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SOUTHEAST MISSOURI IRON METALLOGENIC PROVINCE: CHARACTERISTICS AND GENERAL CHEMISTRY

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Abstract – The Southeast Missouri Iron Metallogenic Province is comprised of eight known major and numerous minor magnetite and hematite deposits. It is hosted by the Middle Proterozoic Saint Francois granite-rhyolite terrane. Host rocks are rhyolites, trachytes, and andesites. Ore is associated with, although not necessarily hosted by, magnetite trachytes. Deposits are associated with caldera subsidence structures and, sometimes, trachyte ring intrusions. Deposits are within or near margins of these structures. Areal association of the deposits with a major Proterozoic tectonic zone, possibly a transform fault, suggests additional tectonic/structural control on ore emplacement. Magnetite and hematite have been produced in the province; currently, only magnetite is produced. Potential exists for production of rare earth elements, copper, and gold.

A characteristic alteration suite is associated with the iron oxide mineralisation. The suite includes silicification, potassium metasomatism, and alteration of host rock to actinolite, chlorite, garnet and epidote. While several alteration types are associated with each deposit, every type is not seen at each deposit. Chemistry suggests that magnetite and hematite deposits in the province have a unique chemical signature when compared to magnetite not directly associated with the major deposits. In addition, hematite that is an oxidation product of magnetite has a different chemical signature than presumed primary hematite.

Introduction

The Southeast Missouri Iron Metallogenic Province (Kisvarsanyi and Proctor, 1967) is hosted by the 1.48 to 1.45 Ga St. Francois granite-rhyolite terrane. The province is comprised of eight known major and numerous minor magnetite and hematite deposits (Fig. 1). Iron has been mined continuously in the province since 1815, with over 100 million tonnes produced (Missouri Division of Geology and Land Survey files). Reserves are estimated at nearly 1 billion tonnes (Arundale and Martin, 1970). Shallow and near-surface hematite deposits (Iron Mountain, Pilot Knob upper ore body) were the major sources until 1963. Iron Mountain was the most productive, and was mined almost continuously in surface and underground workings from 1836 to 1966 (Nason, 1892; Hayes and Guild, 1967). Aeromagnetic surveys in the 1940s led to discovery of the large subsurface magnetite-hematite deposits (Pea Ridge, Bourbon, Kratz Spring, Camels Hump, and lower Pilot Knob), and the Boss Fe-Cu deposit. Pea Ridge, which began operations in 1964, is the only operating underground iron mine in the United States, and is Missouri's only active iron producer. It contains massive to breccia-hosted magnetite ore. Pilot Knob consists of two ore bodies, an upper bedded hematite deposit, and a lower massive magnetite deposit. Bourbon, Kratz Spring and Camels Hump are massive to breccia-hosted magnetite bodies. Iron Mountain is massive and breccia-hosted hematite ore oxidised from magnetite; some magnetite remains. Boss contains sub-economic gold and copper mineralisation with magnetite, and is entirely breccia hosted.

Geological History of the St. Francois Terrane

The St. Francois terrane underlies most of southeast Missouri, and is exposed in the St. Francois Mountains (Kisvarsanyi and Seeger, 1993). It is part of an extensive volcanic and shallow-intrusive terrane extending from Michigan and Ohio through Illinois, Missouri, and Oklahoma to as far southwest as Arizona. This terrane is located between the Churchill (1.7 Ga) and Grenville (1.0 Ga) provinces and is one of the least-known Precambrian provinces of North America (Kisvarsanyi and Kisvarsanyi, 1989). The age of the St. Francois terrane is bracketed by suggested dates of 1.3 to 1.5 Ga (Bickford and Mose, 1975); zircons from granites yielded U-Pb isotopic ages of 1.48 to 1.45 Ga (Bickford, 1988). Granite is the predominant rock type in the subsurface; the rest of the terrane is primarily rhyolite, rhyolitic-composition rocks, and intermediate-alkalic rocks (Fig. 2).

Kisvarsanyi (1980, 1981) recognised three types of granitic rocks in the St. Francois terrane: subvolcanic massifs, ring intrusions, and central plutons. Subvolcanic massifs, intrusive equivalents of coeval rhyolitic ash-flow tuffs, are fine-grained, red, epizonal biotite alkali granites with granophyric and rapakivi textures. Magnetite is a ubiquitous accessory mineral. Ring intrusions, emplaced in ring fractures related to caldera collapse, include intermediate- to high-silica amphibole granite and biotite-hornblende granite. Central plutons, emplaced in resurgent calderas, are comprised of medium- to coarse-grained, high-silica

