorado and adjacent areas. Apparently younger, layered mafic complexes that intrude the metamorphic suite and have been drilled at several localities in Missouri are also discussed in this section.

Metallic Sulfide Deposits Associated With Metamorphic Rocks

In Colorado, two types of Precambrian metallic sulfide deposits have been recognized (Taylor and others, 1983): (1) massive and disseminated sulfides, chiefly composed of zinc and copper but also containing gold, silver, and lead; and (2) disseminated copper in sulfides and tungsten in the mineral scheelite. The deposits are stratiform and were formed about 1.8 Ga, contemporaneously with their gneissic protolith, and were metamorphosed during Precambrian regional metamorphism.

The Precambrian stratiform deposits of both copper-zinc and tungsten-copper types in Colorado occur in both metavolcanic and metasedimentary rocks. They tend to cluster spatially and follow specific stratigraphic zones, but no regional structural control on their distribution is evident (Taylor and others, 1984). In general, the most favorable host rocks are units having alternating feldspathic and calcium-magnesium-rich layers, but some deposits, particularly of tungsten-copper type, are contained in calc-silicate and hornblende gneiss. Quartzite is an unfavorable host rock. The deposits range in size from small pods to lenticular masses some tens of feet thick and as much as several thousand feet across. Shapes are complex and modified by folding. An idealized stratiform sulfide deposit consists of a central core rich in chalcopyrite, sphalerite, gahnite (zincian spinel), and galena that passes laterally into pyrite-rich material and, in the distal margins, to magnetite- and manganiferous garnet-bearing rocks (Taylor and others, 1984). The largest known stratiform sulfide deposit in Colorado, the Sedalia mine near Salida, produced about 90,000 tons of ore (chiefly copper and zinc sulfates) from the weathered, oxidized zone of a primary sulfide deposit (Sheridan and Raymond, 1984). The nearby Pecos mine, near Santa Fe, N. Mex., is a massive sulfide deposit of much larger size; it has been a major producer of zinc, lead, copper, gold, and silver. Tungsten stratiform deposits (Tweto, 1960) tend to occur as widely scattered, overall low grade concentrations of apparent minor economic significance.

In the buried basement of the midcontinent region, areas of bimodal volcanism would be particularly favorable for the occurrence of stratiform sulfide deposits of the type known in Colorado and adjacent areas. Chromium, nickel, and cobalt geochemical signatures, which apparently result from the composition of mafic rock layers rather than from the deposits themselves, are associated with favorable gneiss bodies (Taylor and others, 1984). Tungsten tends to be associated with both the zinc-copper and tungsten-copper deposit types and could be a guide to favorable areas. Geophysical methods possibly could be utilized effectively to search for concealed deposits in areas of moderately thin Paleozoic cover.

Metallic Deposits Associated With Layered Mafic Complexes

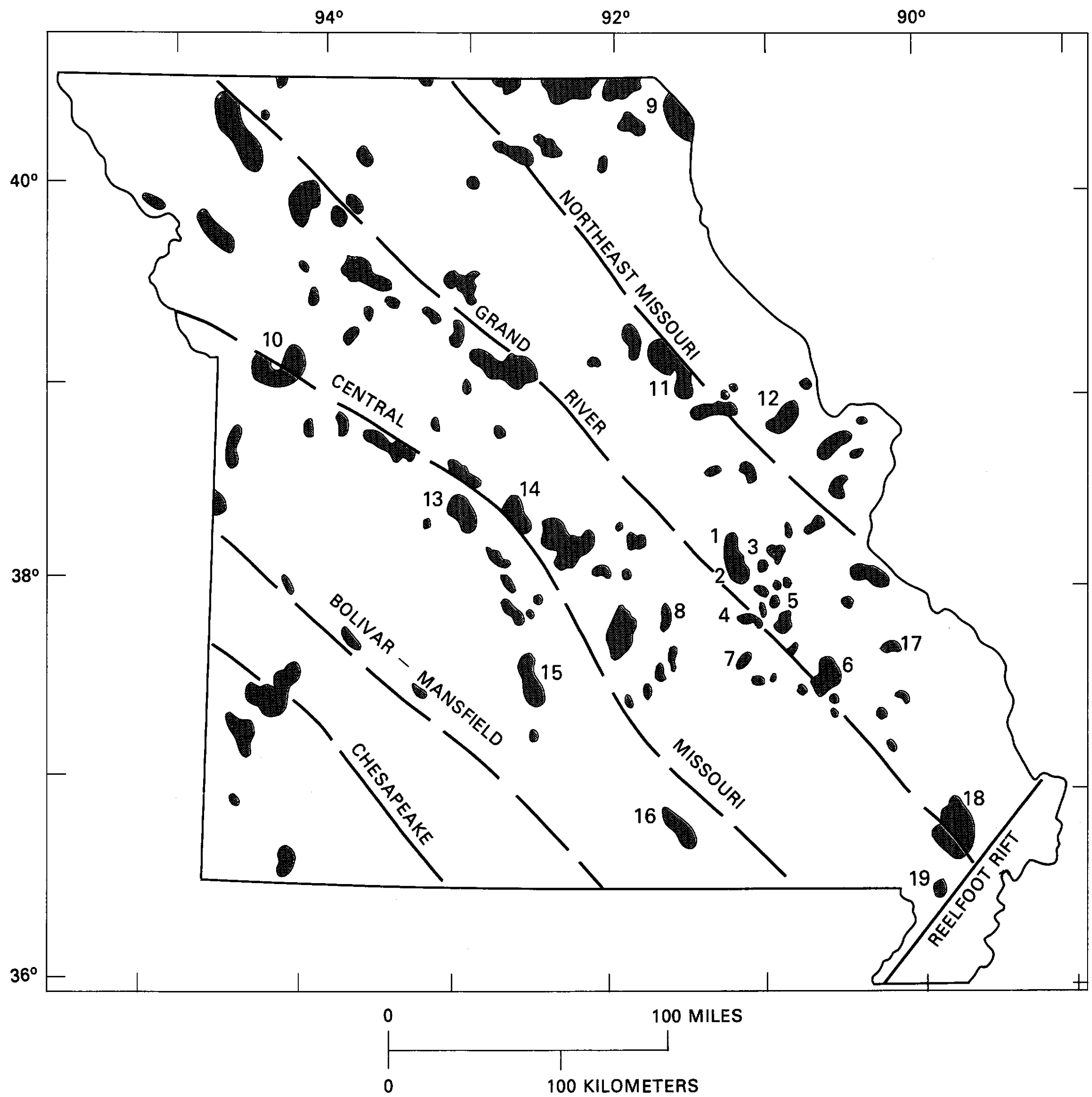
Several layered mafic complexes in Missouri (fig. 12), which produce pronounced magnetic anomalies, have been tested by exploratory drill holes because of their presumed potential economic importance. Such intrusions in cratonic settings elsewhere are major sources of iron-nickel-copper-cobalt ores and platinum-chromium-titanium ores (Naldrett, 1981). They include such well-known deposits as the Bushveld Complex in South Africa, the Stillwater Complex in Montana, and the Norilśk-Talnakh Complex in the U.S.S.R.

In Missouri, one complex, the Orla pluton (loc. 15, fig. 12), has been tested by five core holes that penetrated a total of 1,723 ft (525 m) of gabbroic rocks. The Orla pluton intrudes the older gneisses and schists of the Central Plains orogen. At its deepest drilled level, the complex is a fresh pyroxene gabbro composed of diallage, hypersthene, calcic plagioclase, trace olivine, much disseminated magnetite and chalcopyrite, and biotite. The gabbro is pervasively intruded by granitic dikes and veins. Zircons from one such vein yielded an age of 1.47 Ga (Bickford, Harrower, and others, 1981), which is the same age as the St. Francois granite-rhyolite terrane. The pervasive emplacement of granitic magma under mesozonal conditions produced extensive metasomatic alteration in the gabbro. Pyroxenes were uralitized, late biotite formed around earlier formed mafic minerals, and the gabbro was essentially converted to an epidiorite.

By combining drill core information from the other mafic plutons shown on figure 12 with that from Orla, certain generalizations can be made about these layered complexes. They typically (1) have a differentiated cap of diorite and quartz diorite; (2) grade through gabbro, norite, and troctolite with depth; (3) locally contain anorthositic lenses; and (4) are cut by granite (Kisvarsanyi, 1984). These rocks deserve further exploration even though they are covered by as much as 3,280 ft (1,000 m) of Phanerozoic sedimentary rocks, because some bodies contain as much as 15 percent by volume of disseminated pyrrhotite, pentlandite, chalcopyrite, and magnetite.

