Strategic and Critical Minerals in the Midcontinent Region, United States

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Geology and Mineral Paragenesis of the Pea Ridge Iron Ore Mine, Washington County, Missouri—Origin of the Rare-Earth-Element- and Gold-Bearing Breccia Pipes

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Abstract

Breccia pipes containing rare-earth elements (REE) and gold are a potentially significant economic target in the Pea Ridge iron ore mine, Washington County, Missouri. The Pea Ridge deposit is one of eight known volcanic-hosted iron ore deposits in the Middle Proterozoic St. Francois terrane that are similar to the Olympic Dam type of deposits of Australia. The iron orebody is steeply dipping and tabular shaped, and it cuts across the host rhyolite. The footwall of the deposit is zoned from the massive apatite-bearing magnetite core outward to heterolithic breccia, pseudobreccia, a specular hematite zone, and an extensive silicified zone. The hanging wall is zoned from the massive magnetite core outward to heterolithic breccia, pseudobreccia, and an amphibole skarn zone. The REE-rich breccia pipes cut through the various rock types along the footwall at or near contacts. They are typically about 60 m long and 15 m wide, and they extend at least 120 m vertically. The pipes consist of fragments of rhyolite host rock and zones of massive magnetite, specular hematite, and silicified rocks supported in a matrix of rock flour, barite, feldspar, monazite, apatite, chlorite, xenotime, and, locally, gold. Total REE oxide content of samples of the groundmass material, which are not diluted with lithic fragments, average about 20 weight percent. Grades from working faces in the mine are lower, averaging about 12 weight percent. Gold distribution is erratic, but concentrations are as high as 371 parts per million.

The Pea Ridge iron deposit represents an intrusion-type deposit in which the magnetite orebody stoped upward into the host rhyolite and created the various breccia zones around the margins of the deposit. The REE-bearing breccia pipes probably formed from late-stage magmatic-hydrothermal fluids that evolved from the main magnetite orebody. Sanidine phenocrysts (or xenocrysts) in the breccia pipes confirm a magmatic component for their origin. The magmatic-hydrothermal fluids underwent second boiling and decompression and caused crystallization and release of a volatile phase. Fluid-inclusion evidence of boiling includes a mixed population of vapor-rich fluid inclusions coexisting with liquid-rich inclusions in quartz from the REE-bearing breccia pipes. The concomitant volume increase associated with boiling released significant mechanical energy and caused fracturing and brecciation of the wallrock. The REE-bearing fluid and crystal mixture streamed upward along zones of weakness (faults and contacts), entrained and milled wallrock fragments, and formed the breccia pipes.

The REE- and, locally, gold-bearing breccia pipes associated with the Pea Ridge iron deposit are attractive targets in the midcontinent of the United States for exploration of large deposits of iron, copper, REE, gold, and uranium similar to the Olympic Dam deposit in Australia.

INTRODUCTION

This study of the Pea Ridge mine is part of a 5-year cooperative effort between the Missouri Department of Natural Resources–Geology and Land Survey and the U.S. Geological Survey (USGS) under the USGS Midcontinent Strategic and Critical Minerals Project. One of the overall goals of the cooperative effort is to provide a genetic and predictive model for the possible occurrence of iron, copper, REE, and gold deposits in the midcontinent region that may be similar to the Olympic Dam deposit of Australia (Oreskes and Einaudi, 1990). Initial work centered on the Pea Ridge deposit inasmuch as it offers the most complete lateral and vertical view of this deposit type in the midcontinent region. This report presents observations and hypotheses generated from our mine mapping program. Traverses that cross lithologic contacts and structural features in the mine were selected in order to establish paragenetic relationships and to serve as a base for geochemical and petrographic studies.

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GEOLOGIC SETTING

Middle Proterozoic rocks of the St. Francois terrane, which includes rhyolitic ash-flow tuffs, lava flows, and coeval granitic plutons, host Missouri's Precambrian iron ore deposits. Zircon crystals from the granite bodies have yielded U-Pb isotopic ages of 1,480–1,450 Ma (Bickford, 1988). Kisvarsanyi (1980, 1981) recognized three types of granitic rocks in the St. Francois terrane: subvolcanic massifs, ring intrusions, and central plutons (fig. A1). The subvolcanic massifs, which are intrusive equivalents of coeval rhyolitic rocks, are epizonal biotite granite having granophyric and rapakivi textures and containing perthitic alkali feldspar; biotite is the characteristic mafic mineral. Magnetite is a ubiquitous accessory mineral. Ring intrusions, which include intermediate- to high-silica amphibole granite, biotite-hornblende granite, adamellite, and syenite, were emplaced in ring fractures related to caldera collapse and cauldron subsidence. In contrast, central plutons of high-silica, two-mica granite were emplaced in resurgent cauldrons. The central plutons have distinct accessory minerals, such as fluorite, topaz, allanite, monazite, garnet, and cassiterite, and a characteristic trace-element suite that includes elevated abundances of Sn, W, Nb, Y, Be, Li, Rb, Ba, and F. The central plutons have a unique negative magnetic anomaly signature (Kisvarsanyi, 1984; Kisvarsanyi and Kisvarsanyi, 1989). Most authors agree that the magmas were generated from melting of previously accreted crustal material (Nelson and DePaolo, 1985). Kisvarsanyi (1975) proposed that the St. Francois terrane formed in an anorogenic extensional tectonic setting (failed cratonic rift environment), whereas Patchett and Ruiz (1989) suggested that these rocks are not anorogenic, but formed during orogenic-accretionary processes associated with the early stages of the Grenville Orogeny.

The St. Francois terrane hosts eight known magnetite and hematite deposits (fig. A1), which together constitute an iron metallogenic province (Kisvarsanyi and Proctor, 1967; Snyder, 1969). The iron deposits occur as both intrusive and replacement bodies within volcanic rocks of the terrane. The deposits may be genetically related to the host anorogenic rhyolite rocks, as suggested by Day and others (1989) for the Pea Ridge deposit.

The southeastern Missouri iron metallogenic province contains reserves estimated at nearly 1 billion tonnes of iron ore (Arundale and Martin, 1970). Iron ore has been continuously produced from the province since 1815, except for one year during the Great Depression. Until 1963, Precambrian hematite deposits were the major source of iron ore in Missouri; since the opening of the Pea Ridge mine in 1964, all iron ore production has been from subsurface Precambrian magnetite deposits. The Pilot Knob underground mine opened in 1967 and produced slightly more than 9.8 million tonnes of usable iron ore before closing in 1980. Since 1980, the Pea Ridge mine has been the State's only iron ore producer, and it is the only remaining underground iron mine in the nation. To date, about 41.6 million tonnes of usable iron ore have been produced from the Pea Ridge mine.

