The Midcontinent of the United States—Permissive Terrane for an Olympic Dam–Type Deposit?

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The Midcontinent of the United States—Permissive Terrane for an Olympic Dam–Type Deposit?

Edited by WALDEN P. PRATT and P.K. SIMS

Midcontinent Strategic and Critical Minerals Project 1988
Workshop Report

U.S. GEOLOGICAL SURVEY BULLETIN 1932

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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Introduction

By Walden P. Pratt *and* P.K. Sims

The Olympic Dam (Roxby Downs) deposit in South Australia is one of the world's largest ore deposits. Primarily a hydrothermal iron oxide deposit, its approximately 2 billion metric tons (tonnes) of rock contain an estimated 32 million tonnes of copper, 1.2 million tonnes of uranium oxide, 1.2 million kg of gold, and significant concentrations of rare-earth elements (REE) and silver (Roberts and Hudson, 1983; Olympic Dam Marketing Pty. Ltd., 1987). The host rocks are multistage breccias that contain a large component of granitic and some possible felsic debris in a hydrothermal, iron oxide-dominated matrix. On the basis of drilling prior to mine development these rocks were thought to be conglomerates in a graben, but recent work disputes the existence of the graben and indicates that the host rock is a large, branching breccia body that includes significant bodies of internal sediment (Olympic Dam Marketing Pty. Ltd., 1987; Einaudi and Oreskes, this volume). The deposit was discovered in 1975, at a depth of 350 m, after drilling of a stratigraphic test hole sited on coincident magnetic and gravity highs at their intersection with a major airphoto lineament; paradoxically, the orebody thus far drilled out accounts for the large gravity anomaly but not the observed magnetic one, which is attributed to a large, as yet undiscovered, magnetic body at greater depth.

Hauck and Kendall (1984) and Meyer (1988) proposed that the Olympic Dam deposit can be considered the type example of an Olympic Dam "class" of ore deposits characterized by iron-rich copper-gold-uranium-REE-phosphorus-fluorine ores in potassium-rich granites and equivalent porphyries. In their view, other deposits in this class include Kiruna (Sweden), Bayan Obo (Inner Mongolia), and Pea Ridge (Missouri).

Is the Pea Ridge deposit really of the Olympic Dam type? And could there be more of these giant deposits in the United States? Recently, there has been growing recognition that the Precambrian basement in the Midcontinent region of the United States, especially the St. Francois and Spavinaw Proterozoic anorogenic granitic terranes in and adjacent to southern Missouri, may have high potential for an Olympic Dam–type deposit (Hauck and Kendall, 1984; Sims and others, 1988a, b). Indeed, in 1981 UMETCO, a subsidiary of Union Carbide Corporation, began an exploration project in search of such a deposit in southwestern Missouri, on the basis of gravity and aeromagnetic anomalies, but stopped the project when metal prices dropped in 1982, after drilling two unsuccessful basement holes in Polk and Webster Counties (E.W. Kendall, oral commun., February 3, 1988). With the broader potential in mind, we convened a workshop in Denver, Colo., February 2–3, 1988, under the auspices of the U.S. Geological Survey's (USGS) Midcontinent Strategic and Critical Minerals Project, with a dual purpose: (1) to review current data and hypotheses on the type deposit, on the permissive Midcontinent terranes, and on Union Carbide's exploration program, and (2) to design plans for an interdisciplinary research project to try to identify potential Olympic Dam target regions in the Midcontinent. Thirty-five people attended the workshop, 25 from the USGS and 10 having diverse affiliations but including direct and indirect ties to Olympic Dam, the Union Carbide program, and the Missouri and Kansas State geological surveys. Ten people spoke on a variety of topics ranging from general (tectonic setting) to detailed (hematite breccias), from geologic to geophysical modeling, and from Olympic Dam to the Midcontinent to Kiruna, Sweden (see program following references). The participants then divided into three working groups and wrote specifications for various tasks under the general headings of regional compilations and field studies, topical studies, and physicochemical processes of ore deposition in Olympic Dam–type deposits in the Midcontinent. Later, with the assistance of the working group leaders, we integrated these specifications into a single proposal. In the interest of public service, we are happy to share the details of this proposal with the exploration community for whatever use it may be, in whole or in part, as a possible plan of attack on a problem of great interest.

Manuscript approved for publication January 22, 1990.

This volume includes four papers from the workshop (three complete and one abstract) and one modified paper, as well as the integrated project proposal. An epilogue contains two short papers constituting an update on one aspect of the project proposal—mapping of the possibly analogous Pea Ridge iron ore deposit of southeast Missouri.

Many of the participants expressed the feeling that the workshop was an appropriate tribute to the late Charles Meyer, formerly of the Anaconda Company (1940–53) and the University of California at Berkeley (1953–80) (Hunt, 1988). Meyer's enthusiastic recognition of the potential for Olympic Dam-type deposits in the Midcontinent, as communicated to several of the participants, was a key motivation that led eventually to this meeting, and but for his untimely death in November 1987 he would have taken part in it himself.

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USGS Midcontinent Olympic Dam Workshop—Program

Tuesday, February 2, 1988

PART I—SCHEDULED SPEAKERS

8:00 Welcoming remarks, *David A. Lindsey, Chief, Branch of Central Mineral Resources, USGS*

8:05 Miscellaneous announcements and introductions, *Walden P. Pratt, USGS*

8:15 Tectonic setting, origin, and evolution of Middle Proterozoic iron oxide-rich ore deposits, *Steven A. Hauck, University of Minnesota-Duluth*

8:45 Breccias at the Olympic Dam mine, *Tommy B. Thompson, Colorado State University*

9:15 Origin of hematite breccias at the Olympic Dam ore deposit, *Naomi Oreskes, Stanford University and Western Mining Corporation*

10:00 Break

10:30 The geophysical signature of Olympic Dam and Midcontinent U.S.A. analogs, *William J. Hinze, Purdue University*

11:00 Usefulness of regional geologic information in developing an exploration model: a case history, *Ernest W. Kendall, Union Carbide Corporation*

11:30 Midcontinent Proterozoic terranes permissive for Olympic Dam–type mineralization, *Paul K. Sims, USGS*

Noon Lunch break

1:00 General features of the St. Francois and Spavinaw granitic terranes, *Eva B. Kisvarsanyi, Missouri Geological Survey*

PART II—INFORMAL COMMUNICATIONS

An outsider's visit to Olympic Dam, *Warren I. Finch, USGS*

Sulfide mineralization at the Olympic Dam mine, *Naomi Oreskes, Stanford University and Western Mining Corporation*

Breccias from the Missouri iron deposits, *Timothy S. Hayes, USGS*

Some observations of the Kiruna district, Sweden, *Murray W. Hitzman, Chevron Resources Company*

PART 1

Petrogenesis and Tectonic Setting of Middle Proterozoic Iron Oxide–Rich Ore Deposits—An Ore Deposit Model for Olympic Dam–Type Mineralization

By Steven A. Hauck[1]

Abstract

Late Early Proterozoic to Middle Proterozoic (1.8–1.0 Ga) iron oxide–rich deposits are a family (magmatic-exhalative) of ore deposits transitional between Archean to Early Proterozoic banded iron formations and Paleozoic iron oxide deposits. The Middle Proterozoic was a transitional tectonic period in which older Archean to Early Proterozoic shields became stabilized. Cratonic stabilization occurred after an Early Proterozoic orogeny and is represented by an anorogenic assemblage consisting of extensive, subalkaline felsic volcanic rocks, rapakivi granite-anorthosite massifs, continental sedimentary rocks, and minor alkalic mafic to intermediate volcanic rocks and characterized by vertical tectonic style. The anorogenic assemblage originated by underplating of the crust by a mantle hot spot or plume line. Iron oxide–rich ore deposits are associated with this anorogenic assemblage and are related to tensional faults and caldera collapse structures and alkaline intermediate volcanic rocks.

The iron oxide–rich deposits are composed of magnetite and (or) hematite, as well as economically important, major to accessory amounts of Ti, P, U, light rare-earth elements (REE), base and precious metals, Ba, and F. Quartz, fluorapatite, and amphibole are the primary gangue minerals.

Liquid immiscibility of an alkaline magma produces an iron-rich fraction that differentiates to form iron oxide–rich ore deposits. Assimilation of older banded iron formation by ascending magmas may contribute to the iron content of the magmas. The ability of liquid immiscibility to produce an iron oxide–rich phase depends on the composition (P and Ti) of the original magma, temperature and pressure, and the oxygen fugacity of the magma. The final composition of the iron oxide–rich deposit depends on (1) when and where in the crust the iron-rich fraction is released, (2) the oxygen fugacity, and (3) the degree of differentiation. Examples of various types of iron oxide–rich deposits include:

1. Lower crust—Fe-Ti-P deposits associated with anorthosites;
2. Subvolcanic—Fe±P±Cu-precious metals deposits in Missouri, U.S.A.; Olympic Dam, South Australia; and Kiruna, Sweden; and
3. Exhalative—Olympic Dam (Greenfield) Formation, South Australia; Missouri, U.S.A.; Kiruna, Sweden; and Bayan Obo Fe-light REE deposit, Inner Mongolia, People's Republic of China.

A very low grade metamorphic or hydrothermal event commonly followed thickening of the crust by this Precambrian anorogenic assemblage. After this period of cratonic stabilization, intrusion of carbonatites, kimberlites, or alkaline complexes into younger sedimentary rocks was followed by an abortive rifting event.

INTRODUCTION

The Middle Proterozoic was a period of transitional tectonism during which the Archean greenstone belt tectonic style slowly evolved into the present-day "Wilson Cycle" plate tectonic style. (Note: Middle Proterozoic will be used in this paper, for brevity, to include the time period 1.8–1.0 Ga.) The Middle Proterozoic is dominated, for the most part, by three major types of lithologic terranes:

1. Anorthosite massif-rapakivi granite/granulite facies terranes, such as the Adirondacks, New York; Labrador-Quebec, Canada; and Musgrave Block, South Australia.

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2. Extensive bimodal, felsic-dominated volcanic terranes and associated clastic-filled tensional basins, such as the Gawler Volcanics, South Australia; Norbotten County, northern Sweden; and Missouri, U.S.A.

3. Large, clastic-filled tensional sedimentary basins and minor, associated bimodal, felsic-dominated volcanic and volcaniclastic rocks such as the Wernecke Mountains, Yukon, Canada; McArthur River Basin, Northern Territory, Australia; Athabasca and Hornby Bay basins, Canada; and Belt and Purcell Supergroups, U.S.A. and Canada.

In all three types of terranes, plutonic and volcanic rocks, if present, were passively emplaced and represent a period of anorogenic activity. The dominant tectonic activity that formed the sedimentary basins was extensional. These terranes are at the margins of or within older shields that have had a complex history of deformation (Rogers and others, 1984). They define a period of global cratonic stabilization that is characterized by crustal thickening resulting from passive emplacement of igneous rocks, clastic sedimentation, and extensional tectonism. This cratonic stabilization is a transitional phase between the Archean and Phanerozoic plate tectonic styles (fig. 1).

Middle Proterozoic iron oxide–rich ore deposits characterize the first two terranes. Ore deposits characteristic of the third terrane can be divided into two groups: (1) Pb-Zn-Ag and Cu±Co mineral deposits associated with nearshore to deeper basin sedimentary and associated volcanic rocks, such as McArthur River and Mt. Isa, Australia, and Belt and Purcell Supergroups (Troy, Blackhawk and Sullivan mines), and (2) large unconformity-type uranium deposits associated with the Athabasca and Kimbolgie basins. This report addresses only the relationships between the first two terranes and their associated iron oxide–rich ore deposits.

Many authors (Gole and Klein, 1981; Meyer, 1981, 1985; Gross, 1983; Rundquist, 1984a, b) have noted that the large banded iron formations (bif) of both Lake Superior and Algoma types were not formed after about 1.8 Ga. The Algoma-type bif developed in deep water in tectonically active areas, whereas the Lake Superior–type

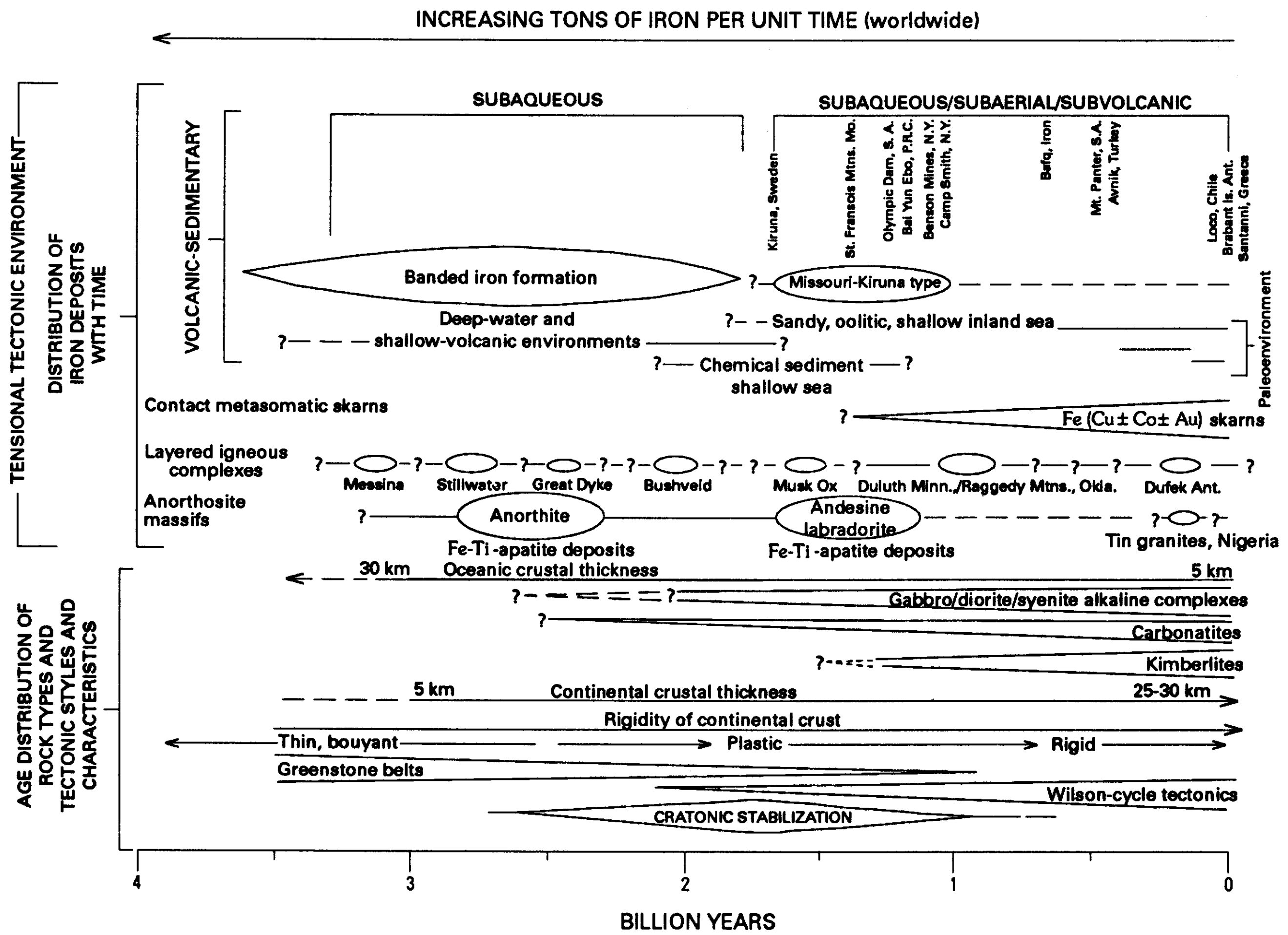


Figure 1. Tectonic evolution of iron oxide–rich ore deposits. This study and compiled from many sources.

bif developed in relatively shallow water on stable continental platforms and marginal cratonic basins (Kimberley, 1978; Gross, 1980, 1983). Both types of bif probably have hydrothermal exhalative origins (Cameron, 1983; Gross, 1983) and formed under tensional tectonic conditions. According to Meyer (1981, 1985) and Gross (1983), bif's are absent from the Middle Proterozoic but reappear in the Late Proterozoic and Phanerozoic, primarily as smaller Algoma-type, deep-water deposits.

Many other types of ore deposits, such as Archean porphyry copper and Archean gold (Homestake, Kalgoorlie, Witwatersrand), are absent in the geologic record from about 1.8 Ga to the Late Proterozoic (Hutchinson, 1981; Meyer, 1981, 1985; Rundquist, 1984a, b). The only exceptions are large Pb-Zn-Ag deposits such as McArthur River, Australia; unconformity uranium deposits; Cu-Ag±Co deposits such as Troy-Blackhawk, Montana; iron oxide–rich Kiruna and Missouri ore deposits (fig. 1); and iron oxide deposits in the Adirondacks of New York (McLelland, 1986). The Middle Proterozoic iron oxide–rich deposits contain 20–70 percent Fe, form single deposits or groups of deposits containing greater than 1 billion tons of ore, and represent a new family of ore deposits (Hauck and Kendall, 1984). In the iron ores, Cu, Au, U, Ag, light rare-earth elements (REE), P, and other trace elements can be economically or geochemically significant.

As will be described, these deposits originated as magmatic segregation deposits that evolved into hydrothermal exhalative iron oxide–rich ore deposits. They may be genetically related to the Fe-Ti phosphate deposits associated with anorthosite massifs.

Figure 2 shows the location of four of the largest known Middle Proterozoic iron oxide–rich ore districts. The following discussion concentrates on the geologic and tectonic setting of the host rocks and the ore deposits and the evolution of this family of deposits.

This report is a partially updated version of a report written in 1984 for UMETCO Minerals Company, a subsidiary of Union Carbide Corporation. It is the result of a collective effort by myself, Dr. W.J. Hinze, Dr. E.W. Kendall, and Dr. S.S. Adams, during 1978–1982, to develop a mineral exploration model for Olympic Dam-type ore deposits, principally for the United States; however, I take full responsibility for the contents and conclusions of this paper.

Acknowledgments.—Permission to publish this report has been graciously given by UMETCO Minerals Company. The report could not have been written without the support of Union Carbide's exploration management, in particular, D. Mathias, J.S. Hollingsworth, and E.W. Kendall. Useful discussions with other staff geologists during 1979–1982 are gratefully acknowledged. The translation of three Chinese papers on Bayan Obo was graciously provided by Cai Baochang

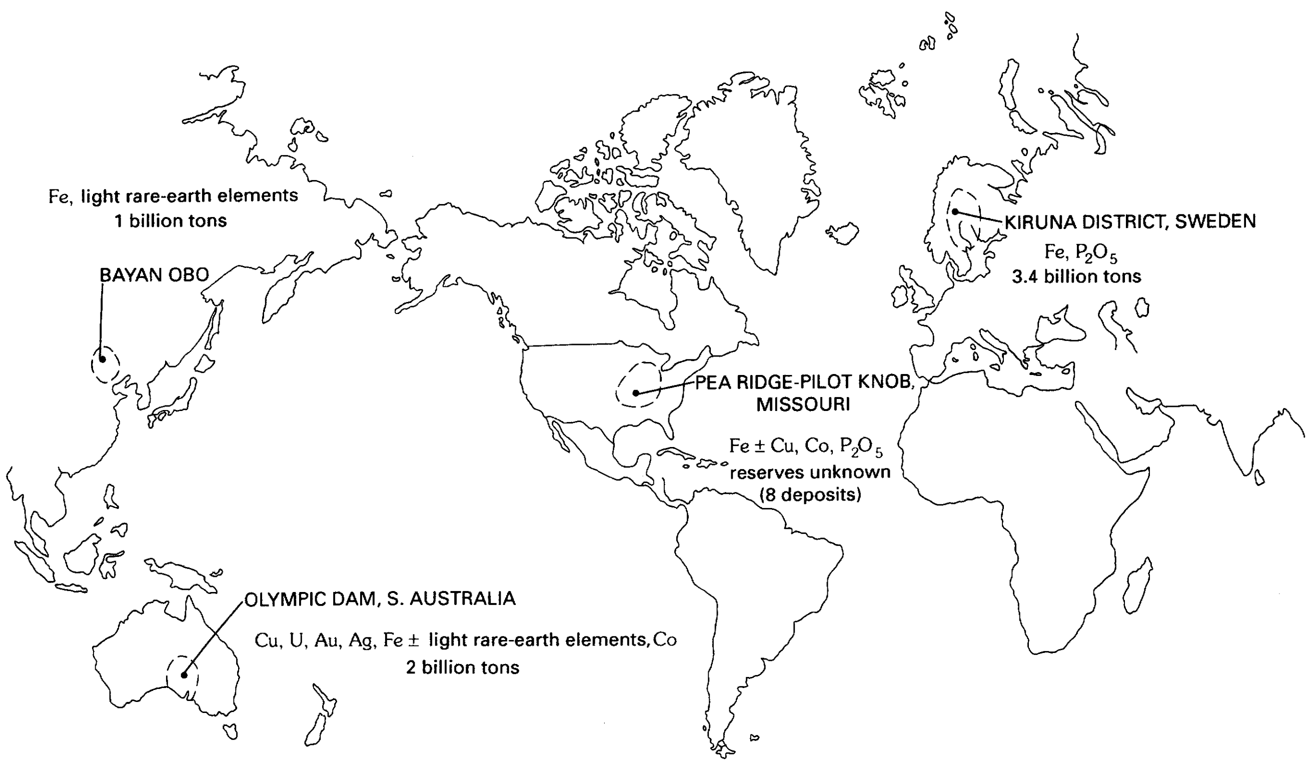


Figure 2. Middle Proterozoic iron oxide–rich districts known to contain about 1 billion tons of ore.

of The Geological Survey of Liaoning, Xinchengzi, Shenyang, Liaoning, People's Republic of China. His efforts have added to my knowledge of this important ore deposit. I thank Mr. J. Suthard for introducing me to Mr. Cai and his capabilities. Final appreciation goes to W.P. Pratt (USGS) for providing me the opportunity to present the ideas in this paper and to P.K. Sims (USGS) for his comments and review of the paper's contents.

GEOLOGY AND TECTONIC SETTING OF ORE DEPOSITS

South Australia

Regional Geology

The Olympic Dam Cu-Au-U-Fe deposit is within Middle Proterozoic rocks on the Stuart Shelf of the Gawler craton (fig. 3). The Gawler craton consists of a core of relics of Late Archean to Early Proterozoic (2.5–2.3 Ga) gneisses (fig. 3) (Cooper and others, 1976; Branch, 1978; Daly and others, 1979; Fanning and others, 1979, 1981; Daly, 1981) and peripheral and overlying Early Proterozoic (2.1–1.8 Ga) metasedimentary rocks including Lake Superior-type banded iron formation (fig. 4) (Miles, 1954; Furber and Cook, 1975; Parker, 1978; Lemon, 1979; Ramsay and Oliver, 1979). Similar metasedimentary rocks and iron formations are to the northwest in the Tarcoola region (figs. 3, 4) (Daly, Webb, and Whitehead, 1978; Daly, Benbow, and Blissett, 1979; Daly, 1981) and to the northeast in the Mount Woods Inlier (figs. 3, 4) (Flint and Benbow, 1977; Benbow and Flint, 1979). These Early Proterozoic metasedimentary rocks were deposited unconformably on the Late Archean basement and, particularly in the northeastern Eyre Peninsula, were affected by the Kimban orogeny (Parker and Lemon, 1982), an event that consisted mainly of amphibolite-facies metamorphism and deformation between about 1.82 and 1.58 Ga. Syn- and post-tectonic granites were emplaced during the orogeny.

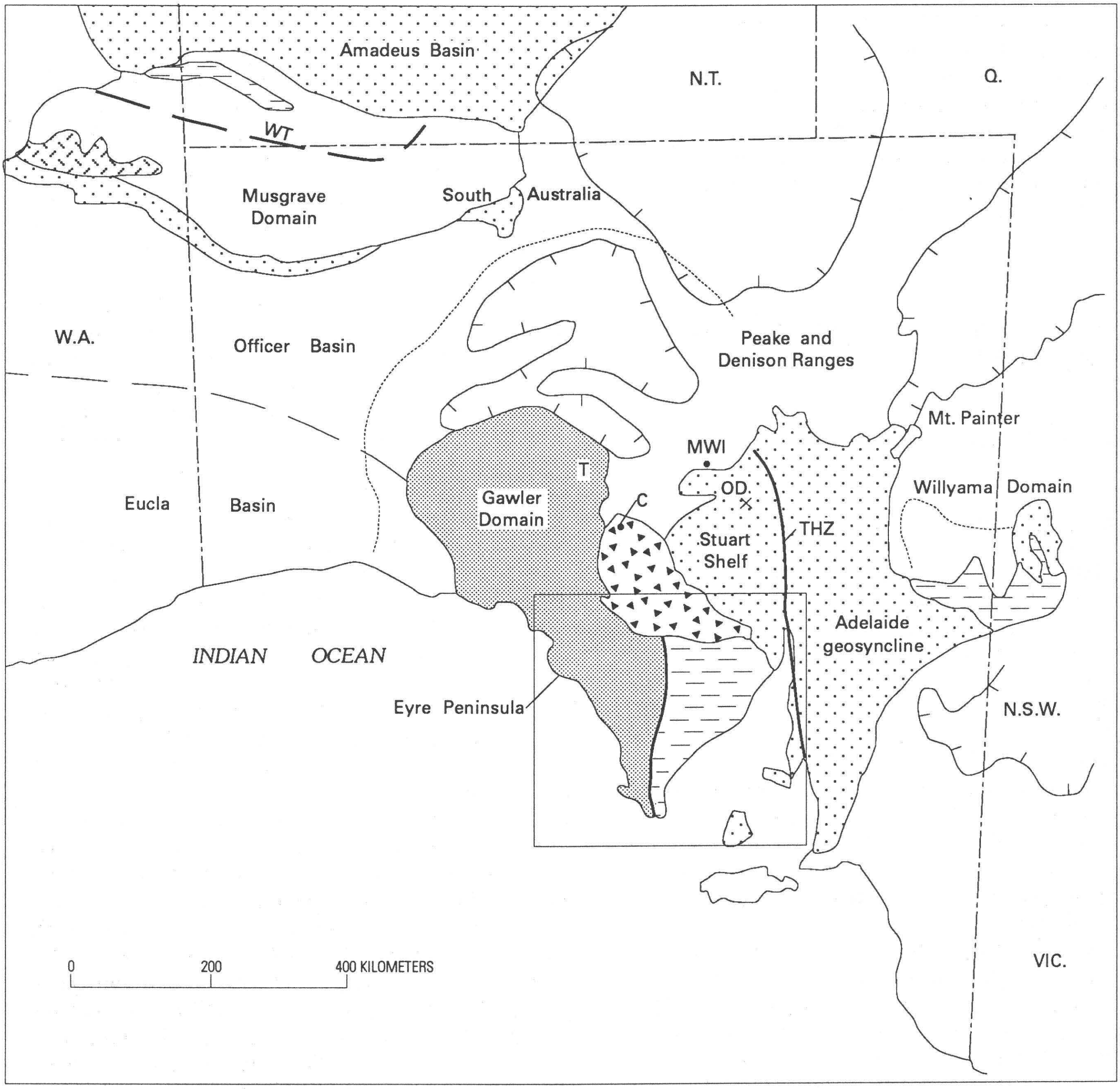
Prior to the last phase of deformation (~1.6 Ga) of the Kimban orogeny, clastic and volcaniclastic rocks of the Middle Proterozoic Moonabie Formation and bimodal rocks of the McGregor Volcanics were deposited in a local fault-bounded graben or grabens along the eastern side of the craton (fig. 4) (Crawford and Forbes, 1969; Nixon, 1975; Giles and others, 1979; Parker and Lemon, 1982). The McGregor Volcanics are dominantly felsic but contain minor basalt; andesite is absent. According to Giles and others (1979), the basalts evolved from melting of the mantle, whereas the dacites and rhyolites originated from melting of a dry, basic granulitic lower crustal source. Giles and others (1979) suggested that mantle diapirism was the heat source.

The Wandearah Metasiltstone overlies the Moonabie Formation and McGregor Volcanics (fig. 4); it consists of a volcaniclastic sandstone, underlain in turn by glauconitic (?) and dolomitic siltstone, pink feldspar tuff, sandstone, a basaltic lava flow about 10 m thick, and a dolomitic siltstone conglomerate (Blissett, 1977). The formation is overlain by an unaltered basaltic flow (Roopena? Volcanics) that is geochemically similar to the mafic rocks of the McGregor Volcanics and to the Gawler Range Volcanics (Giles and Teale, 1979a). Metasiltstone beneath this flow has been altered to graphitic phyllite, and at one place the metasiltstone has been brecciated and extensively altered to hematite (Mason and others, 1978).

The Corunna Conglomerate overlies the Wandearah Metasiltstone; it consists of continentally derived sedimentary rocks that were deposited in grabens (fig. 4) (Rutland and others, 1981). Flint and Parker (1981) correlated similar unmetamorphosed sedimentary rocks of the Blue Range Beds with the Corunna Conglomerate (fig. 3). These beds are primarily nonmarine sandstone and conglomerate equivalent to the basal part of the Corunna unit and are associated with faulting.

The Tarcoola Formation (fig. 3) (Daly, 1981) in the central part of the craton (figs. 3, 4) may be correlative with the Corunna Conglomerate. The lower part of the Tarcoola Formation consists of continentally derived quartz-rich sedimentary rocks. The basal conglomerate consists of earlier bif fragments in a matrix of a fine hematite and traces of copper carbonate (Daly, 1981). The basal sequence has been intruded and metamorphosed by a younger, Hiltaba-type postorogenic granite. The entire basal sequence is 200 m thick and was deposited in relatively shallow water. Overlying the basal sequence is 400 m of finely laminated green claystone. Daly (1981) believed the Tarcoola Formation is 1,511 million years old based on an age date from an interbedded tuffaceous rhyolite. Thus, these rocks are time equivalent with the Corunna Conglomerate and Gawler Range Volcanics and are therefore possibly correlative with the Olympic Dam Cu-U-Au-Ag-Fe deposit (fig. 4) (Webb and others, 1986; Fanning and others, 1988), especially because they are iron rich and copper mineralized.

The Gawler Range Volcanics were erupted at 1,516–1,631 Ma (Cooper and others, 1985), simultaneous with deposition of the Corunna Conglomerate. Recent U-Pb dating by Fanning and others (1988), gives an age of 1,592±2 Ma for the Gawler Range Volcanics. Rb-Sr ages of 1,500–1,530 Ma indicate later resetting of the Rb-Sr isotopic systems (Blissett and Radke, 1979;



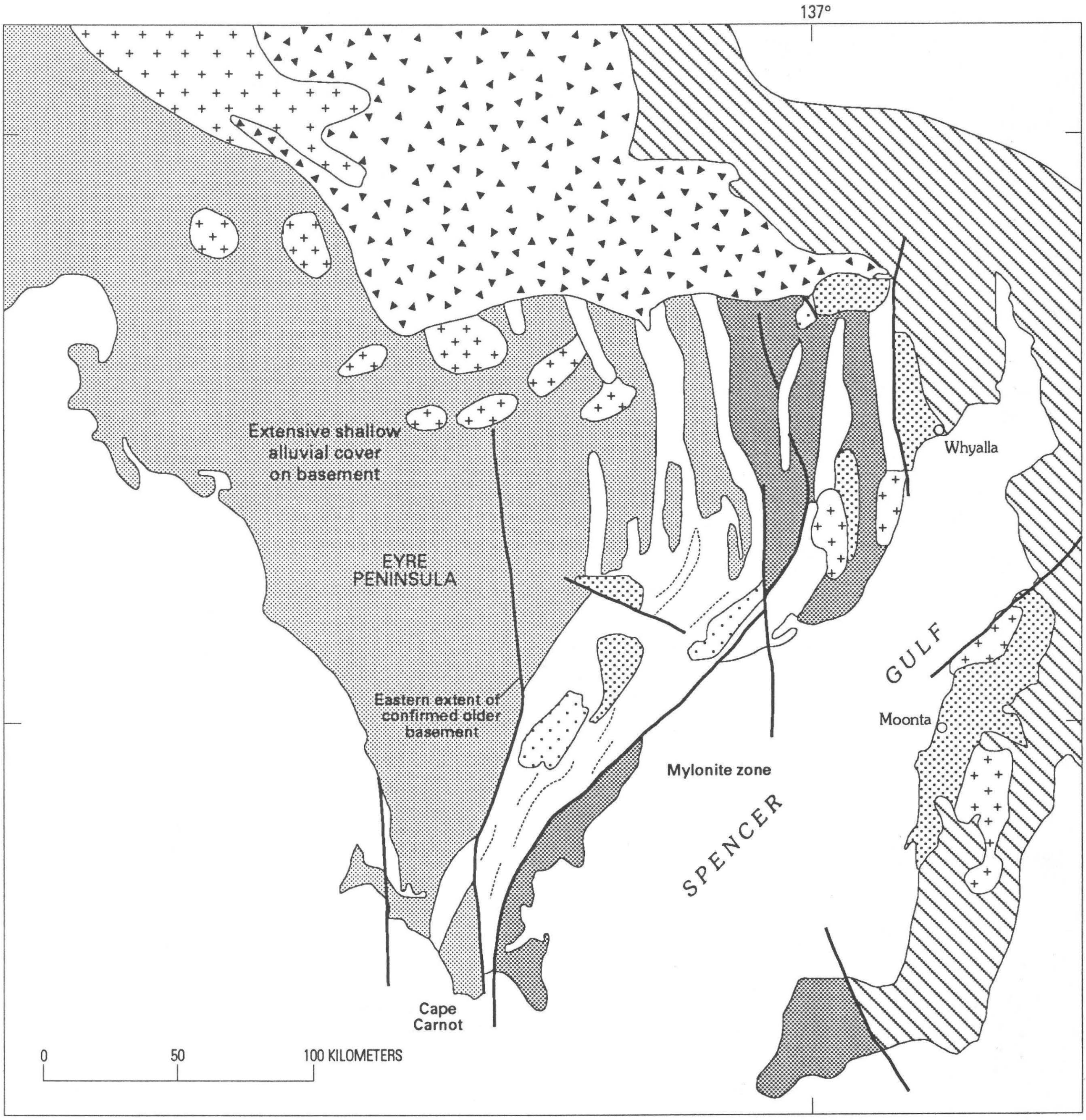
EXPLANATION

- Permian-Triassic basin
- Adelaidean rocks
- Tollu Volcanics
- Gawler Range Volcanics
- Middle and Early Proterozoic rocks
- Local Archean relics

Abbreviations

MWI	Mt. Woods inlier
C	Chandabooka caldera and Chitanilga Volcanic Complex region
OD	Olympic Dam
T	Tarcoola
THZ	Torrens hinge zone
WT	Woodroffe thrust fault
········	Craton margin

Figure 3 (above and facing page). Tectonic and generalized geologic maps of the Gawler craton, South Australia. Modified from Flint and Parker (1981) and Rutland and others (1981).