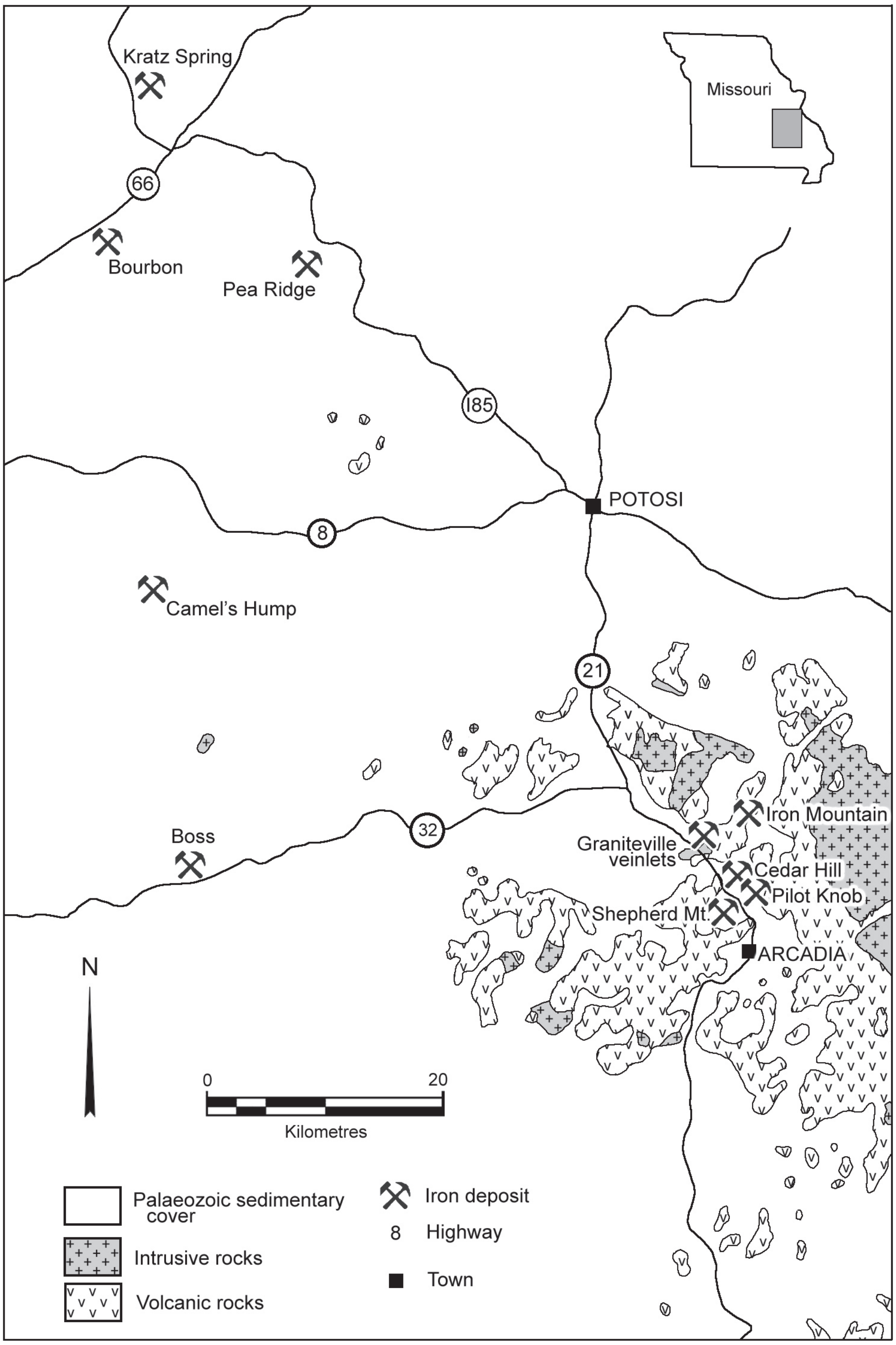


Figure 1: Exposed geology and locations of iron deposits of the Southeast Missouri Iron Metallogenic Province (after Kisvarsanyi and Kisvarsanyi).

two-mica alkali granite. They have a distinctive accessory mineral assemblage of fluorite, topaz, allanite, monazite, garnet, and cassiterite, and a characteristic trace element suite with anomalously high values of Sn, W, Nb, Y, Be, Li, Rb, Ba, and F. The plutons have a distinctive circular or oval negative magnetic anomaly signature (Kisvarsanyi, 1984; Kisvarsanyi and Kisvarsanyi, 1989).

Volcanic rocks are dominantly rhyolite ash-flow tuffs with some felsites, and typically contain alkali feldspar phenocrysts and iron-rich mafic minerals. They are remarkably fresh and unaltered in both outcrop and core sample, despite devitrification and (sometimes) recrystallisation. Densely welded ash-flow tuffs display little post-magmatic alteration beyond devitrification, and may closely approximate the original composition. The volcanic rocks display variable and often random attitudes within short distances, possibly the result of megabrecciation (Kisvarsanyi, 1981).

An intermediate-alkalic and iron-rich "trachytic" suite includes magnetite trachyte, trachyte, trachybasalt, trachyandesite, monzogranite, and syenite. This suite