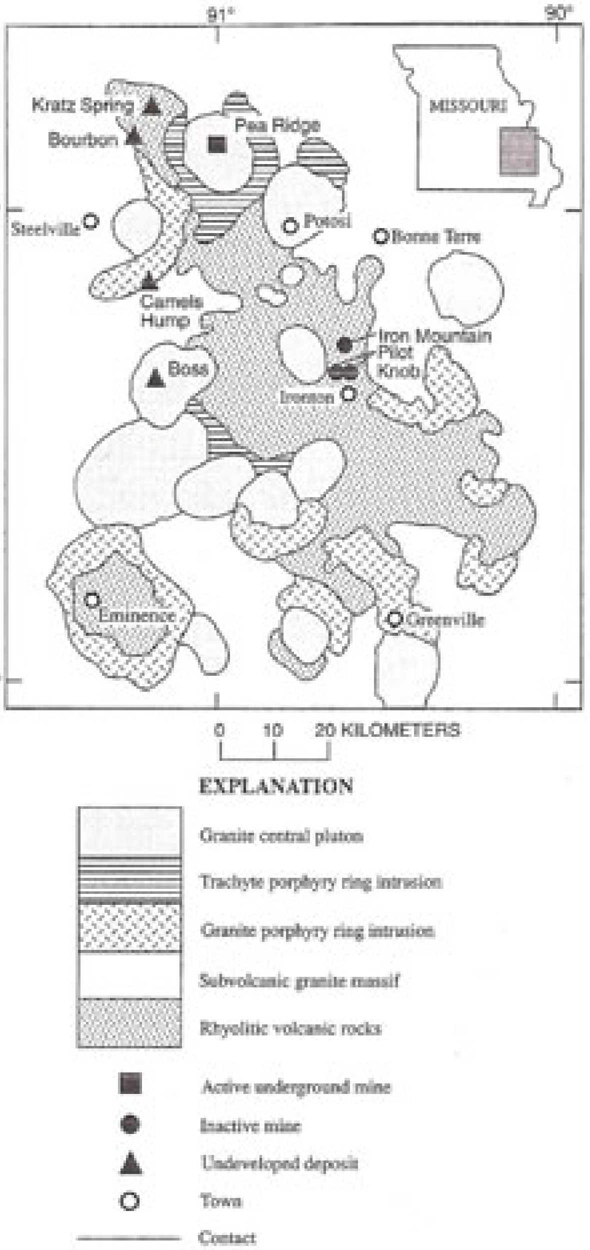

Figure A1. Geologic map of the Middle Proterozoic St. Francois terrane, southeastern Missouri, showing locations of eight known magnetite and hematite deposits (modified after Kisvarsanyi, 1981).

GEOLOGY OF THE DEPOSIT

The Pea Ridge magnetite-apatite deposit is a tabular body that is discordant to bedding of the rhyolitic host rocks. The orebody strikes roughly N. 55° E. and dips

75°–90° SE. (Husman, 1989). Xenotime from a quartz vein that cuts the iron ore yielded a U-Pb age of 1.46 Ga (W.R. Van Schmus, University of Kansas, written commun., 1988), which is a minimum age for the deposit; this age is within the age range of 1.45–1.48 Ga for the St. Francois terrane as reported by Bickford and Mose (1975) and Bickford (1988).

Rocks of the Pea Ridge deposit are divided into four zones: (1) the amphibole-quartz zone; (2) the magnetite zone, which is made up of massive magnetite, magnetite-cemented heterolithic breccia, and pseudobreccia; (3) the specular hematite zone; and (4) the silicified zone. Other rock types include magnetite veins, quartz veins, aplite dikes, mafic dikes, and a unique banded rock. REE-bearing breccia pipes cut rocks of the footwall. Figures A2 and A4 present the paragenetic relationships in the deposit, and figure A3 is a geologic map of the 2,275-ft level.

Amphibole-Quartz Zone

The amphibole-quartz zone occurs in both the hanging wall and footwall of the deposit. It consists of massive, coarse-grained actinolite (blades as much as 5 cm long) and interstitial apatite, magnetite, pyrite, chalcopyrite, and calcite. Quartz is present as both interstitial grains and as massive pods 1–50 cm in diameter. From the eastern edge of the deposit westward, the amphibole-quartz zone thins in the hanging wall from massive amphibole-quartz rock into host rock in which fractures are filled with amphibole and have silicified walls (Emery, 1968). Locally, contacts grade into host rhyolite wallrock, which exhibits incipient stages of amphibole replacement. Farther from the contact, veins of magnetite cut massive actinolite. The footwall zone is less brecciated and contains fewer quartz pods than the amphibole-quartz zone in the hanging wall.

This zone represents a skarn alteration front that preceded the emplacement of the magnetite orebody. The protolith of the amphibole-quartz zone is the host rhyolite. Metasomatic replacement of the protolith has partially destroyed obvious textural or chemical evidence of the original rock type. Relict textures of rhyolitic wallrock have been noted in amphibole-quartz fragments along the hanging wall (J.R. Husman, The Doe Run Company, oral commun., 1990).

Magnetite Zone

In previous reports, the magnetite and rhyolite porphyry breccia zones (Emery, 1968) and the magnetite and brecciated wallrock-magnetite zones (Nuelle and others, 1989) were treated separately. However, further mapping and documentation of temporal relations have shown that the massive magnetite orebody and magnetite-bearing breccias were contemporaneous and that it is useful to treat the magnetite orebody as a zone composed of subzones of massive magnetite, magnetite-cemented heterolithic breccia, and pseudobreccia.

Massive Magnetite

Ore faces in the massive magnetite contain as much as 65 volume percent magnetite, with average grades ranging from 47 to 55 percent magnetic iron (Emery, 1968). The texture varies from massive and shiny ore having subconchoidal fracture to finely crystalline and granular. Some ore has a porphyritic texture in which magnetite (or martite after magnetite) and hematite megacrysts are in a massive, fine-grained magnetite groundmass. Gangue minerals in the magnetite ore are predominantly apatite, quartz, pyrite, and monazite, and minor ferroactinolite, biotite, chlorite (after biotite), fluorite, barite, grunerite, and talc (fig. A2). The gangue forms interstitial intergrowths, net-textured veinlets, and pods within the massive magnetite ore.

Magnetite-Cemented Heterolithic Breccia

This breccia is characterized by fragments of host rhyolite, chloritized rhyolite, and rock from the amphibole-quartz zone in a matrix of massive magnetite and (or) hematite. It occurs discontinuously along the margins of the orebody, but is particularly well developed along the hanging wall (fig. A3).

The breccia was formed in a manner similar to an intrusion breccia as described by Laznicka (1988). In situ exfoliation of wallrock fragments, filling of the planes of the exfoliated sheets with magnetite, and the presence of wallrock schlieren suggest that the magnetite ore fluid had rheological properties similar to an intrusive magma.