EXPLANATION

- Adelaidean and Paleozoic sedimentary rocks

Unconformity ca. 1,100 Ma

- Posttectonic granite
- Gawler Range Volcanics
- Middle Proterozoic sedimentary rocks (Blue Range Beds and Corunna Conglomerate)

Unconformity ca. 1,550 Ma

- Syntectonic granite
- Lincoln Complex
- Hutchison Group, BIF shown by dotted line

Unconformity ca. 2,100 Ma

- Sleaford Complex
- Major fault

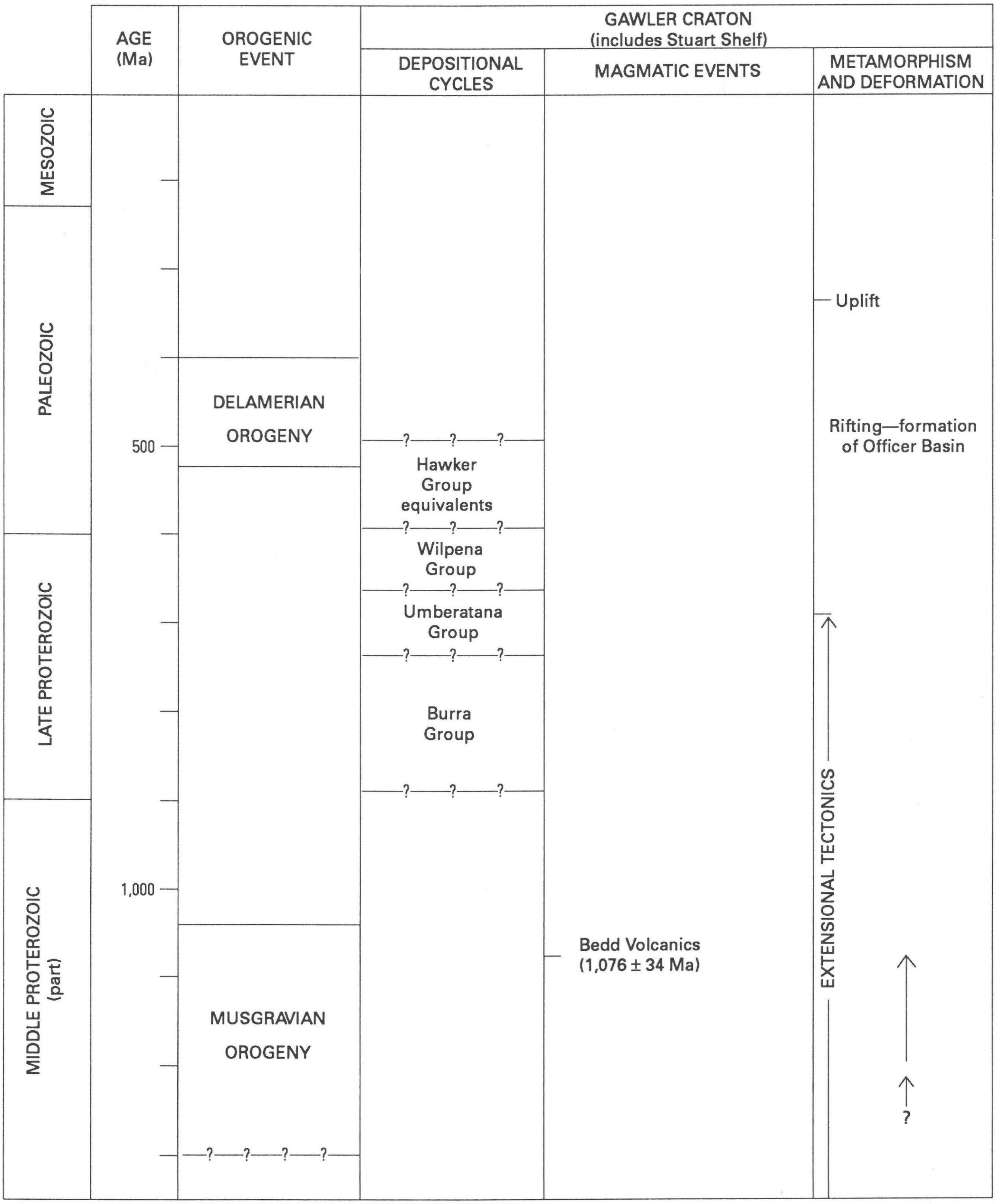
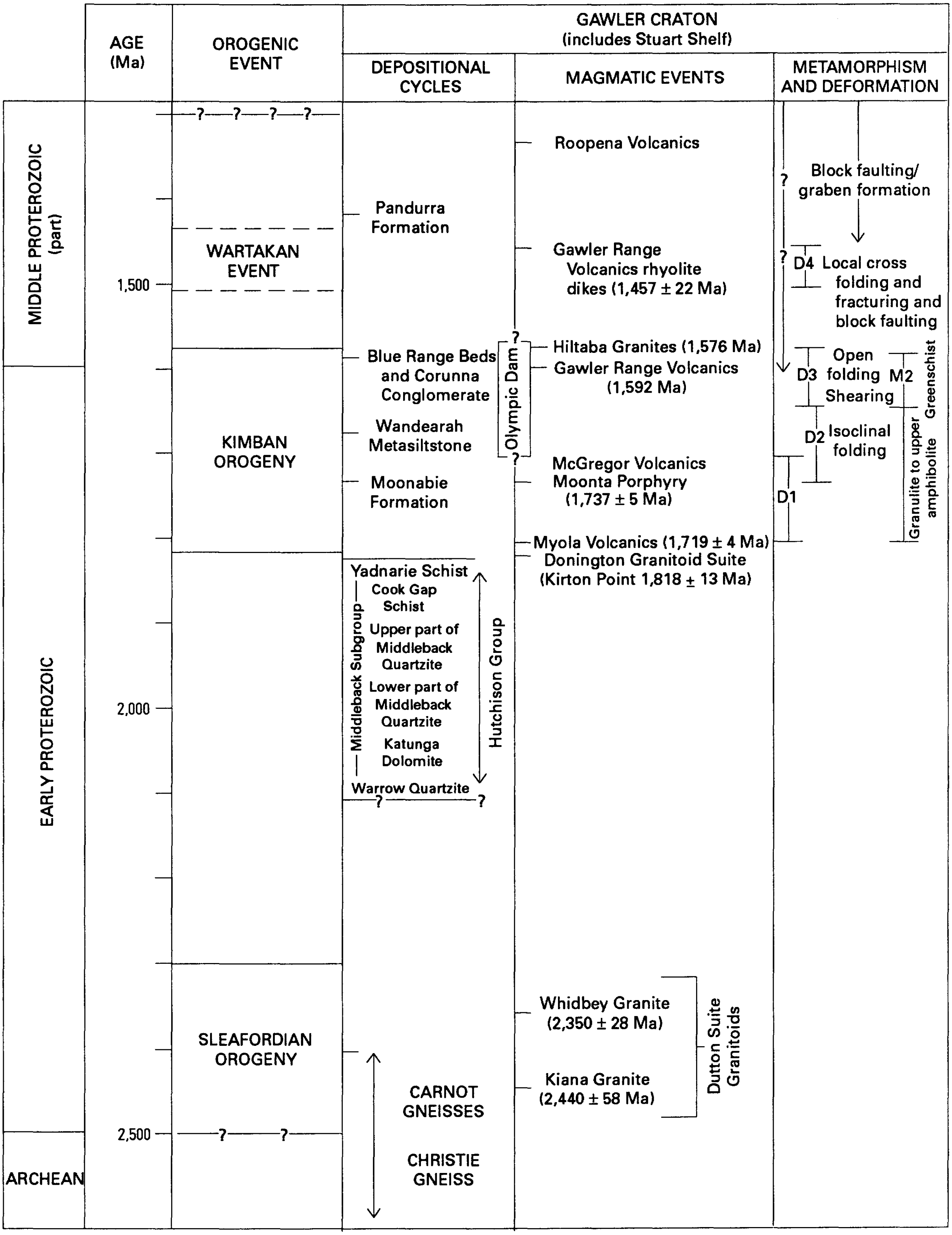


Figure 4 (above and facing page). Tectonic evolution of the Gawler craton, South Australia, including the Stuart Shelf and Mt. Woods Inlier. Modified from Compston and Arriens (1968), Thomson (1970), Harrington and others (1973), Cooper and others (1976), Flint and Benbow (1977), Giles (1977), Glen and others (1977), Webb and Thomson (1977), Mason and others (1978), Parker (1978), Webb and Horr (1978), Benbow and Flint (1979), Blissett and Radke (1979), Daly and others (1979), Fanning and others (1979, 1981, 1983, 1988), Giles and others (1979), Mortimer and others (1979), Webb (1979), Webb and Coats (1980), Daly (1981), Flint and Parker (1981), McWilliams (1981), Preiss and Forbes (1981), Rutland and others (1981), Parker and Lemon (1982), Cooper and others (1985), and Webb and others (1986).


AGE (Ma)
OROGENIC EVENT
GAWLER CRATON (includes Stuart Shelf)
DEPOSITIONAL CYCLES
MAGMATIC EVENTS
METAMORPHISM AND DEFORMATION
MIDDLE PROTEROZOIC (part)
EARLY PROTEROZOIC
ARCHEAN
1,500
2,000
2,500
WARTAKAN EVENT
KIMBAN OROGENY
SLEAFORDIAN OROGENY
Pandurra Formation
Blue Range Beds and Corunna Conglomerate
Wandearah Metasiltstone
Moonabie Formation
Yadnarie Schist
Cook Gap Schist
Upper part of Middleback Quartzite
Lower part of Middleback Quartzite
Katunga Dolomite
Warrow Quartzite
Middleback Subgroup
Hutchison Group
CARNOT GNEISSES
CHRISTIE GNEISS
Olympic Dam
Roopena Volcanics
Gawler Range Volcanics rhyolite dikes (1,457 ± 22 Ma)
Hiltaba Granites (1,576 Ma)
Gawler Range Volcanics (1,592 Ma)
McGregor Volcanics
Moonta Porphyry (1,737 ± 5 Ma)
Myola Volcanics (1,719 ± 4 Ma)
Donington Granitoid Suite (Kirton Point 1,818 ± 13 Ma)
Whidbey Granite (2,350 ± 28 Ma)
Kiana Granite (2,440 ± 58 Ma)
Dutton Suite Granitoids
Block faulting/ graben formation
D4 Local cross folding and fracturing and block faulting
D3 Open folding Shearing
M2
D2 Isoclinal folding
D1
Greenschist
Granulite to upper amphibolite

Webb, 1979; Fanning and others, 1988). The Gawler Range Volcanics are flat lying, cover an area of 25,000 km^2, and are primarily felsic (Branch, 1978; Blissett and Radke, 1979). Giles and Teale (1979b, 1981) reported geochemically similar volcanic rocks associated with some interbedded sedimentary rocks from the eastern side of the Adelaidean geosyncline southeast of the Mt. Painter Inlier. These volcanic rocks are geochemically similar to the Pepegoona Porphyry (1,309±129 Ma), which is exposed within the Mt. Painter Inlier (Coats and Blissett, 1971; Giles and Teale, 1979b). Thus, Gawler Range Volcanics or similar rocks probably occupy a much larger area than proposed by Branch (1978) and others.

The Gawler Range Volcanics consist of felsic-dominated flow rocks and ash-flow and air-fall tuffs (Crawford, 1963; Blissett, 1975; Turner, 1975; Giles, 1977, 1979, 1988; Branch, 1978; Blissett and Radke, 1979) that presumably originated from partial melting of a basic granulitic lower crustal source (Branch, 1978; Giles, 1979). Primitive potassic andesites and basalts associated with the Chandabooka Caldera of the Chitanilga Volcanic Complex (fig. 3) possibly originated from a relatively shallow (<50 km), large ion lithophile element-enriched zone of the mantle (Branch, 1978; Giles, 1979, 1988). Post-tectonic, S-type granites (Hiltaba; 1,576 Ma), which are probably comagmatic with the Gawler Range Volcanics (Blissett, 1975; Branch, 1978; Blissett and Radke, 1979; Cooper and others, 1985), intrude the Gawler Range Volcanics. Minor amounts of Cu, Au, Sn, and F and high radioactivity are associated with these granites (Crawford, 1963; Branch, 1978; Daly, 1981). Webb (1979) indicated that some mafic intrusions also were emplaced early in this postorogenic episode. Post-Hiltaba felsic and mafic dikes (1,457 Ma) define the end of this volcanic-plutonic episode (Branch, 1978; Daly, 1981; Parker and Lemon, 1982).

The Wartakan event from 1,500 to 1,425 Ma (fig. 4) was the last tectonic event on the Gawler craton (Thomson, 1970; Parker and Lemon, 1982; Fanning and others, 1988). It was minor in significance and may be related to emplacement of Hiltaba-type postorogenic granites; it was followed by emplacement of 1,457-million-year-old rhyolite dikes. At the end of this event cratonization of the Gawler craton was complete (Webb, 1979; Parker and Lemon, 1982). The last significant event on the stable craton after about 1.4 Ga and deposition of the basal units of the Adelaidean geosyncline at 1,076 Ma was emplacement of pre-Adelaidean dolerite (Compston and Arriens, 1968; Mason and others, 1978; Giles and Teale, 1979a; Webb, 1979; Roberts and Hudson, 1983).

The Torrens hinge zone (THZ) (fig. 3) separates the Gawler craton from the Adelaidean geosyncline on the east. It is a complex fault zone that separates the more deformed and thicker sedimentary rocks of the geosyncline from the thinner, relatively undeformed Middle Proterozoic and Adelaidean sedimentary rocks of the Stuart Shelf (Thomson, 1970; Preiss and Forbes, 1981; Rutland and others, 1981). At least during Burra Group sedimentation (fig. 4), the THZ was a zone of normal faulting (Lambert and others, 1987).

On the Stuart Shelf, the Pandurra Formation unconformably overlies the Roopena Volcanics. These red sandstones and arkoses were deposited in fluvial environments on downfaulted basement blocks and on the crystalline basement (Mason and others, 1978; Rutland and others, 1981). Equivalents to the Pandurra Formation have not yet been identified within the Adelaidean geosyncline. Rb-Sr dating of shale and siltstone from the Pandurra yield an age of 1,424±51 Ma, which may represent the age of deposition (Fanning and others, 1983); however, this age is in conflict with a 1,317±30-Ma age (Compston and others, 1966) for the underlying Roopena Volcanics. Because the Pandurra Formation unconformably overlies Olympic Dam-type Cu-U-Au mineralization at the Acropolis prospect west of Olympic Dam, the age of the formation places a minimum constraint on the age of this mineralization (Fanning and others, 1983).

Eruption of the continental Roopena Volcanics (eastern Gawler craton) and deposition of associated red metasiltstone occurred about 1,317 Ma. Because the Roopena Volcanics are unconformably overlain by the approximately 1.4-billion-year-old Pandurra Formation, there is either a discrepancy in the age dating or previously undocumented tectonism (thrusting?). Overlying the Roopena Volcanics is a hematitized felsic porphyry that petrographically resembles felsic volcanic rocks of the McGregor and Gawler Range Volcanics. Giles and Teale (1979a) suggested that the Roopena Volcanics formed in the same tectonic environment as the bimodal McGregor and Gawler Range Volcanics; however, the Roopena Volcanics unconformably overlie the Moonabie Formation and the rhyolite of the McGregor Volcanics (Mason and others, 1978). Therefore, the exact stratigraphic position of the Roopena Volcanics is still in question, but their geochemistry and petrography support an origin in a tectonic environment similar to that of the overlying and underlying volcanic rocks.

Unconformably overlying the Pandurra Formation are the mafic Beda Volcanics and associated arkosic sandstone and conglomerate of the Backy Point Beds (Mason and others, 1978). The Beda Volcanics differ geochemically from the Roopena Volcanics, the Roopena having higher Al_2O_3 , P_2O_5 , Ce, Y, and Zr (Giles and Teale, 1979a). The Beda Volcanics have been dated at 1,076±34 Ma (Webb and Horr, 1978; Webb and Coats, 1980). Giles and Teale (1979a) determined from geochemical studies that the Beda Volcanics and stratigraphically related Depot Creek Volcanics formed in a tensional tectonic environment in which there was active faulting; that is, the THZ. Basaltic doleritic dikes cut the Pandurra Formation and have been interpreted as roots of feeders to the Beda Volcanics (Mason and others, 1978). These dikes are associated with regional northwest-trending linear magnetic anomalies on the Stuart Shelf (Mason and others, 1978; Anderson, 1980). At Olympic Dam, an unaltered dolerite dike cuts the orebody but not the unconformably overlying Tregolana Shale of the Late Proterozoic Wilpena Group (Roberts and Hudson, 1983). If the 1.3-Ga age of Compston and others (1966) for the Roopena is correct, the age of the Olympic Dam deposit is constrained between approximately 1.3 and 1.1 Ga. On the other hand, if the 1.4-Ga age for the Pandurra Formation is correct, then 1.4 Ga is a minimum age for the deposit.

The remainder of the stratigraphic succession in the Adelaidean geosyncline includes a 10-km-thick sequence of Late Proterozoic and Cambrian sedimentary rocks. These strata have been intruded by alkaline rocks and were folded during the Delamerian orogeny, beginning about 500 Ma. This orogeny may have originated by the initiation of rifting in the Officer Basin (fig. 3), which separates the Musgrave block from the Gawler craton (McWilliams, 1981).

Preiss and Forbes (1981) suggested that Late Adelaidean sedimentation in the Adelaidean geosyncline and in the Amadeus Basin is sufficiently similar to warrant lithostratigraphic correlations between the two basins. If the paleomagnetic reconstruction for 1,400 Ma (fig. 5) and the correlation of Adelaidean sedimentary rocks between the two basins are correct, there should also be some correlation between the geology of the Musgrave block and the Gawler block. The Musgrave block consists primarily of 1.4–1.2-billion-year-old, quartzofeldspathic granulite-facies metamorphic rocks that have been intruded by 1.1–1.0-billion-year-old gabbros, dolerites, granites (some rhyolite), ultramafic complexes, and anorthosites (Nesbitt and Talbot, 1966; Arriens and Lambert, 1969; Gray and Oversby, 1972; Gray, 1977, 1978; Gray and Compston, 1978; Gray and Goode, 1981; Rutland, 1981). The precursors of the granulite-facies rocks were felsic (?) and mafic volcanic rocks, ferruginous quartzite or iron formation, and pelite and marble (Gray, 1977; Moore and Goode, 1978) that were deposited about 1.6 Ga (Arriens and Lambert, 1969; Gray, 1978; Gray and Compston, 1978). This supracrustal succession was subsequently deformed four or five times (Collerson and others, 1972). Foliated and nonfoliated sets of dolerite dikes cut this supracrustal assemblage (Collerson and others, 1972). Rutland (1981) suggested that an earlier metamorphic event at 1.8 Ga (Kimban orogeny?) also affected the Musgrave block.

If the paleomagnetic reconstruction of McWilliams (1981) (fig. 5) is correct, the supracrustal succession of the Musgrave block could be equivalent to the Moonabie Formation or Corunna Conglomerate or Tarcoola Formation. Thus, the mafic, ultramafic, and anorthositic intrusive rocks of the Musgrave block would be equivalent in age and would also be possible source rocks for the Beda Volcanics (see fig. 4). Note also that the paleomagnetic reconstruction (fig. 5) correlates the THZ with the Woodroffe thrust.

The last major intrusive event in South Australia was the emplacement, between the Early Permian and the Cenozoic, of one known carbonatite and several kimberlites (Moore, 1973; Ferguson, 1980; Jaques and others, 1985) into Adelaidean rocks in the southern part of the geocline.

The development of grabens containing primarily quartz-rich sedimentary rocks and bimodal volcanic suites from the time of the McGregor Volcanics through the early development of the Adelaidean geosyncline indicates that extensional tectonism was the dominant tectonic process during this period. Olympic Dam and other iron-rich deposits are therefore part of this tectonic process. Equivalent bimodal volcanic rocks (Giles and Teale, 1979b) on the east side of the Adelaidean geosyncline suggest a similar tectonic process.

Olympic Dam Cu-U-Au-Fe Deposit

According to Roberts and Hudson (1983), the Olympic Dam Cu-U-Au-Fe deposit is a stratabound sedimentary-hosted ore deposit within unmetamorphosed, mineralized, monomict and polymict, sedimentary breccias or rudites. Recent work (Einaudi and Oreskes, this volume) shows, however, that the deposit is primarily in an extensive breccia pipe (granite hosted) that has a minor subaqueous expression of iron formation, felsic volcanic rocks, conglomerate, breccia, and hematitic siltstone (Greenfield Formation of Roberts and Hudson, 1983). The deposit is expressed geophysically by coincident magnetic and gravity anomalies. The gravity anomaly is attributed to the orebody, whereas the magnetic anomaly is unexplained but considered probably to overlie a large magnetic body at depth.

The Olympic Dam deposit contains 2 billion metric tons of ore averaging 1.6 percent Cu, 0.64 kg/metric ton U_3O_8, 0.6 g/metric ton Au, 3.0 g/ metric ton Ag, and 15–25 percent iron oxide. The discordancy of the geologic units and the quantity of breccia suggest that multiple hydrothermal events and hydraulic brecciation formed the deposit (Lambert and others, 1987). The mineralogy of the deposit is suggestive of an alkaline igneous source. O'Driscoll (1985) showed that

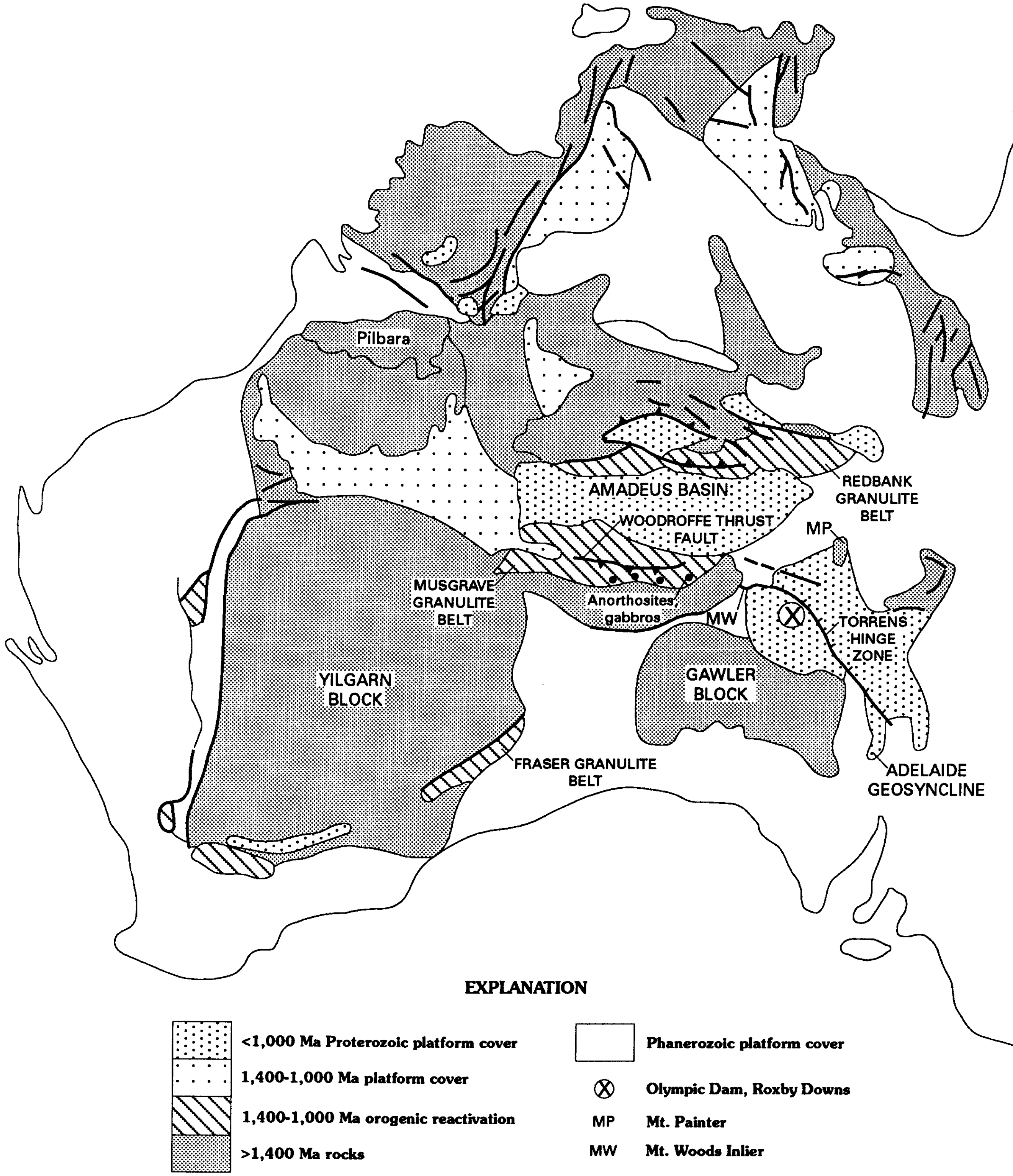


Figure 5. Paleomagnetic reconstruction of Australia during the Middle Proterozoic (1,400 Ma). Modified from McWilliams (1981) and Rutland (1981).

emplacement of the Olympic Dam deposit was related to regional lineaments and suggested that lineament mapping (gravity, magnetic, and so on) was an important tool for locating the deposit.

Two types of copper-mineralized rocks are present in the deposit (Roberts and Hudson, 1983): (1) stratabound bornite-chalcopyrite-pyrite and (2) lenses and crosscutting veins of chalcopyrite-bornite. Uranium, gold, and light REE are found with both types of mineralized rocks. Gangue minerals of the first ore type include hematite, quartz, sericite, and fluorite± carbonate±barite±rutile. Gangue minerals associated with the second type are hematite, fluorite, quartz, sericite, and chlorite. The sulfide minerals generally are disseminated in the matrix with hematite but are also present as massive sulfide clasts. The copper-mineralized rocks are vertically zoned from sulfur-rich, copper-poor minerals—pyrite-chalcopyrite—at the base of the deposit to sulfur-poor copper-rich minerals—bornite-chalcocite—at the top. There is no apparent lateral zonation.

Preliminary sulfur isotope data suggest that there is a magmatic sulfur component in the Olympic Dam mineralization (Lambert and others, 1987). The same type of alteration and mineralization at Mt. Gunson, south of Olympic Dam, exhibits similar isotope values associated with hydraulic fracturing (Lambert and others, 1987) that suggest the mineralization was not confined to a single area on the Gawler craton.

Hematite is the major matrix mineral but is also present as clasts or in veins. Zones of massive hematite and hematite-rich breccia have "sedimentary" textures indicative of simultaneous, rhythmic and sequential deposition. Pisoliths and ooliths of hematite-fluorite-sulfides, uranium-sulfides, siderite-hematite-sulfides, siderite, and siderite-chlorite also are within the stratabound mineralized rocks. Hematite rarely is present as pseudomorphs after magnetite or as inclusions within hematite. Magnetite is present as inclusions in siderite.

Uranium minerals include coffinite, uraninite, and minor brannerite. Both uraninite and coffinite occur with the copper-mineralized rocks and with sericite, hematite, fluorite, and chlorite. Free gold occurs with both varieties of copper-mineralized rocks. Light REE are found in bastnaesite and florencite and with copper sulfide minerals, hematite, sericite, fluorite, and uranium minerals in the matrix.

Hematite, sericite, and chlorite alteration accompanies mineralization. Silica and carbonate alteration are present locally. The diabase is the only unaltered rock within the deposit. There is no visible evidence of supergene enrichment or leaching.

Webb and others (1986) correlated the Wandearah Metasiltstone with the Greenfield Formation at Olympic Dam (Roberts and Hudson, 1983). Giles (1988), however, considered the igneous activity and rifting associated with the development of the Gawler Range Volcanics as probably directly responsible for the formation of Olympic Dam. Such an association places formation of Olympic Dam between 1,615 and 1,570 Ma. Fanning and others (1988) showed the Wandearah Metasiltstone as overlying the Moonabie Formation and McGregor Volcanics. U-Pb dates on the McGregor Volcanics (Fanning and others, 1988) of 1,737±5 Ma place a minimum age for the formation of Olympic Dam deposit.

Sweden

Regional Geology

Sweden is in the western part of the Baltic Shield, which is composed of Archean nuclei and surrounding Proterozoic rocks. In Sweden, Archean rocks crop out only in the area north and east of Kiruna. The Archean rocks and overlying deformed supracrustal metasedimentary and metavolcanic rocks extend southward from the outcrop area within the Karelian schist belt (Karelides) to the Skellefte province or district. The Skellefte province and areas to the south (Svecofennian complex or Svecofennides) consist of mafic to felsic metavolcanic rocks, metagraywacke, and abundant granitic rocks that formed 1.9–1.7 Ga (Patchett and others, 1987). The Svecofennides developed as a succession of island arcs, as the sites of subduction moved south and successive extinct arcs were accreted onto the Archean craton (Park, 1985). In the west, Archean and Early Proterozoic terranes are cut by a major belt of felsic volcanic and granitic rocks, including rapakivi granites that have Rb-Sr whole-rock ages of 1.6–1.7 Ga (Patchett and others, 1987).

Lower Proterozoic rocks in northern Sweden consist of the Greenstone Group (mafic flow rocks) and Kilavaara Quartzite Group (fig. 6). The Greenstone Group contains iron formations and associated limestone and graphitic sedimentary rocks. The mafic flow rocks are subalkaline in composition and oceanic in character. The iron formations are associated with carbonate rocks, phyllites, and mafic volcanic rocks (Lundberg, 1967; Lindroos, 1974). Witschard (1980) proposed that the Greenstone Group formed by incipient rifting during a regional tensional event.

The Early Proterozoic ended with the Svecokarelian orogeny, which included intrusion of prekinematic (1.98–1.84 Ga) and synkinematic (1.78 Ga) granitic rocks (Lundqvist, 1979; Moorman and others, 1982). According to Moorman and others (1982), regional amphibolite-facies metamorphism culminated about

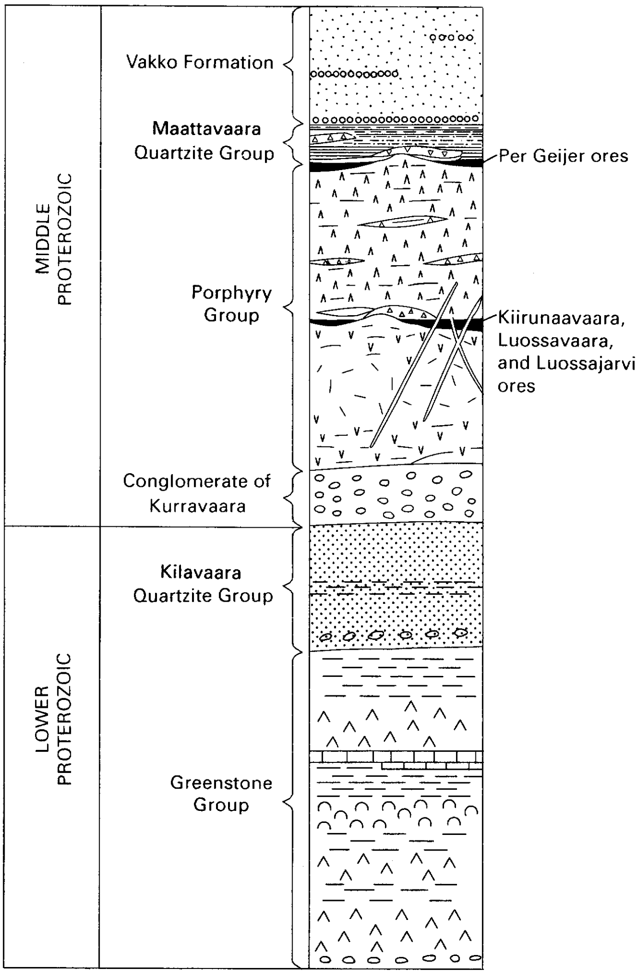


Figure 6. Generalized stratigraphy of Lower and Middle Proterozoic rocks, Kiruna area, northern Sweden. Modified from Parak (1975a) and Lundberg and Smellie (1979).

1.82 Ga in the Bergslagen region in south-central Sweden. The metamorphism generally was accompanied by folding.

The post-Svecokarelian Middle Proterozoic successions are anorogenic. In northern Sweden, a basal conglomerate and (or) felsic porphyries (1.9 Ga; Skiold and Cliff, 1984) of the Porphyry Group overlie Early Proterozoic Greenstone Group and associated rocks. The dominant felsic porphyries are subalkaline in composition, whereas the less prominent intermediate to mafic porphyries (for example, magnetite trachytes of Lundberg and Smellie, 1979) are alkaline (Lundberg and Smellie, 1979; Witschard, 1980; Frietsch, 1984). Conformably overlying the Porphyry Group are sandstones and related rocks of the Maattavaara Quartzite Group (known as the upper part of the Hauki Formation in the Kiruna area). The Middle Proterozoic iron oxide-phosphate and copper ores are within the Porphyry Group and the upper part of the Hauki Formation.

Potassic granites, syenites, and rapakivi granites that range in age from 1,660 to 1,300 million years old intrude the Middle Proterozoic volcanic rocks. Many of the rapakivi granite bodies (massifs) are associated closely with anorthosite, gabbro, and syenite (Kornfalt, 1976). Kornfalt proposed that intrusion of mantle-derived mafic rocks into the lower crust provided the heat source to produce the rapakivi granites; intrusion of the rapakivi massifs occurred in a relatively stable platform and was accompanied by intense block movements.

Metamorphism and folding postdate Middle Proterozoic anorogenic volcanism that Wilson and Akerblom (1982) relate to magmatic activity of an "adino-type" orogeny, especially from 1,750 to 1,500 Ma, and to tensional tectonism, particularly in northern Sweden, at 1,550 Ma. Recent U-Pb dating by Skiold and Cliff (1984) indicates that felsic rocks of the Porphyry Group are 1.9 billion years old; thus, the 1.5-Ga Rb-Sr age is the age of intrusion of the potassic granites and gabbros. Witschard (1980) stated that formation of the Porphyry Group of northern Sweden was related to tensional tectonism. The Middle Proterozoic granites are S-type granites, formed by partial melting of older crustal material, whereas granites in central and southern Sweden are more I-type suites, derived from mantle material (Wilson and Akerblom, 1982). Mafic dikes and continentally derived sedimentary rocks that formed about 1,300–1,200 Ma suggest continued uplift and extension.

Late Proterozoic deposition was followed by deformation and metamorphism (Sveconorwegian orogeny/Grenville?) related to continental collision about 1,050 Ma (Wilson and Akerblom, 1982). The last major tectonic event was formation of the Oslo graben during the Permian. Alkaline complexes, carbonatites, and kimberlites were intruded into the Archean and younger rocks between 1,700 and 281 Ma (Lundqvist, 1979).

Kiruna District

Types of Ores

The Kiruna district in northern Sweden contains 3.4 billion tons of iron oxide-apatite ore averaging 50–60 percent Fe and 0.5–5 percent P (Frietsch, 1980). The ore contains less than 1 percent Ti and generally less than 0.1 percent S and Mn (Grip, 1979). The main ore minerals are magnetite and hematite; the apatite is generally fluorapatite (Frietsch, 1974b). Other accessory minerals include actinolite-tremolite, diopside, pyrite, chalcopyrite, bornite, and calcite. The orebodies are elongate and tabular and generally conformable with the regional stratigraphy.