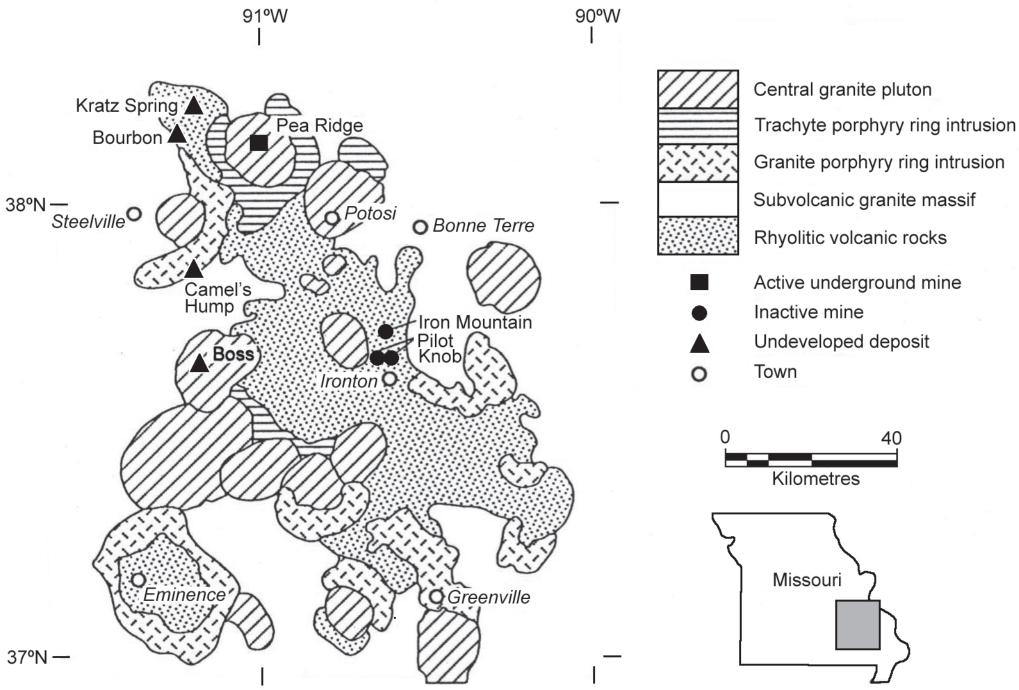


Figure 2: Geologic map of the surface and subsurface, St. Francois terrene (Nuelle *et al.*, 1991).

has a more limited areal distribution than the other suites, and most often occurs as ring intrusions (Kisvarsanyi and Kisvarsanyi, 1989).

Kisvarsanyi (1981) proposed formation of the St. Francois terrane in an anorogenic extensional tectonic setting (failed cratonic rift environment). Magma differentiation and mixing, assimilation, generation of ore magmas, volcanic exhalations, and hydrothermal and fumarolic activity (Kisvarsanyi and Kisvarsanyi, 1989) dominated the setting. Van Schmus (1993) ascribed the St. Francois terrane rocks to a 1.48 to 1.45 Ga extensional event at or near the southeast edge of a proto-continent.

Regional Structure

Curvilinear volcano-plutonic structures and ortho-polygonal regional features (Fig. 3) define the structural framework of southeast Missouri. The superposition of these two styles of faulting and deformation provided a distinctive tectonic setting for ore emplacement (Kisvarsanyi and Kisvarsanyi, 1976a, 1976b; Kisvarsanyi, 1984).

Integration of surface and subsurface geological data with aeromagnetic data helped identify volcano-tectonic features associated with the St. Francois terrane (Pratt *et al.*, 1979; Kisvarsanyi, 1981). Features include major caldera complexes, caldera subsidence structures, ring complexes with or without central plutons, and resurgent calderas with late granite plutons (Kisvarsanyi, 1981). The circular or arcuate structural pattern of these features dominates the terrane, and is well-developed on magnetic maps. Hypabyssal intrusives of intermediate-silica composition are typically expressed as positive magnetic anomalies and are interpreted as ring intrusions emplaced along caldera margins. Most ring structures are from 5 to 15 km in diameter; some are as large as 25 km (Kisvarsanyi, 1981).

Several lineaments of continental scale cross the St. Francois terrane (Arvidson *et al.*, 1984; Cordell and Knepper, 1987), and are reflected on gravity and aeromagnetic maps. Most have northwest-southeast strikes; a few have northeast-southwest and NNE-SSW strikes. The most prominent northwest-southeast lineaments, identified as reactivated basement tectonic zones, are characterised by their regularity, control over emplacement of Proterozoicn plutons, and influence (through fault reactivation) of overlying sedimentary rocks (Kisvarsanyi, 1984). Intersecting linear structures create an ortho-polygonal, block-faulted tectonic pattern that is prominent on satellite imagery and visible to some extent on topographic maps (Kisvarsanyi and Kisvarsanyi, 1976a, 1976b).

Deposit Controls

Iron deposits occur as intrusive and replacement bodies hosted by volcanic or volcanic-related rocks. They may be genetically related to the host anorogenic rhyolites (Day *et al.*, 1989), or to trachyte ring intrusions (Kisvarsanyi and Proctor, 1967). Most major deposits are within or near margins of inferred caldera subsidence structures with granite central plutons and related trachytic ring intrusions. Deposits are in surrounding volcanic rocks (Iron Mountain, Pilot Knob), near pluton margins (Boss), and in overlying volcanic rocks or roof pendants (Pea Ridge). Ore tends to be associated with magnetite trachytes and intermediate-alkalic dikes in ring complexes (Seeger and Kisvarsanyi, 1992).

Major deposits are located on both sides of a northwest-trending regional gravity lineament thought to be the geophysical expression of a major Proterozoic tectonic zone, possibly a transform fault (Kisvarsanyi, 1984). The areal relationship is suggestive of tectonic/structural control on ore emplacement.

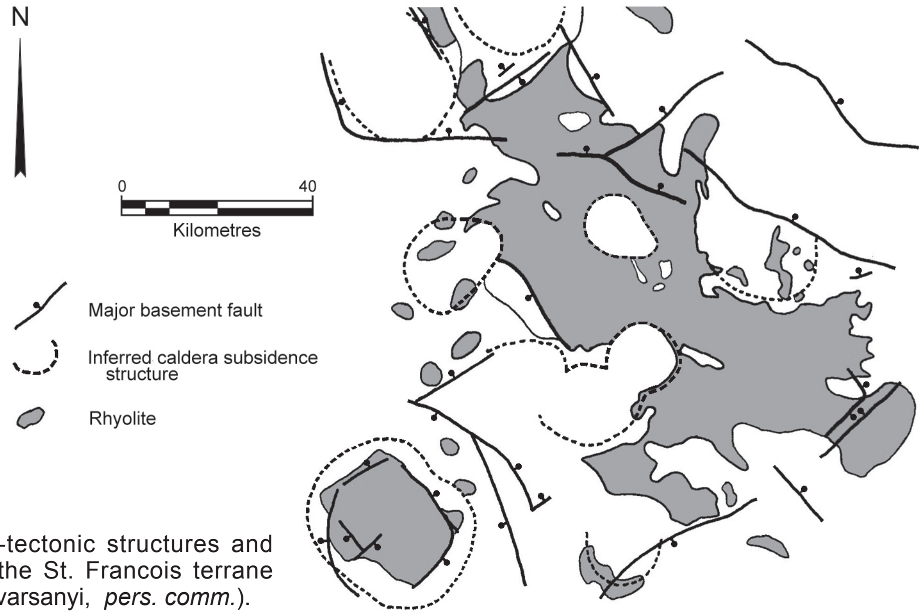


Figure 3: Volcano-tectonic structures and linear faults in the St. Francois terrane (after Eva B. Kisvarsanyi, *pers. comm.*).

