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The Southeast Missouri (USA) Proterozoic iron metallogenic province—Types of deposits and genetic relationships to magnetite–apatite and iron oxide–copper–gold deposits

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ABSTRACT

The Southeast Missouri (USA) iron metallogenic province within the Mesoproterozoic St. Francois Mountains terrane includes eight major iron deposits and approximately 30 minor deposits. Three of the major deposits have been mined: Pilot Knob magnetite, Iron Mountain, and Pea Ridge. These deposits have similarities to "Kiruna-type" iron deposits, and likely formed either by crystallization of iron oxide magma, and/or by hydrothermal replacement of volcanic rocks. Iron oxides within all district deposits are dominantly magnetite and hematite, but the gangue minerals are diverse. At Pilot Knob magnetite the dominant gangue mineral assemblages are albitic plagioclase–K-feldspar–quartz–chlorite; at Iron Mountain, andradite–actinolite–apatite–quartz; and at Pea Ridge, apatite–quartz in the main part of the deposit, plus REE-bearing breccia pipes, discussed below. Pilot Knob magnetite and Pea Ridge have associated carbonates which have been suggested to indicate carbonatitic affinities for these deposits. The Boss–Bixby deposit has been described as an iron oxide–copper–gold (IOCG) deposit, and contains the only significant copper resource known in the district (~40 Mt of 0.8% Cu), as yet undeveloped. The district also has steeply dipping iron oxide vein deposits that represent part of the plumbing system where iron-bearing hydrothermal fluids moved upward towards the surface from the iron orebodies developing at depth. Some of these hydrothermal fluids were exhaled into caldera lakes and formed small deposits composed of laminated, oolitic sedimentary hematite.

1. Introduction

The iron metallogenic province of the Missouri (USA) Proterozoic St. Francois Mountains terrane (SFMT) contains four distinct types of mineral deposits (Table 1): (1) magnetite–hematite bodies that have crystallized from an iron oxide magma and/or from hydrothermal solutions, being similar in some aspects to "Kiruna-type" deposits; (2) iron oxide–copper–gold (IOCG) deposits; (3) steeply dipping hydrothermal magnetite–hematite veins; and (4) sedimentary hematite iron formations that have originated by exhalations of hydrothermal fluids into caldera lakes. Deposits that are to be discussed within this study are as follows: (1) Pilot Knob magnetite, Iron Mountain, Pea Ridge, and Kratz Spring magmatic/hydrothermal deposits; (2) Boss–Bixby, Bourbon, and Camels Hump IOCG deposits; (3) Shepherd Mountain, Shut-Ins, and Hogan hydrothermal veins; and (4) Pilot Knob hematite, Cedar Hill, College Hill, Cuthbertson Mountain, and Russell Mountain sedimentary iron formations. All aforementioned deposits are hosted within rhyolitic to trachytic pyroclastic volcanic units that have U–Pb ages of 1470 ± 30 Ma (Van Schmus et al., 1996). In addition to the high-silica volcanic rocks (principally rhyolitic tuffs), the terrane is composed of epizonal and mesozonal granitic plutons, and subordinate amounts of intermediate- and mafic-composition igneous rocks. The terrane lacks evidence of regional metamorphism or convergent tectonic structures, and has been described as an anorogenic rift by a number of workers (Anderson, 1983; Day et al., 1989; Groves et al., 2010; Hauck, 1990; Hitzman, 2000; Kisvarsanyi, 1981; Sims et al., 1988). However, other authors have interpreted the terrane to record convergence along an active subducting plate margin in an accretionary arc or continental margin arc setting (e.g., Corriveau and Mumin, 2010; Foose and McClelland, 1995; Menuge et al., 2002; Rivers and Corrigan, 2000; Van Schmus, 1993; Walker et al., 2002; Williams, 2010). Skirrow (2010) indicated that a switch from compression to extension was important in the development of IOCG deposits. Clearly, the development of the SFMT and similar terranes is still controversial.

Based on data from outcrops, drill cores, and aeromagnetic maps of the region, Kisvarsanyi (1980, 1981, 1988) inferred that this terrane contains more than a dozen overlapping granitic ring complexes, cauldron subsidence structures with associated ring volcanoes, ring plutons, and resurgent calderas with central plutons (Fig. 1). Kisvarsanyi (1972, 1990) summarized the chemistry of the rhyolite ash-flow tuffs of this terrane, as containing high SiO_2, high K_2O/Na_2O

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Table 1
Missouri Iron district deposits discussed in this paper.