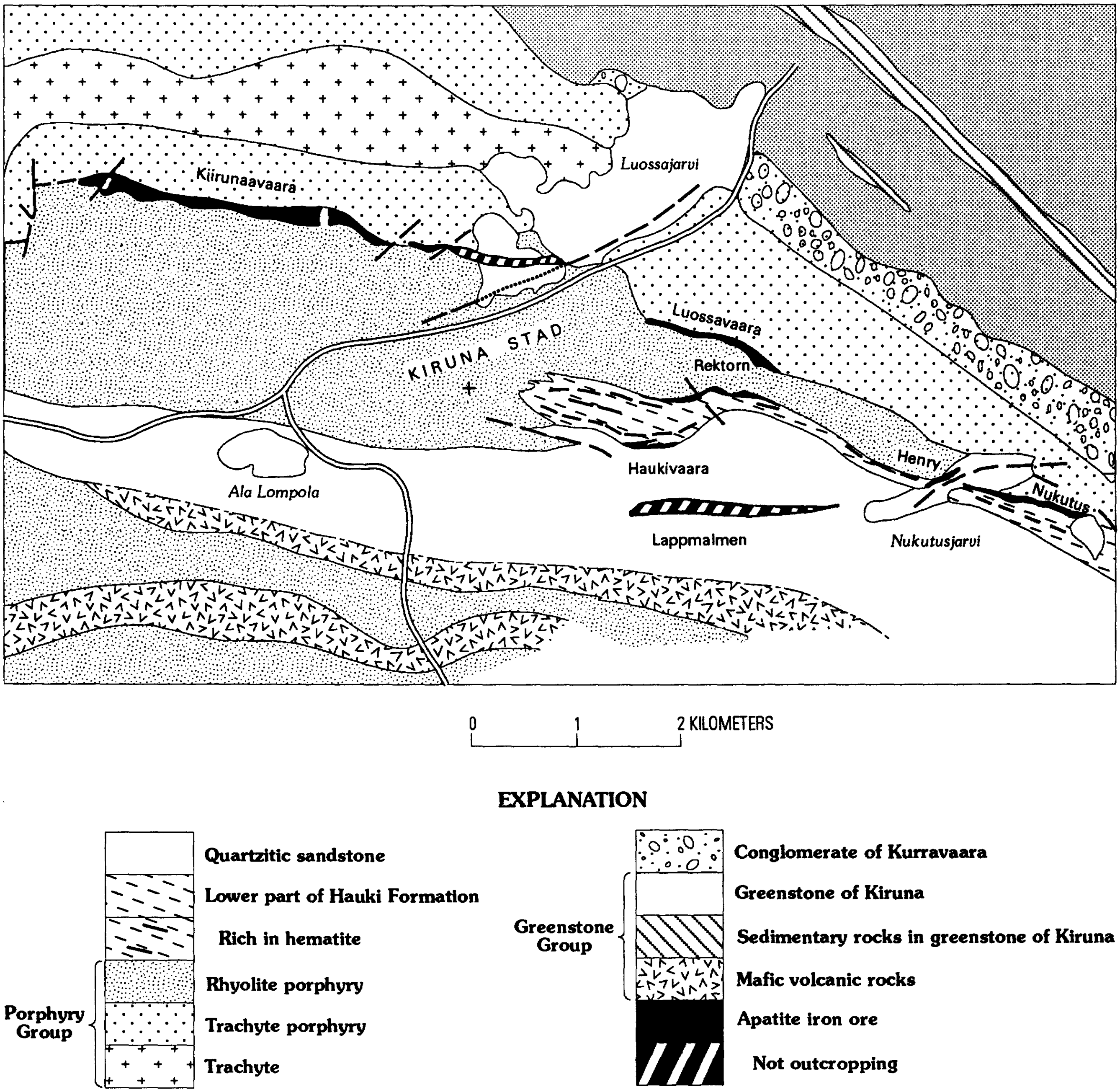


Figure 7. Geology of the Kiruna iron district. Map modified from Frietsch (1982); terminology adapted from Lundberg and Smellie (1979) and Lundqvist (1979).

The district contains three types of iron oxide-apatite orebodies (Geijer and Odman, 1974; Parak, 1975a, b; Frietsch, 1978).

1. *Kiruna-type* ores are primarily magnetite-apatite ores associated with minor hematite and actinolite. The irregular, elongate, disc-shaped orebodies contain varying amounts of red breccia in the hanging wall or footwall. Magnetite trachyte porphyry or trachyte porphyry is nearby or in the footwall. The Kiirunavaara (fig. 7) orebody is an example of this ore type.

2. *Per Geijer–type* ores are stratigraphically higher than Kiruna-type ores. They are characterized by hematite and apatite and associated minor magnetite, quartz, and calcite. The orebodies are tabular and massive and lie on rhyolite. They contain more phosphorus (2–5 percent) than those of the Kiruna type. Ore breccia is minor, but dikes or veins of hematite, hematite-apatite, or apatite are prominent in the footwall. As with wall

rocks of the Kiruna-type ores, the wall rocks have undergone silica and sericite alteration. The Rektorn and Henry deposits are examples of this type (fig. 7).

3. *Hauki–type* ores are generally massive to banded hematite and contain variable quantities of quartz, sericite, calcite, barite, and tourmaline. They are flat lying and are at the stratigraphically highest level in the lower part of the Hauki Formation.

Stratigraphy

In the Kiruna area, the oldest units are mafic volcanic rocks (2.2 Ga; Skiold, 1986), sedimentary rocks, and iron formations of the Early Proterozoic Greenstone Group. The conglomerate of Kurravaara unconformably overlies the Greenstone Group. It is a polymict conglomerate containing pebbles of magnetite trachyte porphyry, limestone, quartz, banded sedimentary rocks, jaspilite, and red felsite (Parak, 1975b).

Volcanic rocks of the 1.9-billion-year-old Porphyry Group overlie the conglomerate of Kurravaara. Trachyte, trachyte porphyry, and magnetite trachyte porphyry (syenite, syenite porphyry, and magnetite syenite porphyry of Parak, 1975b; trachyte terminology after Lundberg and Smellie, 1979) overlie the conglomerate and form the basal part of the Porphyry Group. Geijer and Odman (1974) interpreted these units as caldera fill. The lower contact with the conglomerate and the upper contact with the overlying rhyolite porphyry are generally sharp. At the Ekstromsberg deposit 30 km west-southwest of Kiruna, the magnetite trachyte porphyry and the trachyte porphyry are intercalated with the rhyolite porphyry and are elongate parallel with the orebodies (Frietsch, 1974a). The gray trachyte is composed of plagioclase phenocrysts and quartz-rich amygdules in a matrix of quartz and feldspar. Amygdules and aggregates of augite, actinolite, magnetite, sphene, apatite, biotite, and chlorite may also be present. Pyrite, chalcopyrite, epidote, and zircon are the main accessory minerals. Around the orebodies, the trachytes are magnetite trachytes and the amygdules are aggregates of magnetite and actinolite (Lundberg and Smellie, 1979). Lundberg and Smellie (1979) noted that at the Mertainen deposit, 30 km southeast of Kiruna, magnetite-rich globular structures are throughout the trachyte both adjacent to and some distance from the orebody. They interpreted these structures as indicating immiscible separation, aided by a high volatile content of an iron-rich melt from the trachyte, to form the orebodies at Painirova and Mertainen. The immiscible separation forms the footwall ore breccia and the orebody. Geochemically, the trachyte lavas originated in an alkaline source region.

At Painirova and elsewhere in the Kiruna District, the trachytic flow rocks are locally overlain by volcanic conglomerates, basalts, and tuffaceous sedimentary rocks (fig. 6) (Parak, 1975a, b; Lundberg and Smellie, 1979; Smellie, 1980). In places the volcanic conglomerates have a magnetite matrix. Geijer and Odman (1974) attributed these conglomerates to deposition in local stream channels.

Extensive subalkaline rhyolite porphyries form the next higher major unit and generally lie directly on the trachyte flow rocks. The rhyolite porphyries (quartz-bearing porphyry of Parak, 1975a, b; terminology after Lundberg and Smellie, 1979) have a micropoikilitic texture resulting from devitrification. The rhyolites probably originated as ignimbrites (Offerberg, 1967; Lundberg and Smellie, 1979) and consist of quartz, microcline, and plagioclase and accessory magnetite and apatite±zircon±fluorite±calcite±tourmaline (Parak, 1975b). Phenocrysts are perthite and rarely quartz. The porphyries are generally red. Beds of agglomerates, conglomerates, lenses of iron ore, and one known bed of anhydrite are within the rhyolite porphyries (Parak, 1975b).

The lower part of the Hauki Formation overlies the rhyolite porphyry in the Kiruna area. The basal unit of the Hauki forms the hanging wall of the Per Geijer ores and consists of feldspar spherulites in a matrix of quartz. Geijer and Odman (1974) considered the unit to be silicified obsidian that was affected by emplacement of the Per Geijer ores. Parak (1975a, b), on the other hand, believed the unit is clastic because it is crossbedded and contains thin lenses of hematite and magnetite. Parak (1975b) noted that this unit also contains patches of an unknown radioactive mineral.

Above the basal unit is the trachyte porphyry of the Hauki, a fine-grained gray rock consisting of albite, quartz, muscovite, sericite, biotite, hematite, and magnetite. Accessory minerals include orthite, zircon, tourmaline, apatite, pyrite, chalcopyrite, and bornite (Parak, 1975b). Overlying this unit are sericite quartzite and sericite schist that consist of quartz, sericite, hematite, and potassium feldspar. Accessory minerals are calcite, tourmaline, bornite, and ankerite, as well as rare titanite, fluorite, orthite, and zircon. The banded hematite ores are within the lower part of the Hauki Formation. These ores are always stratigraphically higher than the Per Geijer ores. Similar rock types are present in the Ekstromsberg region. The youngest unit in the Kiruna region consists of conformable quartz sandstones, graywackes, shales, and conglomerates of the Vakko Formation. Potassic granites and some gabbros were intruded into these sequences about 1,525 Ma. Some deformation and local metamorphism and hydrothermal activity (with scapolite) accompanied intrusion of the granites.

Origin of Ores

Frietsch (1970, 1974a, 1978, 1982, 1984) and Geijer and Odman (1974) believed that ores of the Kiruna region originated by magmatic differentiation and are contemporaneous with the enclosing volcanic rocks. Nystrom (1985) and Gilmour (1985) proposed that the iron ores have carbonatitic affinities. On the other hand, Parak (1973, 1975a, b, 1984, 1985) proposed a sedimentary-exhalative origin for the ores; chemical and mechanical sedimentation in a volcanic environment accounts for the textures observed within the ore deposits. Lundberg and Smellie (1979) and Smellie (1980) proposed that:

1. Iron-rich material was assimilated by ascending trachytic lavas.
2. Extreme magmatic differentiation and immiscibility coupled with a high volatile content produced the iron oxide-apatite ores.
3. The iron ores represent every variation of origin, from magmatic deep-seated intrusive to shallow-level intrusive to volcanic extrusive to volcanic sedimentary-exhalative.

Wright (1986) suggested that although the Per Geijer ores may be exhalative in origin, the Kiruna ores were extruded as subaerial volcanic lava flows. Furthermore, he stated (p. 193) that "There is no need to seek a common origin for all the iron ores in the Kiruna district." Frietsch (1984) suggested that the iron deposits are associated with extensive faults that have been repeatedly reactivated. He stated that the Kiruna iron ores are associated with alkaline magmatism and formed during rifting.

Other Ore Deposits of the Kiruna District

Other iron ore deposits in the Kiruna district contain significant base and precious metals. Some of the iron ores in the Nautanen region southeast of Kiruna contain significant copper. At Tjarrojakka, 50 km west-southwest of Kiruna, chalcopyrite, bornite, and magnetite are within tuffaceous zones in the wall rocks of the iron oxide-apatite deposit and within the iron deposit itself (Frietsch, 1980). Grip (1979) indicated that copper mineralization impregnates the ore breccia of the deposit and is accompanied by younger scapolite alteration. Copper deposits at the Tjarrojakka iron deposit probably are stratiform, and the ore reserves are 3.2 million tons at 0.4 percent Cu, or 13 million tons at 0.2 percent Cu (Parak, 1985). Both gold and silver are locally concentrated. At the Gruvberget magnetite-hematite-apatite deposit, 3 km west of Svappavaara (fig. 6), chalcopyrite and bornite, which were previously mined, are found with scapolite in the northern and central parts of the deposit (Grip, 1979). The country rock is an altered trachyte porphyry.

Finally, at Aitik, southeast of Kiruna, a disseminated Cu-Au-Ag deposit of 300 million tons contains an average of 0.4 percent Cu, 0.3 g/ton Au, and 5 g/ton Ag (Zweifel, 1976; Frietsch, 1980). The host rocks are metasedimentary and possibly equivalent to the conglomerate of Kurravaara. Ore minerals are chalcopyrite, pyrite, magnetite, and pyrrhotite, and gangue minerals are quartz, barite, calcite, and fluorite. The host rocks have been metasomatically altered to tourmaline, sericite, and scapolite (Zweifel, 1976; Frietsch, 1980).

Midcontinent Region, United States

Regional Geology

Proterozoic rocks of the Midcontinent region of the United States crop out in the Lake Superior area and in southeast Missouri. Proterozoic rocks between these two regions underlie a Paleozoic cover (Sims, 1985). Data on the basement rocks of the United States (fig. 8) are mostly derived from drill core and cuttings (Kisvarsanyi, 1980, 1981; Bickford, Sides, and Cullers, 1981; Van Schmus and Bickford, 1981; Anderson, 1983; Thomas and others, 1984; Sims, 1985; Bickford and others, 1986; Sims and Peterman, 1986).

Lake Superior Region

Archean rocks of the Superior province of the Canadian Shield extend into the Midcontinent region in Minnesota. The oldest Archean rocks (2.6–3.6 Ga) consist of high-grade gneisses in southern and central Minnesota and central Wisconsin (Van Schmus and Bickford, 1981). Younger Archean greenstone terranes (2.6–2.7 Ga) are north of this older Archean terrane and consist of subaqueous volcanic rocks, derivative sedimentary rocks, and granites (Sims and others, 1987). The Great Lakes tectonic zone (GLTZ) separates these two terranes in Minnesota. Over the GLTZ, Early Proterozoic sediments, including bif, collected in a large basin (Animikie) between about 1.9 and 2.1 Ga (Sims and others, 1987). According to Sims and others (1987), breakup of the North American continent occurred about 1.9 Ga. Following this breakup and the development of oceanic crust, a complex island arc system was formed 1.83–1.89 Ga. Collision of this island arc system with the Archean and Early Proterozoic rocks produced the Penokean orogeny in the western Great Lakes region and northwest Iowa.

In the Wisconsin part of the Lake Superior region, the Penokean orogeny was followed by extrusion of extensive subalkaline rhyolite and emplacement of subalkaline epizonal granites and minor tholeiitic mafic

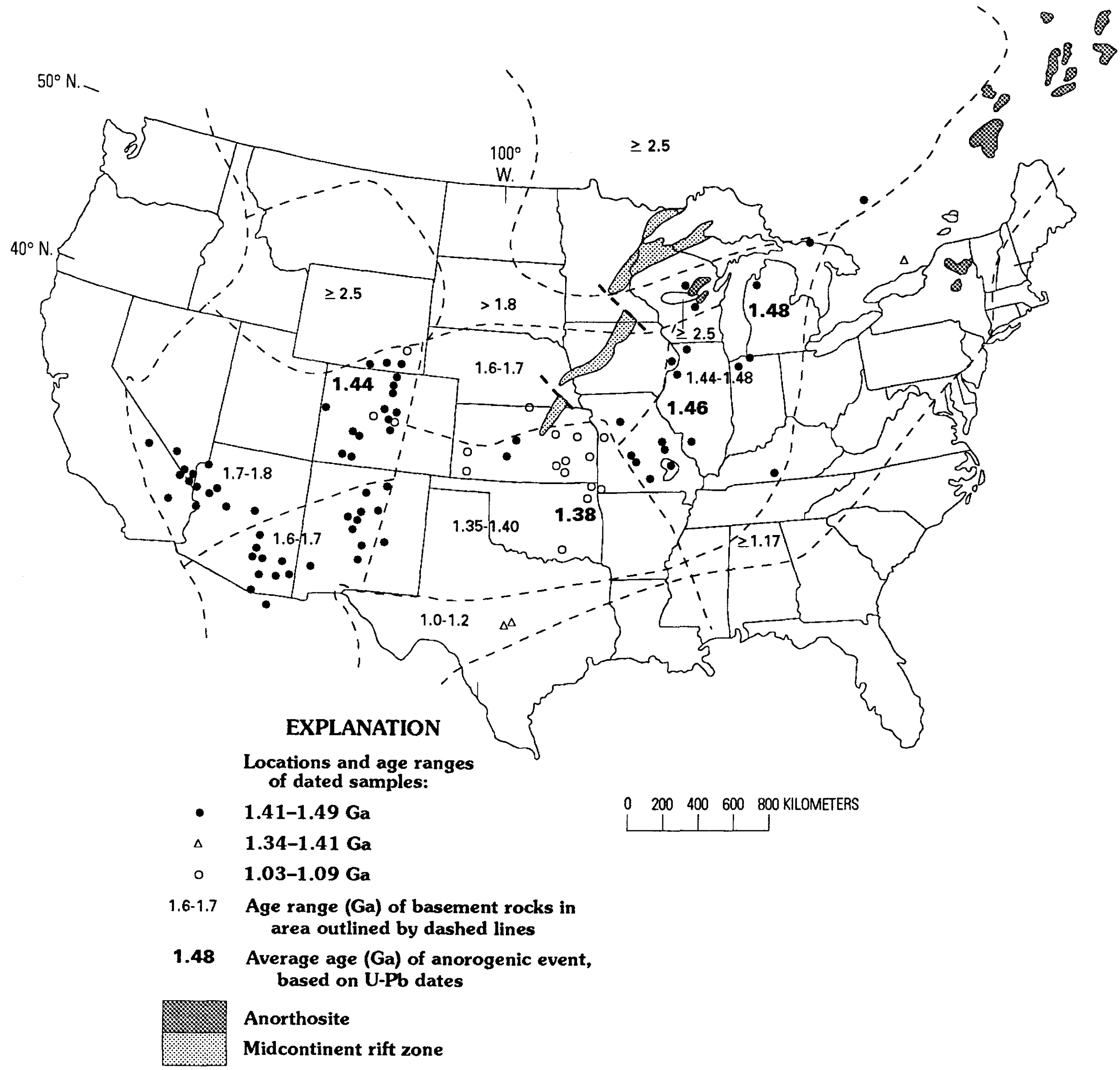


Figure 8. Distribution and age of basement rocks and anorogenic (rapakivi-type) granite-rhyolite complexes of the Midcontinent region of the United States. Modified from Anderson (1983), Hoppe and others (1983), and Thomas and others (1984).

rocks at 1.76 Ga; deposition of fluvial sandstones and minor marine carbonate rocks and shales (the Baraboo interval); mild deformation and resetting of Rb-Sr systems by reheating at 1.63 Ga; and intrusion of the Wolf River rapakivi granite and associated anorthosite at about 1.5 Ga. These suites are the oldest anorogenic rhyolite and granite terranes. Smith (1978, 1983) recognized four chemically and mineralogically distinct anorogenic suites in the 1,760-million-year-old terrane in south-central Wisconsin: (1) peraluminous ash-flow tuffs, (2) metaluminous quartz- and orthoclase-bearing rhyolites and granophyric granites, (3) low-SiO_2 , high-strontium, and REE-depleted granites and rhyolite dikes, and (4) tholeiitic basaltic to andesitic intrusive rocks. The intrusive and extrusive metaluminous and peraluminous rocks originated by fusion of different lower crustal intermediate sources. The third suite formed by partial melting of an intermediate crustal source. Heat for the partial melting may have been provided by ascending mantle-derived tholeiitic magmas of the last suite (Smith, 1983).

Conformable with and locally unconformable with the 1.76-billion-year-old anorogenic granite-rhyolite suite are metasedimentary rocks of the Baraboo interval (1.76–1.63 Ga) (Dalziel and Dott, 1970; Dott, 1983; Greenberg and Brown, 1983, 1984). Rocks of the Baraboo interval are dominantly fluvial sandstones that were deposited on a stable craton (Dott, 1983; Greenberg and Brown, 1984). The area of fluvial deposition eventually was transgressed by a marine succession of carbonate rocks, shales, and iron formations that developed on a stable continental shelf (Dott, 1983). The iron formations are found with ferruginous quartzite (chert?) and ferruginous slate (Greenberg and Brown, 1983). Although the chert-iron-formation-shale sequences are near the top of the Baraboo interval succession, in many cases they rest directly on older basement without intervening fluvial quartzites (Greenberg and Brown, 1984). Rocks of the Baraboo interval may have been deposited in isolated basins, estuaries, highlands, and minor volcanic centers within a larger epicratonic basin (Greenberg and Brown, 1984). The sequences may also be separated by major unconformities. About 1.63 Ga, there was a major resetting of Rb-Sr ages and minor deformation throughout the southern Lake Superior region (Van Schmus, Thurman, and Peterman, 1975; Sims and Peterman, 1980; Van Schmus and Bickford, 1981; Peterman and others, 1985).

At 1.5 Ga, the Wolf River batholith and associated anorthosite were emplaced in central Wisconsin (Van Schmus, Medaris, and Banks, 1975). The batholith may be cogenetic with the anorthosite and was derived by partial melting of an intermediate to tonalitic crustal source (Anderson and Cullers, 1978; Anderson, 1980). Granitic rocks of similar age, composition, and origin are found in the St. Francois Mountains in Missouri and throughout the Midcontinent area (fig. 8) (Bickford, Sides, and Cullers, 1981; Cullers and others, 1981; Anderson, 1983).

Missouri

In southeast Missouri anorogenic rhyolites and epizonal granites (1.5 Ga) crop out in the St. Francois Mountains. These exposures are a small part of much larger anorogenic granite-rhyolite terranes in the Midcontinent subsurface (Bickford, Sides, and Cullers, 1981; Denison, 1981; Van Schmus and Bickford, 1981; Anderson, 1983; Hoppe and others, 1983; Thomas and others, 1984; Bickford and others, 1986). Sm-Nd studies (Nelson and DePaolo, 1982, 1985) on basement rocks in the Midcontinent indicate that these Middle Proterozoic rocks were formed rapidly by partial melting of 1.9–1.7-billion-year-old crust.

The rocks of the St. Francois Mountains consist primarily of undeformed rhyolites and granites (see Kisvarsanyi, this volume). Minor alkaline andesites and trachytic dikes and flows are contemporaneous with, but unrelated to, the rhyolites (Kisvarsanyi, 1981; Kisvarsanyi and Kisvarsanyi, 1981; Sides and Bickford, 1981; this study). Other mafic volcanic rocks, the "Silver Mines Mafic Group," are subalkaline and have both calcalkaline and tholeiitic affinities (Sylvester, 1984). Diabase dikes and gabbro bodies were emplaced late in the regional magmatic history (Amos and Desborough, 1970; Sylvester, 1984). Several caldera complexes and associated ring plutons have been recognized both on the surface and in the subsurface (Kisvarsanyi, 1980, 1981; Bickford, Sides, and Cullers, 1981; Cullers and others, 1981; Sides and others, 1981). The epizonal granitic plutons are penecontemporaneous with the rhyolites and represent frozen magma chambers of calderas (Sides and others, 1981). Like the 1.5-billion-year-old Wolf River batholith in central Wisconsin, the epizonal granites, ring plutons, and associated rhyolitic rocks are all products of partial melting of an intermediate (quartz diorite or graywacke), lower crustal source (Cullers and others, 1981). Kisvarsanyi (1980) suggested that this magmatism resulted from intraplate hot-spot activity. The trachytic rocks, on the other hand, are related to tension fractures and caldera collapse structures (Kisvarsanyi and Kisvarsanyi, 1981; Kisvarsanyi, 1981; this study). Stromatolitic limestones, volcaniclastic rocks, hematitic iron formations, volcanic breccias, and minor volcanic rocks also are related to caldera collapse (Stinchcomb, 1976; Sides, 1981; Sides and others, 1981; this study).

As in Wisconsin, Sweden, and South Australia, Rb-Sr ages of the Missouri rhyolites and granites were reset owing to a loss of radiogenic strontium about 1.3–1.2 Ga (Bickford and Mose, 1975). Wenner and Taylor (1976) concluded from oxygen isotope studies that a regional hydrothermal event involving circulation of meteoric waters affected the St. Francois Mountain area. The event affected the felsic rocks and some of the mafic rocks; that is, it preceded emplacement of some mafic dikes but not others. The event was not related to emplacement of the felsic rocks but may be due to emplacement of Sylvester's (1984) "Skrainka Mafic Group."

Following the granite-rhyolite magmatism at 1.51–1.35 Ga, the Midcontinent rift system developed in the Midcontinent region (fig. 8). Continental tholeiitic mafic flow and intrusive rocks as well as minor felsic volcanic and sedimentary rocks compose the rift, an aborted structure. Southeast and east of the St. Francois Mountains is the late Precambrian and Paleozoic Reelfoot rift (Braile and others, 1982).

The youngest intrusive events in the region were emplacement of Paleozoic to Mesozoic carbonatitic and kimberlitic rocks (Zartman and others, 1967; Cannon and Mudrey, 1981; Basu and others, 1984).

Iron Deposits of Missouri

Field and drill-core studies indicate that the magnetite, magnetite-hematite, and hematite deposits intrude and are contemporaneous with the felsic volcanic sequence (fig. 9) (this study). Trachyte, magnetite trachyte, trachyandesite to basalt, and the iron mineralization originated from the same source (Kisvarsanyi, 1981; Kisvarsanyi and Kisvarsanyi, 1981; this study). Only four of the eight deposits (Pea Ridge, Pilot Knob subcrop, Pilot Knob outcrop, Iron Mountain) have been mined, although the other four (Bourbon, Kratz Springs, Boss-Bixby, and Camels Hump) have been drilled (Smith, 1968; Snyder, 1968; Kisvarsanyi, 1981). The deposits generally contain more than 40 percent Fe and may comprise several hundred million tons of ore. More than 200 million tons of ore are reported at the Bourbon deposit (Snyder, 1968), and more than 102 million tons of ore reserves are reported to remain at the Pea Ridge mine after 20 years of mining (Skillings, 1982). These figures suggest that the iron ore reserves for the district may be as great as 1 billion tons. Magnetite±hematite is the major ore mineral in all of the deposits. Interpretations of the geology of the iron deposits by various authors suggest three different origins for the iron mineralization within the district: (1) intrusive magmatic, (2) late-stage hydrothermal, and (3) exhalative/fumarolic.

The Boss-Bixby deposit is the only one of the eight deposits in which chalcopyrite and bornite are the main copper minerals (Smith, 1968). Accessory minerals include quartz, actinolite, calcite, fluorite, apatite, barite, pyrite, and chlorite. Brandom and others (1985) also found carrollite, cobaltian pyrite, and electrum and suggested that the deposit has many similarities to the Olympic Dam deposit on the basis of mineralogy, tectonic style, and paragenesis.

The Pea Ridge orebody extends below the Precambrian erosion surface vertically for less than 1 km and is 183 m wide (Emery, 1968). Trachytic rocks have been intersected in drill holes within 40 km of the mine and are projected, on the basis of other drill-hole and geophysical data, to form a broad half-arc around the deposit (Kisvarsanyi, 1981). It is not known whether trachytic rocks occur within the mine. As in some of the Kiruna orebodies, five distinct ore zones occur within the Pea Ridge orebody: (1) magnetite±apatite±monazite±fluorite±barite±calcite±quartz±pyrite, (2) specular hematite, (3) quartz-hematite ± fluorite ±barite ± molybdenite± tourmaline, (4) quartz-amphibole, and (5) hanging-wall

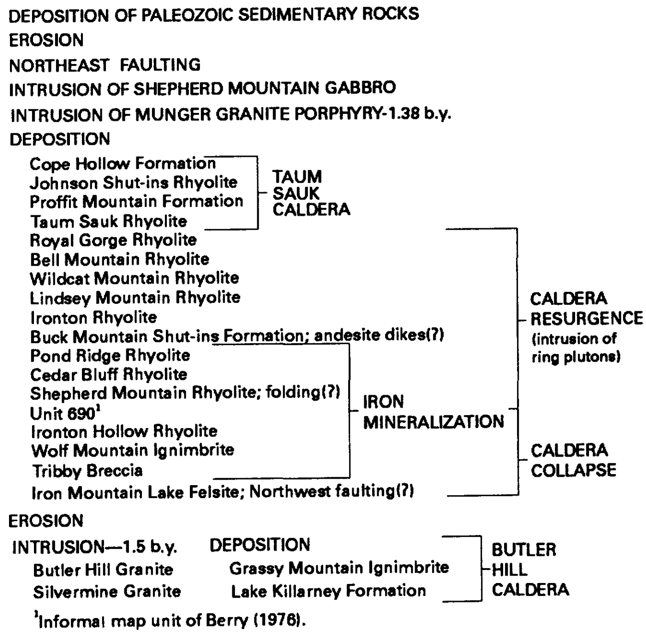


Figure 9. Geologic history of the Butler Hill-Taum Sauk caldera area, St. Francois Mountains, southeast Missouri. Compiled from Anderson (1976), Wracher (1976), Panno (1978), Sides (1981), Sides and others (1981), Panno and Hood (1983), and this study.

ore breccia (Emery, 1968). The deposit also contains cobaltian pyrite (this study).

According to Emery (1968), the orebody was forcefully injected into four volcanic porphyries. Zones 1, 4, and 5 probably originated by forceful injection of an iron-rich magma, whereas zones 2 and 3 formed during late-stage hydrothermal activity (Emery, 1968). The contact between the magnetite and hematite zones is gradational. Similarities between trace mineral contents of the magnetite and hematite-quartz zones suggest that the hematite zone evolved from the magnetite zone by differentiation and an increase in oxygen fugacity.

The Pilot Knob subcrop orebody is similar to the Pea Ridge orebody. It consists of two major types of ore: (1) coarse-grained, friable, massive magnetite±barite±calcite±quartz±orthoclase±molybdenite, and (2) fine-grained, dense, disseminated magnetite±hematite (Murrie, 1973; Pinchock, 1975; Wracher, 1976; Michel and Pasteris, 1981; Panno and Hood, 1983). The contact between the two types of ore is gradational.

The Pilot Knob outcrop orebody consists of finely banded silicic hematitic ores primarily composed of hematite, quartz, sericite, and minor barite (Anderson, 1976). The fine layering is a mixture of hematite-quartz-barite intermixed with waterlaid air-fall tuffs and breccia (Anderson, 1976). The deposit contains relict raindrop impressions, soft sediment deformation, salt casts, cross-bedding, and ripple marks. The ore contains as much as 3 percent Ba (this study).

The Pilot Knob subcrop ore deposit may have formed by forceful injection and replacement of the host rhyolitic ash flow by a magnetite-rich magma, followed by hematite-quartz-rich hydrothermal solution (Michel and Pasteris, 1981; Panno and Hood, 1983). Other studies (Anderson, 1976; this study) propose that the hematite was produced by fumarolic activity within a lacustrine environment. The sedimentary characteristics of the outcrop orebody suggest deposition in a lake in which the fluctuation of the water level was related to volcanism. The source of the hematite-quartz-barite solutions could be the same as that for the Pilot Knob subcrop orebody. The hot-spring origin for this deposit is further supported by interlayering of waterlaid tuffs, stromatolitic limestone, and fine-banded hematitic layers at the Cuthbertson Mountain manganese deposit south of Pilot Knob (Stinchcomb, 1976; this study). Other tuffaceous sedimentary rocks±hematite±copper±gold±silver are at Ketcherside Gap southwest of Cuthbertson Mountain (Stinchcomb, 1976; Sides, 1981; this study). Sides (1981) noted that all of these bedded volcaniclastic sedimentary rocks lie along or near proposed ring faults of a caldera.

One possible interpretation of these data is that the sedimentary rocks originated as intracaldera lake sediments. Figure 9 illustrates the stratigraphic constraints placed on the origin of the iron deposits. If the outcrop orebody originated from the same iron oxide–rich source, as proposed (Anderson, 1976; this study), then the iron deposits are related to caldera collapse. The Tribby Breccia and related units shown on figure 9 are interpreted as having originated during a caldera collapse phase (Sides and others, 1981). Kisvarsanyi and Kisvarsanyi (1981) observed that trachytic rocks and iron orebodies lie along or near centers of caldera ring complexes, and they suggested that emplacement of the orebodies was controlled by tension fractures associated with caldera collapse. Caldera resurgence probably sealed off the iron oxide source conduits. The Iron Mountain deposit also is associated with an andesite host rock and also is within the proposed ring dike of a caldera (Murphy and Ohle, 1968). Furthermore, hematitic alteration±fluorite as veins and zones around the iron oxide orebodies suggest that fluorite may have been a major volatile component.

Inner Mongolia, People's Republic of China

Regional Geology

The Bayan Obo hematite-light REE deposit is on the northern edge of the Sino-Korean craton, which is composed of Archean greenstones and related rocks (Zhang and others, 1984). Lower Proterozoic rocks consist of the Wutai Group, a sequence of schists, gneisses, marbles, and ferruginous sedimentary rocks that were involved about 2.0 Ga in the Wutai orogeny. Intracratonic troughs (aulacogens) formed between 1,950 and 800 Ma along the northern edge of the craton. Clastic rocks, magnesium-carbonate rocks, tillites, sedimentary iron formations, manganese-phosphorite beds, and local submarine volcanic rocks were deposited in the troughs. These units are overlain by schists, slates, phyllites, dolomites, and intermediate and felsic volcanic rocks of the Huto Group. The rocks were deformed by the Zhongtiao or Luliang orogeny about 1.8–1.7 Ga (Zhang and others, 1984), and cratonization is thought to have been completed about 1.5 Ga (He and others, 1983; Zhang and others, 1984). Kimberlites were emplaced into the Sino-Korean craton during the Paleozoic (Basu and others, 1984), Mesozoic, and Cenozoic (Zhang and Liu, 1983).

Bayan Obo Iron Deposits

The Bayan Obo iron oxide deposits consist of three hematite±magnetite orebodies totalling 1 billion tons of ore averaging 30–32 percent Fe, 1–6 percent light REE, 0.10 percent columbite, and 2 percent fluorite (Argall, 1980). The iron orebodies are lenses and pods within dolomitic limestone; the hanging wall is slate. Felsic volcanic rocks (Li, 1983)—subaqueous lavas and tuffs—of the Middle Proterozoic Bayan Obo Group are stratigraphically related to the dolomite. Hercynian granites and alkaline gabbros have been intruded into the Bayan Obo Group (Wang, 1980; Wang and Yang, 1983).

The relationship between the orebodies and these intrusive rocks is not understood. Argall (1980) found sodic amphiboles and pyroxenes in the ore and suggested that the ore deposits are contact metasomatic. Wei and Shangguan (1983), on the other hand, using oxygen isotope studies of the magnetite and hematite from different types of ore, suggested that the ores have a variety of origins, ranging from sedimentary-exhalative to contact metasomatic. Wang (1981) suggested that the light REE mineralization formed under oxidizing conditions. Based on stable isotopes and geochemistry, Bai and Yuan (1983) suggested that the orebodies formed from an igneous carbonatitic-submarine volcanic source. The data are meager but suggest conditions of formation analogous to Olympic Dam (Greenfield Formation), Hauki hematites, and Pilot Knob outcrop orebodies; that is, formation by exhalation of iron-rich fluids into a marine or lacustrine environment during a period of felsic volcanism.

Other Iron Oxide–Rich Ore Deposits

Other iron oxide–rich ore deposits that may belong to this class of ore deposits include the iron deposits of (1) the Adirondack Mountains and (2) the New Jersey–New York Highlands, and (3) the Tennant Creek iron-copper-gold deposits, Northern Territory, Australia.

Adirondacks, New York

McLelland (1986) concluded that anorthosite massifs and associated rocks of the Adirondacks represent a Middle Proterozoic anorogenic, bimodal caldera complex. Chemical trends of the anorthosite and felsic suites are similar to those of the Wolf River batholith of Wisconsin, the Ragunda Complex of Sweden, and the St. Francois Mountains of Missouri. McLelland (1986) also concluded that geochemical trends in the above areas are remarkably similar and further suggested that (1) the low-titanium iron deposits associated with the ash-flow tuffs and sediments, as for example, Benson mines (Crump and Beutner, 1968; Palmer, 1970; Sainey, 1973), were formed by exhalation of iron-rich fluids via hot springs and fumaroles, and (2) the iron deposits are remarkably similar to those in the St. Francois Mountains. The Adirondack low-titanium iron oxide deposits are anomalously high in Mn, Ba, P, and F (McLelland, 1985). Apatite is generally greater than 1 percent but can be as high as 5–10 percent. Uranium can be present with magnetite throughout the felsic sequence (magnetite pegmatites, pegmatites, granites, syenites, and so forth) and also in the exhalative deposits (Nutt, 1982). High-titanium iron deposits are also associated with the anorthosites, as for example at Sanford Lake, New York (Gross, 1968).