Volcanic structures also imposed structural control on deposit emplacement (Kisvarsanyi, 1988). The structures provided favourable fluid migration paths and prepared ground for localisation of ore (Day *et al.*, 1991). Breccias formed by explosive volcanic eruptions and caldera collapse were especially favourable sites. Ring fractures provided preferred paths for ore fluid migration. Ore-hosting breccias are common in the Pea Ridge, Boss, and Iron Mountain deposits. At Pea Ridge, weak zones in the rhyolite host rocks, caused by ring complex development or caldera collapse and resurgence, controlled ore emplacement. At Iron Mountain, andesite subsided along upward curving fractures, resulting in the unusual arcuate shape of the ore body. Fracturing was related to deep crustal currents (Amstutz, 1960) or to relaxation after intrusion (Murphy and Ohle, 1968). In both deposits, injection of ore fluid likely increased brecciation along previously developed fractures, with host rock fragments collapsing into open spaces filled with ore fluid.

Deposit Characteristics

Deposits in the district exhibit similarities in geophysical signatures, host rocks, ore and gangue mineralisation, and alteration, suggesting that the ore fluids had similar compositions and modes of emplacement. High-amplitude positive magnetic anomalies are associated with magnetite-dominant deposits. Positive gravity anomalies with bends or "shoulders," and those superimposed on magnetic anomalies, may also indicate mineralisation (Seeger and Kisvarsanyi, 1992).

Host rocks include acidic and intermediate igneous rocks. Rhyolites host the mineralisation at Pilot Knob, Pea Ridge, and Bourbon. Magnetite trachytes (Seeger and Kisvarsanyi, 1992, 1993) and meta-syenites (Vierrether and Grant, 1993) host the Boss deposit. Murphy and Ohle (1968) identify Iron Mountain host rocks as andesites; Dudley (1998) suggests that they are trachyte or trachyandesite.

Magnetite is the only iron ore currently produced; hematite was produced in the past. Magnetite-hematite proportions vary between deposits, and change vertically and horizontally within individual deposits. Both range from massive to iron oxide-cemented breccia; minor mineralisation occurs as disseminations and clots. Massive ore at Pea Ridge has an average grade of 55% magnetic iron. Magnetite textures vary from massive and shiny with sub-conchoidal fractures to finely crystalline and granular. Hematite ores are specularite to massive and shiny; some have prominent martite (Iron Mountain). Most hematite is secondary, although bladed hematite phenocrysts in magnetite may be primary. Iron ore-wall rock contacts are generally sharp, with local partial to near total replacement of wall rock by iron oxide.

Iron oxide-cemented breccias vary widely in ore content, ranging from stringers to massive ore with minor clasts. Some breccias are unmistakably tectonic. Others are pseudo-breccias, with hydrothermal replacement of the host rock by iron oxide leading to a breccia-like texture (Laznicka, 1988; Nuelle *et al.*, 1991, 1992). Host rock clasts in either type may appear relatively fresh or exhibit minor to complete alteration.

Quartz and apatite are the most common gangue minerals. Others include pyrite, amphibole, biotite, chlorite, fluorite, barite, grunerite, andradite, calcite, and talc (Nuelle *et al.*, 1991, 1992; Dudley, 1998). The gangue forms interstitial intergrowths, net-textured veinlets, and pods within the ore. At Pea Ridge, monazite gangue is associated with apatite in massive magnetite (Sidder *et al.*, 1993).

Deposits in the province have a characteristic alteration suite, although not all types are present in each deposit. Variation between individual deposits is likely due to compositional differences in the host rocks and ore fluids. The suite includes silicification, potassium metasomatism, and alteration of host rock to actinolite, chlorite, garnet and epidote.

Silicification is notable at Pea Ridge, where it is a unit as large or larger than the iron oxide ore body (Seeger *et al.*, 1989). Silicified rock is characterised by massive, white to light gray quartz that replaced rhyolite to varying intensities; areas with greater than 75 % quartz are common. Accessory minerals include potassium feldspar, fluorite, muscovite, biotite, tourmaline, epidote, calcite, barite, rutile, pyrite, chalcopyrite, and chlorite. Sericite is common on fracture and fragment surfaces. At Iron Mountain, quartz was emplaced during a later brecciation event; it lined vugs and replaced amphibole and apatite (Allen and Fahey, 1952; Dudley, 1998).

Potassium metasomatism ranges from sporadic to pervasive within individual deposits and from one deposit to another. All deposits exhibit some degree of metasomatism. At Pea Ridge, it is associated with silicification and is noted by the addition of potassium feldspar to silicified rock and surrounding wall rock (Seeger *et al.*, 1989). It also forms potassium feldspar pegmatite pods, again associated with silicification. At Boss, the entire deposit has undergone potassium enrichment, but visible evidence is sporadic (Seeger and Kisvarsanyi, 1993).

Epidote is a minor alteration product at Pea Ridge, where it is associated with silicification; at Iron Mountain, it is a major alteration unit. Iron Mountain drill cores have numerous zones up to approximately a metre in thickness where epidote (associated with garnet) has replaced andesite. At Bourbon, it altered rhyolite that was cut by magnetite stringers and veins.