Pseudobreccia

Laznicka (1988) described one variety of pseudobreccia as being formed by replacement of host rock, which results in a breccialike appearance; the rock fragments are not produced by physical abrasion, nor are they displaced or rotated. The term "pseudobreccia," as used here, is defined as host rhyolite that has been partially to totally replaced by magnetite and (or) hematite along fractures and has a breccialike appearance. The fragments do not appear to have been rotated or mechanically fragmented.

The pseudobreccia has a sharp contact with the magnetite orebody. Along its outer margins, the pseudobreccia grades inward from iron oxide-cemented crackle breccia to iron oxide-cemented mosaic breccia, and then into rubble breccia near the magnetite orebody. Roundness and metasomatic alteration of the rhyolite fragments increases towards the orebody.

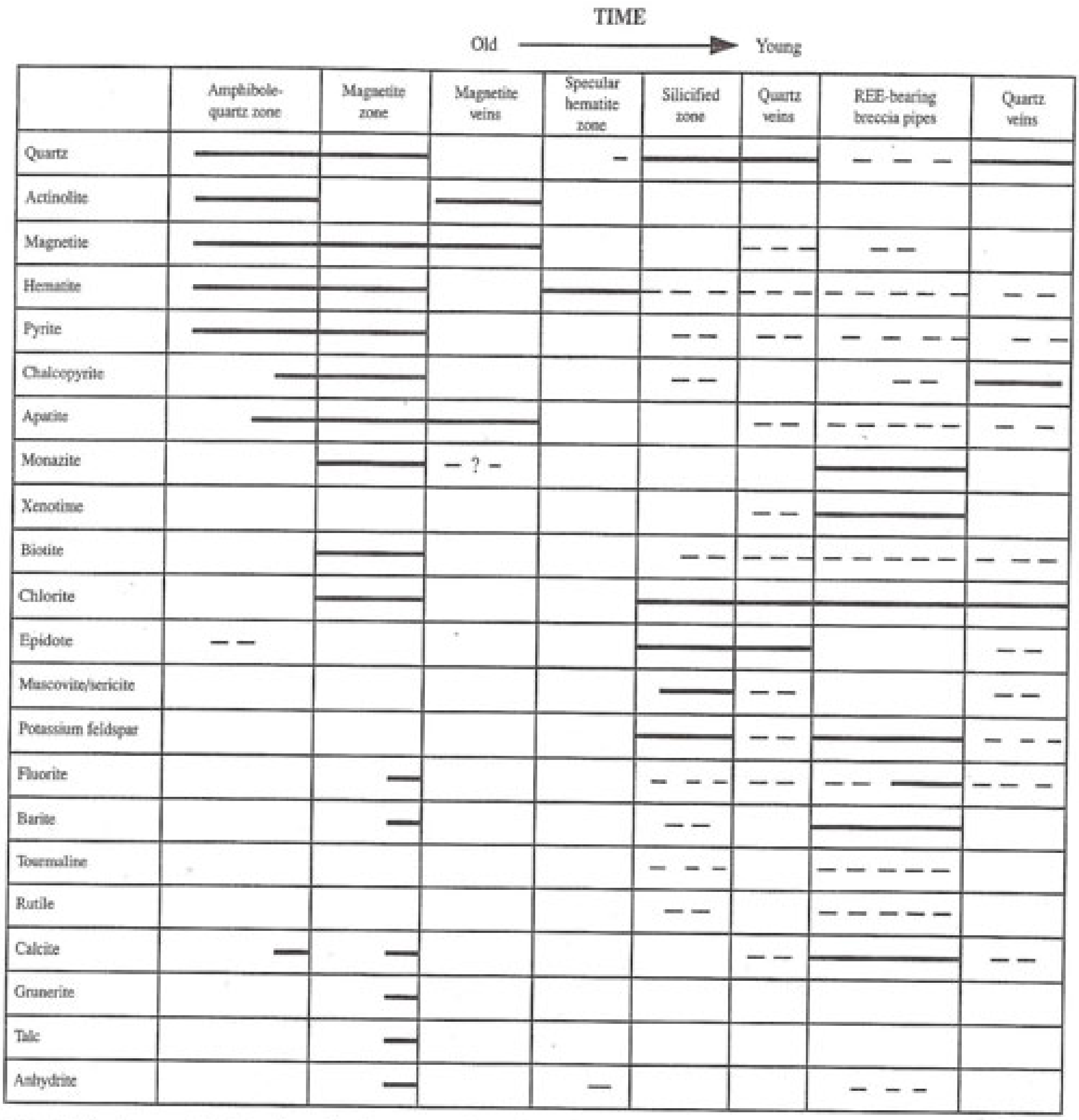

Figure A2. Paragenesis of major and minor minerals in the Pea Ridge mine, Washington County, Mo. Solid line, major deposition; dashed line, minor deposition.

Specular Hematite Zone

The specular hematite (specularite) zone separates the silicified zone from the magnetite orebody along the footwall, and rhyolite host rock from the orebody along the eastern edge of the deposit (fig. A3). The width of the zone varies, and it thins with depth (Husman, 1989). Contacts between the specular hematite zone and the magnetite orebody are commonly gradational, and the hematite contains irregularly distributed patches and areas of magnetite. However, the contacts are sharp locally. The specularite is finely to coarsely crystalline, generally platy, compact, and massive. Most of the specularite is an alteration product of magnetite.

Mapping documents that the specular hematite zone in part formed along fault zones and that the width of the