New Jersey–New York Highlands

The Precambrian geology of the New Jersey–New York Highlands is similar to that of the Adirondacks, as indicated by the rock types and high-grade metamorphism of the felsic volcanic (alaskites) and sedimentary rocks. Uranium, thorium, and REE are associated with the iron oxide deposits (Grauch, 1978; Kastelic, 1980; Baillieul and Indelicato, 1981; Gundersen, 1984), which have been studied by Offield (1967), Sims (1953, 1958), and Sims and Leonard (1952). Kastelic (1980), Grauch (1978), and Gundersen (1984) suggested that some of the iron oxide deposits are the distal facies of a subaqueous volcanogenic massive sulfide deposit. The enrichment of uranium, thorium, and REE in the iron oxide–rich deposits and the apparent presence of subaqueous conditions during their formation in the Late Proterozoic suggest similarity with iron oxide deposits of South Australia, Sweden, and Missouri.

Tennant Creek, Northern Territory, Australia

The copper-gold-bismuth-magnetite-hematite orebodies of the Tennant Creek district are in interbedded volcanic and sedimentary rocks of the early Middle Proterozoic (1,819–1,849 Ma) Warramunga Group (Crohn and Oldershaw, 1965; Black, 1984). The mineralization is believed to be contemporaneous with the main folding event (Black, 1984). The Warramunga Group consists mainly of shales, graywackes, and siltstones but also contains rhyolitic pyroclastic rocks and intrusive quartz-feldspar porphyries that are associated with the mineralization (Large, 1975; Black, 1984). Hematite- and magnetite-rich shales, siltstones, and iron formations are closely associated with the copper-gold-bismuth mineralization (Large, 1975). The magnetite-hematite mineralization is in lenticular, ellipsoidal, and pipelike bodies that crosscut sedimentary features (McNeil, 1966; Large, 1975). Although most studies indicate that the iron oxide–rich copper-gold-bismuth mineralization is epigenetic, the mineralization, regional geology, and host rocks could be interpreted as indicating a syngenetic iron-rich intrusive/exhalative system.

RAPAKIVI GRANITE-ANORTHOSITE MASSIFS

Rapakivi-type granites such as the Wolf River batholith in Wisconsin and the Butler Hill Granite in Missouri are widespread throughout the North American continent and were emplaced within the epizone (±5 km) (Anderson, 1983). At deeper crustal levels (5–13 km), anorthosite is present with the rapakivi granite (Bridgewater and Windley, 1973; Emslie, 1978; Morse, 1982), and at still deeper crustal levels (23–27 km), anorthosite is the main rock-forming unit (Morse, 1982). A direct relationship between anorthosite and rapakivi granite has been proposed for the Wolf River batholith of Wisconsin and the Ragunda massif in Sweden (Kornfalt, 1976; Anderson, 1983): emplacement of the anorthosite provided a heat source for the melting of the lower crust and, therefore, the generation of the rapakivi granite suite (see fig. 13). Anorthosites may be present at depth in the St. Francois Mountains but not yet exposed by erosion (Anderson, 1983). An indirect relationship between the two rock types has been shown in South Australia through paleomagnetic reconstruction (see fig. 5). Giles (1988), on the basis of petrochemical modeling of the Gawler Range Volcanics, suggested that these felsic volcanic rocks were generated under similar conditions and from a similar source area as other Middle Proterozoic anorogenic rapakivi granite suites.

Table 1. Major characteristics of Middle Proterozoic rapakivi granite-anorthosite massifs

[From Bridgewater and Windley (1973), Bridgewater and others (1974), Emslie (1978, 1985), Wiebe (1980), Frost and Lindsley (1981), Philpotts (1981, 1982a, b, 1984), Condie (1982), Morse (1982), Valley and O'Neil (1982), Anderson (1983), Flower (1984), and Taylor and others (1984)]

1. Passively emplaced in anorogenic terranes.

2. Occur within or at margins of Early Proterozoic terranes that have previously undergone a major orogenic event.

3. Preceded or accompanied by amphibolite- or granulite-facies metamorphism in the lower crust.

4. Associated with:
   a. Extensive subalkaline felsic volcanism.
   b. Coeval, local mafic to intermediate volcanic rocks from a mantle source; that is, alkaline volcanic rocks or intraplate continental tholeiite.
   c. Pre-existing zones of structural weakness.
   d. Graben formation, continental clastic sedimentation, and local marine transgressions.

5. Graben formation or caldera collapse structures accompany and postdate emplacement of rapakivi granite.

6. Anorthosite massifs, associated mafic rocks, and cogenetic rapakivi granite are intruded simultaneously or within 500 million years of each other.

7. Rapakivi granitic magmas are subalkalic to marginally peraluminous and are primary melts derived from fusion of the lower crust (27-36 km) by emplacement of anorthosite and related intrusive rocks or other related heat sources:
   a. These relatively dry granitic magmas are distinctively potassium and iron enriched and contain ubiquitous accessory fluorite.
   b. They are emplaced in the epizone.

8. Anorthosite differentiation produced three immiscible liquids:
   a. A silica- and alkali-rich liquid to form quartz mangerite.
   b. An iron-rich melt to form ferrodiorite (jotunite).
   c. Initially dry anorthositic magma.

9. Ferrodiorite magma differentiates to form another, even more iron-rich liquid that produces magnetite-ilmenite-apatite ore deposits. Immiscibility is controlled by the phosphorus or titanium content of the melt or by pressure (depth).

10. Anorthosite and related intrusive rocks, for example, ferrosyenite, can be intruded to depths of less than or equal to 10 km; that is, into the zone of meteoric water.

11. Anorthosite massif-rapakivi granite terranes are related to a mantle plume line possibly associated with an abortive or incipient rifting event or with mafic magma ponding.

Table 1 summarizes the primary characteristics of these rapakivi granite-anorthosite massif terranes. Of primary interest are the relationships between (1) extensive felsic volcanism and the rapakivi granites, (2) rapakivi granites and anorthosite massifs, and (3) iron oxide-titanium-phosphorus deposits associated with anorthosite massifs and volcanic– and volcanic-sedimentary–hosted iron oxide deposits. The last relationship may be important to the origin of iron oxide deposits. Trachytic rocks associated with the subvolcanic– and volcanic-sedimentary–hosted iron oxide deposits are alkaline (see fig. 10) and therefore could be related to the anorthosites or to comagmatic, mantle-derived mafic rocks. This relationship is important because it suggests a genetic link between the origin of the anorthosite-related iron oxide-apatite deposits and the subvolcanic– and volcanic-sedimentary–hosted iron oxide deposits. If, for example, as Valley and O'Neil (1982) and Frost and Lindsley (1981) have indicated, anorthosites and comagmatic mafic rocks can be emplaced at shallow depths (<10 km), then an iron oxide source would be available for the development of subvolcanic– volcanic–volcanic-sedimentary–hosted iron oxide ore deposits.

GEOCHEMISTRY

Rock Geochemistry

Whole-rock and trace element geochemistry can be used to determine the origin (mantle or partial melts of lower crust) of intrusive and extrusive igneous rocks. The geology of each area discussed previously is made up of anorogenic, coeval, bimodal volcanic and intrusive rocks and minor intercalated sedimentary rocks. Subalkaline felsic volcanic and intrusive rocks of a lower crustal source are the dominant rock types. Interlayered with and intrusive into the subalkaline felsic volcanic rocks are subvolcanic to volcanic, alkaline mafic to intermediate trachytic rocks derived from a mantle source. Figure 10 illustrates the bimodal nature of these rock suites (alkaline trachytic rocks and subalkaline felsic rocks) for the Midcontinent (Wisconsin and Missouri), South Australia, Sweden, and the People's Republic of China. Recently, Giles (1988) presented new data for the Gawler Range Volcanics that exhibit similar geochemical results and conclusions (separate mantle and crustal sources for the mafic and felsic rocks, respectively).

The quantity of mafic to intermediate alkaline rocks in these regions is minor. Bickford, Horrower, and others (1981) estimated that this rock suite makes up less than 10 percent of the rocks in the buried Precambrian basement, and this is certainly the case in the St. Francois Mountains of Missouri and in South Australia. In Sweden, on the other hand, magnetite trachytes and trachytes probably make up more than 5 percent of the total rock and possibly as much as 30–40 percent. This generalization is difficult to apply at Bayan Obo.

All of these terranes have been subjected to a postanorogenic, low-grade metamorphic or hydrothermal event that has caused mobility of some elements, especially strontium and rubidium. Therefore, zirconium data were obtained from the literature and by analysis (this report) for rocks of both chemical suites from Missouri and South Australia. A plot of SiO_2 versus Zr/TiO_2 (fig. 11) shows the dual nature of these suites; thus, the post-anorogenic event probably was not sufficiently strong enough to affect the less mobile elements.

Petrochemical modeling by Giles (1988), using geochemical data for the Gawler Range Volcanics, indicates that (1) a refractory sialic residue of mafic-intermediate composition is a realistic source for the Gawler Range Volcanics, (2) low strontium isotope ratios for the volcanic rocks and postorogenic granites (Webb and others, 1986) are consistent with a lower crustal refractory sialic residue source, and (3) the mafic volcanic rock geochemical data indicate a primary mantle source, based on enriched light REE, Sr, Rb, Zr, and Pb

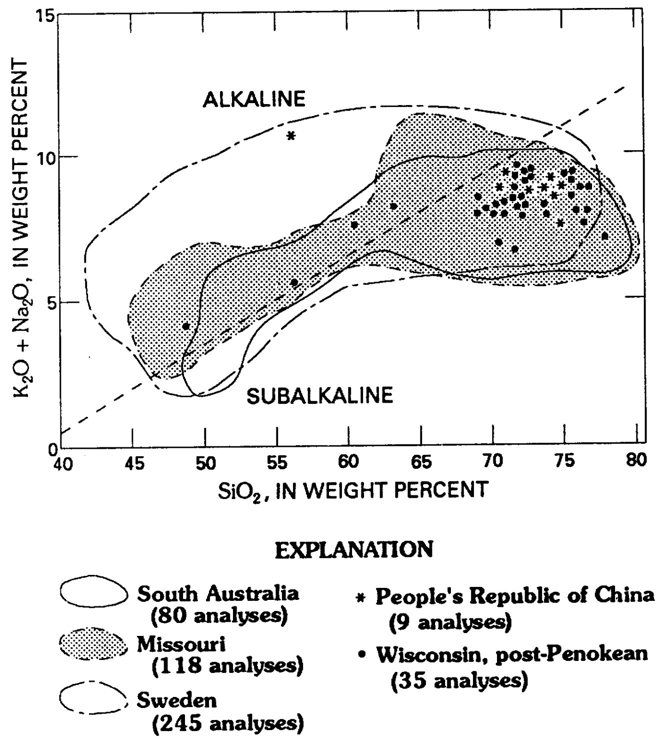


Figure 10. SiO_2 versus K_2O+Na_2O diagram of Middle Proterozoic anorogenic volcanic-plutonic complexes. Data for trachytic rocks from Missouri and Sweden are in the alkaline field; data for the extensive felsic volcanic rock suites in each area are in the subalkaline field. Data from Missouri, Sweden, and the People's Republic of China are both regional and local (associated with the iron oxide deposits) in origin. From numerous sources.

contents. Furthermore, modeling by Cullers and others (1981) indicates partial melting of an intermediate lower crustal source for the origin of the felsic volcanic and intrusive rocks in Missouri. The Middle Proterozoic anorogenic rapakivi granite suite has a "common geochemical fingerprint" of analogous high $Fe_2O_3^t$, TiO_2 , K_2O, REE, Zr, Nb, Y, Rb, and Ba contents as compared to Cenozoic calcalkaline volcanic rocks (Giles, 1988). It also has relatively low Al_2O_3, CaO, and Sr contents as compared with Cenozoic calcalkaline rocks having similar SiO_2 contents. Giles (1988) concluded that similar conditions and source regions were necessary for the generation of the felsic magmas.

Mineral Chemistry

The chemical composition of the various major and minor mineral phases in anorthositic and Missouri-Kiruna–type iron oxide deposits indicates a possible

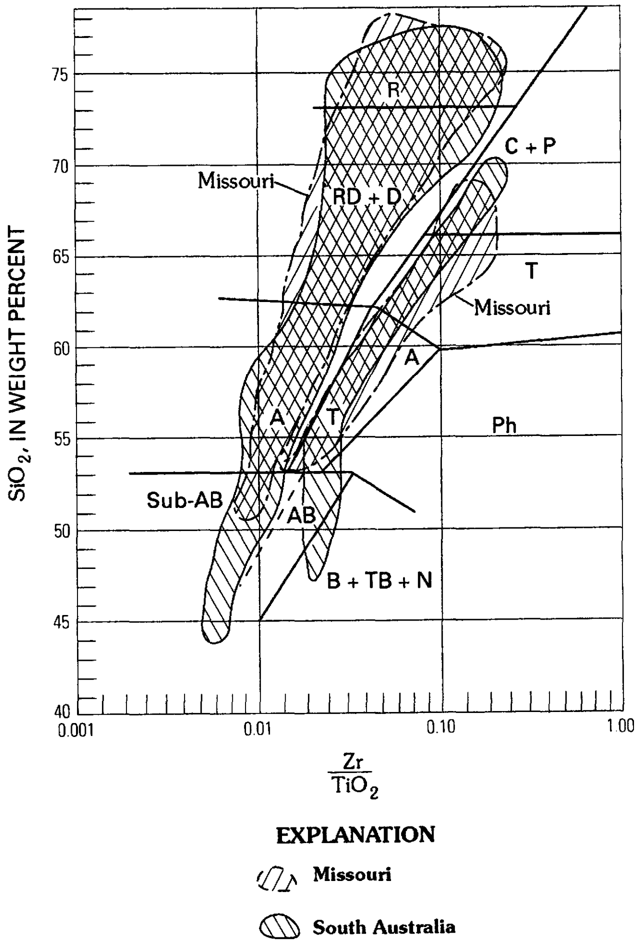


Figure 11. SiO_2 versus Zr/TiO_2 diagram of Middle Proterozoic anorogenic complexes in Missouri and South Australia. Fields: sub-AB, subalkaline basalt; AB, alkali basalt, trachybasalt; B+TB+N, basanite, trachybasanite, nephelinite; A, andesite; RD+D, rhyodacite, dacite; R, rhyolite; Ph, phonolite; T, trachyte; C+P, comendite and pantellerite. From Floyd and Winchester (1978), Giles and Teale (1979a, b, 1981), and this study.

genetic link between the two types of ores. Trace element contents (Ti, V, Cr) of magnetite and hematite have been used to distinguish different genetic types of iron-titanium oxide–apatite deposits (Kisvarsanyi and Proctor, 1967; Frietsch, 1970, 1982; Loberg and Horndahl, 1983). Loberg and Horndahl (1983) proposed two types of iron deposits—orthomagmatic/exhalative and sedimentary bif. The first type can be subdivided into titaniferous (associated with gabbros and anorthosites) and nontitaniferous (Kiruna and Missouri). The orthomagmatic/exhalative group may indicate that a direct relationship exists between intrusive and exhalative iron±apatite deposits formed from the residual solutions of a magnetite magma (Smellie, 1980; Loberg and Horndahl, 1983). Loberg and Horndahl (1983) and Frietsch (1970) also showed that the trace elements in the iron deposits of the older Greenstone Group in Sweden are similar to those in the Kiruna iron oxide-apatite deposits. Some pre-existing iron-rich material may have been assimilated, or the deposits may have had a similar source or origin.

Fluorapatite is a rare to minor component of both anorthositic- and Missouri-Kiruna–type iron oxide deposits. Frietsch (1974b) showed that apatite associated with the Kiruna deposits is fluorapatite. Fleischer (1983) determined, on the basis of REE contents of apatite from different rock-forming environments, that the Kiruna-type ores had an intrusive-magmatic origin. Kolker (1982) noted that the Kiruna ores differ from anorthosite-related iron-titanium oxide–apatite ores in both composition and proportions of iron-titanium oxides and fluorapatite, but that the F:Cl ratio and REE composition of the fluorapatite in the two ore types are similar. Both types of apatites are also enriched in the light REE. Thus, Kolker (1982, p. 1156) stated "Assuming a common magmatic origin, a fundamental difference in the deposits may be attributed to the depth of emplacement***."

Kolker (1982) and Philpotts (1967) found a 2:1 ratio of iron-titanium oxides to fluorapatite in iron-titanium oxide–apatite deposits associated with anorthosites. Kolker further noted that this ratio varies in the Kiruna ores because of the local variation in the amount of fluorapatite. In a study of trace elements in iron-titanium oxides in mafic and anorthositic rocks, Lister (1966) found that the titanium content decreases with progressive differentiation of a magma. If, as Kolker (1982) believes, the difference between the iron-titanium oxide–apatite ores of anorthosites and iron oxide–apatite ores of Kiruna is only depth of emplacement, then the variability of the iron-titanium oxide/apatite ratio and the lack of titanium in the iron oxides could be the result of differentiation of an iron-rich magma.

DISCUSSION

Most iron-titanium oxide–fluorapatite deposits are associated with anorthosite massifs (Philpotts, 1967, 1981). Philpotts proposed, based on field and experimental data, that as crystallization of an anorthositic magma proceeds the residual liquid becomes enriched in silica, alkali elements, and iron. At some point the residual magma encounters a liquid immiscibility field and splits into two fractions—a silica- and alkali-rich liquid and an iron-rich liquid. The silica-rich liquid crystallizes to form the quartz mangerite suite associated with anorthosites. The iron-rich fraction forms the ferrodiorites and iron-titanium oxide–fluorapatite deposits associated with anorthosites.

Feiss and others (1983) proposed that the Cranberry iron oxide deposits in western North Carolina formed in a similar manner. The deposits are REE enriched (Ussler, 1980) and consist of magnetite and clinopyroxene and minor apatite; however, because there are no known anorthosites in this area, they proposed that the iron oxide deposits originated from a ferrodioritic magma formed by liquid immiscibility from the crystallizing Bakersville Gabbro. Continued fractionation of the ferrodioritic magma then produced the Cranberry iron deposits.

Philpotts (1982a, b) showed that liquid immiscibility can occur in subalkaline (calcalkaline, tholeiitic) and alkaline magmas. Because trachytic rocks associated with Middle Proterozoic iron oxide–rich ore deposits are alkaline in composition, anorthositic magmas or mantle-derived alkaline gabbroic magmas are possible sources for these deposits. Van Marcke de Lummen (1985) also suggested that iron-titanium deposits can form through liquid immiscibility in a subalkaline (calcalkaline) magma. Therefore, the data of both Philpotts and Kolker suggest that the extensive, subalkaline felsic volcanic rocks in these provinces could also be a possible source of the metals in these deposits, given the right physicochemical conditions.

The time at which liquid immiscibility occurs depends on the P_2O_5 and TiO_2 contents of the fractionating melt and the oxygen fugacity of the melt. Experimental studies on mafic and felsic melts show that the liquid immiscibility gap expands—that is, extends the pressure range and lowers the temperature—with the addition of significant amounts of P_2O_5 and TiO_2 (Visser and Koster van Groos, 1979). Ryerson and Hess (1980) showed that the addition of phosphorus to a silicate melt will produce a silica-rich and a ferrobasaltic liquid. When liquid immiscibility occurs, phosphorus is strongly partitioned into the iron-rich fraction together with high-charge density cations—Ti, REE, Ta, Ca, Cr, Mn, Zr, Mg, Sr, and Ba (Ryerson and Hess, 1980; Watson, 1976; Naslund, 1983; Philpotts, 1984). Based on a study of iron-titanium oxide–fluorapatite deposits, Kolker (1982) suggested that sulfur is also partitioned to the iron-rich magma when immiscibility occurs. The partitioning of these elements to the iron-rich fraction would account for the presence of these elements in Middle Proterozoic iron oxide–rich ore deposits. Similarly, for the same reasons, base and precious metals and uranium, which are also high-charge density cations, would be partitioned to the iron-rich fraction. When an iron-rich magma enriched in these elements begins to crystallize (for example, apatite and ilmenite), specific elements would be concentrated further in the residual liquid together with silica. This late-stage liquid may be similar in composition to the quartz-hematite zones observed in the Missouri subsurface iron oxide deposits and to the exhalative iron oxide deposits such as Pilot Knob outcrop and Olympic Dam (Greenfield Formation).

In a study of the effect of oxygen fugacity on liquid immiscibility in iron-bearing melts, Naslund (1983) stated that increasing oxygen fugacity increases the liquid immiscibility field. He proposed that the Kiruna iron ores formed by liquid-liquid exsolution from iron-rich melts under high oxygen fugacity and indicated that such high conditions in these magmas could develop through (1) reaction with oxidized wall rocks, (2) loss of hydrogen, or (3) absorption of ground water equilibrated with oxidized wall rocks or the atmosphere. A fourth possibility is the assimilation of previously existing iron oxide–rich ore deposits; that is, Early Proterozoic bif. This possibility has been suggested for the Kiruna deposits by Lundberg and Smellie (1979), Loberg and Horndahl (1983), and Smellie (1980). Assimilation of iron oxide–rich phases would tend to increase the iron content of the ascending magma. Once the magma reached the meteoric water zone, absorption of oxygenated ground water would further increase the oxygen fugacity of the magma. Valley and O'Neil (1982) and Frost and Lindsley (1981) showed that anorthosites and associated ferrodiorites and ferrosyenites can be emplaced at depths of less than 10 km; therefore, an iron-rich magma could be close to the surface in the zone of meteoric water and in an area of high fO_2. A physicochemical study of restraints and conditions necessary for assimilation of lower crustal materials by ultramafic mantle-derived magmas led Sparks (1986) to suggest that high-temperature primitive magmas can assimilate substantial quantities (~50 percent) of lower crustal rock. He also suggested that anorthosites may be hybrids of lower crustal and primitive mantle melts; assimilation of bif or other iron oxide–rich rocks in the lower crust would alter the chemistry of ascending magmas. Sparks (1986) indicated that assimilation is very temperature dependent. The amount of crustal contamination of an ascending magma would decrease with decreasing temperature, and therefore the overall effect of assimilated material on the ascending magma composition would also decrease.

Some iron oxide deposits, such as Boss-Bixby and Olympic Dam, have considerable associated base and precious metals. These metals can be concentrated through partitioning to the iron-rich magma and (or) through assimilation, depending on when assimilation occurs. In South Australia, the iron formation of the Middleback Subgroup could certainly underlie the Olympic Dam deposit inasmuch as bif is present along strike both north (in the Mt. Woods Inlier) and south of the deposit. Anderson (1980) interpreted aeromagnetic data in the Olympic Dam region to represent bif metasedimentary rocks of the Hutchison Group. This interpretation, if correct, could provide a possible source for the iron in the Olympic Dam deposit. Equivalent to the Middleback Subgroup in the Willyama Inlier (fig. 3, east side of Adelaide geosyncline) is the Thackaringa Group (Willis and others, 1983). The Cues and Himalaya Formations and the Rasp Ridge Gneiss of the Thackaringa Group also contain iron formation (magnetite). Associated with the iron formation are copper sulfide minerals (syngenetic) interlayered with massive, stratiform, and disseminated cobaltiferous pyrite in sodic plagioclase-quartz rocks (Willis and others, 1983), and minor Pb-Zn-Ag and barite. If similar rocks underlie Olympic Dam and if partial melting and assimilation associated with an ascending alkaline magma occurred, then an additional or primary source exists for these metals.

Uranium is associated with apatite-bearing rocks in the Thomson Formation of the Early Proterozoic Animikie Group in Minnesota (McSwiggen and others, 1981). Similarly, copper sulfide deposits have been found in the Greenstone Group of northern Sweden. In both cases, similar Early Proterozoic rocks underlying the Middle Proterozoic iron oxide–rich orebodies could be sources for elements other than iron.

Conversely, studies of REE in bif show that the heavy REE are concentrated in bif (Fryer, 1977). Therefore, the final iron oxide orebody should be enriched in heavy REE instead of in light REE as at Olympic Dam and Bayan Obo. Also, Loberg and Horndahl (1983) illustrated a distinct separation between sedimentary bif and magmatic iron deposits on the basis of major and trace elements. If bif contributed to the formation of the Middle Proterozoic iron oxide–rich deposits, then a continuum of trace element values should be present between the two end members, but this does not appear to be the case.

A case for assimilation of an Early Proterozoic source can be made for only two of the four deposits—Kiruna and Olympic Dam. In the Midcontinent, orogenic rocks of the Central Plains orogen (1.7–1.63 Ga) underlie, at least in part, the St. Francois terrane (Sims and Peterman, 1986); however, Early Proterozoic (1.9 Ga) rocks may underlie the Central Plains orogen rocks as inferred from Sm-Nd data (Nelson and DePaolo, 1985), and the composition of those rocks is inferred. The data available for Bayan Obo do not elucidate the presence or composition of any Early Proterozoic rocks, and the origin of the Middle Proterozoic iron oxide–rich deposits may be related to a magmatic source coupled with some contamination by older rocks.

Another possible source for iron and other metals is Archean Algoma-type iron formations and other metalliferous deposits in the lower crust. These are generally very limited in lateral extent, however, and therefore are not likely candidates for an assimilated source.

If the alkaline trachytic rocks observed in Missouri and Sweden represent an iron-rich immiscible fraction, then a silica-rich fraction should also be present. Philpotts (1982a, b) indicated that iron, calcium, and phosphorus partitioning to the iron-rich fraction is less pronounced in alkaline rocks such that some of these elements are partitioned to the silica-rich fraction. As figures 10 and 11 show, there is a wide range in the composition of the associated volcanic rocks. Some of the more felsic alkaline volcanic rocks probably represent the silica-rich immiscible fraction, which would contain more accessory magnetite, sphene, and apatite and be more syenitic. In the Midcontinent, this relationship is less obvious; however, Bickford, Horrower, and others (1981) and Yarger (1981) reported two 1.35-billion-year-old epizonal, magnetite-rich (2 weight percent) granites in the subsurface of east-central Kansas. According to Sims (1985), magnetite-bearing granitic rocks form many small plutons in both Kansas and Missouri. Granites and volcanic rocks similar to these could represent the "missing" silica-rich immiscible fraction.

Early formed iron oxide–rich deposits could have higher contents of titanium and phosphorus in the form of ilmenite and apatite, assuming, of course, that the original magma—for example, a ferrodiorite magma associated with anorthosites—contained sufficient quantities of titanium and phosphorus before immiscibility occurred. As fractionation proceeds, titanium is removed through crystallization of ilmenite and phosphorus removed by precipitation of apatite (some uranium, light REE, and fluorine are also removed). Continued removal of these phases concentrates iron, silica, and barium, along with some fluorine, uranium, and light REE (if any remain) and base and precious metals. Textures at Olympic Dam suggest that sulfide minerals precipitated simultaneously with the iron minerals. This sequence of events is depicted graphically in figure 12. The final result of this differentiation sequence could be a low-temperature, quartz-rich, epithermal gold deposit.

These iron oxide–rich ore deposits can originate through (1) differentiation and immiscibility of a mantle-derived gabbro, as at Cranberry, North Carolina (Feiss and others, 1983), and Misi, Finland (Nuutilainen, 1968), (2) differentiation and immiscibility associated with the formation of a ferrodioritic magma from an anorthosite or related mantle-derived alkaline magma, or (3) partial melting and assimilation of older iron-rich rocks in combination with (1) or (2). Figure 13 illustrates on a hypothetical cross section of the crust the possible pathways in which Middle Proterozoic iron oxide–rich ore deposits could evolve. The diagram combines the observed presence of rocks of the rapakivi granite suite, anorthosite suite, and subalkaline rhyolitic and alkaline

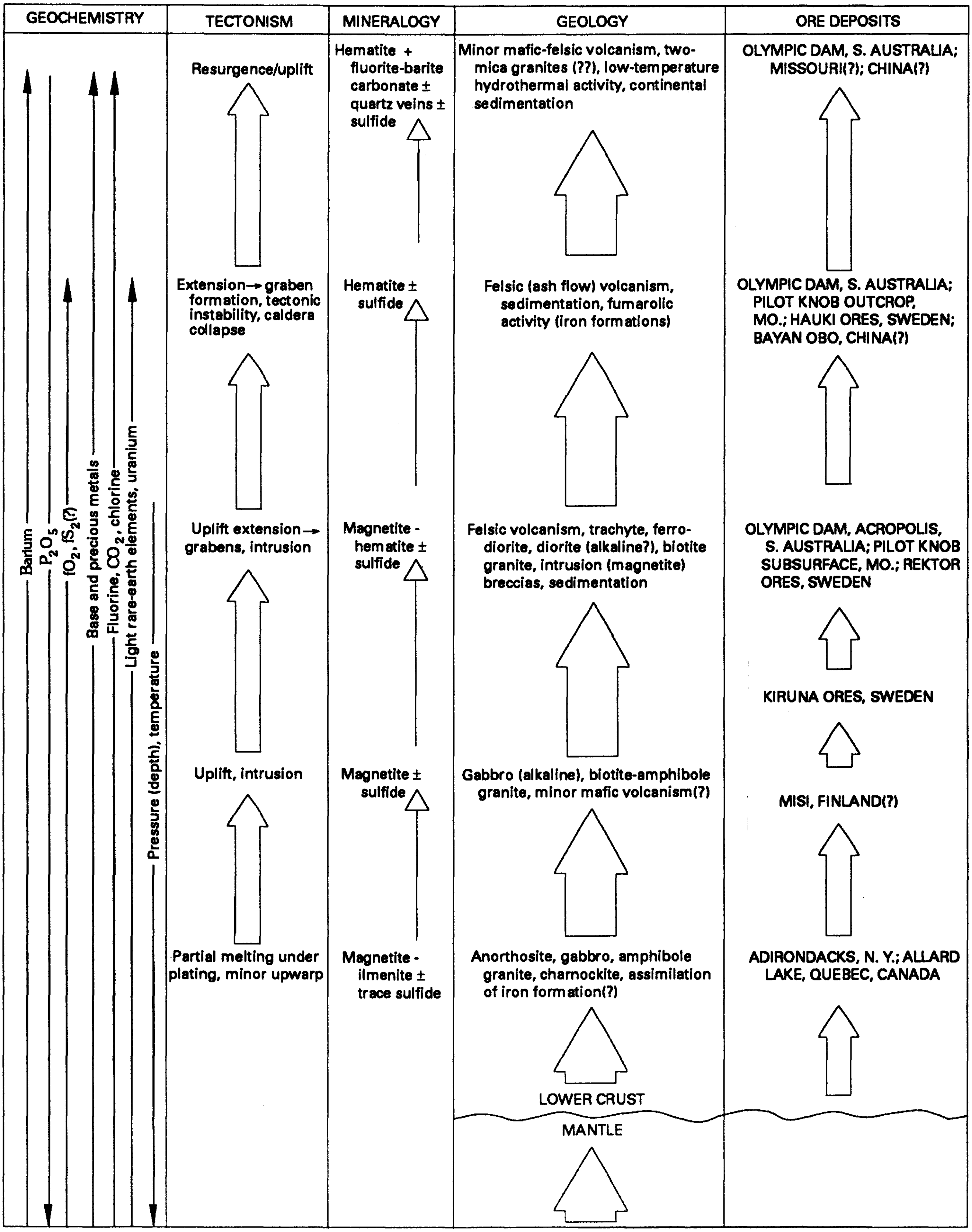


Figure 12. Model for evolution of Middle Proterozoic iron oxide–rich ore deposits. (The bars in the Geochemistry column are based on empirical observations of the mineralogy and geochemistry of the rocks from the literature and from field work.)

trachytic volcanic rocks, and iron oxide–rich sedimentary rocks. The presence of time-equivalent iron oxide–rich sedimentary rocks, for example, at Tarcoola (?) and Olympic Dam (Greenfield Formation), South Australia, and Cuthbertson Mountain and Pilot Knob outcrop, Missouri, associated with iron oxide deposits suggests that these iron oxide–rich magmas could contribute to exhalative iron oxide–rich deposits. The Kiruna Mertainen and Painirova deposits indicate eruption of iron oxide–rich lavas. The intrusive nature of these iron oxide-rich magmas, some having high volatile element contents, produces the intrusive breccias and massive magnetite±hematite orebodies seen at Olympic Dam, Kiruna, and Missouri (Lundberg and Smellie, 1979; Lambert and others, 1987). A mantle plume, plume line, or ponding of a mafic magma is the postulated heat source for the anorogenic event (Flower, 1984; Taylor and others, 1984; Emslie, 1985; Giles, 1988).

Numerous authors have proposed that these Middle Proterozoic anorogenic rock suites were the result of an abortive rifting event (Emslie, 1978; Wiebe, 1980; Morse, 1982; Anderson, 1983; McLelland, 1986; Giles, 1988; this study). Emslie (1985) and this study (fig. 1) suggest that this anorogenic event was a transitional phase between Archean tectonism and Wilson Cycle tectonism. This passive tectonic event caused by underplating of the crust produced post-tectonic silicic magmas, uplift, vertical tectonic style erosion, and continental sedimentation, and therefore a thickening of the crust (Rogers and others, 1984). Crustal thickening is further enhanced by production of younger alkaline, carbonatitic, and kimberlitic magmas. Each of the stabilized crustal areas discussed above was also subjected to a younger abortive rifting event. This period of cratonic stabilization probably was a dominant process during the Middle Proterozoic and coincides with the break observed in the formation of many types of ore deposits (fig. 1) (Gole and Klein, 1981; Meyer, 1981, 1985; Gross, 1983; Rundquist, 1984a, b). The Middle Proterozoic was, therefore, a period of profound tectonic change in the evolution of the Earth.

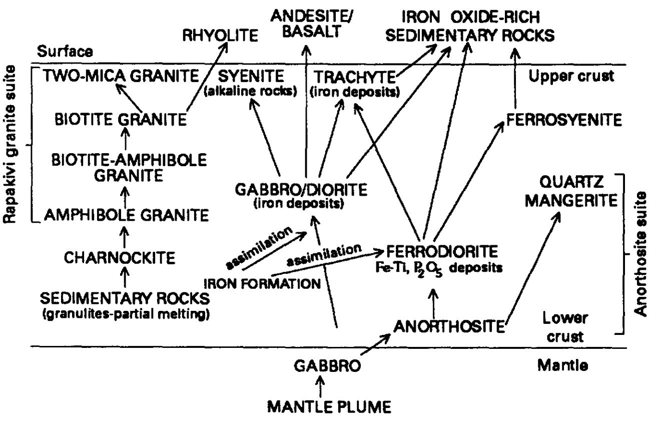


Figure 13. Postulated Middle Proterozoic differentiation sequence to produce iron oxide–rich ore deposits.

A few Paleozoic iron oxide deposits have characteristics similar to the Middle Proterozoic Missouri-Kiruna-type iron oxide deposits. Iron oxide-apatite deposits at Avnik, Turkey, and Bafq, Iran, are associated with subalkaline felsic volcanic rocks and mafic volcanic and intrusive rocks (Forster and Knittel, 1979; Helvaci, 1984). Other characteristics of these deposits compare favorably with those of the Missouri-Kiruna type, and therefore these deposits are classified on figure 1 with Missouri-Kiruna deposits. These deposits, although not anorogenic, illustrate that liquid immiscibility can also occur in subalkaline rocks (for example, Laco, Chile; Park, 1961).