Actinolite comprises major alteration zones at Pea Ridge and Pilot Knob (lower ore body). Host rhyolites are altered to masses of coarse-grained randomly oriented actinolite crystals, often with interstitial quartz, apatite, iron oxide, pyrite, chalcopyrite, and calcite (Nuelle *et al.*, 1991, 1992). At Bourbon, actinolite forms zones several centimetres thick at the boundary between iron oxide mineralisation and rhyolite. At Iron Mountain, actinolite is found as discrete, non-oriented interlocking phenocrysts floating in iron oxide, and as acicular crystals radiating outward from andesite clasts into the iron oxide matrix. In general, actinolite at Iron Mountain appears fresher in magnetite; in hematite it is often chloritised or sausseritised (Murphy and Ohle, 1968).

Andradite garnet is the most common alteration type at Iron Mountain, with two generations. The first, discrete crystals that replaced host rock, preceded iron oxide mineralisation (Allen and Fahey, 1952). The second generation replaced actinolite, and often contains actinolite inclusions and cuts amphibole crystals. It also cuts hematite ore, is cement for brecciated hematite, and is the centre component of hematite veinlets (Murphy and Ohle, 1968). Garnet is a minor alteration product at the Pea Ridge and Pilot Knob (lower) deposits. Andradite zones up to approximately a metre in thickness are seen in Boss drill core intercepts.

Chlorite is found as fist-sized masses on dumps for the Pilot Knob lower ore body; deposit descriptions do not include the distribution of massive chlorite in the mine. At Pea Ridge, it replaces rhyolite fragments in magnetite-cemented breccias. Chlorite fracture coatings are ubiquitous in all deposits.

Potential Ore Minerals

Pea Ridge contains estimated reserves of 200,000 tons of 12 percent REE and traces of gold (L. Tucker, Pea Ridge Iron Ore Co., oral comm.) in four REE-bearing breccia pipes. The pipes occur at or near contacts between major lithologic zones, are steeply dipping (>60^o), and are elongate to ovoid in plan view. Horizontal lengths reach 60 m; widths are as much as 15 m (Nuelle *et al.*, 1991, 1992; Seeger, 1992). Maximum vertical extents are unknown, but one pipe extends a minimum of 120 m (Seeger, 1992).

The pipes contain fragments of rhyolite, hematite, and silicified rock in a groundmass of rock flour (milled rhyolite wall rock and specularite grains), feldspar, chlorite, barite, apatite, quartz, and calcite. REE-bearing minerals include monazite, xenotime, and rare bastnaesite and britholite. Monazite and xenotime occur as 0.5 to 1.0 mm granular crystals, radial crystal aggregates, acicular crystals replacing wall rock microfragments, and irregular crystals filling fractures in barite and feldspar (Nuelle *et al.*, 1991). Thorium and uranium are also present. Total REE oxide concentrations of grab samples range from 4.9 to 37.8 wt.%, with an average of 20.3 wt.% (L. Tucker, oral comm.). U.S. Bureau of Mines bulk samples range from 7 to 25 wt.% and average 12 wt.% (C.W. Vierrether, *pers. comm.*, 1990). Cerium, lanthanum, and yttrium are found in recoverable quantities. Gold is erratically distributed and has been reported as electrum and sylvanite. Concentrations seldom exceed 1 ppm, although individual assays are as high as 371 ppm (Husman, 1989).

The Boss iron-copper deposit, also known as Boss-Bixby (Hagni and Brandom, 1988), has never been developed due to its depth, grade and size. The deposit is located near the contact between trachytic rocks and volcanic country rocks. Mineralisation consists of higher-grade breccia-hosted zones separated by weakly mineralised areas; it occurs as disseminations, breccia matrix, and fracture fill. Magnetite is the main iron oxide mineral; copper mineralisation is primarily chalcopyrite and bornite (Seeger and Kisvarsanyi, 1993).

Pyrite is the earliest sulphide at Boss, followed by chalcopyrite and bornite. Sulphides replace and cut the oxides; replacement of magnetite by chalcopyrite is common (Kisvarsanyi, 1989). Chalcopyrite and bornite are nearly contemporaneous. Both rim magnetite, hematite, and pyrite grains (Hagni and Brandom, 1989), and occur as veins cutting host rocks and iron oxides. Other sulphides include carrollite, molybdenite, cobaltite, chalcocite, covellite, and late sphalerite and galena (Kisvarsanyi and Smith, 1988). Gold has been detected as electrum in a chalcopyrite vein (Hagni and Brandom, 1988), and in assays.