Middle Proterozoic St. Francois Granite-Rhyolite Terrane

The St. Francois granite-rhyolite terrane has been by far the most important metal-producing area in the Proterozoic of the midcontinent. It has been a continuous source of iron ore since 1815 and constitutes an iron metallogenic province (Kisvarsanyi and Proctor, 1967; Snyder, 1969). Cumulative production from the Southeast Missouri district is valued at more than $750 million; the value of ore in the ground is estimated at $600 million (Kisvarsanyi, 1984). Minor deposits of manganese and polymetallic (tin-tungsten-silver-lead-antimony) quartz veins were mined in the St. Francois Mountains in the past.



EXPLANATION

——— Fault — — Tectonic zone

MAGNETITE BODIES	MAFIC PLUTONS
1 Kratz Spring	9 St. Francisville
2 Bourbon	10 Levasy
3 Pea Ridge	11 Benton City
4 Camels Hump	12 Wentzville
5 Floyd Tower	13 Versailles
6 Iron Mountain-Pilot Knob	14 Eldon
7 Boss	15 Orla
8 Lake Springs	16 Peace Valley
	17 Avon
	18 Bloomfield
	19 Malden

Figure 12. High magnetic anomalies (black) in Missouri and their sources as inferred from drill holes and geophysical data. Modified from Kisvarsanyi (1984).

Iron and Copper-Iron Deposits

More than 30 iron and copper-iron deposits are known in the Southeast Missouri district; the majority of them are in the St. Francois Mountains. The six major deposits—Kratz Spring, Bourbon, Pea Ridge, Camels Hump, Boss (copper-iron), and Pilot Knob (lower ore body)—are in the buried part of the terrane and were discovered by the drilling of magnetic anomalies (fig. 12). Only two of the buried ore bodies, Pea Ridge and Pilot Knob, have been developed. The total yield from the Pea Ridge mine is more than 36 million tons of ore; proven reserves are about 100 million tons of ore containing 56 percent iron (Kisvarsanyi, 1984). Production from the Pilot Knob lower ore body from 1968 to 1980 was 19 million tons of ore grading at about 35 percent iron.

The major deposits are of two general types: (1) iron (magnetite-hematite)-apatite plus rare earths and minor sulfides of iron and copper, and (2) copper (bornite-chalcopyrite)-iron (magnetite-hematite) with sulfides of cobalt and molybdenum, and gold. The deposits have been interpreted as magmatic injections at the Pea Ridge (Emery, 1968), Iron Mountain (Murphy and Ohle, 1968), Pilot Knob lower ore body (Wracher, 1976), and Bourbon deposits (Kisvarsanyi and Proctor, 1967; Snyder, 1969); hydrothermal veins and replacements at Cedar Hill, Shepherd Mountain, and other small near-surface deposits; and volcanic exhalative impregnations in bedded air-fall tuffs at the Pilot Knob upper ore body (Anderson, 1976). Recently, Panno and Hood (1983) interpreted both the subsurface and surface ore bodies at Pilot Knob to be replacement deposits. The Boss copper-iron ore body has been considered to be a contact metasomatic deposit (Kisvarsanyi and Proctor, 1967).

The iron deposits consist of nontitaniferous magnetite and hematite ores that have relatively high alkali metal and rare-earth element contents. Apatite, monazite, fluorite, actinolite, garnet, and barite are characteristic associated minerals. Typically, ore magmas had associated hydrothermal and pegmatitic phases, and most deposits exhibit features characteristic of both magmatic and hydrothermal modes of origin. Ore bodies vary in size, shape, and emplacement characteristics; they are associated with silicic to intermediate rocks of the St. Francois granite-rhyolite terrane. However, the Boss deposit is in a syenite intrusion (Kisvarsanyi and Kisvarsanyi, 1977). Because of the similarity of the iron deposits to those at Kiruna, Sweden (Geijer and Odman, 1974; Frietsch, 1978; Wright, 1986), they have commonly been referred to as Kiruna type (Kisvarsanyi and Kisvarsany, 1981).

The iron and copper-iron deposits are considered to be genetically related to the trachyte suite (Kisvarsanyi, 1981), which composes the inferred ring structures in the St. Francois terrane (figs. 8, 13). The suite includes syenite, trachyte, magnetite trachyte, trachyandesite, and trachybasalt. Magnetite is a primary, rock-forming constituent in the trachyte suite and composes as much as 20 percent by volume of the magnetite trachytes. The trachytic rocks are spatially associated with distinctive, partial ring-shaped or arcuate positive magnetic anomalies (Zietz and others, 1984). Crosscutting relationships observed in drill core indicate that the iron and copper-iron mineralization postdate the rhyolite and subvolcanic granite and predate the central pluton and diabase (Kisvarsanyi and Kisvarsanyi, 1981). This timing suggests that the mineralization is temporally as well as spatially related to the emplacement of the ring intrusions.

Chemical analyses indicate that the trachyte suite is enriched in alkalies, iron, and volatiles. In an alkali-silica diagram (fig. 14), most of these rocks lie within the alkaline field, as defined by MacDonald (1968). Rhyolites of the terrane are mostly in the subalkaline field. In an iron-silica diagram (fig. 15), the trachyandesites show significant iron enrichment, the trachytes show somewhat lower iron contents, and both the trachytes and rhyolites show decreasing iron content with increasing silica.

The trachyte suite is generally low in titanium, a feature also characteristic of the ores. Boron and fluorine contents are quite high (fig. 16). Phosphorous (P_2O_5) contents range from 0.3 to 0.4 weight percent (Kisvarsanyi, 1972, 1981). Purified magnetite from different ore bodies has trace element distribution patterns comparable to the trace element signature of the trachyte suite (Kisvarsanyi and Proctor, 1967). In contrast, magnetite from the central plutons and from diabase dikes in the St. Francois terrane has trace element patterns that differ from those of magnetite in the ore bodies.

Kisvarsanyi and Kisvarsanyi (1981) have proposed that rather than being directly derived from the trachyte suite, the iron ores, as well as the associated trachytic rocks, have a common source in an alkalic-intermediate magma. Tension fractures associated with cauldron subsidence and caldera collapse, and the massive brecciation of the volcanic rocks of the terrane probably provided the most favorable sites for the emplacement of these magmas and ore solutions.

Manganese Deposits

Several small manganese prospects in rhyolite are known in the southern part of the St. Francois Mountains (fig. 13). These deposits yielded a few tens of tons of ore in the late 1800's (Grawe, 1943). The ore consists of braunite, pyrolusite, psilomelane, and wad. It occurs as veins in rhyolite, as breccia- and fracture-fillings, and as replacements in bedded air-fall tuffs. Secondary enrichment during weathering locally concentrated manganese and iron oxides in residual clays above the Precambrian-Paleozoic erosional nonconformity.