The Mt. Painter Fe-U-F-REE±Ba deposit within the Mt. Painter Inlier of South Australia (fig. 3) consists of late Delamerian (Late Ordovician and Silurian), orogenic intrusive, granitic-hematitic-chloritic breccias contained within the Lower to Middle Proterozoic Radium Creek Metamorphics (Lambert and others, 1982). Sulfur isotope values for pyrite imply that the deposit formed from magmatic fluids. Oxygen and carbon isotope data also support this origin, although some oxygen isotope data support mixing with meteoric waters. Lambert and others (1982, 1987) contended that the brecciation and related alteration were the result of hydraulic fracturing and hydrothermal activity from ascending granitic magmas. Fumarolic activity associated with this event is represented by banded quartz-hematite beds (Mt. Gee Beds). Many of the granitic complexes emplaced during the Delamerian orogeny are alkaline. The Mt. Painter deposit may also represent the iron-rich fraction of an alkaline magma that has undergone liquid immiscibility.

Einaudi and Burt (1982) indicated that Fe±Cu±Co±Au contact metasomatic skarn deposits are present in oceanic island arcs or rifted continental margins associated with diorite and mafic volcanic rocks. These deposits and the younger iron oxide±apatite deposits shown on figure 1 (for example, Santorini Islands, Greece) are in extensional tectonic environments (Smith and Cronan, 1983; Bostrom and Widenfalk, 1984) and therefore may be similar to the Missouri-Kiruna type, which is envisioned as the product of extensional tectonism. There does not need to be a fundamental change in their mode of origin; that is, immiscibility of a mantle-produced magma. Whether the deposit was formed by submarine fumarolic activity (the Santorini Islands), as a lava flow (El Laco, Chile; Park, 1961), or as a contact metasomatic skarn (Gushan, People's Republic of China; Song and others, 1981), the source probably was alkaline mafic to intermediate intrusive rocks in which iron-rich elements were concentrated by immiscibility and (or) differentiation. The thickness and tectonic stability of the crust in the area of ore formation are also primary controls on the formation of these types of deposits.

The Middle Proterozoic is characterized as a period of cratonic stability and crustal thickening. Crustal thickening resulted from emplacement of post-tectonic, anorogenic rapakivi granite-anorthosite massifs, anorogenic volcanism, and continental sedimentation. Associated with these processes was minor, alkaline mafic to intermediate volcanism and plutonism. Major iron oxide–rich ore districts are directly associated with the alkaline volcanism. Emplacement of iron oxide–rich ore deposits is related to vertical and extensional tectonic features and (or) caldera collapse structures.

The addition of new silica-rich material to the crust generally occurred at the edge of an Archean shield. Such areas had previously undergone deposition of Early Proterozoic continental shelf and island arc material, including banded iron formations, followed by a major orogeny. Underplating of the crust by a mantle plume or plume line caused (1) granulite-facies metamorphism, (2) fusion of the lower crust to produce rapakivi granite suites and then subalkaline felsic volcanic rocks as suggested by Giles (1988) for South Australia, and (3) emplacement of alkaline mafic rocks and anorthosite massifs. As the mafic magmas ascended through the crust, they underwent differentiation and (or) immiscibility. Assimilation and fusion of preexisting iron formation may have contributed to the iron content of the magma and increased the oxygen fugacity of the magma, particularly if the conclusions of Sparks (1986) concerning the formation of anorthosites from crustal contamination of a primitive mantle melt are valid. If immiscibility occurred, iron-rich and silicic- and alkali-rich fractions formed. When and if immiscibility occurred depends on the (1) composition of the original melt (phosphorus and titanium contents), (2) pressure, (3) temperature, and (4) oxygen fugacity. When immiscibility occurred, Fe, Ca, Ti, P, Ba, REE, and other elements were partitioned to the iron-rich phase. The iron-rich magma then differentiated to form alkaline intermediate rocks and iron oxide–rich deposits. The silica-rich magma formed alkali-rich intrusive and extrusive rocks having abnormally high magnetite-apatite-sphene contents. Experimental data indicate that an iron-rich melt could originate through liquid immiscibility from subalkaline magmas; however, field data, in the form of near-ore alkaline trachytic rocks, support an alkaline source.

The iron oxide deposits range from subvolcanic/intrusive to extrusive/exhalative depending upon availability of structural conduits to the surface. The deposits are primarily magnetite and (or) hematite and contain major to accessory quantities of fluorapatite, barite, fluorite, sulfides, light REE, uranium, and precious metals. The final composition and location (surface versus subsurface) of the ore deposit depends on (1) when and where (pressure, temperature) in the crust liquid immiscibility occurred, (2) oxygen fugacity, (3) amount of differentiation after immiscible separation, (4) addition of meteoric components, and (5) structural constraints. The ore deposits individually, or as a group, generally contain more than 1 billion tons of ore.

Following the emplacement of this anorogenic suite and associated iron oxide deposits, the rocks were subjected to a very low grade metamorphic or hydrothermal event that at least reset the Rb-Sr age dates. The region may have been subjected to uplift and erosion and deposition of younger sediments. Late-stage rifting and emplacement of kimberlites, carbonatites, and alkaline igneous complexes completed the cratonic history.

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Geologic Setting and Ages of Proterozoic Anorogenic Rhyolite-Granite Terranes in the Central United States

By P.K. Sims

Abstract

Four episodes of anorogenic magmatism have been recognized in the central part of the United States. From oldest to youngest, these are represented by the newly recognized 1,835-Ma granite-rhyolite assemblage in central Wisconsin, the 1,760-Ma rhyolite-granite terrane in southern Wisconsin, the 1,480-Ma St. Francois granite-rhyolite terrane of southeast Missouri, and the 1,400–1,350 Ma Spavinaw granite-rhyolite terrane in northeast Oklahoma, southern Kansas, and adjacent Missouri. Successive episodes of magmatic activity become younger southward and overlie and intrude older orogenic provinces. The rhyolite-granite complexes of the two older episodes overlap rocks (1,890–1,840 Ma) of the Penokean orogen and those of the two younger ones, which are contiguous, overlap rocks (1,780–1,630 Ma) of the Central Plains orogen. Each of the terranes is characterized by rhyolite ash-flow tuff (ignimbrite) and anorogenic (A-type) granite.

INTRODUCTION

The purpose of this paper is to discuss the regional geologic framework of the known anorogenic granite-rhyolite terranes in the northern Midcontinent of the United States, terranes presumed to be highly favorable as potential hosts for mineral deposits similar to that at Olympic Dam in South Australia (Roberts and Hudson, 1983).

The Olympic Dam deposit is essentially a hematite-rich iron deposit that has economic concentrations of associated copper, uranium, gold, and light rare-earth elements (REE) (Roberts, 1986). It is spatially, and probably genetically, related to approximately 1.5-Ga anorogenic volcanic-plutonic rocks in the Gawler craton described by Branch (1978). In this respect, it has a setting similar to that of the Kiruna-type iron deposits in northern Sweden (Lundberg and Smellie, 1979) and in the St. Francois Mountains of southeast Missouri (Kisvarsanyi, 1981). All of these deposits contain vast tonnages of iron ore, anomalous to economic concentrations of base and precious metals, and anomalous amounts of barium, fluorine, uranium, thorium, and light REE. For these reasons, the Middle Proterozoic anorogenic St. Francois terrane, in particular, and other Proterozoic anorogenic terranes in the central United States are considered favorable as potential hosts for base- and precious-metal-bearing iron deposits similar to Olympic Dam.

BASEMENT GEOLOGIC TERRANES

The geologic framework of the basement rocks in the northern Midcontinent of the United States has been outlined previously (Sims and others, 1987) and is discussed only briefly here.

Data on Precambrian basement rocks in the northern Midcontinent are inadequate to prepare a comprehensive geologic map that delineates individual lithologic units. Accordingly, in preparing the recent basement map (Sims, 1985, 1989), the Precambrian rocks were mapped in terms of tectonostratigraphic terranes, a concept similar to that now being widely applied in the Cordillera of western North America. I use the term "terrane" for a geologic entity of regional extent that is characterized by a geologic history that differs from adjacent terranes; this definition departs from that used in the Cordillera (Jones and others, 1983) only in that a terrane need not be fault bounded.

Eight major terranes have been identified and delineated in the northern Midcontinent (fig. 14). From oldest to youngest, these are (1) Archean gneiss terrane (age, 2.6–3.6 Ga) of Superior craton; (2) Late Archean greenstone-granite terrane (age, 2.6–2.75 Ga) of Superior craton; (3) Early Proterozoic Wisconsin magmatic terrane (age, 1.84–1.89 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, 1.63–1.78 Ga); (6) Middle Proterozoic St.

Francois granite-rhyolite terrane (age 1.45–1.48 Ga); (7) Middle Proterozoic Spavinaw granite-rhyolite terrane (age, 1.35–1.40 Ga); and (8) Middle Proterozoic Midcontinent rift system (age, 1.0–1.2 Ga). Other coherent rock bodies of lesser areal extent include quartzites (age, ~1.63–1.82 Ga) and the anorthosite and 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 oceanic-arc complexes, dominantly juvenile material, that were accreted to the North American continent; most other terranes are continental crust that evolved in extensional environments and were vertical additions to the crust.

With respect to tectonic history, the Early Proterozoic Penokean orogen was the site of convergence along the southeast margin of the Archean Superior craton that culminated with the collision between the Wisconsin magmatic terrane and the craton at about 1,860 Ma (Sims and others, 1989). Later, rifting of the composite Archean–Early Proterozoic craton in what is now the central United States led to arc magmatism in the interval 1,780–1,630 Ma and collision of the rocks of the Central Plains orogen with the composite continental crust (Sims and Peterman, 1986).

ANOROGENIC GRANITE-RHYOLITE TERRANES

Four distinct episodes of anorogenic magmatism have been recognized and partly delineated in the northern Midcontinent. From oldest to youngest, these are (1) 1,835-Ma granite-rhyolite in central Wisconsin, (2) 1,760-Ma rhyolite-granite in southern Wisconsin, (3) 1,450–1,480-Ma granite-rhyolite in the St. Francois Mountains, southeast Missouri, and (4) 1,350–1,400-Ma granite-rhyolite in northeast Oklahoma and adjacent areas. Successive episodes of magmatic activity become younger southward. The two older periods of anorogenic magmatism, in Wisconsin, followed the Penokean orogeny (~1,860 Ma); the rhyolite-granite complexes intruded and overlapped rocks of the orogen. The two younger periods followed the Central Plains orogeny and stabilization of the crust (~1,630 Ma); the rocks overlapped older rocks of the Central Plains orogen.

The oldest (1,835 Ma) known anorogenic magmatism, recognized only recently (Sims, 1990) as a distinct magmatic interval, consists of two small areas of rhyolitic rocks, each about 25 km^2 in area, and several plutons of comagmatic red alkali feldspar leucogranite that intrude older, Early Proterozoic arc-volcanic rocks (age, 1,840–1,880 Ma) and Archean gneisses within an area of about 1,300 km^2 (locality *A*, fig. 14). The rhyolitic rocks consist mainly of massive to flow-banded rhyolite that contains spherulites and lithophysae, felsic crystal and lithic tuff, volcanogenic graywacke (turbidites), and welded tuff. The granites contain abundant microcline microperthite, lesser weakly zoned sodic plagioclase, and sparse biotite and fluorite. Cataclastic textures are nearly ubiquitous, and metamorphism is weak. Both the rhyolite and the granite are extensively altered: biotite is mostly altered to hematite and chlorite or less commonly to epidote and sericite, and hematite typically forms inclusions in feldspar and dustlike fillings in cracks.

The granite and rhyolite are peraluminous and have alkaline affinities, high FeO/FeO + MgO (>0.80), K_2O/Na_2O (>1.0), Ba/Sr, and K/Rb (>300) ratios, and large negative europium anomalies (table 2). They are remarkably similar chemically to the rhyolite and granite of the 1,760-Ma age group in southern Wisconsin (table 1) (Smith, 1978, 1983). Associated mineral deposits are unknown.

The second oldest anorogenic magmatic terrane, the 1,760-Ma rhyolite-granite terrane of southern Wisconsin, is poorly exposed within an area of about 10,000 km^2 as isolated inliers in the Fox River valley and tributaries (locality *B*, fig. 14) (Smith, 1978, 1983). The rhyolite consists of interbedded ash-flow tuff and volcaniclastic sedimentary rocks of both peraluminous and metaluminous suites (Anderson and others, 1980). The associated cogenetic granites, which are particularly poorly exposed, are granophyric and possibly intruded their own volcanic cover. An undated diorite body and associated basaltic dikes are spatially associated with the rhyolite. The rhyolite is dominantly gray, but the granite at the village of Redgranite and elsewhere is dark red as a result of hematite and chlorite alteration of the sparse biotite and hematite filling of cracks in the rock. The rocks are mildly deformed on northeast-trending fold axes, have weak to moderate cataclastic textures, and are weakly metamorphosed (lower greenschist facies). Magnetite is sufficiently abundant as an accessory mineral to produce a modest aeromagnetic anomaly. Presumably, the rocks overlie and intrude older (1,890–1,830 Ma) rocks of the Penokean orogen. The peraluminous and metaluminous suites (table 1) are considered cogenetic and possibly comagmatic and have been interpreted as having been derived from partial melting of separate sources of intermediate composition (Smith, 1983). The diorite and associated basalt probably were derived by partial melting of a mantle source and should have provided the heat source for partial melting of crust. No known mineral deposits are associated with this anorogenic suite.

The 1.45–1.48-Ga granite-rhyolite of the St. Francois terrane (Kisvarsanyi, 1981) contrasts with the older anorogenic terranes in that it occupies a vast area in the

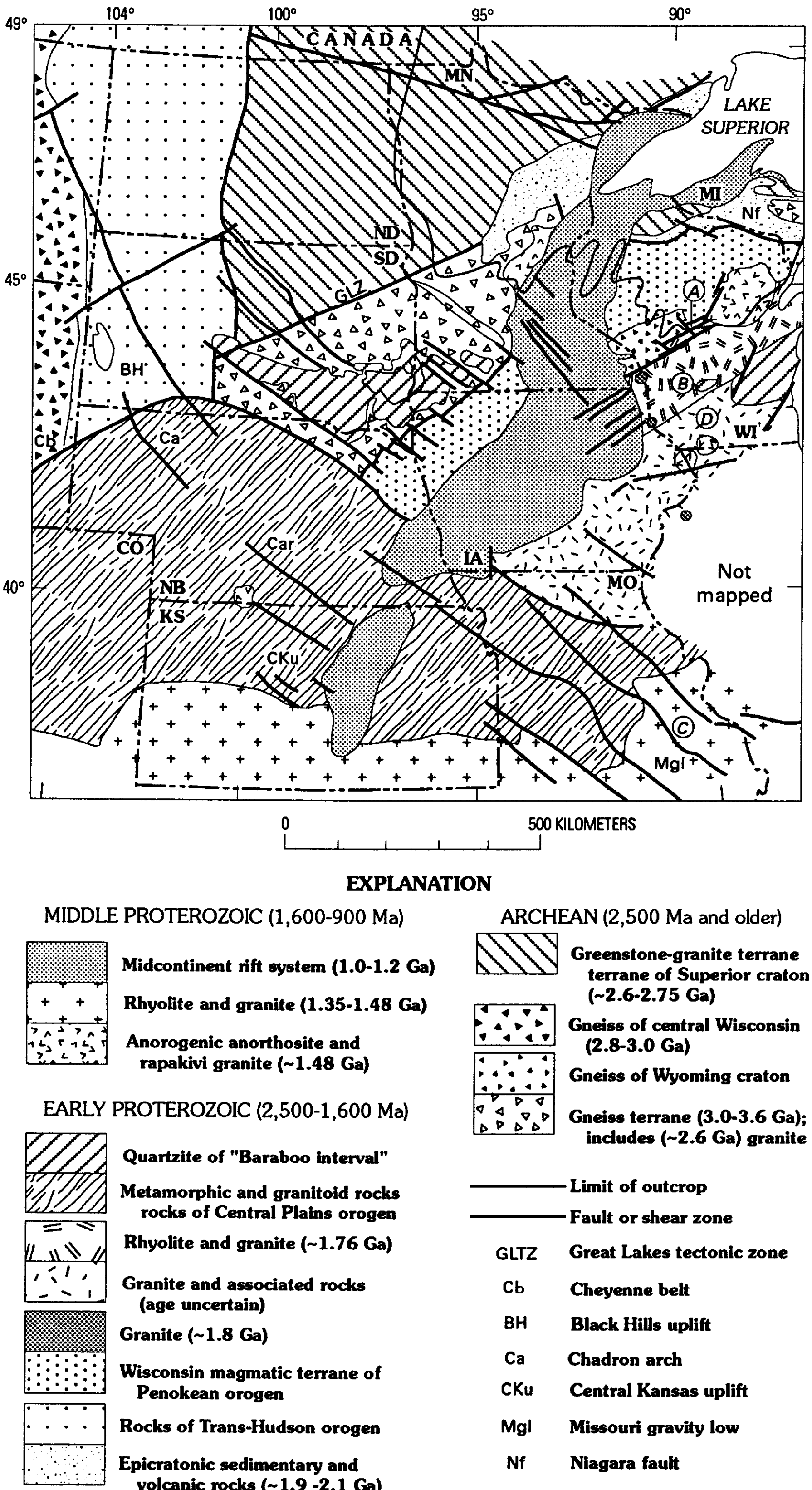

Figure 14. Precambrian basement terranes in the northern Midcontinent region of the United States. Circled italic letters refer to locations discussed in text. Modified from Sims (1985).

Midcontinent region and apparently is of somewhat more diverse composition. Bickford and others (1986) assigned these rocks to their "Eastern granite-rhyolite province," which extends from Missouri into Ohio; more recently, von Breemen and Davidson (1988) showed from isotopic ages that the rocks apparently extend into the Grenville province immediately east of Lake Huron. In the type area, the St. Francois Mountains (locality *C*, fig. 14) and adjacent covered areas in southeast Missouri known through drilling, this terrane is characterized by inferred volcanotectonic features including ring complexes, cauldron subsidence structures with ring volcanoes and ring plutons, and resurgent calderas with central plutons (Pratt and others, 1979; Kisvarsanyi, 1980, 1981; Sides and others, 1981), thus establishing a tectonic environment comparable to that of some of the classic ring complexes of the world, such as the Mesozoic ring complexes of northern Nigeria (Bowden and Turner, 1974). In the St. Francois terrane, the dominant rocks are silicic volcanic rocks, mainly ash-flow tuff, and comagmatic subvolcanic granophyric and perthitic alkali feldspar granite (Bickford and others, 1981). Ring intrusions are trachyte to trachyandesite and related porphyritic low-silica intrusive rocks. Central plutons are high-silica, evolved large-ion lithophile element, two-mica ("tin") granite, inferred to have been emplaced in resurgent cauldrons (Kisvarsanyi, 1981). The chemistry of the rocks is summarized in Sims and others (1987) and discussed in more detail by Kisvarsanyi (1972), Bickford and others (1981), and Cullers and others (1981). Average analyses of four major rock types are listed in table 2. The famed magnetite-hematite-apatite deposits of the area are spatially associated with the trachytic suite of Kisvarsanyi (1981), whereas Sn-W-Ag-Pb-Sb vein deposits are possibly genetically related to the so-called "tin granites."

Regional, almost pervasive alteration of the volcanic and granitic rocks in the St. Francois terrane was recognized by Anderson (1970). Typically, alkali feldspar is altered to patchy or veined, highly turbid, red microperthite, and plagioclase is albitized. Primary mafic minerals are changed to magnetite, hematite, chlorite, epidote, and calcite. The resulting mineral assemblages are characteristic of propylitic alteration. Also, secondary potassium feldspar is commonly concentrated adjacent to fractures or mafic dikes. Anderson (1970) noted that the intensity of the alteration—mainly shown by increasing redness of the feldspars—increases from northeast to southwest in the exposed parts of the St. Francois Mountains.

Wenner and Taylor (1976) showed by regional variations in ^{18}O in the exposed terrane that ^{18}O is enriched from northeast to southwest, in the same direction as the increasing redness of the feldspars—that is, increasing intensity of hematite alteration. They also noted that some of the mafic rocks (mainly dikes) that intrude the rhyolites and granites "have suffered very little ^{18}O enrichment compared to the nearby rhyolites that they intrude" (p. 1590), and they concluded (p. 1591) "that the high-^{18}O alteration event must have peaked in intensity *before* certain other dikes and sills (mafic intrusions) were intruded." The age of the widespread hydrothermal meteoric alteration is uncertain inasmuch as none of the unaltered mafic dikes has been isotopically dated. Wenner and Taylor (1976) stated that "it seems certain that the pervasive high-^{18}O hydrothermal alteration event occurred later than 1,400 m.y. ago" (p. 1593), inasmuch as an altered body of this age (Munger Granite Porphyry) in the southwestern part of the region has a U-Pb zircon age of 1,400 Ma (Bickford and Mose, 1975). They further concluded that the alteration could have occurred 1,100–1,200 m.y. ago, a time of widespread Rb-Sr and K-Ar reset ages. Unpublished lead isotope data reported by Pratt and others (1979, p. 5), however, indicate that the mafic rocks are evidently about the same age as other igneous rocks (1,400–1,500 Ma) of the region; accordingly, the hydrothermal alteration must have followed shortly after crystallization of the rhyolite and granite.

The fourth and youngest of the granite-rhyolite terranes, the Spavinaw (Thomas and others, 1984), composes the "Western granite-rhyolite province" of Bickford and others (1986) and occupies an area comparable to St. Francois terrane. It is known mainly from the subsurface in Oklahoma (Denison, 1981; Denison and others, 1984). Apparently, the volcanic and granitic rocks are grossly equivalent lithologically to the rhyolite and subvolcanic granite of the St. Francois terrane, but data on the chemistry of the rocks are meager (Bickford and others, 1981).

Sims and others (1987) suggested that the granitic plutons of the Middle Proterozoic Transcontinental anorogenic province (Silver and others, 1977; Anderson, 1983) correspond to deeper levels, now exposed by erosion, of the St. Francois and Spavinaw granite-rhyolite terranes and thus possibly are the mesozonal equivalent of the epizonal terranes. Within the area of concern to this report, four bodies are known, the largest of which is the Wolf River batholith in Wisconsin (Anderson and Cullers, 1978; Anderson, 1980) (fig. 1). These plutons are chemically similar to the rocks in the granite-rhyolite terranes in that they are highly silicic, have high Fe/Mg and F and low Ca, Mg, and Sr, and are enriched in large-ion lithophile elements (K, Rb, Ba, REE, and U). Anderson (1980) estimated that the granites in the Wolf River batholith crystallized at depths less than 3.8 km. In contrast to most other anorogenic plutons in the

Table 2. Chemical analyses of representative samples of rhyolite and granite, Proterozoic anorogenic terranes, central United States

[Leaders (--) indicate not determined; blank indicates sample not analyzed for element]

	1,835-Ma age group				1,760-Ma age group		St. Francois terrane						
Number	1	2	3	4	5	6	7	8	9	10	11	12	13
MAJOR ELEMENT OXIDES (weight percent)													
SiO_2	75.6	75.8	75.9	75.7	71.8	76.14	68.62	75.77	76.34	75.06			
Al_2O_3	11.8	11.9	11.9	12.2	14.23	11.79	14.40	12.36	11.40	11.48			
Fe_2O_3	2.19	2.26	1.95	1.12	1.47	1.10	3.31	1.35	2.18	2.51			
FeO				1.87	0.98	0.88	--	--	--	--			
MgO	0.13	<0.10	0.11	0.03	0.29	0.09	0.93	0.15	0.05	0.05			
CaO	0.66	0.65	0.53	0.40	1.23	0.45	1.79	0.49	0.25	0.22			
Na_2O	3.76	3.81	3.79	3.70	3.98	3.16	4.03	3.44	3.67	2.54			
K_2O	4.26	4.18	4.53	4.61	4.30	5.65	3.86	4.80	4.58	5.70			
H_2O^+	--	--	--	0.22	1.12	0.58	--	--	--	--			
H_2^-	--	--	--	--	0.06	0.01	--	--	--	--			
TiO_2	0.15	0.16	0.12	0.07	0.27	0.24	0.44	0.17	0.18	0.21			
MnO	<0.02	<0.02	0.2	0.2	0.10	0.02	0.08	0.04	0.06	--			
P_2O_5	<0.05	<0.05	<0.05	0.04	0.09	0.01	--	--	--	--			
LOI	0.60	0.33	0.35	--	--	--	1.68	--	2.15	3.39			

DESCRIPTIONS AND LOCALITIES

1,835-Ma age group

Major oxide analyses by X-ray fluorescence: analysts, J. Taggart, A. Bartell, and D. Siems. Minor elements, Ba through Ce, by X-ray fluorescence analysis: analyst, John Jackson. Minor elements, Sc through Lu, by instrumental neutron activation analysis: analyst, J. Mee.

1. Granophyric granite, Cary Mound, Wood County, Wisconsin. Sample W299 collected by K.J. Schulz. Lat 44°31' N., long 90°15' W.
2. Spherulitic rhyolite, Cary Mound, Wood County, Wisconsin. Sample W298-2 collected by K.J. Schulz. Lat 44°31' N., long 90°16' W.
3. Alkali feldspar granite, quarry northeast of Cary Mound. Sample W849 collected by K.J. Schulz. Lat 44°32' N., long 90°10' W.
4. Red leucogranite, Cold Springs granite quarry, northeast of Wausau, Marathon County, Wisconsin. Sample 23 reported in LaBerge and Myers (1983). Analyzed at Pennsylvania State University.

1,760-Ma age group

Source: Smith (1983). Major oxide analyses by wet chemical methods. Minor element analyses (Rb, Sr, Pb, Zn) by atomic absorption spectrometry. All other minor element analyses by optical emission spectrography.

5. Peraluminous rhyolite, average of 10 samples.
6. Granite at Redgranite, Wisconsin.

St. Francois terrane

Samples 7-10 reported in Bickford and others (1981); samples 11-13 reported in Cullers and others (1981).

7. "Silvermine granite"; medium grained; average of 5 samples.
8. "Butler Hill granite"; average of 44 samples.
9. "Grassy Mountain ignimbrite"; average of 15 samples.
10. "Taum Sauk rhyolite"; average of 6 samples.
11. "Silvermine granite."
12. "Butler Hill granite."
13. "Grassy Mountain ignimbrite."

Transcontinental province, which belong to the magnetite series, the Wolf River rocks belong to the ilmenite series of Ishihara (1977). A large anorogenic body penetrated by drilling in Stevenson County, Illinois (locality *D*, fig. 14), is altered near the unconformity beneath Paleozoic sedimentary rocks and is enriched in ^{18}O and in many incompatible elements relative to deeper samples (Kyser, 1986). Kyser interpreted the alteration to have resulted from interaction with formation waters typical of the Illinois Basin at temperatures greater than 300 °C.

POSSIBLE SIGNIFICANCE OF HYDROTHERMAL ALTERATION

Propylitic alteration indicated by reddened feldspars and the replacement of mafic silicate minerals in the rhyolite-granite complexes characterizes the 1,835-Ma group and the 1,480-Ma St. Francois terrane, as well as a part of the 1,760-Ma rhyolite-granite terrane. For the 1,835-Ma group, the hematitic alteration seems to be confined to the rocks of this age group, suggesting that it is a late-stage hydrothermal alteration related to this

Table 2. Continued

Number	1	2	3	4	5	6	7	8	9	10	11	12	13
					MINOR ELEMENTS (parts per million)								
Ba	1,390	1,660	1,236	--	661	390	940	389	200	271			
Rb	70	55	94		125	202	119	224	163	229			
Sr	41	73	32		126	21	198	56	12	35			
Zr	395	415	267		224	590							
Y	54	54	54										
Nb	27	28	28										
Ni	<5	<5	<5										
Cr	<20	<20	<20		18	8							
Cu	<5	<5	<5										
Zn	35	47	45										
La	85	91	83		47.3	98							
Ce	165	182	161	--	90.0	225.2							
Sc	1.045	1.21	0.78	--	8.76	3.12					8.3	4.2	4.1
Cr	<2	2.0	<4										
Co	0.68	0.41	0.44		5.81	0.81					15.4		17.9
Ni	<21	<13	18										
Zn	19	33.8	28										
As	>2	<2	<2										
Sb	0.1	0.082	0.56										
Rb	78.5	61.8	105										
Sr	59	74	36										
Ba	1,470	1,760	1,310										
Cs	0.203	0.126	0.32										
Zr	434	421	333										
Hf	10.4	10.05	9.69		4.91	11.85							
Ta	2.18	2.23	2.48										
Th	15.6	15.19	16.7		13.79	24.1					6.8	22.6	10.9
U	3.66	3.67	4.29										
Au	<5	<7	<7										
La	100.7	111	81.9		47.3	98.5					30.4	54.9	33.98
Ce	194	204	159		90.0	225.2					60.5	117	66.4
Nd	73.9	80.9	62.1		37.8	74.5							
Sm	14.5	15.02	12.84		6.7	13.8					6.10	9.4	7.2
Eu	2.19	2.49	1.61		1.8	0.7					1.44	0.59	0.63
Tb	1.69	1.71	1.61		0.9	2.7					1.26	1.67	1.78
Yb	6.48	6.35	6.76		3.6	9.1					4.90	7.82	7.86
Lu	0.926	0.907	0.942		0.5	1.4					0.63	1.23	1.02
Rb/Sr	1.71	0.75	2.94	--	0.99	9.62	0.60	4.0	13.58	6.54			
Ba/Sr	33.9	227	38.6	--	5.24	18.6	4.75	6.95	16.67	7.74			

particular magmatic system. In the 1,480-Ma St. Francois terrane, Wenner and Taylor (1976) showed that the propylitic alteration resulted from a regional, high-^{18}O, hydrothermal-meteoric alteration event that transgressed intrusive bodies and in part at least preceded crystallization of mafic dikes that cut the rhyolite-granite complexes. Probably the alteration event occurred 1,400–1,500 Ma. Mafic dikes of probable similar age cut the Pea Ridge iron deposit (Emery, 1968) and other iron bodies in the area, and accordingly the regional alteration could be approximately the same age as the iron mineralization, in which case both could be genetically related, the regional alteration being a lower temperature halo around the higher temperature replacement iron deposits. The demonstration that the hydrothermal fluids causing the regional alteration originated as meteoric surface waters (Wenner and Taylor, 1976) could explain the close association of hematite and magnetite in several of the iron deposits in the St. Francois terrane. Perhaps the hematite bodies are a later replacement of primary magnetite bodies, which developed from more oxidized meteoric waters.

DISCUSSION AND SUMMARY

The anorogenic magmatism in the Midcontinent occurred in areas that already had undergone orogeny, and it now is distinguished as A-type (Loiselle and Wones, 1979) and "within plate" (Pearce and others, 1984) magmatism and contrasts with orogenic assemblages both petrographically and chemically. The anorogenic bodies are dominantly magnetite bearing (Anderson, 1983) and belong to the magnetite series of Ishihara (1977). It is generally agreed from chemical modeling (Cullers and others, 1981; Smith, 1983) that the anorogenic magmas were derived by partial melting of older crust, and this origin is consistent with neodymium data that indicate mantle separation ages for the rocks, regardless of crystallization age, in the range 1,700–1,900 Ma (Nelson and DePaolo, 1985).

The 1,760-Ma granite-rhyolite magmatism in southern Wisconsin overlapped in time the convergent orogenic activity related to the Central Plains orogen and its westward analogues (Bickford and others, 1986). Possibly, this magmatism in Wisconsin reflects extension that accompanied the accretion of rocks of the Central Plain orogen, similar to that described by Karig (1971) from the Mariana Islands in the South Pacific.

Widespread anorogenic magmatism did not begin, however, until 1,450–1,480 Ma, about 100 m.y. after the North American continent had stabilized. It was followed about 100 m.y. later by the 1,350–1,400-Ma anorogenic activity in the Western granite-rhyolite province (Bickford and others, 1986). These magmatic events took place along and near the Middle Proterozoic continental margin, almost certainly as a result of regional extension, but the underlying cause of extension remains equivocal.

The tectonic environment of Middle Proterozoic anorogenic magmatic events seems particularly analogous to that in South Australia at the time the Olympic Dam deposit was formed (Roberts and Hudson, 1983), and these anorogenic terranes in the Midcontinent region are favorable for the occurrence of deposits similar to Olympic Dam.

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General Features of the St. Francois and Spavinaw Granite-Rhyolite Terranes and the Precambrian Metallogenic Region of Southeast Missouri

By Eva B. Kisvarsanyi[1]

Abstract

The Midcontinent region of the United States is underlain by extensive anorogenic granite-rhyolite terranes that share a number of common features with the Proterozoic terrane in South Australia that hosts the giant Olympic Dam copper-uranium-gold deposit. These terranes have similar ages (1.4–1.7 Ga), geologic settings (rifted continental crust), magmatic associations (silicic-alkalic igneous rock suites), and metal suites dominated by iron. The best described and most complexly mineralized of the Midcontinent terranes, the 1.45–1.48-Ga St. Francois terrane in southeastern Missouri, is known from surface exposures as well as more than 500 core holes, and contains 6 major and more than 30 smaller orebodies. The Spavinaw terrane is 100 m.y. younger than the St. Francois and underlies adjoining parts of Kansas, Oklahoma, Missouri, and Arkansas; it is known mostly from drill holes and is not a mineral producer. Both the St. Francois and Spavinaw terranes are characterized by epizonal granite and rhyolite dominated by potassium feldspar; they contain iron-rich mafic minerals and are enriched in the lithophile elements (Li, Be, Y, Nb, Zr, U, Th, F, and rare-earth elements). The analogy between the St. Francois and South Australian terranes is further strengthened by similarities of their respective styles of mineralization. The similarities between the St. Francois and Spavinaw terranes and the basement terrane in South Australia single them out in the Midcontinent as excellent targets for exploration for ore deposits that could be favorably compared with the Olympic Dam deposit.

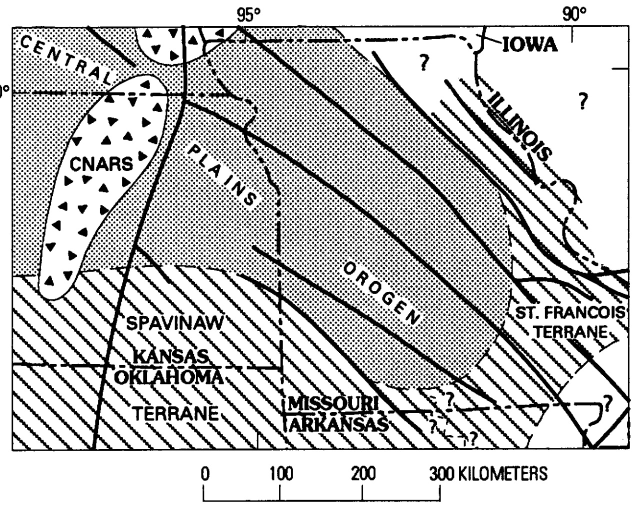

Figure 15. Major Proterozoic terranes in the Midcontinent region of the United States. CNARS, Keweenawan basalts and clastic rocks associated with the central North American rift system. Modified from Sims (1989).