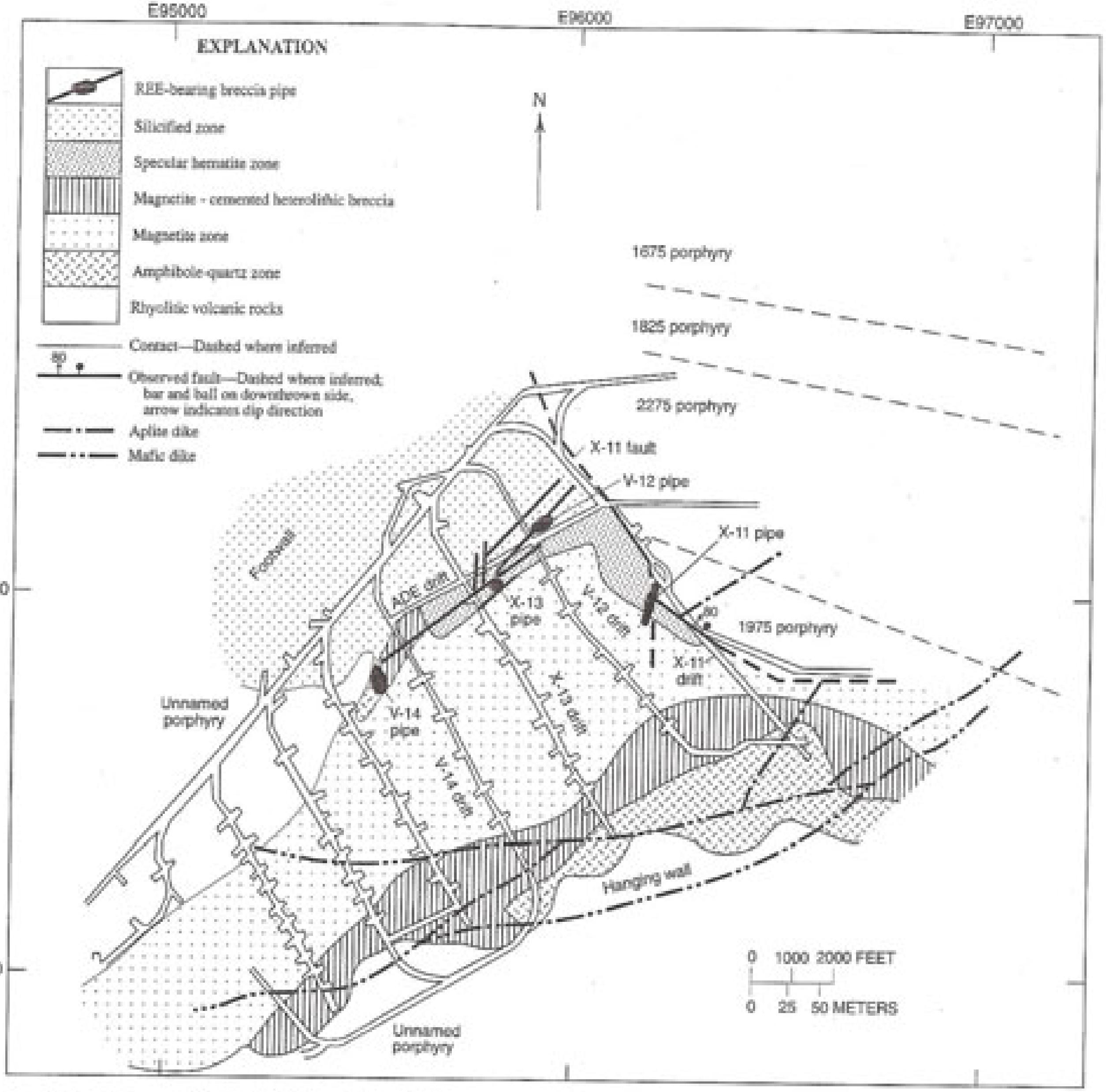

Figure A3. Geologic map of the 2,275-ft level, Pea Ridge mine, Washington County, Mo. (modified after Hussman, 1989).

zone varies proportionally with the width of the fault zones. The specularite is locally sheared and foliated parallel to the orientation of post-ore faults.

Silicified Zone

Silicified wallrock is extensively developed in the footwall (fig. A3). Horizontal underground drilling of the footwall northward away from the orebody on the 2,275-ft level penetrated 120 m of silicified rock without exiting the zone, and surface drill holes more than 400 m north of the

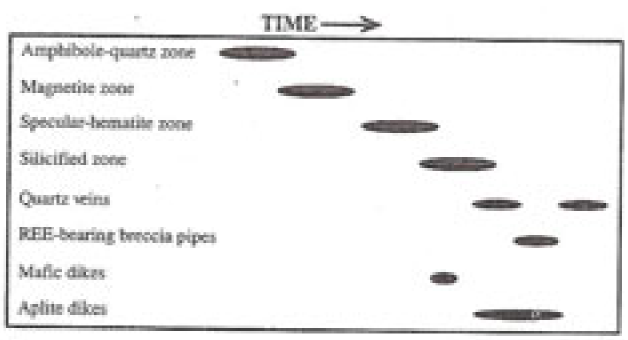

Figure A4. Paragenetic sequence of the rock types in the Pea Ridge mine, Washington County, Mo.

orebody intersected silicified volcanic rock. The silicified zone is characterized by massive, white to light-gray quartz that replaced the host rhyolite wallrock to varying extents; areas that are greater than 75 percent quartz are not uncommon. Potassic alteration associated with silicification included the addition of potassium feldspar to the wallrock. Potassium feldspar flooding converted the grayish or reddish-brown volcanic rocks to bright moderate-reddish-orange rock. Locally, quartz and potassium feldspar form pegmatitic pods and veins. Accessory minerals in the silicified zone include fluorite, muscovite, biotite, tourmaline, chlorite after biotite, epidote, calcite, barite, rutile, pyrite, and chalcopyrite. In addition, Husman (1989) noted monazite, apatite, and topaz.

The silicified zone is a product of both open-space filling and replacement. An increase in the number of fractures from the wallrock into the silicified zone suggests that stockwork fracture systems may have controlled silicification. On the 2,275-ft level, along the X-11 drift, silicification is associated with a high-angle fault. Sericite along fractures and fragment surfaces shows that sericitization accompanied silicification. The silicified zone grades into areas of fracture-fill quartz veins. Silicification also extends several meters into the specular hematite zone. Younger sets of quartz veins cut both the zone and the adjacent wallrock. Relict breccia textures in the silicified zone suggest that brecciated zones were conduits that were later rehealed by silica (Seeger and others, 1989).

Mafic Dikes

Mafic dikes cut across the host rhyolite, the magnetite orebody, and the silicified zone. Contact with the REE-bearing breccia pipes was not observed. The temporal relationship between the mafic and aplite dikes is ambiguous (fig. A4). Emery (1968) observed mafic dikes that are cut by aplite dikes. However, our mapping indicates that a mafic dike also cuts an aplite dike.

The dikes are black to dark greenish gray and have a greasy luster. They range in thickness from less than 1 cm to more than 3 m and occur in two fracture systems. One fracture system strikes N. 60° E. and dips 60°–80° SE., whereas the other strikes N. 85° W. and dips 60°–80° SW. (Emery, 1968).

Pervasive chloritic alteration partially obscures the original composition of the dikes. However, major and trace-element data indicate that the dikes are tholeiitic basalt (W.C. Day, unpub. data, 1990). These dikes are similar to those emplaced throughout the St. Francois terrane during the waning stages of rhyolitic volcanism (Bickford, 1988).

Aplite Dikes

Aplite dikes cut the host rhyolite and the magnetite orebody. Contacts with the REE-bearing breccia pipes are not exposed, and their relative ages are therefore unknown. The mutually crosscutting relation between the aplite dikes and rocks of the silicified zone indicates that their emplacement was coeval (fig. A4).