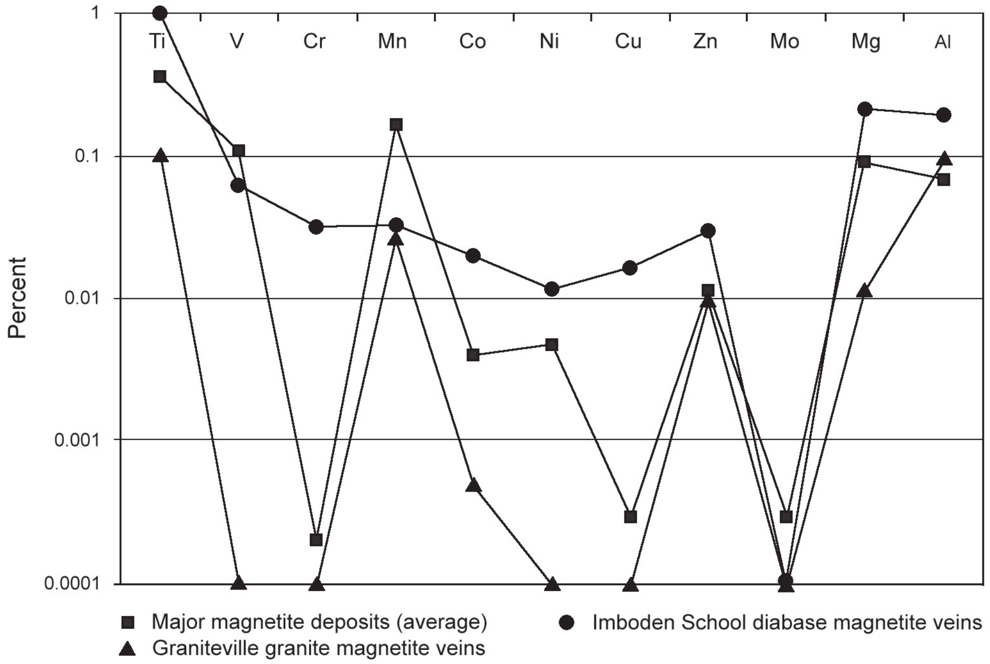


Figure 4: Spider diagram comparing averaged chemical content of selected elements for three major magnetite deposits (Iron Mountain, Pea Ridge and Bourbon) to vein magnetite in the Imboden School diabase and the Graniteville granite, St. Francois Mountains. Data from the Boss deposit was not included due to its anomalous copper, cobalt and chromium contents. Data after Kisvarsanyi and Proctor (1967).

Deposit Chemistry

The iron deposits are generally enriched in V and Co, and depleted in Ti, Cr and Ni. Most exhibit marked alkali metal enrichments, particularly in potassium. They have notable, although variable, enrichments in P, S, F, CO_2, Cu, and Mo. REEs, U, Cu, and Au are locally important, especially at Pea Ridge and Boss (Seeger and Kisvarsanyi, 1992).

Chemically, the deposits are distinct from other magnetite in the St. Francois terrane (Fig. 4). The content of selected elements in three deposits (Iron Mountain, Pea Ridge, and Bourbon) is markedly different from magnetite veins in diabase and granite. Magnetite veins associated with the Graniteville granite pluton are similar to the deposits, although relatively depleted in most elements. The similarity supports a postulated relationship between deposit emplacement and late central granite plutons (Kisvarsanyi, 1981). Magnetite associated with diabase exhibits dissimilar chemistry, and is enriched in numerous elements when compared to the deposits. Both vein signatures suggest that the iron oxide deposits have a unique trace element signature.

Fig. 5 individually illustrates the content of selected elements in magnetite from four of the deposits - Boss,

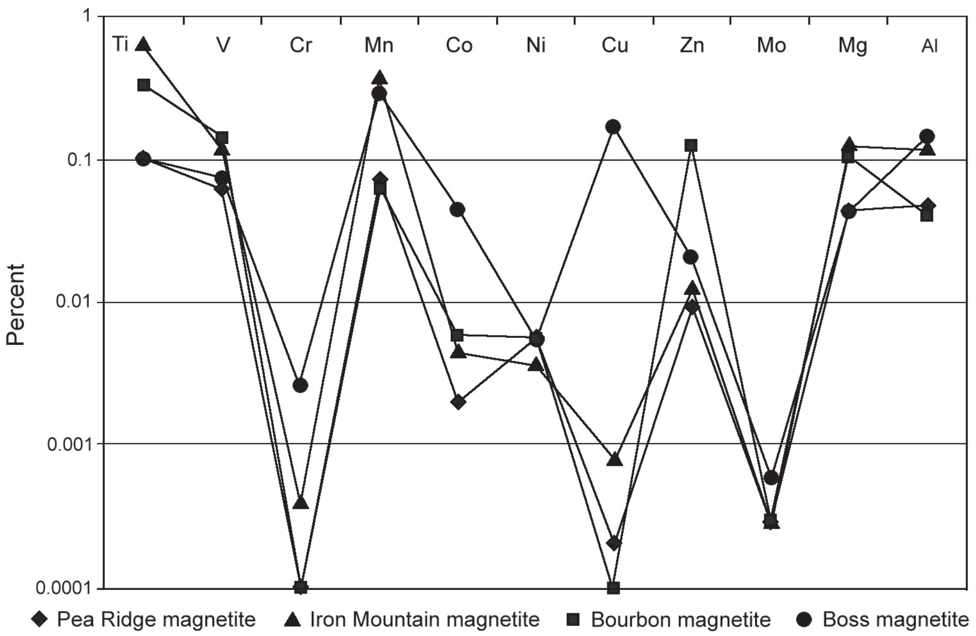


Figure 5: Spider diagram comparing content of selected elements for four magnetite deposits in the Southeast Missouri Iron Metallogenic Province. Data after Kisvarsanyi and Proctor (1967).