INTRODUCTION

The St. Francois and Spavinaw terranes of the Midcontinent of the United States are Middle Proterozoic epizonal terranes that have well-constrained crystallization ages (Bickford and others, 1981; Thomas and others, 1984). The terranes are similar to each other in composition and mode of emplacement, but they formed approximately 100 m.y. apart. The St. Francois terrane is older (1.45–1.48 Ga), is exposed in its type locality in the St. Francois Mountains, and underlies Paleozoic strata throughout most of southeast Missouri. The younger Spavinaw terrane (1.35–1.40 Ga) crops out near Spavinaw in northeast Oklahoma and underlies adjoining parts of Kansas, Oklahoma, Missouri, and Arkansas (fig. 15). Recent geochronologic data indicate that isolated plutons of Spavinaw age are present within the St. Francois terrane in southeast Missouri (Latham and others, 1988).

The epizonal terranes are composed dominantly of anorogenic (alkaline and anhydrous) granitic rocks and associated rhyolites. Their areal distribution overlaps the south side of the Early Proterozoic Central Plains oro-

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gen, a terrane of metasedimentary and metaigneous rocks (Sims and Peterman, 1986). The contact between the orogenic and anorogenic terranes is covered by Paleozoic strata. This contact is believed to be an erosional contact resulting from uplift that resulted in removal of the cover of epizonal rocks from the orogenic terrane in central Missouri (Sims and others, 1987). Mesozonal granitic rocks of both St. Francois and Spavinaw age locally perforate the Central Plains orogenic terrane and represent the preserved roots of the epizonal terranes (Sims and others, 1987).

The contact between the St. Francois and Spavinaw terranes is obscure and in fact may not be one of sharp demarcation. Scattered younger ages in southeastern Missouri suggest that the Spavinaw thermal event was widespread and may have overlapped areally into the St. Francois terrane.

The general petrologic, geochemical, and tectonic characteristics of the St. Francois and Spavinaw terranes are broadly similar to those of the Middle Proterozoic rocks that host the giant Olympic Dam copper-uranium-gold deposit at Roxby Downs, South Australia. Furthermore, the St. Francois terrane is a metallogenic province containing six major volcanic-hosted magnetite-hematite deposits, one copper-iron deposit, and more than thirty smaller deposits of iron, manganese, and copper. One group of subeconomic deposits in the Silver Mine district is similar to the high-temperature tin-tungsten-silver-lead veins at Cornwall (Lowell, 1976). Sims and others (1987) suggested that the geology of the Middle Proterozoic anorogenic terranes in the Midcontinent is permissive for the occurrence of one or more deposits of the Olympic Dam type. The purpose of this paper, therefore, is to review the general characteristics of the St. Francois and Spavinaw terranes as determined from outcrop and subsurface data and to briefly describe their ore deposits.

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St. Francois Granite-Rhyolite Terrane

The St. Francois terrane is exposed in a 900-km^2 region in the St. Francois Mountains, at the crest of the Ozark dome in southeast Missouri, where it has been studied extensively (Tolman and Robertson, 1969; Anderson, 1970; Berry and Bickford, 1972; Kisvarsanyi, 1972; Pratt and others, 1979; Sides and others, 1981). Here, the St. Francois terrane includes the St. Francois Mountains Volcanic Supergroup and the St. Francois Mountains Intrusive Suite. Data from more than 500 drill holes indicate that the terrane extends below the cover of Paleozoic strata and underlies most of southeast Missouri (Kisvarsanyi, 1981), having an inferred areal extent of at least 100,000 km^2. Its boundaries are not well defined because drill-hole data are scarce to the east toward the Illinois Basin and to the south into the Mississippi embayment; however, Hoppe and others (1983) have suggested that a similar granite-rhyolite terrane underlies most of Illinois, Indiana, and western Kentucky, as far east as the Grenville boundary. U/Pb ages on zircons indicate a 1.48-Ga crystallization age for the St. Francois terrane, but the terrane contains some younger (1.38 Ga) plutons (Bickford and others, 1981; Latham and others, 1988). The terrane may extend as far west as the Decaturville cryptoexplosion structure (Offield and Pohn, 1979) and the mafic complex at Orla (Kisvarsanyi, 1988) in central Missouri, as suggested by 1.47-Ga plutons that intrude the older metamorphic rocks in that area.

Correlation of surface and subsurface geologic data and analysis of aeromagnetic maps in southeast Missouri show that the St. Francois terrane 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. 16) (Kisvarsanyi, 1980, 1981). These volcanotectonic 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 mostly removed by pre-Paleozoic erosion, as much as 1,700 m of rhyolite ash-flow tuffs is preserved locally. The thickest succession of volcanic rocks has been mapped from outcrops in the St. Francois Mountains, in the area of the Taum Sauk volcanotectonic depression (Anderson, 1970; Cordell, 1979) or caldera (Berry and Bickford, 1972). The bulk of the volcanic rocks are confined to a northwest-trending belt (fig. 16), a topographic high having its peak in the outcrop area, that forms a buried ridge of knobs extending as far northwest as the Missouri River (see fig. 3, 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 and the Grand River and Northeast Missouri tectonic zones, as defined by Kisvarsanyi (1984), suggests that their emplacement and distribution are controlled by structures in the older terrane. Mesozonal granite of the Transcontinental anorogenic province (Sims and others, 1987), and of the same age as the St. Francois terrane (Bickford and others, 1981), has been identified along the projected northwestward extension of the St. Francois volcanic terrane in north-central Missouri. This lends additional support to the postulated tectonic control of the older terrane on the emplacement of the younger.

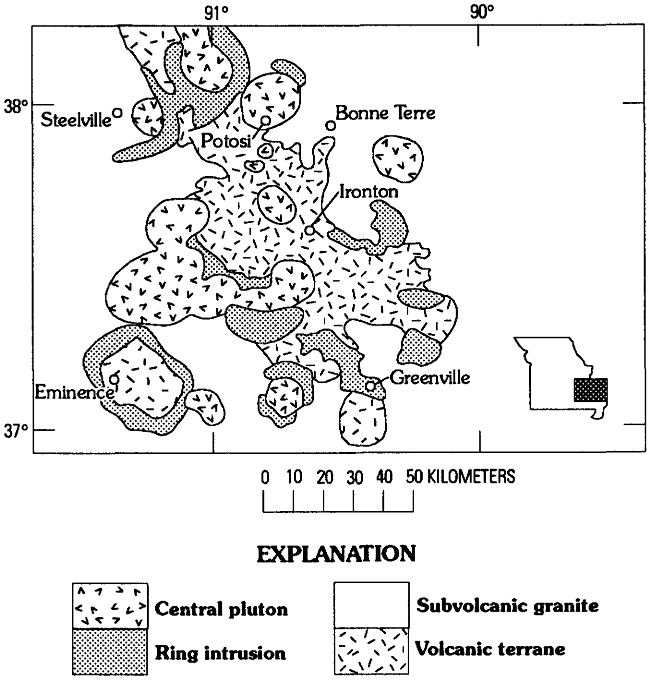

Figure 16. Geology of the St. Francois terrane, southeast Missouri, as interpreted from outcrop, drill-hole, and aeromagnetic data. Modified from Kisvarsanyi (1981).

Volcanic rocks of the St. Francois terrane are predominantly rhyolite ash-flow tuffs containing very high SiO_2, K_2O/Na_2O ratios, Fe/Mg ratios, and F abundances and low CaO, MgO, and Al_2O_3 abundances (Kisvarsanyi, 1972). They are characterized by perthitic alkali feldspar phenocrysts and iron-rich mafic minerals, including fayalite, ferrosilite, and ferrohastingsite. Although some of the rocks are transitional to comendites, their agpaitic index is always less than 1 (Kisvarsanyi, 1981). Intermediate and mafic rocks are notably rare and of small volume, although the volcanic suite is identified as bimodal because of the presence of minor basaltic flow rocks interlayered with rhyolite in the Taum Sauk area (Blades and Bickford, 1976). The intermediate rocks are chiefly trachyte and trachyandesite (Anderson, 1970; Kisvarsanyi, 1981). In general, the suite is distinguished from those of calc-alkaline petrogenetic provinces of subduction zones and compressional tectonic regimes by the absence of andesites and by alkali-rich chemistry.

Granitic rocks of the St. Francois terrane have been classified into three distinct types on the basis of composition and mode of occurrence (Kisvarsanyi, 1980, 1981): (1) subvolcanic granite massifs, (2) ring intrusions, and (3) central plutons. The subvolcanic granite massifs are comagmatic with the rhyolites and represent their intrusive equivalents. They are typical epizonal rocks having granophyric textures and containing perthitic alkali feldspar; biotite is the characteristic mafic mineral and magnetite is ubiquitous. Near their contact with the intruded rhyolites, the subvolcanic granite 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" discussed by Anderson (1983). The subvolcanic granite massifs are inferred to be the most widespread component of the St. Francois epizonal terrane (fig. 16). Wherever they are identified in drill holes, they are assumed to have been once covered by rhyolite that was stripped off during prolonged pre-Paleozoic erosion.

The ring intrusions are intermediate- to high-silica rocks whose emplacement was controlled by ring fractures related to caldera collapse and cauldron subsidence (fig. 16). 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 typically are high-silica, two-mica granites having distinctive accessory minerals and trace element suites (Kisvarsanyi, 1980, 1981). Accessory minerals include abundant fluorite, topaz, apatite, spinel, allanite, sphene, and cassiterite. Because of their relative enrichment in Sn, Li, Be, Rb, Ba, Y, Nb, U, Th, and F, the granites have been described as "tin granites" (Kisvarsanyi, 1980). They are inferred to have been emplaced in resurgent cauldrons, are circular to oval in plan, and are identified in the subsurface by distinctive negative magnetic anomalies.

Some and perhaps all of the 1.45- to 1.48-Ga granitic plutons of the Transcontinental anorogenic province possibly represent deeper analogues of the epizonal St. Francois terrane (Sims and others, 1987). Both the rapakivi massifs and tin granite plutons, intruding and partly assimilating rocks of the older crustal terrane, have been identified in the buried basement. It is fortuitous that unmetamorphosed volcanic rocks of Middle Proterozoic age are preserved at all in southeast Missouri because these rocks must have been protected in low-lying depressions, possibly rift valleys, whereas the surrounding regions were stripped of their supracrustal cover.

The older crustal terrane of the Central Plains orogen is inferred to underlie the younger epizonal terranes southward. Sm/Nd isotope data (Nelson and DePaolo, 1985) imply a 1.8- to 2.0-Ga crustal source from which the epizonal rocks in the southern Midcontinent were derived by partial melting. This is consistent with earlier data (Cullers and others, 1981), which indicate that at least 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 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 that existed within or near the margin of the Proterozoic North American continent. A rift-related genesis for the terrane was proposed by G. Kisvarsanyi (1975), an idea further developed by E.B. Kisvarsanyi (1980) as supporting trace element data became available. The terrane has many of the petrological and geochemical attributes of Proterozoic rifts and related extensional structures proposed for North America (Emslie, 1978; Anderson, 1983), except for anorthosite massifs, which have not been encountered in drill holes.

In terms of one of the proposed models for the evolution of new continental crust dominated by granitic rocks (Bowden and Turner, 1974), peraluminous and peralkaline igneous suites are derived through mantle pluming, crustal arching, and partial melting of a granodioritic lower crust and a granitic upper crust. This model does not require the presence of large volumes of basaltic rocks in association with the extensional structures because basaltic volcanism is not a major component of the crust-forming process. In the St. Francois terrane, the absence of large volumes of basaltic rocks precludes development of the type of rifting that led to extensive crustal separation; however, postorogenic mantle arching and attendant crustal melting is postulated to have led to the development of extensional structures where new sialic crust was formed. In contrast to the younger, Keweenawan rift system, the 1.48-Ga tensional event did not lead to crustal separation and the emplacement of large volumes of basaltic magma.

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 present in a few small outcrops of micrographic granite porphyry near Spavinaw, in Mayes County, northeast Oklahoma. Data from more than 300 drill holes indicate, however, that the terrane underlies most of northeast Oklahoma, eastern Kansas, southwest Missouri, and northern Arkansas (Denison, 1981, 1984; Kisvarsanyi, 1984; Thomas and others, 1984) and thus is an extensive Middle Proterozoic epizonal terrane in the southern part of the Midcontinent. As used in this report, the Spavinaw terrane includes all of the rocks of the northeastern Oklahoma province (Washington Volcanic Group, Spavinaw Granite Group, Osage Microgranite; all of Denison, 1981) and the Central Oklahoma Granite Group mapped in the subsurface by Denison (1981).

Volcanic rocks of the Spavinaw terrane (Washington Volcanic Group) are dominantly rhyolite, locally converted to metarhyolite (hornfels) by thermal metamorphism, and lesser dacite, trachyte, and andesite. Published chemical analyses of various rock units from selected drill holes in northeast Oklahoma suggest that rocks of intermediate composition are more widespread and (or) volumetrically 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 identical to those in the St. Francois terrane.

The volcanic rocks are on the northern and southern flanks of the broad, pre-sediment Spavinaw arch (Denison, 1966), which extends from central Oklahoma east-northeastward 240 km into southwest Missouri. The arch is underlain by micrographic granite porphyry and fine-grained granophyre of the Spavinaw Granite Group. 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 rapakivi plutons (1.35–1.40 Ga) (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 within the Transcontinental anorogenic province. Some of the rapakivi granite bodies in Missouri contain as much as 20 ppm Sn, 30 ppm Nb, and 5 ppm Be (E.L. Mosier, written commun., 1985) and have geochemical signatures similar to the tin granites identified in the St. Francois terrane (Kisvarsanyi, 1980). The available data, particularly the lack of aeromagnetic maps at 1:62,500 scale, do not permit delineation of ring complexes in the Spavinaw terrane as has been done in the St. Francois terrane.

The Spavinaw and the St. Francois rocks are essentially anorogenic epizonal granites and rhyolites that have not been regionally metamorphosed; thus, it is assumed that each terrane formed in comparable tectonic regimes by similar crustal processes. If a pre-rift, 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. It is possible that the thermal anomalies in the mantle and attendant magma generation shifted southwestward with time from the St.

Francois to the Spavinaw terrane. Although the 1.35- to 1.40-Ga Spavinaw terrane forms a fairly well defined, apparently continuous terrane in the four-State area of Kansas, Missouri, Oklahoma, and Arkansas, some 1.38-Ga plutons have been identified within the St. Francois terrane in southeastern Missouri (Thomas and others, 1984; Bickford and Mose, 1975; Latham and others, 1988), and other "exceptions" are likely to be present. These may indicate that thermal activity was almost continuous in the southern Midcontinent during the Middle Proterozoic but culminated in different areas at different times.

ORE DEPOSITS OF THE ST. FRANCOIS TERRANE

In terms of past production and future potential, the St. Francois terrane is one of the most important Precambrian metallogenic regions of the Midcontinent. It has been a continuous source of iron ore since 1815, with a cumulative production valued at more than $750 million and estimated reserves valued at $600 million in several undeveloped deposits. The terrane is also known for minor deposits of manganese and tin-tungsten-silver-lead veins (Silver Mine district). Furthermore, the terrane may have an enormous future potential for complex Olympic Dam–type deposits of copper, uranium, REE, and gold.

Iron Oxide-Rich Deposits

More than 30 iron ore deposits are known in the Precambrian rocks of southeast Missouri and constitute an iron metallogenic province of major significance. The majority of the deposits are in the exposed Precambrian rocks of the St. Francois Mountains and include the historically important Iron Mountain and Pilot Knob (upper orebody) deposits (fig. 17), which supplied iron for the Union cause during the Civil War. The six major deposits—Kratz Spring, Bourbon, Pea Ridge, Camels Hump, Boss (a copper-iron orebody of complex mineralogy), and Pilot Knob (lower orebody)—are in buried Precambrian rocks and were discovered by drilling on positive magnetic anomalies. Only the Pea Ridge and Pilot Knob (lower orebody) deposits have been developed; the Pilot Knob mine was shut down permanently in 1980, after 12 years of operation during which it produced 20 million tons of ore averaging between 35 and 40 percent Fe. The Pea Ridge mine is the only currently active iron mine in the district; except for a temporary shutdown in 1977–79, it has been in production since 1964. Ore grade at Pea Ridge is higher than at Pilot Knob, averaging between 53 and 57 percent Fe. Other areas in the St. Francois terrane where drilling has disclosed significant iron mineralization include the Lake Spring, Missionary Ridge, and Floyd Tower magnetic anomalies (fig. 17).

The Precambrian iron ore deposits of southeast Missouri have been classified as "Kiruna type" by Kisvarsanyi and Proctor (1967) because of many similarities to the Precambrian, volcanic-hosted, magnetite-apatite deposits in the Kiruna district of Norbotten, northern Sweden. The Missouri deposits, however, display a wide variety of features ranging from magmatic injection through hydrothermal veins and disseminations and contact metasomatic replacements to volcanic exhalative impregnations. Because of the wide range of features, various theories have been advocated for the genesis of the orebodies (see Emery, 1968, for Pea Ridge; Murphy

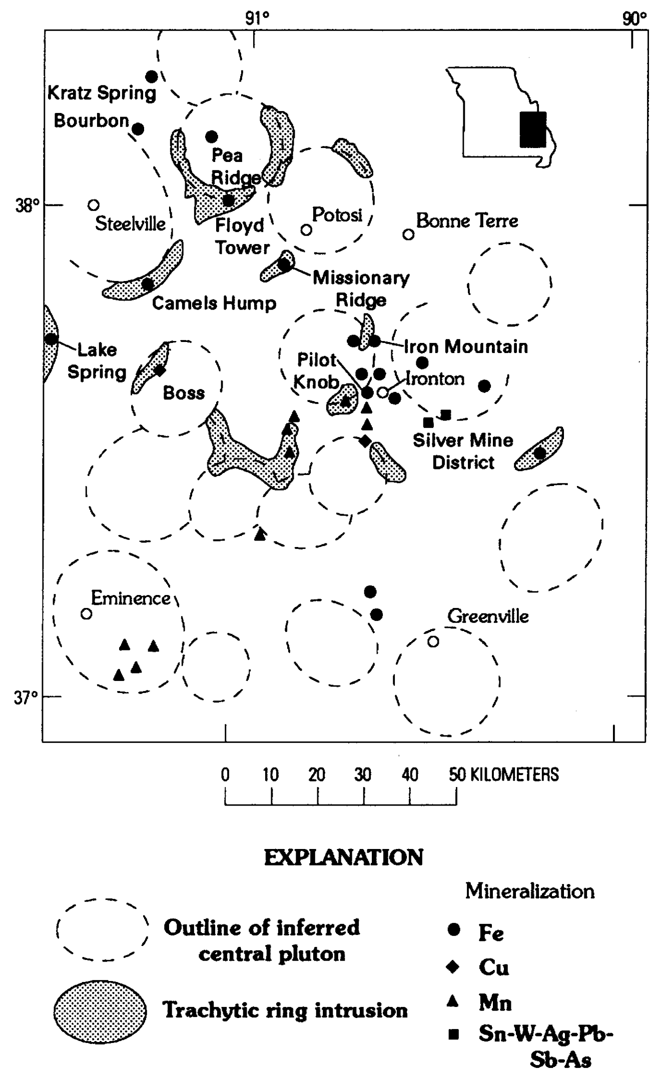

Figure 17. Ring structures, alkaline-intermediate rocks, and mineralization in the St. Francois terrane, southeast Missouri.

and Ohle, 1968, for Iron Mountain; Kisvarsanyi and Proctor, 1967, for Bourbon, Boss, and the small surface iron orebodies; Wracher, 1976, and Panno and Hood, 1983, for the Pilot Knob lower orebody; Anderson, 1976, and Ryan, 1981, for the Pilot Knob upper orebody; and Snyder, 1969, for a general review of all the Precambrian iron deposits of the terrane).

The principal ore minerals are magnetite and hematite; the Boss deposit contains appreciable amounts of copper sulfide minerals. The major deposits have a complex gangue mineral assemblage that includes garnet, quartz, calcite, actinolite, apatite, dolomite, fluorite, pyrite, and barite. At the Pea Ridge mine, a phosphate (apatite) concentrate has been recovered as a byproduct and used as a fertilizer; reportedly, an REE concentrate consisting chiefly of monazite has also been recovered.

The Boss deposit displays by far the most complex ore mineralogy. It was explored during the 1950's and 1960's by intensive drilling that produced approximately 100,000 ft of Precambrian core. Kisvarsanyi and Smith (1988) reported chalcopyrite, bornite, pyrite, molybdenite, cobaltite, sphalerite, galena, chalcocite, and covellite in the ore in addition to iron oxide minerals, ilmenite, and rutile. They also reported potassium feldspar, garnet, biotite, muscovite (sericite), actinolite, epidote, chlorite, calcite, fluorite, and gypsum, but no apatite, and classified the mineralization as a high-temperature contact metasomatic deposit. Hagni and Brandom (1988) reported electrum, consisting of about 90 percent Au and 10 percent Ag, and an unspecified telluride mineral in the Boss ore.

The orebodies display a variety of shapes and emplacement characteristics. There are tabular, dikelike, disc-shaped, cone-sheetlike, stratiform, and irregular orebodies known among them. Many of the orebodies are steeply inclined and were emplaced as massive fracture fillings. A significant component of most of the major deposits, notably Pea Ridge, Pilot Knob (lower orebody), and Iron Mountain, is breccia ore characterized by angular volcanic-rock clasts of diverse sizes cemented by the ore minerals. The orebodies seem to be spatially associated with Precambrian volcanotectonic features, such as calderas and ring-fracture systems in the St. Francois terrane (fig. 17). Fracturing and massive brecciation of the volcanic rocks resulting from cauldron subsidence and caldera collapse probably controlled emplacement of the deposits and provided favorable sites for ore deposition (Kisvarsanyi and Kisvarsanyi, 1981).

A distinctive suite of alkaline-intermediate rocks, consisting of syenite, trachyte, magnetite trachyte, and trachyandesite (the trachyte suite of Kisvarsanyi, 1981), has been recognized in association with many of the deposits. This suite of rocks typically forms ring intrusions in the St. Francois terrane. Crosscutting relationships observed in the mines and in drill cores indicate that the timing of the mineralization is related to that of the ring intrusions. A common source, an alkaline-intermediate magma, for both the trachyte suite of rocks and the iron ores has been postulated (Kisvarsanyi and Kisvarsanyi, 1981).

Manganese Deposits

Several small manganese prospects in rhyolite are known in the southern part of the St. Francois Mountains (fig. 17). These deposits are of historical interest, most of them having produced only 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.

The most productive of the old mines was the Cuthbertson or Marble Creek mine, which produced about 3,000 short tons of manganese ores and concentrates, containing more than 50 percent Mn, during intermittent mining between 1872 and 1958 (Dorr, 1967). The mineralization is of the stratiform type in waterlaid, bedded tuffs. Interbedding of the manganiferous tuffs with thin beds of travertine suggests that the deposit formed in a crater lake–type 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 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.

The Silver Mine District

Deposits in the Silver Mine district 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 (fig. 17). The Silvermine Granite, one of the ring intrusions in the terrane, is cut by polymetallic quartz veins that have accompanying extensive greisenization of the wall rock. The mineral suite includes argentiferous galena, wolframite, arsenopyrite, sphalerite, cassiterite, chalcopyrite, covellite, hematite, stolzite, and scheelite—similar to the deposits of Cornwall and Saxony (Tolman, 1933; Lowell, 1976). Hagni (1984) identified argentiferous tennantite, antimonpearcite, and berryite in the main sulfide stage of mineralization and concluded that the base metal sulfide minerals 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 mineralization post-dates 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 for silver from 1877 to 1894 and produced an estimated 3,000 ounces, as well as some 50 tons of lead. Between 1916 and 1946, an estimated 120 short tons of tungsten concentrates was 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 below about 200 ft 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. 17) suggests structural control for the emplacement of the deposits. Similar deposits may be associated with buried ring complexes elsewhere in the region. The Silver Mine–type deposits are considered to be part of an important nonferrous metallogenic epoch that was related to later stages of Precambrian igneous activity, possibly, to resurgence in some calderas.

The Olympic Dam Analogy

The discovery in 1975 of the Olympic Dam deposit at Roxby Downs, South Australia, and subsequent reports about its apparently unique mineralization and giant size inspired the development of new exploration concepts pertaining to iron oxide–rich Middle Proterozoic deposits in the Midcontinent of the United States. Hauck and Kendall (1984; Hauck, this volume) developed an exploration model for an Olympic Dam-type deposit in the region and suggested a genetic similarity between the Precambrian iron ores of the Kiruna district, southeast Missouri, and South Australia. Several exploration companies apparently developed similar models at about the same time, and at least 10 exploration holes have been drilled in southern Missouri with the elusive Olympic Dam–type deposit as the target. This exploration activity was abruptly terminated in mid-1983 when the U.S. minerals industry suffered a major setback.

The fundamental analogies between the regional geologic settings of the Olympic Dam deposit (Roberts and Hudson, 1983; Hauck, this volume) and the Precambrian metallogenic region of southeast Missouri are:

1. Stable cratonic region;
2. Extensional tectonic regime;
3. Long, linear, fault-controlled tectonic elements;
4. Local accumulation of clastic sediments and breccias;
5. Similar age of the host rocks (about 1.5 Ga); and
6. Similar petrology and geochemistry of the host rocks (alkaline, anorogenic, bimodal volcanic-plutonic suite, and enrichment in iron, REE, phosphorus, fluorine, and other incompatible elements).

Sims and others (1987) noted these analogies and concluded that the anorogenic terranes of the Precambrian basement in the Midcontinent are generally favorable for the occurrence of Olympic Dam–type deposits. They attributed particular importance to the local accumulation of clastic rocks in fault-controlled basins, as in the graben defined by the Chesapeake and Bolivar-Mansfield tectonic zones in southwest Missouri (Kisvarsanyi, 1984), because the Olympic Dam mineralization reportedly was emplaced within a thick sequence of coarse clastic sedimentary rocks and granitic breccias (Roberts and Hudson, 1983).

CONCLUSIONS AND RECOMMENDATIONS

As results of ongoing research emerge on the Olympic Dam deposit itself (Einaudi and Oreskes, this volume) and as specific comparisons continue to be made with the Midcontinent deposits, the analogies between the Olympic Dam and Midcontinent deposits appear to be more numerous, and the potential for an Olympic Dam–type deposit in the Midcontinent is greatly enhanced. The discovery of gold and telluride minerals in the Boss copper-iron deposit (Hagni and Brandom, 1988) increases the similarities between the respective mineralizations. In the Pea Ridge orebody, a thorium-REE vein, abundant copper sulfide minerals with gold, and anomalous concentrations of tin have recently been recognized (Pea Ridge Iron Ore Company, oral commun., 1988). In view of the new data, a reexamination of all the iron oxide–rich deposits of the St. Francois terrane is warranted. A comprehensive and coordinated research effort should undertake the study of the metallogenesis of all known orebodies, including those of the Silver Mine district, in order to understand the complex magmatic, hydrothermal, tectonic, and sedimentary processes that produced the diverse deposits of the region.

A comprehensive research effort directed at the St. Francois metallogenic terrane could conceivably answer some unresolved questions about the Olympic Dam deposit itself. It should address some of the following questions:

1. Are Olympic Dam breccias analogous to the volcanic breccias associated with the Missouri iron ores?

2. Is the Olympic Dam deposit similar to the hematite-rich breccias and bedded iron ores in the St. Francois terrane, and is it therefore a more evolved, higher (crustal) level deposit in a similar, complex, evolving, magmatic and hydrothermal ore system?

3. Is the magnetic anomaly at Olympic Dam the expression of a Pea Ridge-type orebody below the level of the hematite-rich deposit?

4. Are the REE, gold, silver, tin, copper, uranium, and thorium enrichments in the ores the imprint of a later, Silver Mine–type metallogenic process (the "transgressive mineralization" of Roberts and Hudson, 1983)?

5. What is the source and derivation of the iron, the all-important and pervasive component of both the Proterozoic host rocks and ores?

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Progress Toward An Occurrence Model for Proterozoic Iron Oxide Deposits—A Comparison Between the Ore Provinces of South Australia and Southeast Missouri

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Abstract

The Stuart Shelf region of South Australia and the St. Francois Mountains of southeast Missouri host iron-rich mineral deposits in alkalic igneous settings of mid-Proterozoic age. These deposits have been known historically as sources of iron ore, but they may also contain economic concentrations of copper, uranium, gold, silver, and (or) rare-earth elements. The largest of these are the Olympic Dam deposit in Australia and the Pea Ridge deposit in Missouri. Striking similarities exist both between the Olympic Dam and Pea Ridge deposits and between the general features of the two ore provinces. In addition to a broad similarity of age and regional setting, the deposits display similarities in large-scale wall-rock alteration and replacement, open-space veining and hydrothermal brecciation, abundant carbonate, barite, and (or) fluorite gangue minerals, and variable but locally significant abundances of copper-iron sulfide minerals. Variation among deposits of one province is as great as variation between deposits of different provinces and may be attributed to differences in wall-rock composition, structural control, depth of formation, and (or) metal content of local basement. We conclude that it is useful and appropriate to think of Olympic Dam and Pea Ridge and, by extension, other deposits in these regions, as belonging to the same class of mineral deposit, and that the observed diversity reflects the same fundamental process operating in different local environments.

There is general agreement on the tectonic setting of these deposits, but considerable controversy as to the nature of the ore fluid, mechanisms of ore emplacement, and interpretation of elemental abundances. Most interpretations center on either (1) hydrothermal alteration and replacement or (2) immiscible iron oxide magma injection. Although these two hypotheses are not mutually exclusive, in many cases these contrasting interpretations are based on the same outcrop. At both Olympic Dam and Pea Ridge, the field relations and ore textures do not require that an iron oxide magma was involved at any stage of the mineralizing process. In contrast, many aspects of the field relations, ore textures, mineralogy, and wall-rock alteration require that an aqueous hydrothermal fluid was involved at some stage. Furthermore, evidence from Olympic Dam suggests that fluids were circulated in a major, disruptive hydrothermal system, capable of mobilizing a variety of elements including rare-earth elements and physically transporting rock fragments. The conflict between these various interpretations, and their implications for understanding Proterozoic tectonic evolution, make these deposits an important topic for future study.

INTRODUCTION

In this paper we compare the iron provinces of the Stuart Shelf region, South Australia, and the St. Francois Mountains, southeast Missouri. The mineral deposits in these areas, including the world-class Olympic Dam copper, uranium, gold, silver, and rare-earth element (REE) deposit in South Australia, are iron-rich rocks that are found in alkalic igneous settings of mid-Proterozoic age (Meyer, 1988a). Analogous types of deposits are found on other continents, including Europe (Kiruna, Sweden) and Asia (Bayan Obo, Inner Mongolia, People's Republic of China). The origin of these deposits and their classification into deposit types have been the subject of much speculation in the recent literature. For this reason, we felt that it would be useful to provide a summary based on our personal observations, recent unpublished field studies, and publications that are of limited circulation and therefore not generally available.

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Although emphasis is placed on the comparison between the Olympic Dam deposit and the Pea Ridge deposit of southeast Missouri, a broader perspective on the scale of entire metallogenic provinces, which takes into account several deposits, is necessary in order to avoid overly provincial conclusions.

We conclude that striking similarities exist at all scales, and that the geological characteristics of both provinces and their mineral deposits reflect similar petrotectonic histories and ore-forming processes. The same features (such as metal suite and deposit morphology) are not shared by all iron deposits in both provinces, but one would not expect this to be the case. Diversity reflects variations on the same fundamental ore-forming process operating in different local environments. It is this variability and the links between deposit types that invites study.

One goal would be to list and describe essential features of these deposits on the basis of comparison, but this goal remains to be achieved and depends on further study. We hope that the present report contributes to a better definition of research directions to be pursued in both provinces as we move toward a genetic understanding.

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THE CONTEXT: ANALOGIES BETWEEN OLYMPIC DAM AND OTHER DEPOSITS

The size and economic significance of the Olympic Dam Cu-U-Au-Ag deposit have led to considerable discussion regarding its origin and inspired reexamination of similar deposits. Roberts and Hudson (1983) concluded that Olympic Dam is a new type of stratabound sediment-hosted ore deposit having features that can be explained by low-temperature syngenetic or diagenetic processes. However, a number of authors (for example, N.G. Maund, B.P. Minerals, oral commun., 1982; Goodell and Keller, 1984; Hauck and Kendall, 1984; Brandom and others, 1985; Meyer, 1988a, b) noted similarities between Olympic Dam and the magnetite-apatite deposits of Kiruna, Sweden, the southeast Missouri iron province, and the iron-REE deposit of Bayan Obo, Inner Mongolia. Other workers (Bell, 1982; Youles, 1984) have drawn analogies between Olympic Dam and the hydrothermal Fe-Cu-U-REE breccias of Mount Painter, South Australia, and the Wernecke Mountains, Yukon.

Hauck and Kendall (1984) and Meyer (1988a) summarized the features of a subset of the deposits listed above as: "iron deposits *** in oxidized alkalic igneous settings of mid-Proterozoic age" (Meyer, 1988a, p. 13). Meyer divided the subset into two deposit types: "Kiruna-type Iron Ores" (Kiruna and southeast Missouri), and "Olympic Dam-Type Cu-U-Au Ores" (Olympic Dam, Mt. Painter, and Bayan Obo). Presumably, Meyer did not treat all of these deposits as one type because of the differences in relative metal content (the Kiruna and Missouri deposits have much lower uranium and REE contents) and in gangue mineralogy (the Kiruna and Missouri deposits contain less carbonate minerals). Considering these differences to be only variations on a theme, the common features for the subset as a whole has the following characteristics (based on Hauck and Kendall, 1984; Meyer, 1988a):

1. Subvolcanic environment in rifted continental crust setting is associated with 1.7–1.1-Ga alkalic rock suite.
2. Ores are associated with an anorogenic, dominantly felsic, alkalic rock suite ranging from "red" granite and rapakivi granite to mangerite and charnockite and various volcanic equivalents.
3. Igneous rocks contain abundant iron oxide minerals as accessories, and alkali feldspars are brick red due to exsolved hematite.
4. Mineral deposits commonly exceed 1 billion tons of greater than 20 percent Fe (as magnetite and (or) hematite) and contain various lithophile elements such as uranium and REE, fluorine, and phosphorus.
5. Sulfide minerals may also be present, especially those of copper, and these commonly are intimately associated with iron oxide minerals.
6. Carbonate minerals, fluorite, and barite are common but not ubiquitous.

COMPARISON OF STUART SHELF AND SOUTHEAST MISSOURI IRON PROVINCES

"It is a well-known fact that the pre-Cambrian iron mineralization in southeastern Missouri exhibits considerable local diversity in mode of occurrence and mineral assemblage" (Meyer, 1939, p. 128). This statement also applies to the iron deposits of the Stuart Shelf region. The differences in characteristic features, combined with differences in interpretation of the same field relations, have led to considerable controversy on genetic hypotheses. The summary of key features that follows proceeds from regional to mineralogical scales; we conclude with a discussion of genetic hypotheses.

Age

Mineral deposits in the two provinces formed at virtually the same time in the mid-Proterozoic. The age of Olympic Dam deposit is less than 1,600 Ma (U-Pb zircon age of granite host rock; Mortimer and others, 1988) and greater than 680 Ma (Rb-Sr age of cover sediments; Webb and others, 1983). Unpublished isotopic age data on sericite and pitchblende (L.B. Gustafson, oral commun., 1979; N.N.A. Trueman, oral commun., 1985), relative lead and strontium isotope closure dates for apatite and biotite (Mortimer and others, 1988), and geologic relations (see later) suggest that the hydrothermal activity that produced Olympic Dam could be 100–200 m.y. younger than the granite host (Oreskes and Einaudi, 1990). Such an age would overlap with 1,525–1,450-million-year silicic volcanic and plutonic rocks exposed in the Gawler Ranges to the southwest (Webb and others, 1986) and thought to extend under the Stuart Shelf (see later).