	Name of deposit	Type of deposit	Mineralogy	Host rock	Production	Knowledge from what type of data
1	Pilot Knob magnetite	Magmatic/hydrothermal—"Kiruna-type"	Magnetite, minor hematite	Rhyolitic/trachytic pyroclastics	20 Mt of 35–40% iron	Core and published information
2	Iron Mountain	Magmatic/hydrothermal—"Kiruna-type"	Hematite–magnetite	Trachyte/trachyandesite	9 Mt iron ore concentrates	Core and published information
3	Pea Ridge	Magmatic/hydrothermal—"Kiruna-type"	Magnetite, minor hematite	Rhyolitic pyroclastics	41 Mt by 1992	Core and published information
4	Kratz Spring	Magmatic/hydrothermal—"Kiruna-type"?	Magnetite	"Felsitic host rocks" (Snyder, 1969)	No production	Published statements
5	Boss–Bixby	IOCG (iron oxide–copper–gold)	Magnetite, hematite, Co-bearing chalcopyrite, bornite	Highly altered syenite dike	40 Mt 0.8% Cu, undeveloped	Core, M.S. thesis, published information
6	Bourbon	IOCG (iron oxide–copper–gold)?	Similar to Boss–Bixby (Day et al., 2001)	No published information	No production	Core and published information
7	Camels Hump	IOCG (iron oxide–copper–gold)?	Similar to Boss–Bixby (Day et al., 2001)	No published information	No production	Published statements
8	Shepherd Mountain	Hydrothermal vein	Magnetite, hematite, quartz	Rhyolitic pyroclastics	75,000 tons	Outcrop and published information
9	Shut-Ins	Hydrothermal vein	Hematite, magnetite	Rhyolitic pyroclastics	No production	Outcrop
10	Hogan	Hydrothermal vein/vent	Hematite, jasperoid	Rhyolitic pyroclastics	No production	Outcrop
11	Pilot Knob hematite	Sedimentary	hematite	Rhyolitic pyroclastics	1.6 Mt hematite ore	Outcrop and published information
12	Cedar Hill	Sedimentary	Hematite	Rhyolitic pyroclastics	25,000 tons	Outcrop
13	College Hill	Sedimentary	Hematite	Rhyolitic pyroclastics	No production	Outcrop
14	Cuthbertson Mountain	Sedimentary	Hematite, Mn-oxides/hydroxides	Rhyolitic pyroclastics	No production	Outcrop
15	Russell Mountain	Sedimentary	Hematite	Rhyolitic pyroclastics	3000 tons	Outcrop

ratios and Fe/Mg ratios, and high F abundances, and low CaO, MgO, and Al_2O_3. U–Pb geochronology of zircons yields crystallization ages of 1.36–1.5 Ga for the plutonic–volcanic rocks that characterize this terrane (Bickford and Mose, 1975; Van Schmus et al., 1996).

2. Mineralogical and analytical techniques

Mineral analyses were performed on the Cameca SX100 electron microprobe at the Central Science Laboratory, University of Tasmania, Australia. The beam energies were 20 keV and 15 nA for oxides and sulfides, with 15 keV and 30 nA used for silicates and carbonates. Beam diameter was usually 5 μm, but 20 μm diameters were used occasionally to test for compositional homogeneity. Effects of beam diameter on analyses were tested, replicate analyses of the same grain in the UTAS2 hornblende standard with 5, 10, 20, and 30 μm beams were performed, and results were consistent within analytical error. Microprobe spectrometers were calibrated against known mineral standards before each session began, and each analytical session was bracketed with multiple analyses of known ilmenite, marcasite, hornblende, and dolomite standards, as appropriate. Detection limits were calculated independently for each analysis, and typically were 0.02–0.04 wt.%, depending on the element, except for S and F, which were typically 0.08–0.10 wt.%. All results at or below their detection limits are removed from the tabulation.

Whole rock analyses for Pilot Knob magnetite and Pea Ridge were done by Acme Labs, Vancouver, Canada, using ICP-emission spectrometry following a lithium metaborate/tetraborate fusion and digestion by dilute nitric acid. In addition, a separate split was digested in aqua regia and analyzed by ICP mass spectrometry for precious and base metals.

Plagioclase compositions were initially determined optically as crushed grain mounts with oils using the Tsuboi method of fast-ray refractive index (Nesse, 2004). All thin section blocks were stained for K-feldspar using a hydrofluoric acid leach and staining with sodium cobaltinitrite; selected blocks were stained for plagioclase using potassium rhodizonate (Bailey and Stevens, 1960).

3. "Kiruna-type" magnetite–hematite deposits

3.1. Pilot Knob magnetite

The Pilot Knob magnetite (PKM) deposit is located in Iron County, Missouri (Fig. 1) and was mined from 1968 to 1980, producing 20 Mt of ore averaging 35–40% iron (Kisvarsanyi, 1990). The deposit consists of a series of tabular, sill-like bodies that strike northwest and dip moderately to the southwest (Fig. 2a), approximately parallel to layering within the host sequence of Mesoproterozoic, pink to gray, rhyolitic pyroclastic rocks. The approximate dimensions of the deposit were 500 m strike length, 700 m dip length, with 100 m thickness. The deposit does not crop out and was discovered by drilling in the 1950s and 60s of an aeromagnetic anomaly. Because the deposit is covered by approximately 100 m of Cambrian sedimentary rocks, no geologic map exists of the local area. The orebody was exposed on the Precambrian unconformity and is angularly overlain by the basal Upper Cambrian Lamotte Sandstone; the updip edge was partially replaced by hematite during its erosional exposure (Wracher, 1976). The Shepherd Mountain Gabbro, a 120 m thick, near-horizontal dike that cuts the deposit (Fig. 2a), has a whole rock Sm–Nd isochron age of 1333 ± 56 Ma (Lowell and Rämö, 1999), providing a minimum age of emplacement for the deposit.

The ores at PKM can be divided into two broad types, comprising relatively homogeneous higher-grade, black granular magnetite that forms the bulk of the orebody, and relatively heterogeneous lower-grade magnetite forming an envelope around the higher-grade ores. Higher-grade ores are composed not only of fine- to medium-grained, low-Ti magnetite with interspersed granular silicate minerals, mainly albitic plagioclase (Fig. 3a), but also of K-feldspar, quartz, and chlorite