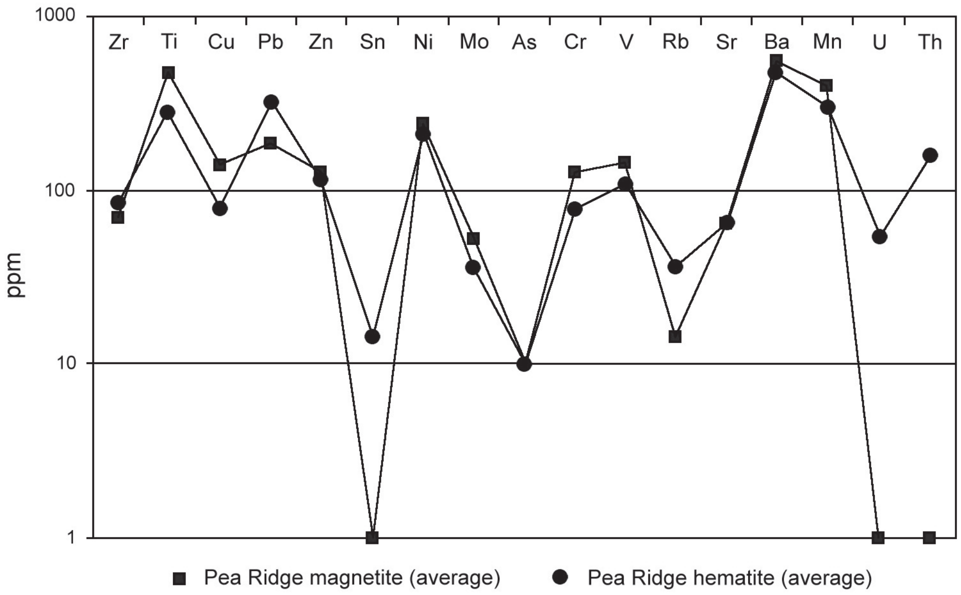


Figure 6: Spider diagram comparing averaged data on selected elements in magnetite and hematite from three drill-holes (2275-foot level) in the Pea Ridge Mine. Data courtesy of the Pea Ridge Iron Ore Company.

Iron Mountain, Pea Ridge and Bourbon. Values are similar, with the exception of Cu, Co, and Cr values for Boss; these are high due to the associated copper sulphide mineralisation. Similarities in Zn and Ni may be due to enrichment or depletion by later Mississippi Valley-type mineralising fluids.

Magnetite and hematite analyses from underground drillholes at Pea Ridge suggest that the hematite is an oxidation product of magnetite rather than primary in origin. Similar concentrations of most elements remain after oxidation to hematite (Fig. 6). Relative to magnetite, the hematite is depleted in Ti, Cu, Mo, Cr, and Sr, and enriched in Zr, Pb, Sn, and Rb. Uranium and thorium enrichments in hematite are related to emplacement of REE-bearing breccia pipes.

Fig. 7 compares values for secondary hematite at Pea Ridge with those for postulated primary hematite (Cedar Hill), hematite at Pilot Knob (upper), and averaged data for major magnetite deposits. Magnetite and secondary hematite show similar enrichments in relation to Cedar Hill hematite. The most marked differences are in V, Mn, and Mg. Both are depleted in Mo and Cu, suggesting that this is related to hematite formation, whether of primary or secondary origin. Similarities between values for Cedar Hill and Pilot Knob (upper) suggest that Pilot Knob (upper) may be, at least in part, primary hematite.

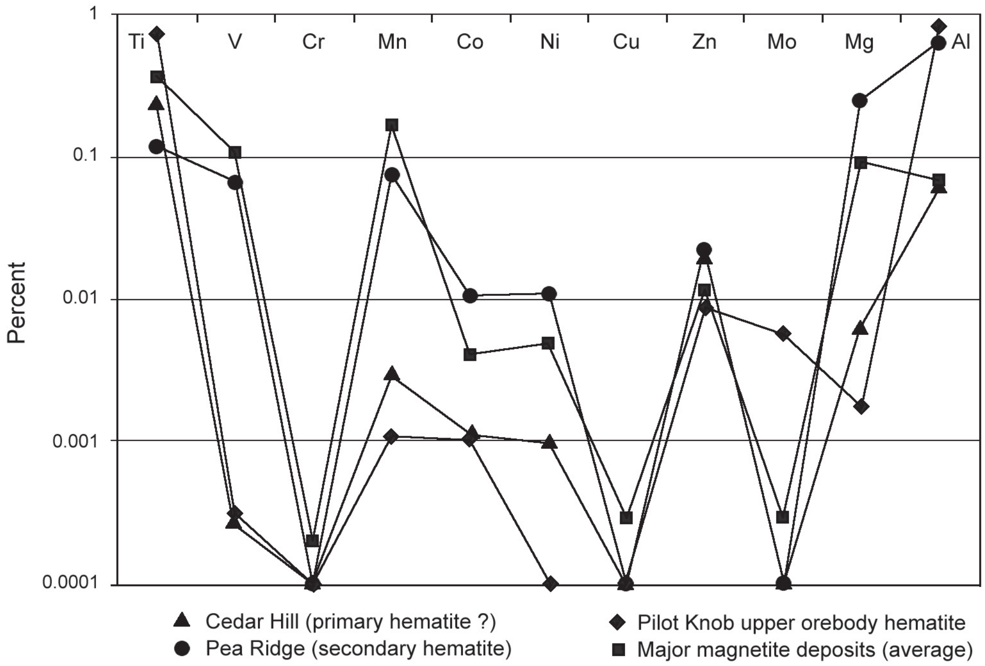


Figure 7: Spider diagram comparing averaged chemical content of selected elements for three major magnetite deposits (Iron Mountain, Pea Ridge and Bourbon) to hematite from Pea Ridge, Pilot Knob upper orebody and Cedar Hill. Data after Kisvarsanyi and Proctor (1967).

Figure 8: (right) Diagrammatic sketch of development of shallow magma chambers and immiscible fluids (after W.C. Day, *pers. comm.*).