Most workers in the southeast Missouri iron province have concluded that the mineral deposits of the province are coeval with some of the igneous activity in the St. Francois terrane (Singewald and Milton, 1929; Meyer, 1939; Kisvarsanyi and Proctor, 1967), which has been dated by U-Pb methods on zircon at 1,480 Ma, with some late plutons at 1,380 Ma (Bickford and Mose, 1975; Bickford and others, 1981).

Regional Setting

The two iron provinces share many features in their regional setting, including an association with silicic-alkalic volcanism and plutonism in a cratonic rift setting. In South Australia, the deposits are in the unexposed, pre-Adelaidean basement of the Stuart Shelf. Exploratory drilling shows that the basement consists of gneiss, calcareous and hematitic metasedimentary rocks, and deformed granite (Paterson, 1986a; Parker, 1987) that are intruded by undeformed Middle Proterozoic granite that hosts the ores at Olympic Dam. Although volcanic rocks are a minor component at Olympic Dam, felsic to intermediate ash-flow tuffs and flow rocks and granitic rocks are major components of the wall rocks in other deposits of the Stuart Shelf, such as Acropolis (Paterson, 1986a, b). The Stuart Shelf is bounded to the south and west by the Gawler craton, a province of Archean to Early Proterozoic gneiss complexes and metasedimentary rocks that was intruded by syntectonic (Kimban orogeny) granites at 1,800–1,600 Ma (Webb and others, 1986). The Kimban orogeny was followed by anorogenic silicic volcanism (Gawler Range Volcanics) at 1,525–1,490 Ma and the emplacement of high-level, alkali-rich granitic plutons (Hiltaba Suite) at 1,500–1,450 Ma (Rutland and others, 1980; Cooper and others, 1985; Webb and others, 1986). It is now generally recognized that Proterozoic basement rocks of the Stuart Shelf are broadly correlative with rocks of the Gawler craton (Roberts and Hudson, 1983; Paterson, 1986a; Parker, 1987; Mortimer and others, 1988). Silicic volcanism and plutonism at about 1,525–1,450 Ma occurred in a broad, east-northeast trending, intracratonic belt from the Gawler Ranges Province to the Stuart Shelf and possibly extended (under the present Adelaidean cover) as far east as the Mount Painter region. Northwest-trending photolineaments may reflect extensional grabens (O'Driscoll, 1982; Roberts and Hudson, 1983), superimposed on the east-northeast-trending granite terrane at about 1,400 Ma, that controlled the disposition of continental red-beds (Pandurra Formation) and younger dolerite dike swarms and intrusions (Parker, 1987).

Iron deposits of southeast Missouri are found in a Middle Proterozoic continental setting within the St. Francois terrane, which consists predominantly of alkalic rhyolite and associated granite and lesser amounts of basalt, trachyte, and trachyandesite (Kisvarsanyi, 1981). Emplacement of igneous rocks was probably controlled by northwest-trending basement structures of Early Proterozoic age (Sims and others, 1987). The terrane is thought to consist of numerous ring dike complexes and resurgent calderas (Kisvarsanyi, 1980, 1981; Sides and others, 1981), and a continental rift setting has been proposed (Kisvarsanyi, 1975; Kisvarsanyi, 1980).

Province Dimensions and Clustering of Deposits

The linear array of deposits and the dimensions of the two provinces are strikingly similar. Both ore provinces are related to an igneous terrane that measures on the order of tens of thousands of square kilometers, and both contain a linear clustering of numerous individual deposits.

The Stuart Shelf province contains six major known iron occurrences (Olympic Dam, Acropolis, Wirrda Well, Oak Dam, Dromedary Dam, and Bopeechee) (fig. 18); numerous small magnetic anomalies have not been drilled (Paterson, 1986a). The deposits define a province that is elongate north-northwest for a distance of 110 km, from Bopeechee on the north to Oak Dam on the south; the province is 35 km wide, from Acropolis on the west to Wirrda Well on the east. The deposits are 15–30 km apart.

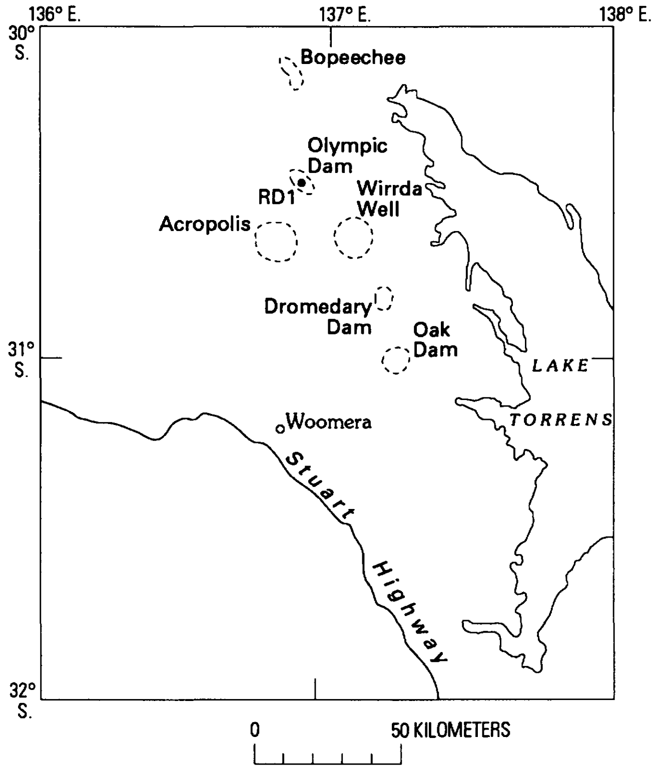

Figure 18. Major iron occurrences (delineated by dashed lines) on the Stuart Shelf of South Australia.

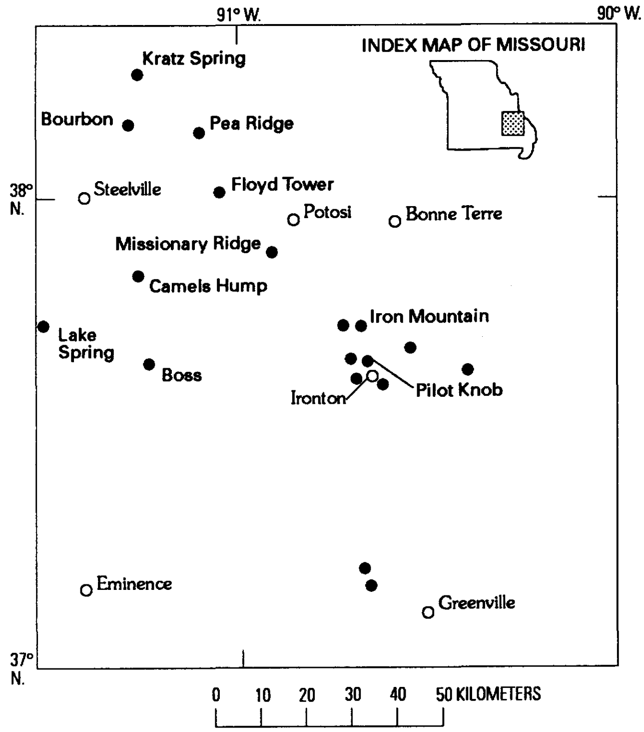

Figure 19. Missouri iron deposits (solid circles). Modified from Kisvarsanyi (this volume, fig. 17).

The southeast Missouri province contains 6 major known iron deposits and 24 others of lesser known importance (Sims and others, 1987). Districts and deposits define a province that is elongate north-northwest for a distance of 125 km, from Kratz Spring on the north to Greenville on the south; the province is 46 km wide, from Boss on the west to Iron Mountain on the east (fig. 19) (Kisvarsanyi, 1988, fig. 5). The deposits are 10–30 km apart.

Magmatic Affiliation

A spatial correlation between deposits and anorogenic silicic-alkalic igneous rock suites is recognized in both provinces, although the magmatic histories are complex and the genetic relationships between mineral deposits and a given magma type or magmatic episode remain to be demonstrated, particularly in the Stuart Shelf. Meyer (1988a, b) suggested that a regional genetic connection exists between Proterozoic iron deposits worldwide, crustal melts that included banded iron formation in their source regions, and carbonatites, although direct evidence of carbonatites is lacking on a local scale.

Iron deposits on the Stuart Shelf are within a wide textural variety of granitic and volcanic rocks. The granite of Olympic Dam, host to the orebody, is a pink to yellowish-green, coarse- to medium-grained, equigranular biotite granite. It has characteristics of alkalic granites (Roberts and Hudson, 1983). Mortimer and others (1988) classified it as a quartz syenite but may have in part studied altered granite. Similar granites and granitic gneisses are wall rocks in other deposits of the Stuart Shelf (Paterson, 1986a). At the Acropolis deposit diorite, potassium-rich granite, gneissic granite, and alkali quartz syenite are present (and all are altered and (or) mineralized). A thick sequence of volcanic rocks is preserved at Acropolis; extensive hematization and chloritization mask the original rock types, but they are porphyritic and probably are felsic to intermediate flow rocks and ash-flow tuffs (Paterson, 1986b).

The granite of Olympic Dam is too coarse grained to represent a subvolcanic intrusion, and, inasmuch as all the evidence points to a near-surface origin for the ore deposit (Oreskes and Einaudi, 1990; Reeve and others, 1990), we do not believe that there is a close temporal and genetic relation between ore-forming hydrothermal activity and the granite of Olympic Dam. Local felsic porphyry dikes, altered and dismembered by faults and breccia columns, may be an expression of the volcanic link, but nothing is known about the original composition of the volcanic rock. Undated diorite plugs and dolerite dikes cut the mineral deposits (Roberts and Hudson, 1983; Paterson, 1986a; Reeve and others, 1990) and therefore are younger. Roberts and Hudson (1983) suggested that there may be a link between the high contents of potassium, REE, barium, and fluorine in the Olympic Dam deposit and unidentified alkaline igneous activity in the region.

The St. Francois terrane is mostly composed of silicic-alkalic igneous rocks containing very high abundances of fluorine and SiO_2, high K_2O/Na_2O and Fe/Mg ratios, and low abundances of CaO, MgO, and Al_2O_3. The rocks are characterized by alkali feldspar phenocrysts and iron-rich mafic minerals (see summary, Sims and others, 1987). Volcanic rocks consist chiefly of rhyolite ash-flow tuffs and porphyritic flows; these are the host rocks for the majority of iron deposits. Comagmatic intrusions include fine-grained granophyre and coarse-grained rapakivi granite. In addition to the rhyolite host rocks, some deposits are hosted in other igneous rock types as well: at Boss-Bixby a syenite stock is mineralized (Snyder, 1968; Kisvarsanyi and Smith, 1988), and at Iron Mountain much of the ore is in an andesite flow (Murphy and Ohle, 1968). The iron ores postdate the alkali rhyolites and related intrusive rocks described above and predate high-silica, two-mica "tin granites" (Kisvarsanyi and Kisvarsanyi, 1977; Kisvarsanyi, 1981). At the Pea Ridge mine, younger mafic dikes and aplitic quartz-alkali feldspar dikes cut the magnetite ore breccias (Emery, 1968); recent mapping indicates that muscovite-biotite granite pegmatites and quartz-cassiterite veins, possibly related to the two-mica granites, also cut the orebody (L. Nuelle, M. Marikos, and M. Einaudi, unpub. data, 1988). Kisvarsanyi (1981) proposed a genetic relation between the iron ores of southeast Missouri and a suite of subvolcanic ring intrusions of trachyte, syenite, and trachyandesite. Trace element data suggest that these rocks were derived from partial melts of older crustal rocks (Cullers and others, 1981).

Morphology and Structural Control of Orebodies

Except for the broad regional controls involving possible continental rifts or other forms of deep crustal structures, the structural control for the localization of individual deposits is poorly known in both provinces. Orebody morphologies may be controlled by local features of secondary rock permeability such as fault or shear zones and intrusive contacts (leading to steep, dike- or pipe-like morphology) and by zones of high primary rock permeability such as porous tuffs, poorly welded portions of ash-flow tuffs, and certain sedimentary strata (producing tabular-concordant morphology).

Perhaps the best established structural control is in the Olympic Dam deposit. Here, we have shown (Oreskes and Einaudi, 1990) that the heterolithic hematite-granite breccia bodies, many of which are elongate and dikelike, strike north-northwest, parallel with regional photolinears. These breccias commonly display steeply dipping, wavy foliation broadly parallel with the orientation of the breccias. We interpret the overall deposit morphology and foliation to reflect structural control by preexisting, steep north-northwest-striking faults that were probably active during formation of the breccias (Oreskes and Einaudi, 1990). Toward the margins of the hematitic breccias, discontinuous layers of crushed granite are interleaved with hematite-quartz microbreccia. Similar textures were described by Meyer (1939, p. 132) in the magnetite-hematite fissure veins on Shepherd Mountain, near Pilot Knob, southeast Missouri, as "flecks and stringers of red feldspathic material penetrate the granular ore in crudely parallel bands." The feldspathic material consists of "severely altered" and locally "fractured and twisted" coarse-grained feldspar. Meyer concluded that these layers are hydrothermal in origin and were subjected to differential stress after they formed. The fissure veins on Shepherd Mountain were thought to be representative of channelways for hydrothermal solutions that formed higher level stratabound replacement ores in favorable horizons such as the concordant hematite ores in bedded pyroclastic rocks at the summit of Pilot Knob (Meyer, 1939, p. 194–195).

Snyder (1968) described the overall morphology of the Pea Ridge magnetite body as a discordant, vertical, dikelike mass, crescentic in plan view, with an 800 m strike length, 100 m thickness, and vertical extent beyond the limit of drilling at 700 m. This view of the deposit morphology may change as we assess the extent of post-ore faulting and the timing of ore formation relative to the age of the enclosing volcanic rocks, which also dip steeply. If the magnetite orebody formed in a vertical attitude, it would have had to postdate significant tilting of the enclosing volcanic rocks. Other massive iron deposits of the Missouri province display variable morphology, including (1) dome-shaped shells having vertical limbs at Iron Mountain, interpreted as vaulted collapse structures (Murphy and Ohle, 1968); (2) irregular, steeply dipping bodies parallel with intrusive margins at Boss-Bixby (Snyder, 1968; Kisvarsanyi and Smith, 1988); and (3) tabular-concordant bodies in unwelded portions of ash-flow tuffs at the Pilot Knob subsurface deposit (Panno and Hood, 1983) and in well-bedded volcaniclastic breccias and sedimentary rocks at the Pilot Knob surface deposit (Meyer, 1939).

Textures of Orebodies and Relation to Wall Rocks

Massive iron oxide-bearing rocks, various types of breccias having an iron oxide matrix, and layering, foliation, or stratification are common features of iron ores in both provinces. Most of the textures can be ascribed to hydrothermal processes including large-scale wall-rock replacement, which in many cases preserves wall-rock textures; open-space veining accompanying fracturing; and hydrothermal brecciation accompanying massive iron oxide mineralization. Where original unfaulted contacts are preserved, some degree of gradation between massive iron oxide bodies and their enclosing wall rocks is observed; sharp contacts between the two rarely have been described except for open-space veins. This gradation is expressed in a variety of ways including increased density of veins or abundance of iron oxide disseminations or decreased abundance and size of wall-rock fragments toward the center of the deposit.

The most striking feature of the breccias of Olympic Dam is lacking in the deposits that have been described in southeast Missouri: vast volumes of heterolithic, matrix-supported breccias consisting of 30–70 percent iron oxide matrix and fragments generally less than 10 cm in diameter. Also missing from the southeast Missouri deposits are examples of the iron oxide (quartz) microbreccia and local accretionary lapilli (related to fluidization?) that constitute the central core of the Olympic Dam deposit (Oreskes and Einaudi, 1990). These breccia types can be considered, however, to be the result of local variations in the intensity of the brecciation process; many other features of orebody textures are common to both provinces. These include finely laminated hematitic siltstones and hematitic volcaniclastic conglomerates at Olympic Dam (Oreskes and Einaudi, 1990), Oak Dam (Parker, 1987) and the Pilot Knob surface deposit (Meyer, 1939); magnetite veins and veinlets at Acropolis, Olympic Dam (Paterson, 1986b; Oreskes and Einaudi, 1990), Pea Ridge, Pilot Knob, Boss Bixby, and Iron Mountain (Meyer, 1939; Murphy and Ohle, 1968), and iron oxide disseminations in associated igneous rocks on a broad scale.

The hematitic siltstones at Olympic Dam and the Pilot Knob surface deposit are remarkably similar in appearance. At Olympic Dam, we found "hematite clasts" within these siltstones and believe that at least some detrital hematite component is present, although much of the fine-grained euhedral hematite dispersed through the beds may have been precipitated (or recrystallized?) in situ before the silts were lithified. At the Pilot Knob surface deposit, Meyer (1939) and Panno and Hood (1983) interpreted the textures as evidence of replacement of matrix siltstone and of selective replacement of porous volcanic clasts by iron oxide minerals. Anderson (1976) and Nold (1988), on the other hand, concluded that these clasts were mineralized before incorporation into the sedimentary breccia and that the bulk of evidence favors syngenetic deposition of hematite in a sedimentary environment.

In contrast with the sedimentary rocks, evidence from igneous rocks for replacement by iron oxide minerals is widespread and relatively unambiguous. At Olympic Dam, we recognized both relict granite textures in the subsurface in hematite rock on scales of tens of meters and relict feldspar phenocrysts (pseudomorphed by hematite) in thin sections of even the most massive ore (Oreskes and Einaudi, 1990). At Pilot Knob, Panno and Hood (1983) described gradational contacts between ore and tuff; glass shards and pumice fragments in the ore convinced them that ore replaced tuff. At Iron Mountain, local gradational contacts between ore and andesite wall rocks were interpreted by Murphy and Ohle (1968) to be the result of replacement.

At Pea Ridge, preliminary underground mapping reveals that at least some of the margins of the deposit are subparallel with compaction or flow foliation in the enclosing volcanic rocks. Conformity of ore with "flow structures" in the volcanic host rock was noted at other deposits in southeast Missouri, including Bourbon and Kratz Springs (Snyder, 1968). This parallelism is particularly evident at Pea Ridge in those areas where magnetite-hematite bodies are in unfaulted contact with their original volcanic wall rocks and where the process of wall-rock replacement can be seen through the progressive increase in abundance of veins and streaks of iron oxide minerals within the rock foliation. Wall-rock clasts are most abundant in the hematitic borders of the ore and are less common within the core of massive magnetite. The generally massive, textureless nature of the magnetite bodies at Pea Ridge is reminiscent of magnetite bodies at Acropolis, South Australia.

The absence of relict igneous minerals in massive iron oxide bodies or in matrices of ore breccias is not conclusive evidence for the mechanism of ore emplacement. Such relations could indicate either that precursor rock or rock flour was totally replaced or that mineralization occurred in open spaces. Unambiguous evidence for the latter mechanism is provided by Murphy and Ohle (1968) in their description of banded ore veins at Iron Mountain; on the basis of these and other textures, Murphy and Ohle concluded that most of the ore formed in open spaces.

Metal Suites

The Olympic Dam deposit contains more than 2 billion metric tons of rock having an average grade of 20 percent Fe, 1.6 percent Cu, 0.5 kg/t uranium oxide, 0.5 g/t Au, 3.5 g/t Ag, and greater than 1,500 ppm REE. In addition to these elements, Olympic Dam is highly anomalous in Ba, F, S, $CO_3^=$, and P and is slightly anomalous in Co, Ni, Cr, As, and Te (Roberts and Hudson, 1983, 1984). Acropolis contains significant Cu, U, and REE in massive magnetite bodies; one drill hole intersected 66 m of 0.7 percent Cu and 35 ppm U_3O_8 (Paterson, 1986b). Subeconomic U, Cu, and Au concentrations are associated with magnetite-hematite at Wirrda Well, and subeconomic uranium and REE concentrations are associated with hematite at Oak Dam (Parker, 1987). Based on metal grades, it has commonly been stated that drilling on the Stuart Shelf has not found another Olympic Dam; however, based on broader geologic relations as summarized above, numerous mineral deposits similar to Olympic Dam exist in the basement of the Stuart Shelf. Just as in the southeast Missouri province, these deposits exhibit extreme variations in their contents of metals other than iron. Some of these variations, particularly in copper and uranium, may be the result of supergene enrichment processes (Meyer, 1988a; Oreskes and Einaudi, 1990). Differences in metal contents also may reflect exposure of different levels in the original systems. These variations may be expressed in part by variations in the proportion of magnetite to hematite in the ores; the hematite-dominant ores of Olympic Dam could be the more near surface expression of magnetite-dominant ores such as those drilled at Acropolis. Variations in magnetite/hematite proportions as a function of depth have been recognized in the southeast Missouri ores (Snyder, 1968).

The majority of known deposits in southeast Missouri lack the degree of enrichment in metals (other than iron) that is exhibited by Olympic Dam; they also lack a comparable enrichment in F, P, and $CO_3^{=}$; however, Olympic Dam so far is unique in the Stuart Shelf. The southeast Missouri deposits are slightly anomalous in phosphorus and fluorine and commonly are locally enriched in copper (Murphy and Ohle, 1968; Snyder, 1968); Boss-Bixby represents a sulfide-rich end member that has elevated concentrations of Cu, Co, Ni, Mo, Pb, and Zn as well as Fe (Kisvarsanyi and Proctor, 1967; Kisvarsanyi and Smith, 1988). At Pea Ridge, local areas of highly anomalous REE oxides (as high as several percent in some samples) and gold (intercepts 3–4 ft long of 0.15–3.8 ppm Au) recently have been found on the outer fringe of the iron oxide bodies (L. Tucker, oral commun., 1988); these occurrences certainly help to strengthen the analogy between Olympic Dam and Pea Ridge.

Gangue Minerals and their Paragenesis in Massive Ore

The massive iron oxide ores in both provinces contain very sparse gangue minerals: gangue minerals are intergrown with iron oxide minerals, are clasts within breccias, and are veins that cut breccias. Chlorite and carbonate minerals are the most abundant and ubiquitous, and fluorite, apatite, barite, quartz, sericite, and feldspar are common in many deposits. The sulfide content is extremely variable among deposits.

At Olympic Dam, sericite, chlorite, siderite, fluorite, barite, and monazite are characteristic of the main stage of brecciation and iron oxide deposition. Except for sericite and chlorite, these minerals continued to be deposited later in crosscutting veins. Relict igneous quartz is the most abundant gangue mineral in the breccia bodies and comprises from 10 to 40 percent of the rock. Hydrothermal quartz, on the other hand, is conspicuously absent from the main stage of Fe-Cu-REE mineralization (Oreskes and Einaudi, 1990) but is present in minor amounts in late-stage veins (Roberts and Hudson, 1983). Disseminated copper and iron sulfide minerals, which are not gangue minerals at Olympic Dam, constitute some 5–10 percent of the breccia bodies outside the "barren" hematite core and probably formed in the waning stages of hematite breccia formation.

Breccias at Olympic Dam contain more sulfide and carbonate minerals and less hydrothermal quartz than most southeast Missouri deposits. At Pea Ridge, Emery (1968) reported that quartz is present in the magnetite ores as a fine-grained intergrowth with magnetite and in vugs accompanied by fluorite, barite, calcite, and hematite. Additional gangue minerals include apatite and pyrite. The hematite ores contain a similar suite of gangue minerals, but pyrite is absent (Emery, 1968). Recent mapping at Pea Ridge shows that barite locally is abundant in hematite zones and visible quartz is present dominantly in late veins associated with crosscutting granite pegmatites (L.M. Nuelle, M.A. Marikos, and M.A. Einaudi, unpub. data, 1988).

Quartz also accompanied iron oxide deposition in the Pilot Knob area. In the veins of Shepherd Mountain, Singewald and Milton (1929) and Meyer (1939) reported a paragenetic sequence of early quartz-hematite, followed by quartz-chlorite-magnetite-pyrite, and late quartz-chlorite-orthoclase-hematite. Accessory gangue minerals in veins include apatite, epidote, zircon, and locally garnet. In contrast to the vein deposits, the bedded hematitic ores at Pilot Knob contain no pyrite, and sericite is present rather than orthoclase. Meyer (1939) concluded that the paragenetic sequence is early quartz-hematite, followed by quartz-sericite-magnetite, and late quartz-sericite-hematite. Accessory gangue minerals include tourmaline, sphene, and apatite.

Iron Mountain is clearly anomalous in terms of gangue mineralogy: the deposit contains abundant andradite garnet (Murphy and Ohle, 1968). This anomaly may reflect wall-rock control in which andesite is a local source for calcium; some interaction between ore fluids and wall rocks is recognized in the alteration of andesite fragments and wall rock to epidote and chlorite. Garnet is present as pseudomorphs after early actinolite, in veins that cut hematite, and in the centers of hematite veinlets associated with quartz and calcite. Quartz is the most abundant gangue mineral overall, and calcite is almost as abundant; both probably formed late relative to iron oxide minerals and garnet. Accessory gangue minerals include apatite, dolomite, fluorite, barite, galena, pyrite, chalcopyrite, and bornite.

Wall-Rock Alteration

Variations in wall-rock alteration between deposits of the two provinces are poorly known but may depend at least in part on original wall-rock composition. In deposits where wall rocks are dominantly felsic, such as Olympic Dam (Roberts and Hudson, 1983), Pilot Knob (Meyer, 1939), and Pea Ridge (Emery, 1968), wall-rock alteration is dominated by potassic assemblages including alkali feldspar and sericite, and silicification commonly is present; in deposits where mafic and (or) intermediate rocks are present, such as at Iron Mountain (Murphy and Ohle, 1968), alteration is dominated by more calcic assemblages including actinolite and epidote. In this context, the widespread actinolite-matrix breccia and actinolized fragments in the "hanging wall" of Pea Ridge are anomalous because of the rhyolite wall rocks and may be the result of alteration of mafic dike fragments (Emery, 1968). Hematitic (or magnetitic) and chloritic alteration, particularly of mafic mineral grains in igneous rocks, is common in all deposits.

Clearly defined wall-rock alteration halos on margins of fractures and veins in igneous rocks generally are absent at Olympic Dam but are characteristic of most of the deposits under consideration. At Olympic Dam, sericitic alteration of granite is widespread beyond the ore zones, but sericite gradually increases toward the hematite breccia complex. In our petrographic studies, we have documented a replacement sequence that involves feldspar→sericite→hematite (Oreskes and Einaudi, 1990). It is unknown whether the orange to brick-red color of alkali feldspar in the granite of Olympic Dam represents (1) an alteration feature related to the ore-forming events, (2) an earlier alteration feature unrelated to the ore-forming event, or (3) a primary feature of the granite. In Acropolis drill core, orange alkali feldspar is in magnetite veins with apatite and locally appears to be concentrated in volcanic rocks on the margins of massive magnetite bodies (personal observations, 1986); however, numerous barren intercepts also contain red granite and granitic gneiss. Brick-red granite is characteristic of the Stuart Shelf basement, as it is of other Proterozoic alkalic granite terranes, and its significance remains to be understood.

At Pea Ridge, some types of wall-rock alteration do appear as halos on fractures and veins. Most striking is the orange alkali feldspar found as envelopes on fractures and on hematite veinlets in rhyolite; locally, these fractures probably were reopened during a later chlorite-forming event. The relation of this alkali feldspar to iron oxide mineralization is unclear and is further complicated by the presence of late pegmatites and quartz veins that also introduce alkali feldspar (L. M. Nuelle, M. A. Marikos, and M. Einaudi, unpub. data, 1988).

Genetic Hypotheses

The diversity of genetic hypotheses centers chiefly on the nature of the ore fluid, the mechanisms of ore emplacement, and the interpretation of elemental abundances in ore rather than on the broader questions of tectonic setting and igneous heritage.

Olympic Dam.—Roberts and Hudson (1983) concluded that Olympic Dam represents a very unusual example of a syngenetic/diagenetic, low-temperature hydrothermal deposit in a subaerial playa-lake–graben environment. Deposition of hematite, sulfide minerals, uranium, REE, fluorite, siderite, and barite was from low-temperature hydrothermal fluids linked to alkaline volcanic activity that infiltrated laterally from outside the known mineralized zone. Thinly bedded hematitic sedimentary rocks ("banded iron formation" of Roberts and Hudson) are considered to be of fumarolic–playa-lake origin. The source of copper, iron, and gold is thought to have been mafic igneous rocks in the basement. The syngenetic, sediment-hosted component of the interpretation for the orebody as a whole has been dropped as the result of further study, including fluid inclusion evidence that saline hydrothermal fluids were involved (Roberts and Hudson, 1984) and underground exposures that indicate many breccia bodies are steeply dipping and crosscutting (Oreskes and Einaudi, 1990; Reeve and others, 1990).

Mt. Painter.—Similarities between Olympic Dam and the Mt. Painter uranium deposit, on the east side of the Adelaide geosyncline, were noted by Youles (1984), who emphasized a connection to anorogenic alkaline magmas. Mt. Painter was interpreted by Lambert and others (1982) as a high-temperature hydrothermal breccia deposit related to epizonal granitic plutonism; local venting of hydrothermal fluids formed laminated hematite-quartz beds. Isotopic data were used by Lambert and others to conclude that sulfur (and, indirectly, iron) had a magmatic source and that hydrothermal fluids represented a mixture of magmatic/metamorphic and meteoric water. Uranium and fluorine were thought to have been derived from older Proterozoic basement.

Pilot Knob.—A hydrothermal replacement origin for bedded ores in the volcaniclastic sediments of the Pilot Knob surface deposit was proposed by early workers (Crane, 1912; Geijer, 1915; Singewald and Milton, 1929); in particular, Singewald and Milton (1929) presented evidence that they felt invalidated the suggestion by Spurr (1927) that these ores were black-sand beach deposits. Meyer (1939) generated additional evidence for hydrothermal replacement and suggested that hematitic pebbles, which only superficially resemble iron oxide fragments, actually represent selective replacement of porous or easily replaced material. He concluded that all of the near-surface ores of the Pilot Knob area formed below the surface at depths no greater than several thousand feet from high-temperature hydrothermal fluids originating during the final stages of differentiation of granitic magma. The hydrothermal replacement hypothesis was reiterated more recently by Ridge (1972) and Panno and Hood (1983); however, Panno and Hood concluded, as did Murrie (1973) and Wracher (1976) before them, that basal magnetite breccia ores of the subsurface Pilot Knob orebody probably represent magmatic injections, although the evidence they present is not conclusive. The final chapter on Pilot Knob has not been written: Anderson (1975) and Nold (1988) reopened the possibility that some of the bedded ores at Pilot Knob are detrital accumulations modified by syngenetic precipitation of hematite from subaqueous hot springs. On the scale of the Pilot Knob system, these theories are not mutually exclusive: however, many of these different conclusions are based on the same outcrop.

Pea Ridge and Iron Mountain.—The history of ideas regarding these two deposits would read very much like that summarized above for Pilot Knob, with the difference that the lack of bedded ores simplifies the theories to two end members: (1) high-temperature hydrothermal replacement (Singewald and Milton, 1929) and (2) iron oxide magma injection (Geijer, 1930; Ridge, 1957; Amstutz, 1960; Kisvarsanyi and Proctor, 1967). Murphy and Ohle (1968) did not commit themselves on Iron Mountain; they simply pointed out that several features are consistent with a hydrothermal origin. Emery (1968) favored a modified iron oxide magma theory for Pea Ridge in which late-stage hydrothermal activity formed the hematite cap and the hematite-silica and quartz-amphibole alteration of volcanic rocks.

CONCLUSIONS

The Proterozoic iron provinces of South Australia and southeast Missouri share many common features at the regional, district, and orebody scales. The two provinces are analogous, and iron deposits within them represent similar types; that is, it is appropriate and useful to think of Olympic Dam and Pea Ridge, for example, as belonging to the same class of mineral deposit. Variations between deposits of one province are as great as variations between deposits of different provinces. These variations, as well as the essential common features, need to be better defined. At present, from an economic point of view, the question of commonality of massive iron oxide ores to all deposits is perhaps less interesting than the question of REE and gold enrichment in only a few.

For the deposits summarized above, the field relations and textures of the ores do not require that an iron oxide magma was involved at any stage during mineralization. Hypotheses involving iron oxide magmas for the Missouri ores are based on nondefinitive and ambiguous field relations, on analogies with the controversial magnetite-apatite deposits of Kiruna, Sweden (Geijer, 1930; Freitsch, 1984; Parak, 1984; Gilmour, 1985; Wright, 1986), and on questionable analogy with the El Laco, Chile, magnetite flows (Park, 1961). Many of the field relations and the textures, minerals, and wall-rock alteration features of the deposits summarized above require that an aqueous fluid, and in most cases a hydrothermal fluid, was involved in some stages of the mineralization process.

Where an aqueous fluid is thought to have been involved, diversity of opinion centers on the importance of syngenetic versus epigenetic origins for stratiform hematitic ores (for example, Olympic Dam, Pilot Knob surface). This controversy again is the result of ambiguous field relations, with different interpretations being based on the same exposure. It is identical in its origins to the controversy surrounding other stratiform ore occurrences, such as parts of volcanogenic massive sulfide, stratiform lead-zinc, and stratabound copper deposits. Because field and textural relations are ambiguous in many of these cases, the resolution of this question must be based additionally on fluid inclusion and isotopic data that can resolve relative ages of rock types and ore and that can identify the physicochemical properties of, and sources of components in, the ore fluids.

In conclusion, we suggest the following lines of inquiry for future work.

1. *Relation of iron-rich ores to wall rock.* Detailed geochronological studies, especially attempts to date the ores themselves, will help to clarify which igneous rocks—if any of those presently exposed—are closely related temporally to formation of the ores. Detailed field mapping and petrographic study are prerequisites to identifying unequivocal hydrothermal phases for age dating.

2. *Temperature of deposition of ores.* Currently available data from Olympic Dam suggest that maximum temperatures of deposition of hematitic ores were less than 350 °C (N. Oreskes, 1989, unpub. data). Are magnetite-rich ores deeper, higher temperature phenomena, possibly closer to magmatic sources, or do they reflect differences in the local environment into which ore fluids are emplaced? Detailed fluid inclusion studies of minerals intergrown with or otherwise clearly cogenetic with magnetite are needed to answer this question.

3. *REE transport.* Evidence from Olympic Dam conclusively demonstrates that REE were mobilized as part of the hydrothermal system (Oreskes and Einaudi, 1990). Therefore, the presence of anomalous REE concentrations in iron-rich ores cannot be used a priori as evidence of a magmatic origin via liquid immiscibility. Study of the distribution, abundance, and mineralogy of REE in several deposits of this type should shed light on mechanisms of hydrothermal REE transport.

4. *Source of metals.* Lacking magmatic immiscibility as a direct cause of metal partitioning, the origin of metals in these deposits remains a major unanswered question. Study of minor element geochemistry and radiogenic isotope systematics will help to elucidate the role of local basement in supplying metals to these systems.

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The Geophysical Signature of Olympic Dam and Midcontinent (U.S.A.) Analogs

By William J. Hinze[1]

Abstract

The Olympic Dam deposit was discovered on the basis of hypothesized geologic models utilizing geophysical methods and remote sensing. Geophysical techniques were particularly important in guiding the discovery drill hole because the deposit is completely hidden, being overlain by 350 m of younger flat-lying sedimentary rocks. The initial drill hole was located on isolated but coincident gravity and magnetic anomalies identified on regional anomaly maps. Only these regional data were available for analysis. They indicate that the Olympic Dam deposit lies within a northwest-striking assemblage of intense local anomalies with a regional magnetic and gravity minimum, which was interpreted to represent a downdropped block (of primarily volcanic and volcanogenic sedimentary rocks?) related to the Torrens fault and the Adelaidean rifting event. The ore deposit is associated with an approximately 1,000-nT magnetic anomaly and a 10+-mGal gravity anomaly, both of which are near the northwest fault-bounded margin of the inferred downdropped block. The character of the anomalies is consistent with a northwest-striking minor graben, as was suggested by early geologic interpretations that the host rock of the Olympic Dam deposit is a graben-fill sedimentary breccia. Modeling of the anomalies and results of wave-number domain filtering show that the orebody, on the basis of existing data, can approximately satisfy the gravity anomaly but not the magnetic anomaly. The source of the Olympic Dam anomalies is much shallower than those of similar anomalies observed in the Acropolis and Stuart Creek anomalies—features that have affinities to the Olympic Dam anomaly.