The dikes have variable dips, and they fill fractures that strike N. 25° W. (Emery, 1968). They consist of potassium feldspar and quartz with minor to trace amounts of biotite, and they have a fine-grained, equigranular (aplitic) to pegmatitic texture. Some dikes grade into quartz veins near their terminations. Some dikes have traces of disseminated molybdenite.

The aplite dikes are alaskitic and are high in SiO_2 (72.0–74.7 weight percent and K_2O (6.7–9.8 weight percent). Geochemical modelling of the trace-element abundances demonstrates that the aplite dikes and the host rhyolite are cogenetic (Day and others, 1989). The crosscutting relations of the aplite dikes with the host rhyolite, the magnetite orebody, and the silicified zone indicate that the magnetite ore was emplaced during the regional Middle Proterozoic igneous activity in the St. Francois terrane.

Banded Rock

Banded rock is a relatively rare rock type in the Pea Ridge deposit. It consists of alternating bands of light-gray and dark-gray minerals. The light-gray bands consist of igneous rock fragments, quartz, and potassium feldspar; the dark bands are martite and chlorite. The bands may represent altered horizons in a bedded volcaniclastic sediment. Beds range in thickness from 1 or 2 mm to several centimeters and exhibit ripple marks and graded beds (Marikos and others, 1989a). The banded rock occurs along the footwall near the contact between the specularite and silicified wallrock. Locally, it has a penetrative fabric, as defined by mineral lineations, and has been deformed by a drag fold along a fault zone (ADE drift, 2,275-ft level; fig. A3). The rock grades into specularite, which suggests that it was part of the host rock sequence that was replaced by magnetite (converted later to martite) during orebody emplacement. The protolith was probably a water-laid pyroclastic airfall tuff deposited as a volcaniclastic intraflow sediment.

REE-Bearing Breccia Pipes

Four REE-bearing breccia pipes have been delineated along the footwall and eastern edge of the 2,275-ft level of the orebody (fig. A3). The pipes are at or near the contacts between the major lithologic zones. The contacts with rhyolite and rocks of the silicified zone are abrupt and commonly sheeted; those with the specular hematite zone are irregular and embayed. Locally, apophyses of breccia pipes intrude adjacent rocks along fractures.

The pipes dip steeply (>60°) and are elongate to ovoid in plan view. They range in length from several meters to as much as 60 m and have widths as much as 15 m. Their maximum vertical extents are not known, but the X–13 pipe (fig. A3) extends from the 2,675-ft sublevel to at least the 2,275-ft level, a distance of about 120 m.

The breccia pipes contain fragments of rhyolite, magnetite-hematite ore, and rock of the silicified zone in a groundmass predominantly composed of rock flour, feldspar, chlorite, barite, apatite, monazite, quartz, and calcite (fig. A2). The rock-flour consists of milled volcanic wallrock and disaggregated specularite grains. The volcanic rock fragments grade in size from rock-flour to about 0.5 m in diameter. They are reddened, due to potassium feldspar alteration, and have subrounded to angular edges and moderate to high sphericity. The specularite fragments reach several meters in length, are angular, and have low sphericity. Where specularite fragments are prevalent, they form a tight-fitting, fragment-supported breccia having angular voids between fragments. Where wallrock fragments predominate, they are irregularly distributed and are matrix supported.

Most of the breccia pipe material may have been well indurated. For example, the X–11 pipe (fig. A3) has a particularly hard, fine-grained matrix. Other pipes are now friable because of the coarseness and excellent cleavage of potassium feldspar and barite and post-emplacement brecciation.

Geopetal structures within void spaces in one of the REE-bearing breccia pipes indicate that the magnetite deposit has not been tilted significantly since emplacement of the breccia pipes. The geopetal structure on the 2,440-ft level is characterized by horizontally bedded, granulated rock particles that fill the bottom part of the vug and calcite that fills the upper part of the vug.

The relative age of the REE-bearing breccia pipes is poorly constrained. Rhyolite wallrocks, magnetite ore, and rocks of the silicified zone occur as fragments within the pipes. Thus, the breccia pipes were emplaced after formation of the silicified zone. Aplite dikes cut across rocks of the silicified zone; however, relations between the aplite dikes and the breccia pipes have not been observed.

The absolute age of the REE-bearing breccia pipes can be estimated from a U-Pb date on a xenotime crystal in a quartz vein that is cut by a breccia pipe. The xenotime yielded a date of 1.46 Ga (W.R. Van Schmus, written commun., 1988). It occurs both in quartz veins cut by the REE-bearing breccia pipes and in the pipes themselves (fig. A2). Therefore, formation of the REE- bearing breccia pipes was about 1.46 Ga.

Mineralogy and Chemistry

Barite, potassium feldspar, chlorite, monazite, apatite, quartz, and calcite are the most abundant minerals in the pipes; biotite, fluorite, tourmaline, chalcopyrite, and pyrite are accessory minerals. Marikos and others (1989b) reported anhydrite in some pipes. Barite occurs as massive cement and open-space fill; crystals range from 1 mm to as much as 50 cm long. Sanidine and orthoclase are present as fractured and broken euhedral phenocrysts (or xenocrysts) that are as much as 2 cm in diameter. Apatite forms subhedral to euhedral crystals that range in size from 0.5 to 1.0 cm. Quartz forms both rounded and embayed phenocrysts (or xenocrysts) and secondary overgrowths as cement within the groundmass. Areas of broken barite and potassium feldspar record a post-cementation brecciation event.

REE-bearing minerals in the breccia pipes include monazite, xenotime, and rare bastnaesite and britholite(?). Monazite and xenotime occur as 0.5- to 1.0-mm-long crystals in aggregates having a granular texture, as radial crystal aggregates, as acicular crystals that replaced wallrock microfragments, and less commonly as irregular crystals that fill cracks in barite and potassium feldspar.

Swarms of barite and calcite veins and radioactive zones serve as exploration guides to blind pipes. Barite and calcite vein swarms and crackle breccias adjacent to pipes represent extensions of pipe mineralization. The radioactivity results from thorium and uranium associated with the REE-bearing minerals. The breccia groundmass contains notable amounts of thorium and uranium, averaging 3,321 ppm (parts per million) and 189 ppm, respectively (table A1). The thorium-uranium ratio is about 19, whereas the normal crustal ratio is about 4 (Rose and others, 1979).

The breccia pipe groundmass has variable concentrations of the REE. Data listed in table A1 represent grab samples of groundmass material, and as such do not represent average ore grades of the breccia pipes. Total REE oxide concentrations of our samples range from 4.9 to 37.8 weight percent, averaging 20.3 weight percent. In contrast, ore grades determined from bulk samples range from 7 to 25 weight percent and average about 12 weight percent (C.W. Whitten, U.S. Bureau of Mines, oral commun., 1990). The REE-bearing breccias are enriched in the light REE, having a pronounced negative europium anomaly (fig. A5).