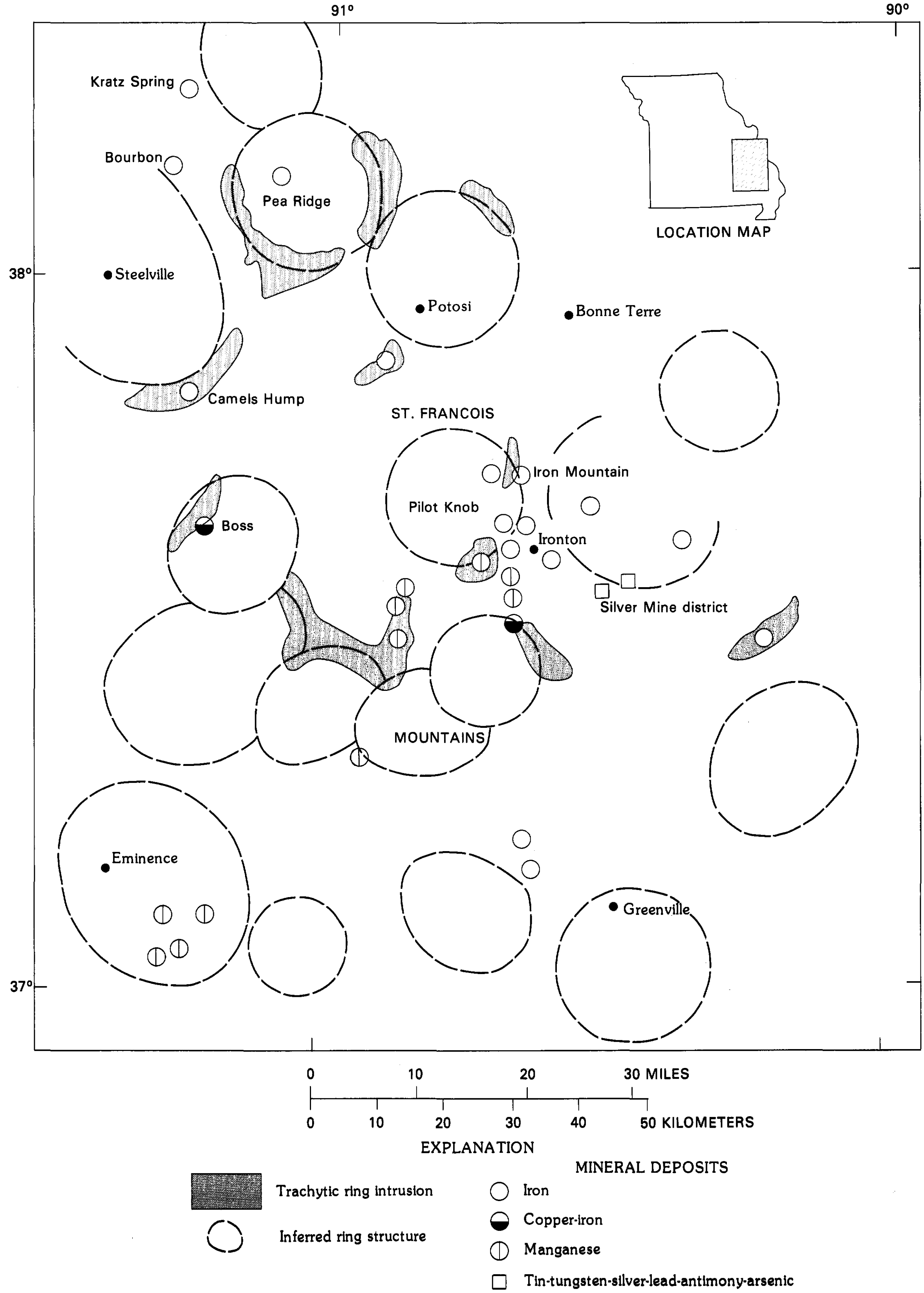


Figure 13. Relationship of ring structures, trachytic ring intrusions, and ore deposits in the St. Francois terrane, southeastern Missouri. Compiled by E.B. Kisvarsanyi (1986).

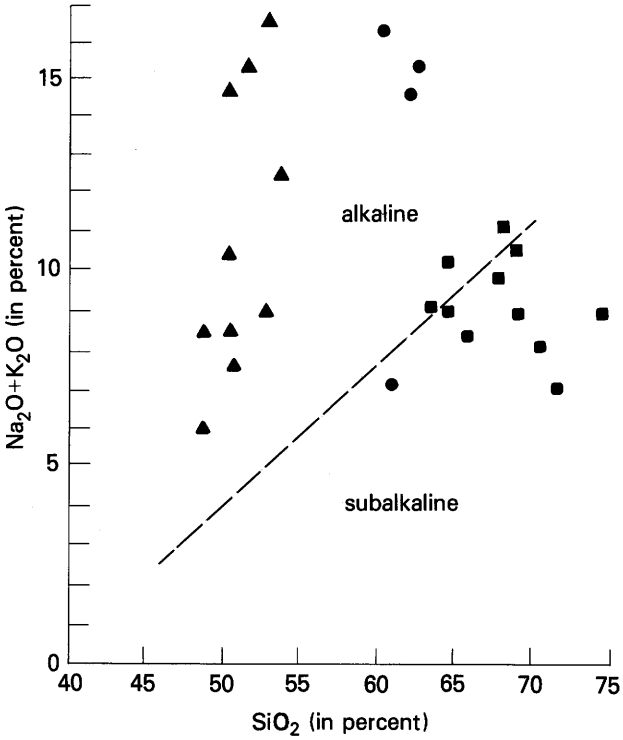


Figure 14. Alkali-silica diagram showing selected volcanic rocks from the St. Francois terrane: triangles are trachyandesites, circles are trachytes, and squares are rhyolites. Alkaline and subalkaline fields from MacDonald (1968). Source of chemical analyses in Kisvarsanyi (1972) and unpublished data in the files of the Missouri Geological Survey.

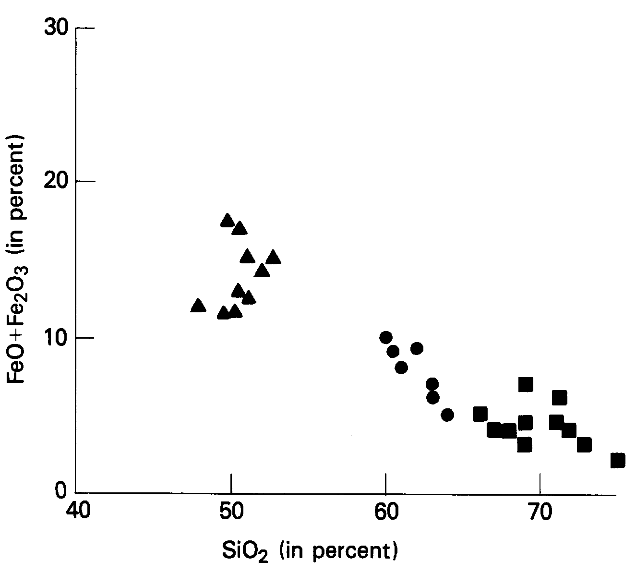


Figure 15. Iron-silica diagram showing selected volcanic rocks from the St. Francois terrane: triangles are trachyandesites, circles are trachytes, and squares are rhyolites. Source of chemical analyses in Kisvarsanyi (1972) and unpublished data in the files of the Missouri Geological Survey.

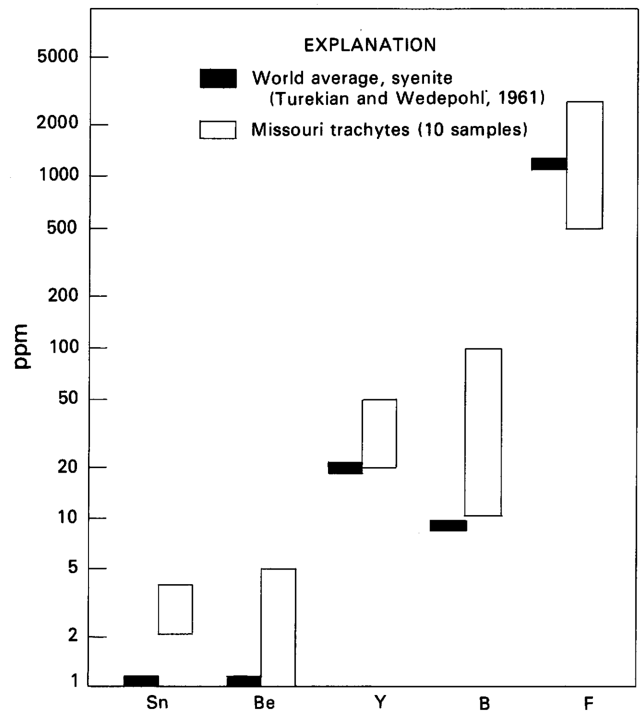


Figure 16. Ranges of selected trace elements in parts per million from the trachyte suite of the St. Francois terrane compared to world averages of syenite from Turekian and Wedepohl (1961). Trace element data from Viets and others (1978).

The most productive of the old mines produced about 3,000 short tons of manganese ores and concentrates, which contained more than 50 percent manganese, during intermittent mining between 1872 and 1958 (Dorr, 1967). The deposit is stratiform in water-laid, bedded tuffs, which are interbedded with thin beds of travertine; this association suggests that the deposit formed in a crater lake environment by fumarolic and hot spring activity. Evidence for some hydrothermal activity is also indicated by veinlets of barite and fluorite that cut the limestone beds (Kisvarsanyi and Kisvarsanyi, 1977).

Similar manganese deposits could have formed near the top of the volcanic pile throughout the St. Francois terrane, and some of them may be preserved in the buried part of the terrane. Craters, calderas, collapsed cauldrons, and ring structures would be the most favorable sites for this type of mineralization. The Precambrian-Paleozoic erosional nonconformity, especially where thick sections of basal clastics and residual clays are present, is considered to be a favorable horizon for secondary concentrations of both manganese and iron, and possibly also of copper.

Vein Deposits of Tin-Tungsten-Silver-Lead-Antimony

Deposits in the Silver Mine district (fig. 13) of the exposed St. Francois terrane represent the only known high-temperature pneumatolytic-hydrothermal (xenothermal) ore-mineral association in the Proterozoic of the southern midcontinent. The Middle Proterozoic Silvermine Granite of Kisvarsanyi (1981), one of the ring intrusions in the terrane (figs. 8, 13), is cut by polymetallic quartz veins that have accompanying greisenization of the wallrock. The mineral suite includes argentiferous galena, wolframite, arsenopyrite, sphalerite, cassiterite, chalcopyrite, covellite, hematite, stolzite, and scheelite and is similar to the deposits of Cornwall and Saxony (Tolman, 1933; Lowell, 1976). Hagni (1984) identified argentiferous tennantite, antimonpearceite, and berryite in the main sulfide stage of mineralization, and concluded that the base-metal sulfides and the silver minerals were deposited under epithermal conditions subsequent to greisenization and deposition of the quartz vein-type minerals. The ore solutions are assumed to have been derived from a "tin-granite" central pluton at depth. The mineral deposits postdate alkali-olivine basalt and tholeiitic olivine-basalt dikes that cut both the Silvermine Granite and rhyolite ash-flow tuffs in the area.