The Proterozoic history of the central United States has many similarities to that of south-central Australia, including the presence of magmatic iron oxide deposits. Regional geophysical studies in the Midcontinent of the United States show widespread development of rifts in the 1,500-Ma anorogenic granite-rhyolite terrane and numerous coincident local gravity and magnetic anomalies similar to those observed on the Stuart Shelf of Australia. These rifts may preserve associated sedimentary rocks, which could be the host for ores derived from magmatic hydrothermal fluids. Modeling of several of these coincident magnetic anomalies in Missouri, south of the St. Francois Mountains iron deposits, indicates sources similar to those modeled for Olympic Dam. However, other regions within the 1,500-Ma orogenic felsic terrane of central North America have similarly favorable geophysical and geological characteristics and should be investigated further.

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PART 2

Midcontinent Strategic and Critical Minerals Project—Proposed Midcontinent Olympic Dam Study

This document proposes an interdisciplinary study whose ultimate goal would be to identify areas in the Midcontinent of the United States that appear to be broadly favorable for the occurrence of Olympic Dam-type ore deposits.

JUSTIFICATION

The Olympic Dam copper-gold-uranium deposit in South Australia is one of the world's largest ore deposits, consisting of an estimated 2 billion metric tons of rock with an average grade of 1.6 percent Cu (32 million tons), 0.6 kg/ton uranium oxide (1.2 million tons), and 0.6 g/ton Au (1.2 million kg). It is buried at a depth of 350 m (1,150 ft) beneath the surface and was discovered in 1975 by a prospecting drill hole sited on coincident gravity and magnetic highs and a major airphoto linear. The host rocks of the deposit are iron oxide–rich breccias of granitic and felsic volcanic rocks, interpreted by Western Mining Company as a breccia in a Middle Proterozoic anorogenic granitic terrane.

A new compilation of data on the basement in the Midcontinent region indicates that parts of this region, especially the St. Francois and Spavinaw granitic terranes in and adjacent to southern Missouri, may have strong potential for Olympic Dam-type deposits. One major mining company (Union Carbide) began an exploration project for such a deposit in southwestern Missouri in 1981, but abandoned it after drilling two unsuccessful holes, when metal prices declined sharply in 1982. At least one other major company has also mounted a preliminary exploration project in this region using a similar exploration model.

The general objectives of the proposed study are to define a working descriptive model for Olympic Dam-type deposits; to compile regional syntheses of the geology, geophysics, and geochemistry of the Midcontinent basement terranes; to investigate the geophysical setting and anomaly characteristics of known or inferred igneous rock units with special reference to anorogenic granites; to make detailed studies of selected iron-ore deposits in the Midcontinent that appear to be analogs of the Olympic Dam deposit; to use a variety of analytical and experimental techniques to determine the processes of formation of the Midcontinent iron-ore deposits; and to apply this new knowledge of processes to the regional syntheses in order to determine areas in the Midcontinent that are potentially favorable for Olympic Dam-type deposits. These objectives would be reached through concurrent and integrated lines of research defined below in terms of specific Tasks.

This proposal is the result of a planning workshop held February 2–3, 1988, under the sponsorship of the U.S. Geological Survey Midcontinent Strategic and Critical Minerals project. A list of participants is attached.

STATEMENT OF TASKS, OBJECTIVES, AND STRATEGIES

Task 1: Definition of a Descriptive Model

Objective

To develop an up-to-date descriptive exploration model for Olympic Dam-type deposits that will be applicable to the Midcontinent.

Strategy

Review all available published and unpublished information on the Olympic Dam deposit; construct a geologic and geophysical working model; discuss it with any available persons who have direct knowledge of the Olympic Dam deposit; if possible, arrange a visit of at least several days duration to Olympic Dam to inspect the type deposit and discuss the model with the personnel who are most familiar with it. Modify the working model accordingly. Key questions to be answered include (1) what are the essential features and processes of the Olympic Dam deposit that would be necessary to form the same type of deposit elsewhere, and (2) which of the Olympic Dam features and processes are variants that would not necessarily be associated with the same type of deposit elsewhere? In other words, what is the essential definition of the Olympic Dam "type"?

Time Frame

Year 1.

Task 2: Regional Geophysical Synthesis

Objective

To compile and upgrade regional geophysical data sets of the Midcontinent to a level commensurate with the overall project objectives.

Strategy

a. Compile and index available data sets of gravity and magnetic surveys for the Midcontinent region.

b. Index available remote-sensing data sets and compile scenes of "global" reflectance (MSS), thermal (HCMM), and thermal/reflectance (AVHRR) data and evaluate for lineament and feature analysis.

c. Prepare derivative maps of geophysical data sets including those to be used in the regional geologic synthesis (Task 3).

d. Compile (and where necessary perform) geophysical property (petrophysical) measurements of Precambrian rock samples for use in modeling of geophysical anomalies.

e. Solicit gravity, magnetic, geoelectric, seismic, and borehole data of private companies, especially companies that have explored in southeast Missouri, as soon as possible. Inquiries should be addressed to Hanna Mining, Union Carbide, New Jersey Zinc, St. Joe Minerals, Cleveland Cliffs, National Lead, and others that may have privately acquired data for small or large areas of the St. Francois terrane.

f. Upgrade aeromagnetic coverage of selected priority areas of the Midcontinent region to 1-km line spacing and publish these as maps and as digital data. All new magnetic surveys should include aeromagnetic gradiometric measurements. Priority regions include the St. Francois and Spavinaw terranes and southern Wisconsin. Gravity coverage of identified areas of high magnetic anomaly should be upgraded to a station spacing of 1 mi or closer as allowed by elevation control.

Time Frame

Items (a), (b), and (e) year 1; items (c) and (d) continuing; item (f), subsequently, subject to availability of funds.

Task 3: Regional Geologic Synthesis

Objective

To upgrade the existing basement geologic map of the region, using all available drill-hole, geophysical, and remote sensing data, compiling data wherever possible in digital format.

Strategy

a. Compile a geologic map of the buried and exposed Precambrian basement surface of the southern Midcontinent region, St. Francois and Spavinaw terranes. The map should include all previously published data and should, especially, be updated and refined using newly available basement drill-hole data. The map should include depth-to-basement contours where the basement is covered and should show collar locations of drill holes examined where possible. The map should cover the area lat 35°–40° N., long 88°–100° W., at a scale of 1:500,000.

b. Compile an annotated list of basement-penetrating drill holes and, where available, their bore-hole logs, and make the list available both in digital (floppy disk) and printed form. Tabulated data should include locations, collar elevations, formation tops, basement depths, Precambrian rock types penetrated, sample storage sites, and notation for any and all geochemical, petrologic, and isotopic work done on the Precambrian samples. All of the area between lat 35°–46° N., long 88°–104° W., should be covered, and this new database should be merged with the similar database from the current study of the Trans-Hudson orogenic belt.

c. Compile a lineament map of the area lat 35°–46° N., long 88°–100° W., from remote sensing imagery of various types and available gravity and magnetic maps and make it available in both printed and digital forms.

d. All of the preceding new data, including the geophysical data under Task 2, should be used in an attempt to produce an interpretive basement terrane map series of the St. Francois and Spavinaw terranes that might include such items as thickness modeling of the anorogenic igneous rocks, terrane boundary refinement, and structural geology of the buried basement.

Time Frame

Year 1 and subsequent followup as new data become available.

Task 4: Regional Geochemical Synthesis

Objective

To expand studies of the regional geochemistry of Midcontinent basement rocks and dispersion halos.

Strategy

Make additional analyses of St. Francois and Spavinaw terrane basement samples, particularly analyses to refine knowledge of elements not well covered by the six-step semiquantitative spectrographic analytical methods used by R. Erickson and coworkers in the Rolla 1°×2° quadrangle UGSG CUSMAP work. The existing Paleozoic geochemical database should be critically reevaluated for clues to geochemical haloes in sedimentary rocks immediately overlying the Precambrian basement. Erickson's sample pulps and many new basement samples that expand areal coverage should be analyzed by methods such as X-ray fluorescence and induction-coupled plasma spectroscopy in order to improve understanding of possible pathfinder elements such as barium, phosphorus, and fluorine. Delayed neutron activation analysis of basement samples for uranium and thorium should be conducted. Phanerozoic-aquifer well waters should be investigated as a sampling medium in areas where covered deposits are known. All this work and previous basement-rock analyses should be compiled into a digital database that can be merged with the drill-hole penetration database of Task 3b. Additionally, special attention should be paid to chemistry of the Precambrian rocks immediately below the Paleozoic unconformity, which may represent a paleoweathering profile in which pathfinder elements could have been concentrated.

Time Frame

Years 1–2.

Task 5: Detailed Midcontinent Site Studies

Objective

To document as thoroughly as possible the geology, geophysical signature, ore mineralogy, paragenesis, petrology, wall-rock alteration, and geochemistry of selected iron oxide deposits in the St. Francois terrane that might have formed from processes analogous to those that formed the Olympic Dam deposit.

Strategy

a. Map or log in detail the workings and (or) cores of the Pea Ridge mine, Boss-Bixby deposit, and Pilot Knob (surface) deposit, and sample them for geochemical and petrogenetic studies and measurement of geophysical properties. These deposit studies should be integrated with the regional systematic geochemical and isotopic studies and detailed geophysical profiles and with studies of St. Francois terrane magmatic evolution. Studies of physical and chemical processes of ore deposition should follow from these mapping and sampling efforts. Of immediate priority are (1) to initiate a mapping and sampling project at Pea Ridge mine, which has, for economic reasons, an uncertain continued mine life, and (2) to secure the Boss core, carefully recovering all core possible from the core rack collapse in the storage building at Bourbon, Missouri.

b. Make detailed magnetic and gravity surveys and additional geochemical and petrophysical analyses of basement drill-hole samples of the Salem–Lake Spring anomaly.

c. Make detailed gravity, magnetic, and, in places, audio-magneto-telluric (AMT) and other geoelectric profiles of selected geologic and geophysical features to search for critical anomaly characteristics that may discriminate mineral deposits from all other features. These should include profiles over anomalies known to be caused by intrusions.

d. Seek (from both private and public sources) and study additional cores from the Iron Mountain and Pilot Knob areas and from other subsurface discoveries such as Camels Hump, Bourbon, and Kratz Spring.

e. Prepare detailed derivative gravity, magnetic, and remote sensing (thematic mapper, SPOT, soyuzcarta, radar) maps of areas selected by geology and geophysics consensus as leading targets.

Time Frame

Item (a)—mine mapping and core logging—should begin as soon as possible and may last 1–3 years. The Pea Ridge mine may close in the near future, and the Boss-Bixby cores as currently stored are in precarious condition. (Mine mapping was actually begun by the Missouri Geological Survey in April 1988.) Item (b) year 1; item (c) year 1 or 2, whenever possible; item (d) years 2–4; item (e) years 4 and 5.

Task 6: Studies of Ore Genesis

Objective

To understand the major processes involved in ore deposition, including the following:

a. Age of the mineral deposits—Establish when the deposits in the St. Francois Mountains were emplaced to determine if they are coeval with any magmatic system exposed or known in the St. Francois Mountains.

b. Metal sources—Determine the processes needed to produce enrichments of iron, copper, REE, and uranium sufficient to form an ore deposit and the sources of these elements.

c. Metal transport—Determine how the metals transported to the site of deposition (magmatic, hydrothermal, or supergene).

d. Depositional mechanisms and environment—Evaluate temperature-pressure effects, mixing, boiling, oxidation, and pH and depositional mechanisms.

e. Plumbing system—Study (1) origins of permeability—fracture versus lithologic—and effects of regional and local structures; (2) chemical solution paths (such as collapse brecciation); (3) explosive processes—gaseous (such as diatreme), magmatic, phreatic, hydrofracturing.

f. Postdepositional modification—Study effects of metamorphism, oxidation, metasomatism, tectonic modification.

Strategy

An understanding of the various parts of the system outlined above can be approached through detailed topical studies based on and conducted in conjunction with the extensive mine, district, and regional geological and geophysical investigations. Particular emphasis should be placed on the Pea Ridge and Boss-Bixby deposits, which represent the oxide-dominant and copper sulfide-rich end member deposits currently known in the region, respectively. The topical studies are generally interrelated and should not be viewed as separate entities. They include:

a. Petrogenetic studies to define host rocks, possible source rocks, ore mineralogy, ore paragenesis, and wall-rock alteration.

b. General geochemical studies.

(1) Chronologic studies—including Ar-Ar, U-Pb, Rb-Sr and Nd-Sm isotopic systems—to determine the age of mineralization, alteration, host rocks, and thermal events (both local and regional).

(2) Stable isotope (C, O, S, H) geochemical investigations to gain information on the source of metals (also using Pb and Sr isotope systematics), the nature and path of the ore-forming fluids, and the physicochemical conditions during ore deposition and various periods of alteration.

(3) Trace element studies of whole-rock systems and individual phases to yield data relevant to the same problems as the stable isotope investigations.

c. Microthermometry, compositional, and quadrupole gas analysis of fluid inclusions to help identify the nature of the ore-forming fluids, transportation mechanism(s) of the various ore metals, and conditions required for ore deposition.

d. Experimental studies of metal transport and complexing in fluorine-rich hydrothermal systems.

e. Modeling (the development of dynamic multiple working hypotheses) of chemical and magmatic processes to provide constraints, directions, and tests for all the genetic studies. Types of required modeling exercises include but are not limited to the following two examples.

(1) Path-calc type modeling (computer-based calculation of reaction paths) to provide information on which metals, as what species, can be transported in a model fluid through rocks of specific compositions and to predict what mineral phases will form as the result of changing physical or chemical environments. This exercise will begin simplistically and become more complex as data become available and as the needed thermodynamic data are obtained.

(2) Modeling of magmatic systems that are most likely to be genetically related to the ore deposits (for example, host granitic rocks, magnetite trachyte, rhyolite, buried anorthosite) to establish the fundamental intensive and extensive parameters controlling their development. (For example, is there a unique source and (or) evolutionary path that an associated parental magma system must undergo in order to develop an Olympic Dam-type deposit?) In this modeling, an attempt should be made to quantitatively establish if any of these magmatic systems are capable of developing the iron-rich fluid phase or exsolved melt responsible for mineralization and, if so, to determine the factors controlling genesis of the fluid or melt. From these results, plausible mechanisms for the development of the iron-rich copper-REE-uranium-bearing ore-forming fluids can be elucidated. If a magmatic origin for the deposits is indicated, the petrogenetic criteria for their development should be defined and then integrated into an ore deposit model useful for exploration.

Time Frame

Item (e) should begin immediately and continue for the duration of the project. Items (a) through (d) should be phased in during year 1 and continued through to the end of the project.)

List of participants, by group

(Asterisk (*) indicates group leader.)

Group 1: Compilations and Field Studies

Timothy S. Hayes*	U.S. Geological Survey (USGS), Mineral Resources
Pieter Berendsen	Kansas Geological Survey
Lin Cordell	USGS, Geophysics
Martin B. Goldhaber	USGS, Geochemistry
Tom Hildenbrand	USGS, Geophysics
William Hinze	Chevron Resources
Murray Hitzman	USGS, Geophysics
Marty Kane	Purdue University
Eva Kisvarsanyi	Missouri Geological Survey
Ernest L. Ohle	University of Arizona
Walden P. Pratt	USGS, Mineral Resources
Paul K. Sims	USGS, Mineral Resources

Group 2: Processes and Mechanisms

Richard I. Grauch*	USGS, Geochemistry
David Frishman	USGS, Mineral Resources
Linda Gundersen	USGS, Sedimentary Processes
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Ernest Kendall	Union Carbide Corporation
Peter J. Modreski	USGS, Mineral Resources
Naomi Oreskes	Stanford University
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Group 3: Topical Studies

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Ken Ludwig	USGS, Isotope Geology
Klaus Schulz	USGS, Mineral Resources
Holly J. Stein	USGS, Mineral Resources
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Group 4: Modeling the Olympic Dam Deposit

Warren I. Finch*	USGS, Sedimentary Processes

PART 3

Methodology for Analysis of the Proterozoic Metallogenic Province of Southeast Missouri—A Blueprint for State and Federal Cooperation (a.k.a. the "Olympic Dam Project")

By Eva B. Kisvarsanyi[1] *and* Charles E. Robertson[1]

Abstract

Southeast Missouri has 6 major (20–200 million tons of ore) and 24 minor magnetite-apatite-hematite deposits that define a Proterozoic metallogenic district 125 km long and 50 km wide, elongated north-northwest. The deposits are hosted by silicic volcanic rocks of the anorogenic St. Francois granite-rhyolite terrane, which is partly exposed in the St. Francois Mountains. Iron mining from shallow surface deposits commenced in 1815 and continued until 1966; since 1964, mining activity has shifted to deposits covered by 400–500 m of Paleozoic strata. The petrotectonic setting of the southeast Missouri deposits is strikingly similar to that of the giant Olympic Dam Cu-Au-Ag-U-REE deposit, the largest among a number of lesser deposits on the Stuart Shelf in South Australia. Both the St. Francois and Stuart Shelf deposits belong to a special class of Proterozoic iron oxide-rich deposits that share a number of common features and may result from similar ore-forming processes.

The St. Francois terrane in southeast Missouri is by far the most accessible of the Proterozoic anorogenic terranes generally considered favorable for hosting Olympic Dam-type deposits in the Midcontinent of the United States. In addition to its extensive outcrops in the St. Francois Mountains, more than 650 drill cores amounting to a cumulative total of 40,000 m are available for study. Furthermore, the Pea Ridge underground mine provides access to one of the major deposits in the northwestern part of the district. As a major component of its Midcontinent Strategic and Critical Minerals Project, the U.S. Geological Survey (USGS), in cooperation with the Missouri Geological Survey (MGS), has undertaken a 5-year multidisciplinary study to develop a descriptive model for Olympic Dam-type deposits and identify areas favorable for hosting such deposits in the region. The project is an extension of the regional geologic and metallogenic synthesis of the northern Midcontinent (Sims and others, 1987) by the USGS and a logical continuation of the Operation Basement program by the MGS. The cooperative research is planned to take advantage of the specific expertise and capabilities of both agencies.

The principal responsibilities of the MGS include but are not limited to (1) compiling a digital data base for drill holes to the Precambrian basement and updating the existing basement map, (2) detailed mapping of accessible Pea Ridge mine workings, in cooperation with the Pea Ridge Iron Ore Company, and sampling for systematic petrographic, ore microscopic, and geochemical analysis (see Marikos and others, this volume), (3) detailed logging and sampling of core from major undeveloped deposits, including 30,000 m of exploration core from the Boss copper-iron orebody, and (4) mapping accessible workings and sampling available core from inactive mines in the St. Francois Mountains. The USGS will be primarily responsible for (1) regional geophysical synthesis, (2) regional geochemical synthesis, and (3) studies of ore depositional processes. Both agencies will collaborate in specific site studies, as in the Pea Ridge mine mapping project, and in various topical studies on ore mineralogy and paragenesis, wall-rock alteration, and lineament and structural analysis and in development of a descriptive model. Status reports will be released as open-file maps and reports; formal reports will be published subsequently by either of the two agencies or in professional journals, as deemed appropriate.

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Geologic Mapping and Evaluation of the Pea Ridge Iron Ore Mine (Washington County, Missouri) for Rare-Earth Element and Precious Metal Potential—A Progress Report

By Mark Alan Marikos[1, 2], Laurence M. Nuelle[1], *and* Cheryl M. Seeger[1]

Abstract

Ongoing geologic mapping of the Pea Ridge deposit has revealed rock types and relations not previously documented in this or any other southeast Missouri Precambrian iron ore deposit. Certain features of the Pea Ridge deposit are similar to those of the Olympic Dam deposit of South Australia, including a breccia pipe complex instrumental in the transportation of iron, copper, rare-earth elements, thorium, uranium, and gold during a late-stage hydrothermal event. We believe that the Pea Ridge deposit represents a deeper, magnetite-rich variant of the hematitic Olympic Dam type and that study of the Pea Ridge deposit may reveal some of the processes responsible for emplacement of iron deposits of the Midcontinent United States and may lead to recovery of metals not currently being recovered from such deposits.

INTRODUCTION

As part of a cooperative effort by the U.S. Geological Survey and the Missouri Department of Natural Resources, Geological Survey Program, the Pea Ridge iron ore deposit is being evaluated as a possible variant of the Olympic Dam deposit of South Australia. The Pea Ridge Iron Ore Company has graciously granted access to the mine for geologic mapping and topical studies to determine ore genesis and to evaluate the deposit for mineral commodities not currently being recovered.

The Pea Ridge deposit, long interpreted as a magmatic intrusion of magnetite into Middle Proterozoic intrusive porphyritic rocks, has been considered to consist of several distinct mineralogical zones (Emery, 1968). Later work by James R. Husman (1989) in the early 1980's refined the understanding of the mineralogy, texture, and distribution of the zones and first documented the distribution patterns of rare-earth elements (REE) and gold. Husman also identified the host rock as volcanic, rather than plutonic.

Our work to date has further refined the mineralogical zonation and delineated a breccia pipe zone, previously undescribed. The zonation is that of orebody scale or assemblage zoning. Our zonal terminology is subject to revision as the investigation proceeds.

The Pea Ridge deposit is more complex than previously reported. The amphibole zone probably represents alteration of a pyroxene body that preceded magnetite emplacement (Marikos, in press). We now know that some magnetite was emplaced by hydrothermal wall-rock replacement or metasomatism. The core of the magnetite body, however, may have been emplaced by a much different mechanism such as magmatic injection or even by supercritical vapor-phase replacement of a breccia complex filled by a very active fluid.

Acknowledgments.—We greatly appreciate the hospitality of the Pea Ridge Iron Ore Company. We thank Robert Z. Reed, President, and John Schoolcraft, Plant Superintendent, for making the mine available for our work and allowing access to company data. We thank Larry J. Tucker, Head Mine Engineer, and Don Roberts, Mine Superintendent, for their time in helping us become familiar with mine working procedures and the mine layout, and especially Larry Tucker, who has been actively sampling and delineating the REE distribution

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for the last several years and has shown us the work done by J. R. Husman as well as himself. We also appreciate the cooperation of all the miners.

MAPPING METHOD

A geological mapping program was designed to document systematically the geologic and mineralogical features of the deposit (Nuelle, Seeger, and Marikos, 1990). The mapping method was mostly developed by the Anaconda Company for mapping porphyry copper deposits. The map scale of 1 in. = 20 ft reveals many features important to the understanding of the deposit, features that would be missed using a smaller scale. Geologic features along drift ribs are projected to a horizontal map plane about 5 ft above the floor. Twenty-one color-coded pencils are used to represent mineralogical and structural features, thereby minimizing note writing and allowing the geologic and mineralogical features to be readily apparent from visual scanning. Rock features such as composition, structure, texture, and vein fillings are plotted on the "rock side" of the field map; alteration features are plotted on the "air side" (that is, the open-space area representing the mine workings) (fig. 20).

The extent of mined-out areas precludes mapping the entire deposit. Instead, we map traverses that cross several geologic boundaries to document ore emplacement and other geologic events. Three levels will be mapped extensively to determine vertical variations in the deposit. Smaller areas on other levels containing significant exposures will be mapped to gain a better understanding of important geologic relationships.

Because of the differences in map scale between company base maps and our maps and the number of color-coded pencils used, map reproduction is difficult. Difficulties, however, are greatly reduced with the use of personal computers. Company mine maps are digitized and stored in data files using GSDRAW (a U.S. Geological Survey computer drafting program). When a traverse is selected, the desired part of the mine map is reproduced at the required scale. This map then becomes the base map for the underground traverse. When underground traverses are complete, the information from all traverses on the same mine level are plotted on a posting sheet, which thus becomes a plan-view geologic map. The detailed compilation maps will be published initially as open-file maps by the Missouri Division of Geology and Land Survey.

MINERALOGICAL ZONES

To date we have defined six mineralogical assemblages, or zones; each zone is characterized by a distinct mineralogy (Nuelle, Marikos, and Seeger, 1990), which largely follows the zones described by Emery (1968).

The *amphibole zone* (Emery's quartz-amphibole zone) is mostly amphibole and varying amounts of quartz, magnetite, and pyrite. Clinopyroxene morphology exhibited by amphibole (ferroactinolite) crystals suggests that the rock was initially a pyroxenite. The pyroxenite may have been a skarn related to initial stages of magnetite emplacement, a separate rock type (such as an intrusive body cutting the host rock), or a mineral aggregate emplaced cogenetically with magnetite emplacement. Much of the quartz in the amphibole zone probably was cogenetic with the original pyroxene—pyroxene crystals (now amphibole) terminate in quartz pods that at one time must have been voids—but some of the quartz pods are veined by the pyroxene. A second, later stage of quartz and pyrite cuts the amphibole zone.

The *magnetite zone* (Emery's magnetite zone) contains more than 60 percent Fe, of which about 55 percent is in magnetite. The magnetite is accompanied by varying amounts of pyrite, chalcopyrite, and apatite. The sulfide minerals probably are paragenetically later than the magnetite, and the apatite probably is mostly coeval with the magnetite. Although we have not yet mapped extensively in the magnetite zone, preliminary reconnaissance mapping shows textures that could be relict breccia textures. If the presence of a preexisting breccia is confirmed, magnetite replacement could have been by a normal hydrothermal process or by a process involving supercritical vapor-phase replacement by invasion of an aggressive fluid.

The *hematite zone* (Emery's specular hematite and quartz-hematite zones) forms much of the outer periphery of the magnetite zone and represents a hydrothermally altered part of the main magnetite orebody. The zone is made up of dominantly specular hematite and minor magnetite, chlorite, barite, and calcite. Apatite is uncommon and occurs as corroded crystals; pyrite is generally absent.

The *brecciated wall-rock–magnetite zone* (Emery's porphyry breccia zone) consists of wall-rock breccias found discontinuously along margins of the magnetite body. Textures range from incipient crackle breccia at the margin to massive magnetite and only sparse wall-rock fragments. Much of the breccia is pseudobreccia (replacement breccia), in which wall-rock fractures were infilled by magnetite and the wall rock adjacent to the fractures was metasomatically replaced by magnetite. Advanced stages of this replacement process resulted in a magnetite matrix-supported breccia in which the wall-rock fragments have not been greatly rotated or abraded.

The *breccia pipe zone*, previously undescribed, consists of at least three breccia bodies containing varying amounts of potassium feldspar, barite, apatite,

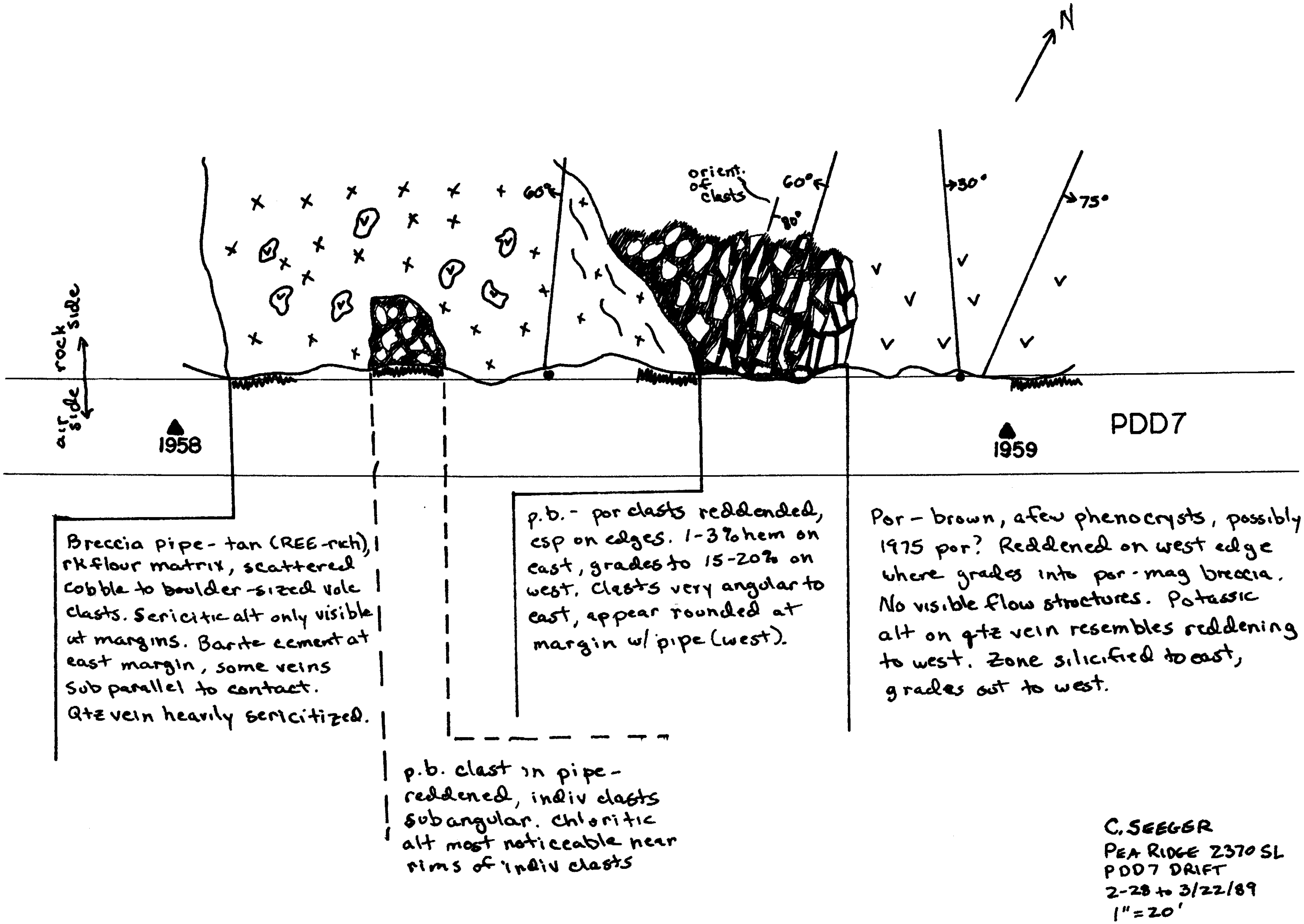

Figure 20. Hypothetical example of an underground traverse map. The rock and mineral features would be plotted in color rather than in black and white as shown here. Minimal field notes accompany the map. Rock features are plotted on the rock side of the drift, and alteration features are plotted on the air side.

thorium, REE phosphate minerals, and rock-flour matrix. A breccia pipe complex cuts magnetite, amphibole rock, host rock, and mafic dikes on the footwall (north) side of the magnetite body and may extend more than 100 m north of the footwall. The soft rock-flour-matrix-supported breccias and some of the silicified breccias are easily mapped by using a gamma-ray scintillometer because of their high thorium content. Although all known pipes are near the footwall, the only accessible exposure of the hanging wall is cut by a felsic dike and slightly radioactive quartz veins; thus, pipes may also be present beyond the hanging wall, south of the magnetite ore. The highest gold abundances are spatially associated with the breccia pipes. In addition, REE oxide contents are as high as and in excess of 10 weight percent.

Lithic fragments in the breccia pipes include volcanic rock, magnetite, hematite, quartz-amphibole rock, felsic dike rock, mafic dike rock, and earlier silicified breccia. Well-rounded and angular fragments are in close proximity to each other and vary in degree of alteration. Mineralogic alterations associated with pipe emplacement are magnetite to hematite, amphibole to chlorite (chamosite), and feldspar to apple-green muscovite. Cement mineralogy is complex and variable and includes combinations of barite, quartz, microcline, anhydrite, fluorite, chamosite, muscovite, calcite, and REE minerals.

The character of the breccia pipe material varies from rock-flour-matrix-supported to silicified breccia. Most of the original textures in silicified rocks have been obliterated. Visible porosity in the breccia pipes ranges from almost zero in silicified rocks to approximately 50 percent in some rock-flour-matrix-supported breccias. Crystal-lined cavity volume is from microscopic to more than a cubic meter.

The *silicified zone* (in part, Emery's quartz-amphibole and quartz-hematite zones) is in wall rock or in other assemblages that were silicified during a relatively late stage quartz-flooding event. The quartz flooding silicified areas of host rock and breccia pipes and obscured original textures. Areas of silicification, as well as other areas, are cut by quartz-feldspar veins that contain variable amounts of barite, fluorite, chalcopyrite, chlorite, monazite, rutile, xenotime, apple-green muscovite, biotite, and pyrite. These quartz veins cut all other zones and fill fractures, sigmoidal dilation voids, and breccia interstices. The veins are irregularly shaped, randomly oriented, of variable thickness, and commonly discontinuous. Where they cut magnetite, the magnetite can be altered to hematite as far as 2 m from the veins, or there may be no visible alteration envelope. Trace amounts of nickel, cobalt, lead, tellurium, and molybdenum minerals also are present in these veins.

MAFIC AND FELSIC DIKES

Postmagnetite mafic dikes intrude the magnetite zone and host rocks; they strike east-west, dip about 70° N. to vertical, and are from 2 cm to more than 4 m thick. Some of these dikes were emplaced before the REE-bearing breccia pipes because fragments of the dike rocks have been observed in the pipes.

Felsic dikes, aplitic to pegmatitic in texture, cut all zones of mineralization in the orebody and thus were emplaced late. Fragments of felsic dikes have also been noted in breccia pipes. Some felsic dikes are cut by quartz-biotite-pyrite veins; these dikes were emplaced before and during breccia pipe formation and hydrothermal activity. On the 2275 level, magnetite-apatite-amphibole veins occupy fractures that have the same orientation as a nearby felsic dike. The dikes are orange, variably oriented, and from 2 cm to 2 m thick. They contain alkali feldspar and quartz, and sparse biotite in some pegmatitic zones. The pegmatitic zones locally segregate into quartz-biotite-feldspar-pyrite-chalcopyrite veins that cut the dikes. Pyrite- and chlorite-filled fractures with halos of feldspathic alteration surround the dikes where the dikes cut host rock.

POSSIBLE INTRAMAAR SEDIMENT

At various places in the mine, a laminated rock of alternating hematite and chlorite-feldspar-illite layers is present. In thin section most of the hematite shows euhedral magnetite morphology, which indicates that the hematite was altered from magnetite. This laminated rock occurs as discrete blocks of arenite that are oriented oblique to the northeasterly dip of the host rock. Many blocks have tight, recumbent folds in places. These blocks have been observed in areas adjacent to breccia pipes and in iron ore. Their fragmentation and orientation suggest that they have been transported, probably downward through breccia pipes. They are presumed to be sedimentary in origin because of the presence of ripple marks and mudcracks. They may have originated as an intramaar sediment and may indicate that an exhalative or sedimentary iron ore deposit once capped (or was at some distance above) the Pea Ridge deposit.

CONCLUSION

Whether or not the Pea Ridge deposit proves to be an Olympic Dam analog, the data gained thus far have revealed insights valuable to future resource assessments in the Midcontinent of the United States. We now know that many "new" types of deposits could exist in this region, and further study of this deposit will provide data useful in exploration. The Pea Ridge mine offers a unique window into this buried terrane and deserves further study. As of this writing, detailed mapping, petrographic studies, and geochemical investigations are continuing. Stable isotope, fluid inclusion, and geophysical studies are planned.

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