Gold is erratically distributed in the breccia pipes. Husman (1989) reported that gold occurs as electrum and sylvanite. Gold concentrations uncommonly exceed 1 ppm, but assays of drill core and chip samples are as high as 371 ppm (Husman, 1989). Our samples have yielded gold values of less than 6 ppb (parts per billion) (table A1). The extremely high concentrations may be due to the "nugget effect," where atypically large grains of gold give a higher assay value than the average for the pipe.

Table A1. Analyses for rare-earth elements (REE), uranium, thorium, and gold in REE-bearing breccia pipes, Pea Ridge mine, Washington County, Mo.

[The REE were determined by the ICP-MS method as outlined by Lichte and others (1987). Uranium and thorium were determined by delayed neutron activation analysis (McKown and Millard, 1987) and gold by graphite furnace (Meier, 1980). <, less than; --, insufficient number of samples above detection limit to calculate meaningful value]

Element	Sample No. (mine level)										
	PR-21 (2,370 ft)	PR-71 (2,370 ft)	PR-72 (2,370 ft)	PR-168 (2,370 ft)	PR-33C (2,440 ft)	PR-33D (2,440 ft)	PR-32 (2,475 ft)	PR-126 (2,675 ft)	PR-127 (2,675 ft)	Average	Standard deviation
	Parts per million										
La	34,000	35,000	22,000	35,000	52,000	18,000	5,700	14,000	12,000	25,300	13,863
Ce	34,000	56,000	33,000	58,000	60,000	29,000	9,500	22,000	20,000	35,722	17,242
Pr	5,400	5,500	3,200	5,800	8,900	2,800	850	2,100	1,900	4,050	2,391
Nd	18,000	19,000	12,000	20,000	31,000	9,700	3,100	7,600	6,700	14,122	8,175
Sm	2,800	2,900	2,100	2,900	4,300	1,500	450	1,200	1,000	2,128	1,140
Eu	420	380	270	360	580	230	51	150	130	286	156
Gd	1,900	1,600	1,700	1,800	2,500	1,200	460	860	680	1,411	622
Tb	360	320	270	350	340	240	68	150	110	245	104
Dy	2,100	1,700	1,500	2,200	1,400	1,700	410	870	630	1,390	594
Ho	400	300	270	450	170	370	86	170	110	258	124
Er	1,200	830	760	1,400	310	1,200	240	530	340	757	409
Tm	190	140	110	240	32	200	33	91	53	121	72
Yb	1,500	990	760	1,800	160	1,600	210	670	390	898	580
U	297	135	192	94	354	284	23	199	121	189	101
Th	4,400	1,940	804	6,160	10,100	2,710	227	1,950	1,600	3,321	2,948
	Weight percent										
RE2O3t*	23.9	29.2	18.2	30.5	37.8	15.8	4.9	11.8	10.3	20.3	10.2
	Parts per billion										
Au	6	<2	<2	2	<4	<4	<4	<2	2	--	--

*Sum of rare earth oxides.

Structure

Faults are a common feature in the mine and appear to have occurred throughout the history of the deposit. Two styles of deformation are present in the deposit. One occurred at the transition between the ductile and brittle deformation regimes, whereas the other was under conditions of brittle deformation. In the former, penetrative fabric defined by mineral lineations, mullions, foliations, and elongation of pseudobreccia fragments is parallel to and within the fault planes. These faults commonly dip at low angles (45° to 60°). Also, on the 2,675-ft sublevel pseudobreccia fragments are elongated within a fault plane. The ductile-brittle deformation resulted from a transpressional event that affected the host rhyolite, magnetite ore, banded rocks, and mafic dikes.

Brittle deformation is recorded by high-angle faults that produced angular fault breccias and clayey fault gouge along fault planes. An example is the fault on the X-11 drift of the 2,275-ft level (fig. A3), where a high-angle reverse fault roughly parallels the iron ore–wallrock contact. Specular hematite was drag folded and developed foliation parallel to the fault plane.

GENESIS OF THE REE-BEARING BRECCIA PIPES

The REE-bearing breccia pipes are similar to magmatic-hydrothermal breccias related to porphyry-type deposits (Sillitoe, 1985). However, they are not entirely analogous due to the disparity between the two types of ore systems (one is a high-grade magnetite body, whereas the other is a porphyry copper deposit having a low metal content). Nonetheless, the geochemical character and the intimate spatial relation of the REE-bearing breccia pipes with the magnetite ore system implies a genetic link between the two.

Magmatic-hydrothermal breccias are commonly associated with subvolcanic ore deposits. The breccias are a result of fluids that exsolve from water-saturated magmas in subvolcanic or plutonic environments. The exsolved fluids undergo second boiling and decompression as they cool. Burnham (1979, 1985) quantified the process of second boiling as the exsolution of a vapor phase from a water-saturated melt, with the reaction: H_2O-saturated melt = crystals + vapor. The violent rapid expulsion of fluid from magma and the increase of volume due to the expansion and