The deposits were mined from 1877 to 1894 and produced an estimated 3,000 oz of silver, as well as some 50 tons of lead. Between 1916 and 1946, an estimated 120 short tons of tungsten concentrates were produced by high-grading the old dumps and mining in shallow surface diggings. Mining operations at the dozen or so small mines and prospects did not extend to more than about 200 ft (61 m) from the surface, and the vertical extent of the ore systems in the district has not been explored or defined. The coincidence of the mineralization with a ring-fracture system (fig. 13), however, suggests structural control for the emplacement of the deposits, and it is possible that similar xenothermal deposits are associated with buried ring complexes elsewhere in the St. Francois terrane.

Uranium-bearing Granitic Rocks as a Possible Heat Source for Mississippi Valley-type Lead-Zinc Deposits

The LILE-enriched central plutons ("tin granites"), such as the exposed Graniteville Granite of Kisvarsanyi (1981) in the St. Francois Mountains, contain as much as 18 ppm uranium and 43 ppm thorium, nearly three times the average of other granite types in the St. Francois terrane (Nash, 1977). The "tin granites" also are abnormally radioactive compared to other common rock types. Accordingly, they can be classified as HHP (high-heat-production) granites. In addition to the exposed granite body, Kisvarsanyi (1981) has inferred the existence of eight such plutons in the buried segment of the St. Francois terrane (fig. 8). Possibly other, similar plutons exist but have not been penetrated by drilling.

The HHP granite plutons possibly could have supplied some of the basinal heat that is indicated by measured fluid-inclusion temperatures of Mississippi Valley-type lead-zinc ore deposits in the midcontinent. A basinal brine theory of Mississippi Valley-type genesis generally has been favored by most workers since its proposal by White (1958). Recently, Bethke (1986) has presented convincing arguments for formation of the Upper Mississippi Valley district lead-zinc deposits by regional ground-water flow across the Illinois basin, which was initiated by uplift of the Pascola arch in post-Early Permian and pre-Late Cretaceous time. Among the constraints on this gravity-driven flow model is an adequate basinal heat flow sufficient to account for the 150–200 °C temperatures commonly measured. Previously, abnormal heat flow in the southern part of the basin generally has been variously attributed to mafic dikes and sills of Permian age (Zartman and others, 1967), the Hicks dome cryptovolcanic structure of presumed Late Cretaceous age (McGinnis and others, 1976), and Mesozoic plutons inferred to exist from gravity and magnetic modeling by Schwalb (1982). The ages of these bodies are consistent with the presumed age range of the ore deposits. The HHP plutons of the St. Francois granite-rhyolite terrane, which is inferred to extend eastward into southern Illinois (Sims, 1985; Bickford and others, 1986), also are apparently situated favorably to be possible heat sources. Radioactive decay of uranium could have resulted in sustained thermal anomalies in the basement near the plutons that would have been sufficient to appreciably heat basinal waters.

Interestingly, the world-class Mississippi Valley-type lead-zinc deposits of the Southeast Missouri district have a close spatial relationship to the HHP plutons, as do the Tri-State zinc-lead deposits of Oklahoma, Kansas, and Missouri and the sphalerite deposits in northern Arkansas. We suggest that heat derived from the subjacent HHP plutons could have been a contributing factor to their genesis (see Leach and Rowan, 1986, for discussion).

Middle Proterozoic Spavinaw Granite-Rhyolite Terrane

The Spavinaw granite-rhyolite terrane has no historic record of mineral production. Petrographic, geochemical, and tectonic analogies with the St. Francois granite-rhyolite terrane suggest, however, that its metallogenesis could be similar to the St. Francois terrane and that the same types of mineral deposits could be expected in both.

Middle Proterozoic Midcontinent Rift System

Stratified rocks of the Keweenawan Supergroup in the Lake Superior region contain the world-famous volcanic- (White, 1968) and sedimentary-hosted (Ensign and others, 1968) copper deposits of the Keweenaw district, Michigan. A major copper resource also occurs in gabbroic rocks of the Duluth Complex in northern Minnesota (Listerud and Meineke, 1977). Although of marginal grade, the copper deposits of the Duluth Complex also contain appreciable quantities of nickel, cobalt, and possibly the platinum-group metals. These deposits are related to rifting processes and to associated mafic igneous activity involving mantle-derived materials. Therefore, it is reasonable to believe that similar deposits can occur elsewhere in the rift system.

Stratiform Copper Deposits

The volcanic- and sedimentary-hosted copper deposits of the Keweenaw district in Michigan contain disseminated mineral deposits. The deposits have distinctive mineralogical and zoning patterns, and the ores tend to have significant quantities of native copper or chalcocite and bornite, but only minor amounts of pyrite. Thus the ores tend to have large copper-iron ratios. These attributes are similar to those that characterize the so-called "rift-related stratiform copper deposits" of Sawkins (1984). Such deposits occur on all continents and range in age from 2,000 Ma to Miocene. However, a significant proportion of the deposits occurs in Middle to Late Proterozoic sequences (Sawkins, 1983), probably because of the widespread rifting that occurred about a billion years ago (Sawkins, 1976).

The volcanic-hosted deposits consist predominantly of native copper that occurs primarily as open-space fillings and replacements in flow tops and conglomerate. The mineralization is controlled both by primary permeability and by tectonic fracturing. White (1968) proposed that the deposits were formed by heated, copper-bearing solutions of metamorphic origin that formed in deeper parts of the rift system where the rocks were compacted and metamorphosed. The ascending solutions deposited native copper in greatest abundance in localities close to the boundary between the epidote and pumpellyite metamorphic zones of Jolly (1974). This genetic model, however, is subject to further review.

The sedimentary-hosted deposits occur in the Keweenawan Nonesuch Formation in dark laminated shale that contains abundant pyrite and organic material, including petroleum. In addition to copper, the deposits contain some silver (A.V. Heyl, oral commun., 1986). Although broadly stratiform, the deposits transgress lithic boundaries on a regional scale and consist predominantly of chalcocite that has replaced pyrite (Ensign and others, 1968). Brown (1971) has convincingly demonstrated that these deposits formed from copper-bearing solutions that flowed through parts of the Nonesuch, probably shortly after its deposition. White (1971) expanded on these observations and proposed a quantitative paleohydrologic model that involved the migration of copper-rich fluids from deeper parts of the rift system and the precipitation of copper at sites where the solutions encountered reducing environments. Weiblen and others (1978) and Morey and Weiblen (1978) proposed that the copper-charged solutions were produced by the diagenetic and low-grade metamorphic breakdown of copper-bearing basaltic detritus in the sedimentary sequences, rather than by leaching of the basalts themselves.

In terms of exploration for additional deposits, four major conclusions can be drawn. First, stratiform copper deposits are a relatively common feature in sedimentary sequences associated with rift systems, regardless of age. These sedimentary sequences always contain at least some evidence of associated mafic magmatism. The rift-related basalts seem to be the ultimate source of the metals. Volcanism can be either contemporaneous with sedimentation or just prior to it. Second, most copper deposits tend to occur within the first reduced sedimentary unit above an oxidized clastic sequence; that is, the deposits form from ascending solutions near sharp Eh boundaries in the sedimentary environments. Third, deposits tend to occur in areas of extensive faulting or in other permeable areas where the copper-bearing solutions can readily migrate from sources to traps. Fourth, the leaching of copper from the source rocks and migration of transporting fluid are promoted by enhanced levels of heat flow.

Redbed Copper Deposits

The redbeds of the Midcontinent rift system possibly could host redbed copper deposits, such as those found in the Middle Proterozoic Belt Supergroup in Montana (Lange and Sherry, 1983), the Permian Creta Formation in Oklahoma (Ripley and others, 1980), and in a variety of Precambrian, Permian, and Cretaceous redbed sequences in the Trans-Pecos region of Texas (Price and others, 1985). Although most of these known deposits are small, the ores are interesting because they typically contain appreciable amounts of silver.

Redbed copper deposits differ from the stratiform copper deposits described above in that they form from descending ground waters that circulate through red (oxidized) sediments and carry copper leached from the host rock until a reducing zone is encountered. The copper is then precipitated either by reduction of sulfate or by reaction with iron sulfide to form chalcocite, chalcopyrite, cubanite, and related copper sulfides. Textural evidence from several deposits (Rose, 1976) indicates that the copper was precipitated after the sediments were deposited but before they were deeply buried.