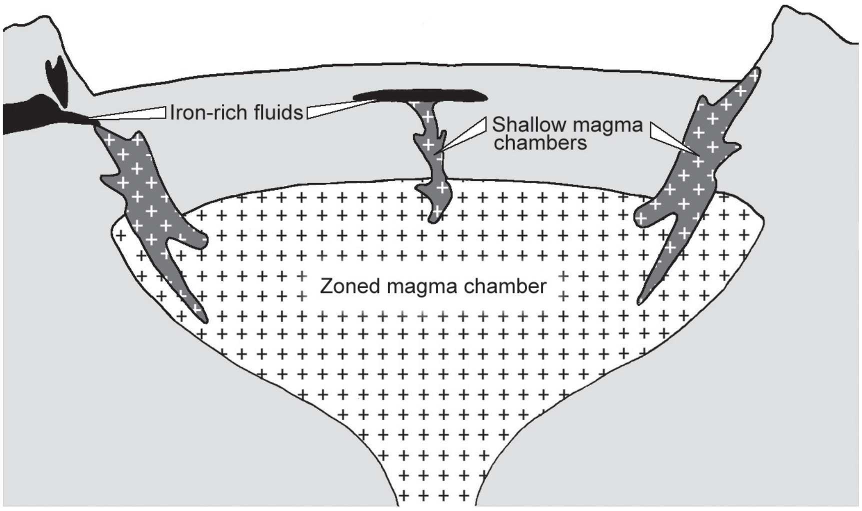
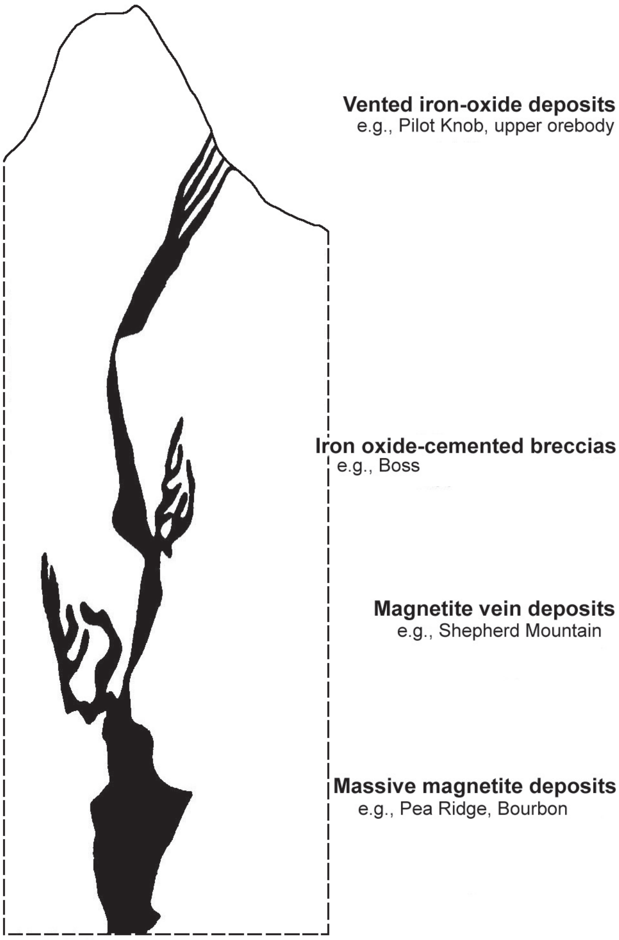


Figure 9: (below) Schematic correlation of Missouri iron deposits (after W.C. Day, *pers. comm.*).



Generalised Genesis

Debate continues on the genesis of the iron deposits. Data exist to support both magmatic intrusive and magmatic hydrothermal models. Whether deposit formation resulted from intrusive or hydrothermal processes, or a combination, the ore fluids all followed similar pathways and developed a distinct vertical distribution of ore deposit types.

During caldera resurgence, structurally weak zones formed due to ring fracture development, ring dike emplacement, and doming-related fracturing of central caldera rocks. Shallow magma chambers in caldera margins and near caldera centres (Fig. 8) developed immiscible iron- and silica-rich fluids. The iron-rich fluids rose through the weakened zones into overlying host rocks (Nuelle *et al.*, 1991, 1992). At depth, and closest to the chambers, large, massive stock-like bodies formed (Fig. 9). Offshoots of ore fluid into host rocks formed large magnetite veins. Shallow breccia-hosted ores developed as ore fluids continued to move up, but were unable to either replace Exhalation or venting of ore fluids at the surface led to development of bedded ores. Oxidation of magnetite by exposure to meteoric water and groundwater resulted in primarily hematite bodies like Iron Mountain. Later emplacement of the silica-rich fluids is in part responsible for host rock alteration (Seeger *et al.*, 1989).

Kisvarsanyi (1981) suggested that the chemical signature of the deposits is the result of similar iron sources. Kisvarsanyi and Proctor (1967) suggested that the sources are magnetite trachytes. Other potential sources noted include rhyolites and granites. Considerable work is still required to determine which, if any, of these theories are correct.

Conclusion

The Southeast Missouri Iron Metallogenic Province is associated with the 1.4 Ga anorogenic St. Francois granite-rhyolite terrane. Major deposits are related to inferred caldera subsidence structures. Host rocks include rhyolite, trachyte and andesite. Primary ores are magnetite and hematite; REEs, gold and copper are present, but not currently recovered. The associated alteration suite includes massive silicification, potassium metasomatism, actinolite, chlorite, epidote and garnet.

Iron deposits of the province have a unique trace element signature when compared to other magnetite in the terrane. The Iron Mountain, Pea Ridge, Bourbon, and Boss deposits all have similar trace element signatures, with the exception of the copper and cobalt values at Boss. Secondary hematite has a geochemical signature very similar to magnetite, especially when compared to postulated primary hematite. However, the oxidation of magnetite to hematite does have a distinct signature of depletion and enrichment of certain elements. Presumed primary hematite has a unique signature, and is generally depleted in trace elements when compared to magnetite.

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