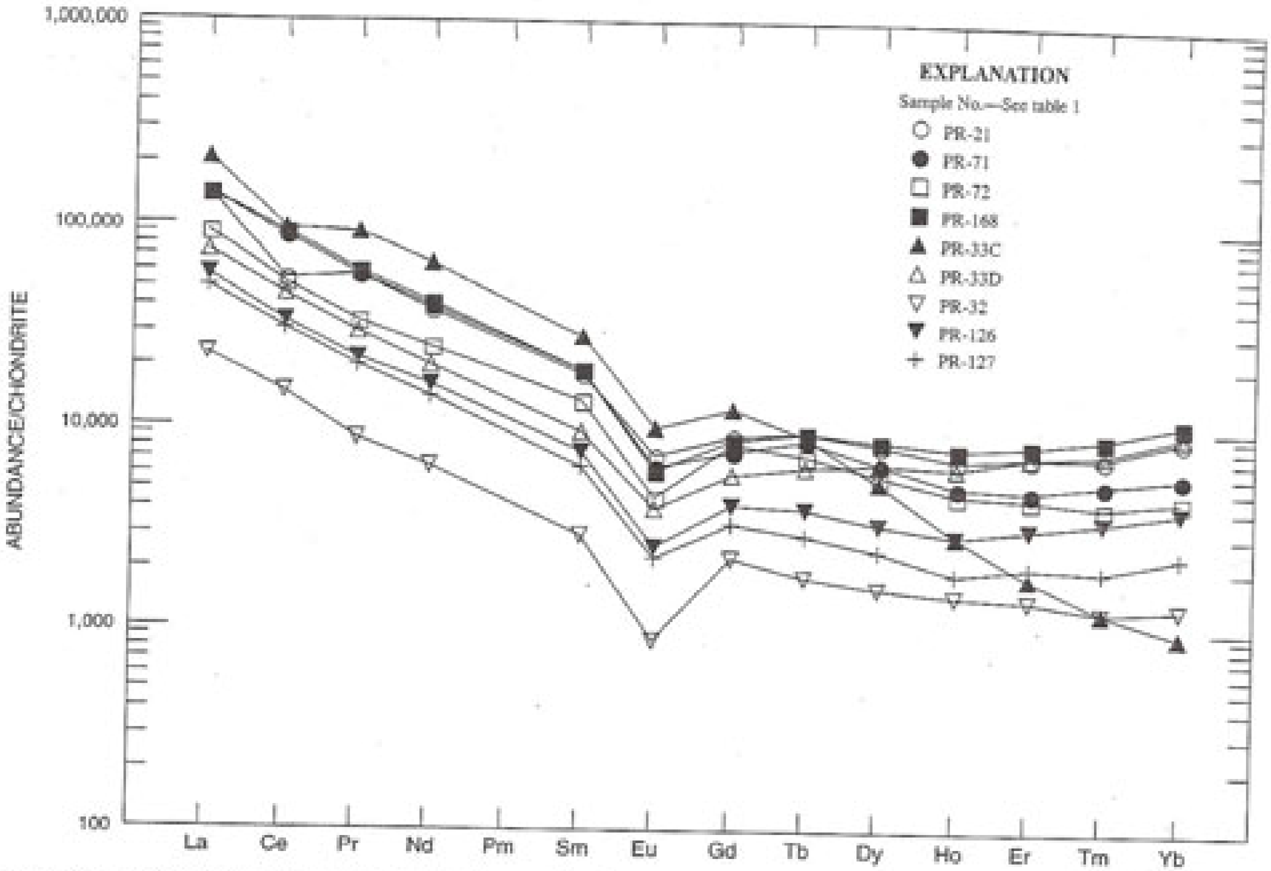

Figure A5. Plot of abundances of rare-earth elements in breccia pipes in the Pea Ridge mine, Washington County, Mo. Abundances normalized to C1 chondrite values of Evensen and others (1978).

subsequent decompression of the vapor phase release sufficient mechanical energy to generate steep tensile fractures in the wallrocks, or reopen existing faults and fractures, and further widen them by hydraulic fracturing of their walls (Burnham, 1985; Sillitoe, 1985). Upward streaming of the magmatic-hydrothermal fluid and vapor results in mixing and milling of fragments, production of rock-flour matrix, and varying degrees of upward transport of material (Sillitoe, 1985).

The REE-bearing breccia pipes were forcefully emplaced into the Pea Ridge magnetite deposit. Rock fragments rounded by abrasion as well as swirl textures of intermixed hematite and rock flour are textural evidence of fluidization during pipe emplacement. Emplacement of breccia pipes appears to have been contolled by lithologic contacts in the footwall along which faults and fractures formed.

According to our proposed magmatic-hydrothermal breccia model, the REE-bearing breccia pipes of the Pea Ridge deposit were emplaced during the waning stages of the magnetite ore system. The magnetite orebody was emplaced as an iron-rich magmatic-hydrothermal fluid. The presence of sanidine phenocrysts (or xenocrysts) confirms a magmatic constituent for the origin of the breccia pipes, and possibly the entire ore system. Late-stage magmatic-hydrothermal fluids, which exsolved from the iron ore system, were enriched in K, Ba, REE, U, Th, P, SO_2, F, Cl, and Au. The volatile phase released during second boiling provided the mechanical energy for brecciation and fracturing of the wallrocks. The REE-bearing fluids streamed upward into the footwall of the magnetite orebody along fractures, faults, and zones of weakness at lithologic contacts.

The fluids entrained fragments of wallrock, magnetite ore, and rocks of the silicified zone and abraded them during transport. Extreme abrasion resulted in the milling of fragments into rock flour. Some of the pipe-fill minerals may have crystallized during second boiling, including sanidine, orthoclase, barite, monazite, apatite, quartz, and other accessory minerals in the groundmass of the breccia pipes. Evidence for boiling includes populations of both vapor-rich and liquid-rich fluid inclusions coexisting in quartz within the groundmass. Some of the fluids may have circulated in the pipes after boiling and replaced microfragments, cemented rock flour and fragments, and formed crystal-lined vugs.

During formation of the breccia pipes, quartz veins adjacent to the pipes were reopened, and breccia pipe minerals of the same suite were deposited in the reopened veins. In addition, crackle breccias and vein swarms of barite and calcite formed adjacent to the pipes. Rebrecciated, recemented fragments record more than one brecciation event during the evolution of the magmatic-hydrothermal system.

SUMMARY

The Pea Ridge deposit is a tabular body of magnetite that stoped upward into the host rhyolitic wallrocks. Development of an amphibole-quartz skarn preceded magnetite deposition. The deposit is crudely zoned successively outward from a massive magnetite core to magnetite-cemented heterolithic breccia, to pseudobreccia, and to distal amphibole-quartz skarn. Other rock types include a specular hematite zone along the footwall and eastern edge of the orebody, massively silicified rock of the footwall, banded volcaniclastic rock, aplite dikes, and mafic dikes.

The specular hematite is in part an alteration of magnetite ore and seems to have developed along fault zones. During and after specularite development, the massive silicified zone formed by open-space filling and wallrock replacement; silicification extends into the hematite zone. Fracture-fill veins of quartz continue from the silicified zone into the adjacent altered rhyolite. Potassium feldspar flooding and sericitization accompanied silicification.

Faults occur throughout the orebody. Some faults developed a penetrative fabric that formed in the ductile-brittle transitional regime. A fault zone along the footwall contains two, and possibly three, REE-bearing breccia pipes; another pipe is along a high-angle reverse fault at the eastern edge of the orebody.

Breccia pipes, containing potentially economic concentrations of REE in monazite and xenotime, cut all rock types. The pipes include fragments of volcanic wallrock, silicified rock, and iron ore. Feldspar, quartz, and barite occur as euhedral phenocrysts in chloritic groundmass. Barite also occurs as massive replacement cement and open-space fill. Monazite and xenotime are present as granular crystals in the groundmass, as replacement of microfragments, as radial aggregates of acicular crystals in the groundmass, and as abraded platy grains that appear to have been transported. Total rare-earth oxide content of select grab samples of the breccia pipe groundmass averages 20 weight percent, whereas bulk ore averages about 12 weight percent. Gold is erratically distributed in the pipes; concentrations are not commonly greater than 1 ppm, but assays as high as 371 ppm have been reported.