The key to formation of this kind of deposit is the development of chloride-bearing ground waters that greatly enhance the solubility of copper (Barnes and others, 1981). Such waters typically form in sabkha settings where evaporation can lead to ground waters with high salinities (Renfro, 1974) and possibly to anhydrite-containing evaporite deposits.

Although neither evaporite deposits nor other evidence for sabkha environments have been recognized in the redbeds of the Midcontinent rift system, Daniels (1982) and Daniels and Elmore (1980) have described stromatolitic zones in the Oronto Group that apparently formed in an arid, periodically desiccated, shallow-water environment that was subjected to large variations in flow regime. High evaporation rates also are indicated by calcite pseudomorphs after gypsum. Similarly, Morey (1974) has described stromatolite-oolite-bearing limestone from Oronto-equivalent rocks in southeastern Minnesota and attributed their formation to organic activity and precipitation in a restricted lacustrine environment. Environments involving extreme chemical precipitation in restricted settings undoubtedly also occurred in other parts of the rift system. As with the stratiform copper deposits, the possibility of the presence of redbed copper deposits is further enhanced by the availability of copper-enriched detritus in the host rocks.

Because this class of copper deposit for the most part lacks the detailed geologic, mineralogic, and geochemical studies needed to establish recognition criteria, any exploration effort in the rift system will require a great deal of drilling, even where overlying rocks are thin. Nevertheless, it may be possible to define the probable proximity of a deposit by using detailed geochemical studies of the paleohydrologic regime. For example, a recently completed hydrochemical study of ground water from the Midcontinent rift system in east-central Minnesota (Lively and Morey, 1985) has defined several major copper anomalies that could be related to either stratiform or redbed deposits in the subsurface.

Magmatic Copper Deposits

Gabbro-hosted copper deposits of the Duluth Complex constitute a large, untapped resource. Nickel, cobalt, and platinum-group elements are important potential byproducts of the copper ore. The copper- and nickel-bearing sulfides, including chalcopyrite, cubanite, and pentlandite, as well as appreciable quantities of pyrrhotite, are dispersed widely in the lower part of the Duluth Complex where it is in contact with carbonaceous and pyritic rocks of Early Proterozoic age. Naldrett (1981) has assigned the deposits to his class of "intrusions feeding flood-basalt activity associated with intracontinental rift zones," and has suggested that the magma was derived directly from a mantle source. Although the magma was the source of the metals, the Early Proterozoic country rocks were the source of the sulfur (Mainwaring and Naldrett, 1977; Weiblen and Morey, 1976; Ripley, 1981). Thus, the sulfides in the Duluth Complex formed by the coincidence of a metal-rich magma being emplaced in a sulfur-rich country rock. As such, it is unlikely that similar copper-nickel deposits will be found elsewhere in the rift system.

Several other aspects of the geology of the Duluth Complex may, however, be applicable to other parts of the rift system. Platinum-group elements in the Duluth Complex have relative proportions similar to those in other magmatic bodies where the elements are concentrated to ore grade (Naldrett and Duke, 1980). Ryan and Weiblen (1984) and Sabelin (1985) have shown that the platinum-group elements occur as discrete phases, either as native elements, as alloys of several native elements, or as several kinds of arsenides and sulfarsenides. These discrete phases occur as disseminated grains in gabbroic or troctolitic units dominated by titaniferous magnetite. Although the present discoveries are not economic, there is a growing belief that platinum-group metals could occur in economic concentrations in those parts of the Duluth Complex dominated by oxide-rich rocks. The significance of oxide-rich units as collectors for the platinum-group metals and the subsequent exsolution of these metals, either as alloys or in ways leading to combination with adjacent sulfides and arsenides to produce typical platinum-group minerals, is poorly documented (Naldrett and Watkinson, 1981). However, if association between oxide-rich rocks and platinum-group metals can be established, other oxide-rich plutonic rocks in the rift system, such as those in southeastern Minnesota and adjoining Iowa (Sims, 1985), may represent significant exploration targets for platinum deposits.

Petroleum Occurrences

For several years, an extraordinary search for petroleum has been underway within the sedimentary rocks of the Midcontinent rift system. The exploration effort stems in part from the fact that rift-related rocks of various ages hold approximately 10 percent of the world's discovered petroleum resources (Klemme, 1980).

Because of its Precambrian age, the Midcontinent rift system would not normally be considered a potential source for oil or gas. However, it has been known for about 25 yr that the Nonesuch Formation contains both solid and liquid hydrocarbon material. The solid hydrocarbons consist in part of bacterial cells, algallike structures, and fungal hyphae (Moore and others, 1969). The liquid phase, which contains a full spectrum of hydrocarbons typical of crude oil, has been extensively described (Hoering, 1976; Hunt, 1979; Meinschein and others, 1964). However, the crude oil contains higher concentrations of alkanes and lower concentrations of aromatics than found in an average crude oil and resembles the paraffinic crude commonly associated with Paleozoic production in Pennsylvania (Barghoorn and others, 1965). There is little doubt that the oil is of organic origin (Moore and others, 1969), and that it was formed under mild catagenic conditions. Sulfide minerals that cannot exist above 95 °C are closely associated with the oil (Brown, 1971) and confirm a low thermal environment. It has been assumed that the Nonesuch oil is indigenous to the host rock (Eglinton and others, 1964) and that it is truly Precambrian in age. Structures and optical activities of alkanes in the Nonesuch oil are indicative of hydrocarbons that have been preserved for a long period of geologic time (Barghoorn and others, 1965). A Rb-Sr isochron age of $1{,}052 \pm 5$ Ma has been obtained from the shaly host rocks (Chaudhuri and Faure, 1967). More recently Ruiz and others (1984) obtained a Rb-Sr age of $1{,}047 \pm 35$ Ma from a calcite-filled vein in the formation. The presence of oil in vugs within the calcite veins implies that the oil was trapped at that time (Kelly and Nishioka, 1985). The fact that the oil is truly Precambrian in age has important implications for petroleum exploration elsewhere in the rift system.

Because the Nonesuch has all the attributes of a hydrocarbon source rock, parts of northern Michigan and Wisconsin have been the center of considerable exploration interest (Dickas, 1984). Although obvious organic-rich beds like those in the Nonesuch have not been recognized in any other part of the rift system, a stratigraphic sequence lithically similar to and presumably correlative with the Oronto Group has been recognized in southeastern Minnesota (Morey, 1977) and adjoining parts of Iowa (Yaghubpur, 1979). In Minnesota, this sequence contains dark shaly units at several stratigraphic levels, and it has been suggested that the shales contain organic material (Lee and Kerr, 1984) and thus have a potential for producing hydrocarbons. However, Hatch and Morey (1985) have shown that the extant organic material in Oronto-like rocks of southeastern Minnesota is thermally mature, which implies deeper burial or higher thermal gradients than the Nonesuch Formation. They concluded that any hydrocarbons generated were probably lost during subsequent erosion as the western flanking basin of the rift system was filled with Bayfield-like sedimentary rocks.

Although Hatch and Morey (1985) have discounted the possibility of producing hydrocarbons from Oronto-like material in southeastern Minnesota, the presence of an organic-rich shale in that area lends credibility to the expectation of organic-rich units in other parts of the rift system. The concept of thick sedimentary sequences containing organic-rich units in tectonic environments where structural and stratigraphic traps typically occur implies that both sources and reservoirs are amply developed within the Midcontinent rift system (Dickas, 1986).

It should be emphasized that the copper and the hydrocarbons are similarly distributed in the Nonesuch Formation. Indeed, the hydrocarbons seem to have exerted a dominant control on localization of the copper mineralization (Kelly and Nishioka, 1985). If this analogy can be extended to other parts of the rift system, any exploration effort for one commodity will have a considerable impact on understanding how the other commodity is distributed. Hydrocarbon exploration is easier in deeply buried terranes than metal exploration, and hence the metal explorationists should follow the search for hydrocarbons in the rift system.

Hydrogen and Nitrogen Occurrences

Relatively high concentrations of hydrogen and nitrogen gas appear to occur in conjunction with the Midcontinent rift system in Kansas (Goebel and others, 1984) and adjoining parts of southwestern Iowa (Herman and others, 1984). The gases contain less than one percent other constituents, such as light hydrocarbons, helium, and carbon dioxide, and therefore have a unique composition. Field size has been estimated at 1.36 trillion cubic feet of hydrogen—the calculated energy equivalent of approximately 56 million barrels of high-gravity oil (AAPG Explorer, 1985, p. 17). Although completed in Mississippian (Kinderhookian) limestone, the producing wells are located near a fundamental fault that bounds the eastern side of the Midcontinent rift system, which was rejuvenated in Late Pennsylvanian time. The source of the gases is uncertain, but the general absence of hydrocarbons and carbon dioxide implies an abiogenic origin. The hydrogen in particular could have formed in several ways including: (1) serpentinization of ultramafic rocks which occur in the general vicinity of the drill holes; (2) mixing of waters of differing ionization potential; and (3) mantle outgassing along the deep bounding faults of the rift system. Although the validity of any or all of these possibilities has not been established, the presence of substantial quantities of hydrogen implies that the gas is being produced in major quantities at this time because the retention time for a fixed amount of the gas is roughly 1,000,000 yr (Petroleum Information, 1984). The presence of trapped hydrogen over the rift system in Kansas also implies that commercial quantities of hydrogen could occur in Phanerozoic rocks that cover other parts of the rift system.

SPECULATIVE METALLOGENY

In addition to the metalliferous deposits known or inferred to be present in the northern midcontinent as discussed above, the region is possibly favorable for the occurrence of Olympic Dam-type deposits and for unconformity-type uranium deposits. These speculations are based mainly on analogies in regional geologic settings.

Possible Olympic Dam-type Deposits

The Olympic Dam deposit at Roxby Downs, South Australia, is a major resource of copper, uranium, gold, and silver. It contains at least 2,000 million metric tons of ore that has an average grade of 1.6 percent copper, 0.06 percent uranium oxide (U_3O_8), 0.6 grams per metric ton of gold, and 3.5 grams per ton of silver (Roxby Management Services Proprietary, Ltd., 1986). The deposit also contains significant amounts of iron, lanthanum, and cerium.

The Olympic Dam deposit is located within the Stuart shelf area of the Adelaide geosyncline, on the eastern flank of the Archean Gawler craton (Roberts and Hudson, 1983; Plumb, 1979). The basement to the flat-lying Late Proterozoic (Adelaidean) to Cambrian sedimentary rocks in the geosyncline consists of rocks of the Gawler domain: (1) reworked Archean gneisses; (2) Early Proterozoic metasedimentary rocks—dominantly quartzite but including iron-formation; and (3) extensive, flat-lying, relatively undeformed, subaerial basalt-rhyolite bimodal volcanic rocks, which are dominated by felsic volcanic rocks—ignimbrites and lesser lavas and agglomerates (Branch, 1978). The felsic volcanic rocks lie within a basinlike feature surrounded by posttectonic granites; the volcanic and associated granitic rocks have Rb-Sr ages between 1.55 and 1.45 Ga (A.W. Webb, 1977, reported in Branch, 1978). Minor volcaniclastic sedimentary rocks, conglomerates, and sandstones are associated with the felsic volcanic rocks.

The Middle Proterozoic rocks that host the Olympic Dam deposit occur within a northwest-trending graben about 13,000 ft (4,000 m) wide that is developed along a major northwest-trending tectonic zone of regional extent (O'Driscoll, 1982). The graben is floored by alkali-feldspar granite and contains narrower troughs filled with a thick sequence of coarse clastic sedimentary rocks. The basin fill includes distinctive hematite-rich breccias and thinly bedded iron-formation. Stratigraphic relationships indicate that volcanism was contemporaneous in the region with sedimentation; the iron-formation is interpreted to have been deposited in a playa lake setting in which the iron was introduced from a fumarolic source (Roberts and Hudson, 1983). The precise relationship of these mineralized rocks to regional stratigraphic units is not known. The mineralized rocks do not crop out; they are unconformably overlain by a 1,150-ft (350-m)-thick cover of the Adelaidean sedimentary rocks, which completely obscure the underlying deposit.

The Olympic Dam deposit is essentially a large stratabound hematite-rich iron deposit that contains large amounts of associated copper, uranium, gold, and light REE. The sulfide assemblages are similar to those associated with stratabound copper deposits. In addition to the stratabound material, much of the deposit consists of transgressive, discordant sulfide-bearing material and associated hematite. Uranium mineralization generally is closely associated with copper zones, whereas gold seems to be concentrated separately. Both the stratabound and the transgressive deposits are epigenetic and formed from hydrothermal solutions that contain sulfur of magmatic derivation (Roberts and Hudson, 1983, 1984).

A general, preliminary model can be formulated for the Olympic Dam deposit. It is necessarily based largely on published descriptions of the deposit (Roberts and Hudson, 1983; Roxby Management Services Proprietary, Ltd., 1986) and on interpretation of the tectonic environment.

1. The tectonic setting of the Olympic Dam deposit was an extensional regime within a stable cratonic region, apparently near the Early Proterozoic continental margin. The region (Gawler domain) had become a stable cratonic platform by about 1.6 Ga (Parker, 1983; Plumb, 1979).

2. Following the culmination of cratonization, narrow, elongate, local(?) fault-controlled depositional basins were formed in and along major northwest-trending tectonic zones; coarse clastic sediments, mainly sedimentary breccias, accumulated in these basins. Volcanism accompanied sedimentation and possibly was bimodal because both mafic and felsic volcanic clasts are present in the breccias. Stratabound deposits of ferrous iron-bearing minerals were formed contemporaneously with sedimentation. This mineralization was followed by additional stratabound mineralization that contained hematite, copper sulfides, uranium, REE-bearing minerals, fluorite, and barite; this additional stage apparently was the main stage of copper-uranium mineralization.

3. Recurrence of fault-related tectonism and hydrothermal activity led to renewed mineralization and reworking of preexisting mineralized rocks and to the formation of transgressive discordant ore bodies and polymict breccias. The tectonism was accompanied by emplacement of additional igneous material.

4. The age of the mineralization can be constrained within broad limits. The lack of penetrative deformational structures in the ores and associated rocks indicates that the ores are younger than the regional ~1.6-Ga orogenic deformational event in the Gawler domain. The ores are older than the widespread, undated dolerite dikes in the region, which are virtually unaltered and do not intrude the Adelaidean cover sequence. Possibly, the mineralization was broadly coeval with the bimodal volcanism documented in the Gawler range, which

occurred at ~1.5 Ga (A.W. Webb, as reported by Branch, 1978).

5. An alkaline igneous (anorogenic) connection for the ores is strongly suggested by the (a) complex multielement association of iron, copper, uranium, precious metals, rare-earth elements, phosphorus, fluorine, and barium; (b) closely associated (spatially) bimodal volcanic rocks and alkali feldspar granite; and (c) moderately oxidized iron-rich ore-bearing solutions.

6. Magmatic processes that possibly can account for the Olympic Dam deposit could have been similar to those proposed for the volcanogenic fluorite-hematite deposits at Vergenoeg in the Bushveld Complex, South Africa (Crocker, 1985). Crocker attributed the Vergenoeg ores to immiscibility between two magma fractions—a silica-sodium-rich melt and an actinolite-rich mafic melt—in a highly differentiated and fractionated Bushveld granitic melt. The immiscibility led to partitioning of iron oxide-fluoride-phosphate and REE cations into the mafic melt. Upward migration of the two immiscible fractions led eventually to violent explosion due to structural failure of the roof, with the consequent deposition of felsic (rhyolitic) pyroclastics followed by the expulsion of the mafic magma fraction, which was converted to magnetite-siderite-fluorite plus residue as a result of pressure release. Further separation of the magma fractions occurred as a consequence of immiscibility or fractional crystallization and yielded the different, spatially segregated iron and fluorite bodies. As at Olympic Dam, stratiform deposits are transected by mineralized, discordant breccia pipes.

In conclusion, it seems probable that the Olympic Dam ores were formed in an extensional environment involving a large evolving, oxidized, iron-rich hydrothermal system associated with active anorogenic magmatism.

The northern midcontinent has several major geologic features that are grossly similar to the setting in which the Olympic Dam deposit was formed, as enumerated below.

(1) The geologic setting of the northern midcontinent region is broadly similar to that of the Gawler craton in South Australia. The region had stabilized by ~1.6 Ga (Sims and Peterman, 1986), following the Central Plains orogeny and its equivalent in the southwestern United States (Bickford and others, 1986). At about 1.5 Ga, approximately 100 m.y. after the culmination of cratonization of the crust, voluminous anorogenic magmatism occurred in a part of the region, which extended from Wisconsin (Anderson, 1983) through northern Illinois (Hoppe and others, 1983) into Missouri. This magmatism is recorded by the discrete rapakivi-type granite plutons and locally associated anorthosite bodies, such as the Wolf River batholith (Van Schmus and others, 1975) in the Transcontinental anorogenic province, and by the anorogenic epizonal rocks of the St. Francois granite-rhyolite terrane (Bickford, Harrower, and others, 1981). About 100 m.y. later, anorogenic magmatism comparable in all essential respects to that in the St. Francois terrane occurred in the area to the west and possibly overlapped the older granite-rhyolite terrane in southern Missouri (Sims, 1985). The younger anorogenic rocks (Spavinaw granite-rhyolite terrane) have crystallization ages in the range of 1.35–1.4 Ga (Thomas and others, 1984). We interpret all the epizonal granite and rhyolite as having formed during region-wide extension. These rocks, as well as the deeper seated anorogenic intrusions of the Transcontinental anorogenic province, are considered to have been derived by partial melting of somewhat older crustal rocks (Cullers and others, 1981; Van Schmus and Bickford, 1981; Nelson and DePaolo, 1985).