The REE-bearing breccia pipes formed as magmatic-hydrothermal breccias, which were localized along fractures, faults, and lithologic contacts. Magmatically derived hydrothermal fluids underwent second boiling, during which both vapor-rich and liquid-rich fluid inclusions were trapped in quartz within the groundmass of the REE-bearing breccia pipes. Euhedral crystals of barite and other accessory minerals may have formed during second boiling. The sanidine phenocrysts (or xenocrysts) indicate that the breccia pipes had a magmatic component. Release of the vapor phase during boiling resulted in fracturing at lithologic contacts. Fluidization, coupled with the upward streaming of magmatic-hydrothermal fluids, resulted in the widening of the fractures and faults and in the brecciation of the wallrock. After boiling, some fluids may have circulated in the pipes and replaced rock microfragments and rock flour, cemented the pipes, and formed crystal-lined vugs.

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REFERENCES CITED

Arundale, J.S., and Martin, J.A., 1970, The mineral industry of Missouri, *in* v. III *of* 1968 Minerals Yearbook: U.S. Bureau of Mines, p. 429–443.

Bickford, M.E., 1988, The formation of continental crust; Part 1. A review of some principles; Part 2. An application to the Proterozoic evolution of southern North America: Geological Society of America Bulletin, v. 100, no. 9, p. 1375–1391.

Bickford, M.E., and Mose, D.G., 1975, Geochronology of Precambrian rocks in the St. Francois Mountains, southeastern Missouri: Geological Society of America Special Paper 165, 48 p.

Burnham, C.W., 1979, Magmas and hydrothermal fluids, *in* Geochemistry of hydrothermal ore deposits (2nd ed.): New York, John Wiley and Sons, p. 71–136.

——— 1985, Energy release in subvolcanic environments—Implications for breccia formation: Economic Geology, v. 80, no. 6, p. 1515–1522.

Day, W.C., Kisvarsanyi, E.B., Nuelle, L.M., Marikos, M.A., and Seeger, C.M., 1989, New data on the origin of the Pea Ridge iron-apatite deposit, southeast Missouri—Implications for Olympic Dam–type deposits: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A132.

Emery, J.A., 1968, Geology of the Pea Ridge iron orebody, *in* Ore deposits of the United States, 1933–1967 (Graton-Sales volume): New York, American Institute of Mining, Metallurgy, and Petroleum Engineers, p. 359–369.

Evensen, N.M., Hamilton, P.J., and O'Nions, R.K., 1978, Rare-earth abundances in chondritic meteorites: Geochimica et Cosmochimica Acta, v. 42, p. 1637–1665.

Husman, J.R., 1989, Gold, rare earth element, and other potential by-products of the Pea Ridge iron ore mine: Missouri Department of Natural Resources, Division of Geology and Land Survey Contributions to Precambrian Geology, No. 21, Open File Report OFR–89–78–MR, 18 p.

Kisvarsanyi, E.B., 1980, Granitic ring complexes and hotspot activity in the St. Francois terrane, midcontinent region, United States: Geology, v. 8, no. 1, p. 43–47.

——— 1981, Geology of the Precambrian St. Francois terrane, southeastern Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey Report of Investigations, No. 64, 58 p.

——— 1984, The Precambrian tectonic framework of Missouri as interpreted from the magnetic anomaly map: Missouri Department of Natural Resources, Division of Geology and Land Survey Contributions to Precambrian Geology, No. 14, 19 p.

Kisvarsanyi, E.B., and Kisvarsanyi, G., 1989, Alkaline granite ring complexes and metallogeny in the Middle Proterozoic St. Francois terrane, southeastern Missouri, U.S.A.: Geological Association of Canada Special Paper 38, 14 p.

Kisvarsanyi, G., 1975, Genesis of the Precambrian St. Francois terrane, midcontinent, U.S.A.—A field guide to the Precambrian geology of the St. Francois Mountains, Missouri: Cape Girardeau, Mo., Southeast Missouri State University, p. 49–54.

Kisvarsanyi, G., and Proctor, P.D., 1967, Trace element content of magnetites and hematites, southeast Missouri iron metallogenic province, U.S.A.: Economic Geology, v. 62, p. 449–471.

Laznicka, P., 1988, Breccias and coarse fragmentites, *in* Developments in economic geology: New York, Elsevier, v. 25, 832 p.

Lichte, F.E., Meier, A.L., and Crock, J.G., 1987, Determination of the rare earth elements in geological materials by inductive coupled plasma mass spectrometry: Analytical Chemistry, p. 1150–1157.

Marikos, M.A., Seeger, C.M., and Nuelle, L.M., 1989a, Geology of the Pea Ridge mine (field trip stop No. 1), *in* "Olympic Dam–type" deposits and geology of Middle Proterozoic rocks in the St. Francois Mountains terrane, Missouri: Society of Economic Geologists Guidebook Series, v. 4, p. 41–54.

——— 1989b, REE-mineralized breccia pipes in the Pea Ridge deposit of southeast Missouri: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A34.

McKown, D.M., and Millard, H.T., Jr., 1987, Determination of uranium and thorium by delayed neutron counting: U.S. Geological Survey Bulletin 1770, p. I1–I12.

Meier, A.L., 1980, Flameless atomic-absorption determination of gold in geological materials: Journal of Geochemical Exploration, v. 13, no. 1, p. 77–85.

Nelson, B.K., and DePaolo, D.J., 1985, Rapid production of continental crust 1.7–1.9 B.Y. ago—Nd isotopic evidence from the basement of the North American midcontinent: Geological Society of America Bulletin, v. 96, no. 6, p. 746–754.

Nuelle, L.M., Seeger, C.M., Marikos, M.A., and Day, W.C., 1989, Mineral assemblages of the Pea Ridge Fe-REE deposit—Implications of an Olympic Dam–type variant in southeast Missouri: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A34.

Oreskes, N., and Einaudi, M.T., 1990, Origin of rare earth element–enriched hematite breccias at the Olympic Dam Cu-U-Au-Ag deposit, Roxby Downs, South Australia: Economic Geology, v. 85, no. 1, p. 1–28.

Patchett, J.P., and Ruiz, J., 1989, Nd isotopes and the origin of Grenville-age rocks in Texas—Implications for Proterozoic evolution of the United States mid-continent region: Journal of Geology, v. 97, p. 685–695.

Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, Geochemistry in mineral exploration (2nd ed.): New York, Academic Press, 657 p.

Seeger, C.M., Nuelle, L.M., and Marikos, M.A., 1989, Massive silicification and late stage quartz veining in the Pea Ridge Fe-REE deposit, southeast Missouri: Geological Society of America Abstracts with Programs, v. 21, no. 6, p. A34.

Sillitoe, R.H., 1985, Ore-related breccias in volcanoplutonic arcs: Economic Geology, v. 80, no. 6, p. 1467–1514.

Snyder, F.G., 1969, Precambrian iron deposits in Missouri, *in* Magmatic ore deposits—A symposium: Economic Geology Monograph 4, p. 231–238.