2. Clastic sedimentary rocks that are inferred to have been deposited concurrently with or perhaps later than the 1.35–1.4–Ga granite-rhyolite magmatism of the Spavinaw terrane accumulated at least locally in the southern part of the northern midcontinent region, apparently in one or more fault-controlled basins along the major northwest-trending Chesapeake and Bolivar-Mansfield tectonic zones (Sims, 1985). Drilling has penetrated sedimentary accumulations in Vernon County, Mo., and adjacent Bourbon County, Kans., Cedar County, Mo., and Fulton County, Ark. (fig. 17). The sedimentary rocks include conglomerates containing clasts of rhyolite and granite as well as argillite, quartzite, and arkose. The sedimentary rocks reflect local tectonic instability, probably resulting from reactivation of the northwest-trending faults. The rocks are variably altered to albite, epidote, chlorite, and calcite, and at one locality (Cedar County) are iron rich (mainly magnetite). Samples from this locality contain as much as 10 percent iron and anomalous concentrations of chromium (as much as 50 ppm), nickel (as much as 100 ppm), and cobalt (as much as 50 ppm). Such rocks are possibly analogous to the sedimentary rocks hosting the stratabound iron-copper-uranium deposits at Olympic Dam, but so far as is known, they lack detectable copper, uranium, and precious metals, which make up the ores at Olympic Dam.

3. As discussed earlier, the anorogenic rocks of the St. Francois granite-rhyolite terrane are strongly differentiated and enriched in alkalies, iron, and volatiles; some are enriched in LILE, including rubidium, barium, gallium, yttrium, REE, zirconium, thorium, niobium, tin, lithium, and uranium. Major, high-grade iron deposits and local copper-iron deposits are genetically and spatially associated with the anorogenic suite and display a wide variety of ore types, including magmatic, hydrothermal, and exhalative deposits, and thus indicate the existence of evolved, oxidized magmatic-hydrothermal systems. Although these systems are dominated by iron, they

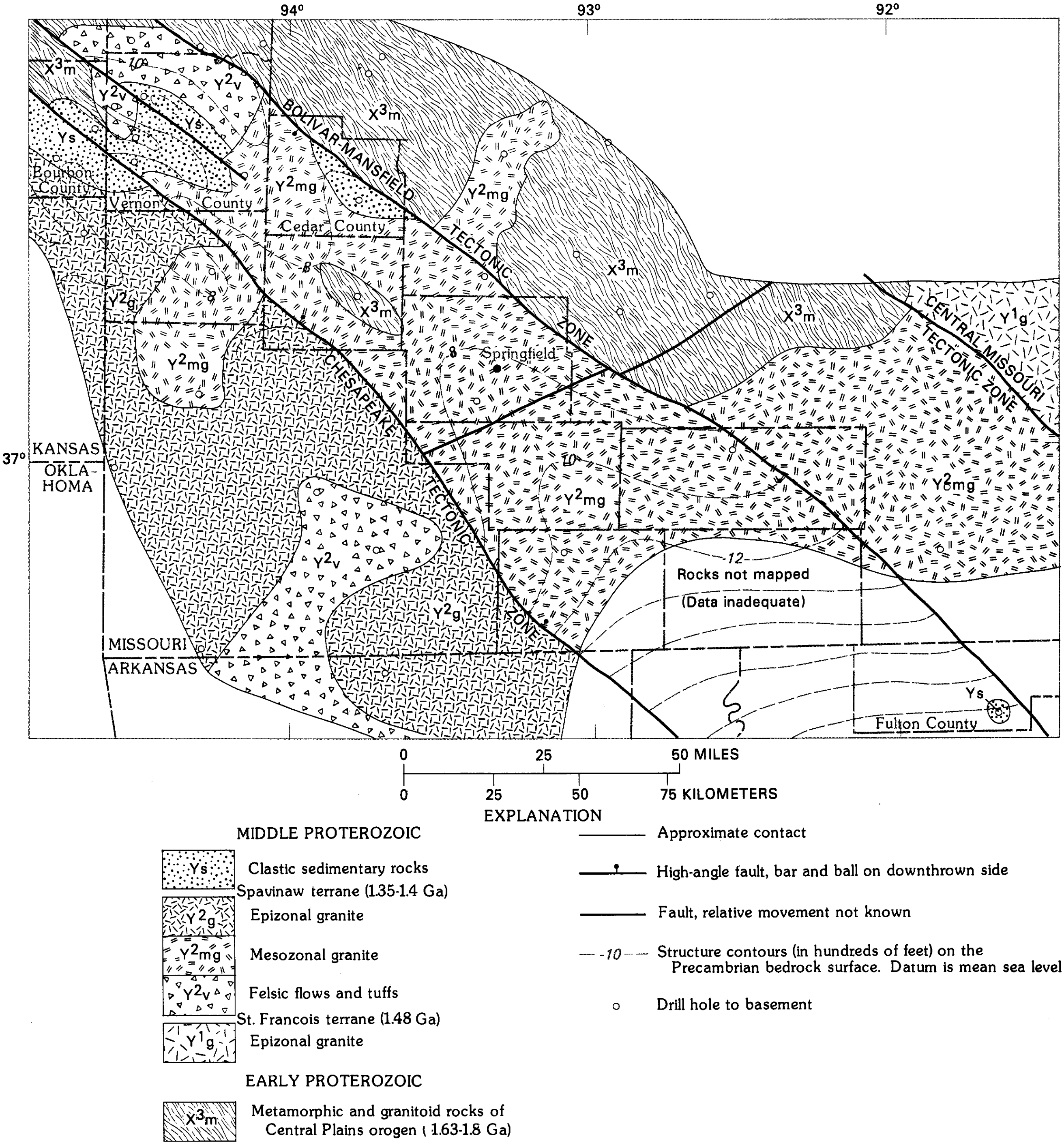


Figure 17. Geologic map of the Precambrian basement rocks in southwestern Missouri and adjacent areas. Modified from Sims (1985). Geology and structure contours by E.B. Kisvarsanyi (1984).

contain anomalous concentrations of copper and have associated volatiles, including fluorine. Similar deposit types and highly differentiated anorogenic rocks can be expected to be present in the Spavinaw granite-rhyolite terrane because of the closely similar rock chemistries. Considering the large area covered by the Middle Proterozoic anorogenic terranes and their evolved magmatic-hydrothermal systems, it can reasonably be inferred that mineral deposits of Olympic Dam type could exist somewhere in these terranes. If the sedimentary rocks in southwestern Missouri and adjacent areas (fig. 17) are in part at least contemporaneous with anorogenic magmatism, ore-bearing fluids from the magmas could have been introduced into the sedimentary pile.

Previously, Hauck and Kendall (1984) suggested that several areas in the central United States, from Missouri to the Great Lakes region, are favorable for the occurrence of iron oxide-rich deposits of the type present at Olympic Dam, Australia, Kiruna, Sweden, the St. Francois Mountains, and elsewhere.They proposed that this type of ore body composes a diverse family of economically significant, multicommodity, genetically related deposits that are intermediate in age between Early Proterozoic banded iron-formations and Phanerozoic ironstones. They emphasized, in the same way we do, that these deposits (1) occur within tensional basins on the margins of Archean shields, (2) were formed during a global period of cratonic stabilization, and (3) are genetically related to magmas derived from postorogenic lower crustal melting.

Possible Unconformity-Type Uranium Deposits in Quartzite of the Baraboo Interval

Quartzite of the Baraboo interval was deposited in an intracratonic setting within the northern part of the midcontinent region. The quartz arenites are dominantly fluvial deposits that lie unconformably on complex metamorphic terranes of older Archean and Early Proterozoic age. Because of the composition and tectonic environment of the quartz arenites, Ojakangas (1976) and Cheney (1981) have suggested that these rocks are favorable for the occurrence of possibly large unconformity-type uranium deposits. They based their suggestions on general criteria for unconformity-related vein-breccia uranium deposits, as defined by Mathews (1978). Considerable drilling in search of uranium during the past decade, especially in the Sioux Quartzite in southwestern Minnesota, has not encountered uranium concentrations, however.

The type area of unconformity-type, or Athabasca-type (Cheney, 1981), uranium deposits in North America is the Athabasca basin in northern Saskatchewan, Canada. The deposits are spatially associated with and presumably genetically related to a major regional unconformity between metamorphosed Archean and Early Proterozoic basement rocks and overlying unmetamorphosed red sandstone of the Middle Proterozoic Athabasca Formation. Pre-Athabasca weathering preceded deposition of the sandstone. Deposits that occur in the Pine Creek geosyncline in the Northern Territory in Australia (Ferguson and Goleby, 1980) are similar to those in Saskatchewan in terms of geologic setting and age, host rock alteration, mineralogy, geochemistry, and general spatial association with graphitic and carbonaceous tocks. The age of the mineralization in Saskatchewan is estimated to be ~900–1,250 Ma, that is, 200–400 m.y. younger than the host rock (Athabasca Formation; Cumming and Rimsaite, 1979). The age of the uranium mineralization is approximately coincident with the time of emplacement of a regional set of diabase dikes (Hoeve and others, 1980).

The uranium deposits in the Athabasca area (Hoeve and others, 1980) occur in the sandstone immediately above the unconformity and in fractures in the basement rocks, as veins, breccia-fillings, and disseminated impregnations. A structural control is indicated by the occurrence of uranium minerals, mainly uraninite and coffinite, in fractures, some of which moved repeatedly during the mineralization. Associated alteration in the basement rocks, the pre-Athabasca weathered rocks, and the sandstone above the unconformity is recorded by abundant chlorite, sericite, and tourmaline, and evidence of magnesia metasomatism. Amorphous hydrocarbons are present in most deposits. The uranium deposits are uncommonly high in grade (as much as several tens of percent uranium), and the uranium commonly has associated nickel-, cobalt-, arsenic-, copper-, and zinc-bearing minerals, mainly as base-metal sulfides and sulfarsenides, which at places constitute ore minerals. Quartz, carbonate minerals, siderite, chlorite, sericite, and adularia are common gangue minerals. Pagel (1977) has reported that fluid inclusions in gangue quartz from one mine indicate a temperature of formation of 160 ± 10 °C and a pressure of less than 1 kilobar.

Several models involving supergene, magmatic, and diagenetic-metamorphic waters, or combinations of each, have been proposed to account for the Athabasca unconformity-type uranium deposits. Of these, the diagenetic-hydrothermal model of Hoeve and Sibbald (1978), modified by Hoeve and others (1980), seems most applicable. This model relates uranium mineralization to diagenetic processes in the Athabasca Formation. Under conditions of deep burial, oxidizing, uraniferous saline waters in the Athabasca interacted with graphite-bearing rocks of the subjacent basement to yield reducing solutions containing carbon dioxide and methane. Mineralization resulted from interaction of the reducing solution and the oxidizing diagenetic solution that carried the ore components, in the vicinity of the unconformity.

The quartz arenites of the northern midcontinent are similar in tectonic setting, age, and lithology to the Athabasca Formation in northern Saskatchewan. They were deposited on older Archean and Early Proterozoic metamorphic and granitoid rocks, and the region has been stable since deposition. The Sioux Quartzite, in particular, is virtually unmetamorphosed and only mildly deformed. The quartzites, however, almost certainly are older than the Athabasca inasmuch as one body (the McCaslin Quartzite in northern Wisconsin) is cut by an intrusive pluton related to the 1.48-Ga Wolf River batholith and all bodies are inferred to be at least 1.63 Ga (Van Schmus and Bickford, 1981). The quartzites are mineralogically mature and consist mainly of framework quartz grains; conglomeratic beds are commonly present near the base; hematitic clayey matrix and beds of red argillite have been altered by diagenesis to sericite, muscovite, kaolinite, diaspore, and pyrophyllite (Morey, 1983b). A weathered profile occurs beneath the Sioux Quartzite (Southwick and Mossler, 1984).

Radon, helium, and dissolved U_3O_8 are anomalously concentrated in water wells near the basal contact of the Sioux Quartzite in the Cottonwood basin of southwestern Minnesota. Southwick and Lively (1984) noted that the anomalies could be related to a concealed uranium deposit, but suggested that the radon anomalies more likely indicate concentrations of radium rather than uranium.

Other metallogenetic aspects of unconformity-type uranium deposits, as outlined by Hoeve and others (1980), are largely unknown, partly because of poor exposures in the midcontinent. Graphitic- or carbonaceous-bearing basement rocks are not known in the vicinity of quartzite outcrops, and the chloritic alteration that characterizes the unconformity-type uranium deposits has not been recognized. Regardless of these apparently negative aspects, we suggest that further exploration, including deep drilling into the basement, is warranted because of the possible potential for giant uranium deposits (Cheney, 1981).

SUMMARY AND CONCLUSIONS

The northern midcontinent is a critical region for understanding the construction of the North American Precambrian craton. It is a collage of tectonostratigraphic terranes ranging in age from Archean to Middle Proterozoic that record several major crust-forming events and the erosion and deposition of platformal, epicratonic successions. Assembly of the craton was accomplished largely by 1.6 Ga, through lateral accretion of oceanic arc complexes to preexisting continental crust. Following construction of the composite craton, new additions to the crust were mainly through vertical addition of diachronous Middle Proterozoic (1.48 and 1.35–1.4 Ga) subaerial rhyolite and cogenetic granite, which were derived from and deposited on older (1.8–1.6 Ga) crustal rocks. A major, younger addition to the North American craton was the mafic magmatism and accompanying clastic sedimentation within the aborted Midcontinent rift system (1.2–1.1 Ga).

The tectonic processes that led to the development of the Precambrian composite crust in the midcontinent produced a variety of ore-generating environments (table 1). Oceanic-arc complexes—the Late Archean greenstone-granite terrane, the Early Proterozoic Wisconsin magmatic terrane of the Penokean orogen, and the Early Proterozoic rocks of the Central Plains orogen—contain known and potential stratabound zinc-copper massive sulfide deposits, gold deposits, and iron-formations of Algoma type. In addition, the Archean gneiss terrane, at least in part, may be a highly metamorphosed and tectonized greenstone belt; minable deposits have not been delineated within it, however. The volcanic-hosted massive sulfide deposits in the Early Proterozoic calc-alkaline Wisconsin magmatic terrane have lithologic and chemical similarities to the Miocene Kuroko-type massive sulfide deposits and, by analogy, possibly formed in an arc-related rift within a convergent margin environment.

The remaining terranes in the midcontinent are continental crustal segments that evolved in extensional environments during the Early and Middle Proterozoic. The Early Proterozoic sedimentary-bimodal volcanic Marquette Range Supergroup, which contains the large Superior-type iron deposits of the Lake Superior region, is interpreted as a passive margin sequence (Schulz and others, in press) that developed on the southern margin of the Superior Archean craton. The iron deposits do not extend into the subsurface, except possibly for small deposits in northwestern Iowa (Sims, 1985; Yaghubpur, 1979).

The 1.76-Ga rhyolite-granite terrane of southern Wisconsin initiated a period of extensive alkali-rich anorogenic magmatism in the midcontinent region as a result of crustal melting that persisted intermittently until 1.35 Ga. The 1.76-Ga anorogenic magmatism occurred virtually simultaneously with the orogenic magmatism in the Central Plains orogen and areas to the west (Bickford and Boardman, 1984), and perhaps reflects rifting related to the more southerly orogenic tectonism. Mineral deposits of potential economic value are not known to be associated with the 1.76-Ga anorogenic magmatism, but its lithologic and chemical similarities to the younger ore-bearing St. Francois granite-rhyolite terrane are favorable for it to contain iron-rich bodies and possibly other types of mineral deposits. The 1.48-Ga anorogenic magmatism, represented by the anorthosite-rapakivi granite assemblages in the Transcontinental anorogenic province, such as the Wolf River batholith, and the epizonal granite-rhyolite of the St. Francois terrane, are possibly manifestations of the exposure of different erosional levels, exposing on the one hand a predominant mesozonal igneous suite and on the other hand an epizonal igneous suite. This episode of anorogenic magmatism produced the valuable iron and copper-iron ores of the St. Francois terrane. It was followed about 100 m.y. later by very similar granite-rhyolite anorogenic magmatism in the Spavinaw terrane to the south and west.

The youngest event related to the prolonged extensional environment during the Proterozoic was development of the Midcontinent rift system, an aborted rift filled by mafic volcanics and hypabyssal intrusive rocks and derivative sedimentary rocks. It contains known, large rift-related stratiform copper deposits and magmatic copper-nickel and possible platinum-group elements; possibilities are excellent that similar deposits exist in the subsurface.

The gross tectonic environment of the Middle Proterozoic anorogenic terranes in the southern part of the region is remarkably similar to that of the giant Olympic Dam deposit in South Australia (Roberts and Hudson, 1983) and of other iron-rich deposits of comparable age (Hauck and Kendall, 1984). Accordingly this area merits consideration as an exploration target for such a deposit.

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