Review of geology, alteration and origin of iron oxide–apatite deposits in the Cretaceous Ningwu basin, Lower Yangtze River Valley, eastern China: Implications for ore genesis and geodynamic setting

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A B S T R A C T

In the Cretaceous Ningwu volcano-sedimentary basin in the Yangtze River Valley metallogenic belt, eastern China, there are three areas with a dense distribution of magnetite or hematite deposits: the Meishan deposit in the north; Washan, Nanshan and Taocun deposits in the center; and the Zhongjiu and Gushan deposits in the south. The mineralization in the Ningwu basin is associated mainly with subvolcanic intrusions, consisting of gabbro–diorite porphyry and/or gabbro–diorite. Alteration zoning of these deposits is pronounced, and includes: (1) an upper light colored zone of argillic, kaolinite, silica, carbonate and pyritic alteration; (2) a middle dark colored zone of diopside, fluorapatite–magnetite, phlogopite, and garnet with fluorapatite–magnetite; (3) a lower light colored zone of extensive albitic alteration. However, at the Gushan iron deposit, the lower light colored zone and the middle dark colored zone are absent, whereas the principal alteration is represented by silicification, kaolinization, and carbonatization.

The iron oxide–apatite deposits in the Ningwu basin are typically magmatic–metasomatic origin and are similar to the Kiruna-type deposits in Scandinavia, particularly with respect to mineral assemblages, fabric and structure of the iron ores, occurrence of the orebodies and wall rock alteration. The iron oxide–apatite deposits of the Ningwu basin contain magnetite and/or hematite, with diopside or actinolite and apatite gangue. They were formed in a rift or extensional environment and the mineralization is associated with alkaline magmatism. The time interval between magmatism and related mineralization is very short.

1. Introduction

Many apatite-bearing magnetite and/or hematite mineral systems, including world-class Meishan, Washan, and Gushan iron deposits, have been discovered in the Ningwu area in eastern China. These deposits, named ‘porphyry iron deposit’ in the Chinese literature, are associated in time and space with continental volcanic and sub-volcanic rocks (Ningwu Research Group, 1978). Systematic exploration was conducted in the 1970s and 1980s. The different types of iron deposits, their genesis, alteration zoning and age were extensively studied and more fully described in papers by Chang et al. (1991), Chen et al. (1981), Institute of Geochemistry, Chinese Academy of Sciences (1987), Gu and Ruan (1988), Lin (1999), Li and Xie (1984), Lu et al. (1990), Ningwu Research Group (1978), Tang et al. (1998), Zhai et al. (1992), Zhang (1979), Yu and Mao (2004) and Mao et al. (2006). However, little detailed work on the Ningwu mining district has been published in international journals up until now, except for few studies on specific aspects (e.g., Ishihara et al., 1986; Mao et al., 2006; Pan and Dong, 1999; Zhigang, 1990).

This paper aims to fill this gap with the objective of (1) presenting a detailed review of the geological characteristics of the iron deposits in the Ningwu area; (2) interpreting the iron metallogenesis; and (3) comparing these iron deposits in the Cretaceous Ningwu basin with the Kiruna-type iron deposit in terms of geology, alteration and metallogenic processes.

2. Geological setting

As one of seven mining districts in the Lower Yangtze River valley metallogenic belt, East China, the Ningwu basin is situated at the northern margin of the Yangtze Craton, to the east of the Tangcheng-Lujiang Fault (see Figs. 1 and 2 in Pan and Dong, 1999), and to the south of the Dabieshan ultra-high pressure metamorphic belt. The Cretaceous Ningwu basin is a NNE-trending rhomboid-shaped faulted basin (Ningwu Research Group, 1978; Zhigang, 1990; Fig. 1), bounded by the Fangshan–Xiaodanyang Fault in the east, the Yangtze River (Changjiang) fault zone in the west, the Nanjing–Hushu Fault in the north and the Sanshanjie–Xuancheng Fault in the south (outside the
The iron deposits and occurrences exposed in the basin have a total estimated reserve of 500 million tons of iron.

Ishihara et al. (1986) and Zhigang (1990) briefly described the lithostratigraphic sequence and volcanic rocks of the Ningwu basin. The stratigraphy, from bottom to top, comprises the Lower–Middle Triassic Qinglong Group, Upper Triassic Huangmaqing Formation, Lower–Middle Jurassic Xiangshan Group and Upper Jurassic Xihengshan Formation (Ningwu Research Group, 1978). The Qinglong Group and Huangmaqing Formation are distributed mainly in the southern (e.g., Zhongshan and Gusan), eastern (e.g., Shizhichangshan) and northern parts (e.g., Fenghuangshan) of the volcano-sedimentary basin. The Lower–Middle Triassic Qinglong Group, more than 500 m thick, consists of limestone and intercalated calcareous shale, dolomitic limestone, gypsum and anhydrite layers of lagoon facies. The gypsum and
Fig. 2. (a) Geology at the −200 m level and (b) alteration zone cross-section of the Meishan deposit (modified from Chen et al., 1981).
anhydrite layers are well-exposed in the uppermost Qinglong Group and they are up to 90 m thick in the Ningwu district. The Upper Triassic marine and continental Huangmaqing Formation, 500 to 800 m thick, consists of calcareous siltstone, silty shale and shale, and is locally intercalated thin layered limestone and coal seams. Overlying the Huangmaqing Formation is the 1500 m-thick Lower–Middle Jurassic Xiangshan Group. The continental Xiangshan Group is exposed in the eastern and western margin of the volcano-sedimentary basin, and is composed of grayish-white quartz sandstone, feldspathic sandstone, and locally intercalated siltstone and shale in the lower part (1000 m-thick), reddish-purple and grayish-white medium-grained feldspathic quartz sandstone, fine-grained sandstone, marlstone in the upper part (500 m-thick). The 1620 m-thick Upper Jurassic Xihengshan Formation, which unconformably overlies the Xiangshan Group and is itself

Fig. 3. (a) Geological map and (b) ore type cross-section of the Washan iron deposit (after Zhai et al., 1992). BMF is the Bijiashan–Mashan Fault; YAF is Yanghuatang–Washan Fault.
overlain by Longwangshan cycle volcanic rocks, belongs to molasse-like formation and are uniquely distributed around Hanfushan. The Upper Jurassic Xihengshan Formation is characterized by grayish-purple polymictic conglomerate, sandstone and medium to coarse-grained feldspathic quartz sandstone with locally intercalated tuff breccia, andesite and thin coal seam in the lower part (1000 m-thick) whereas gray polymictic conglomerate, marlstone with interbedded medium to coarse-grained feldspathic quartz sandstone, purplish-red calcareous siltstone in the upper part (618 m-thick).

The volcanic rocks of the Ningwu basin are subaerial and intruded by cogenetic subvolcanic and plutonic rocks. The Cretaceous volcanic belt in the basin is 3 to 16 km-wide and is divided into Longwangshan, Dawangshan, Gushan and Niangniangshan cycles from base to top. The Longwangshan cycle, which rests unconformably on basement rocks of Upper Triassic Huangmaqiing Formation, Lower–Middle Jurassic Xiangshan Group or Upper Jurassic Xihengshan Formation, is distributed along the eastern margin (e.g., from Longwanshan to Yuntaishan where it is 513 m-thick) and in the northern part (e.g., around Meishan and Niushoushan where it is 210 m-thick) of the volcano-sedimentary basin (Fig. 1). The Longwangshan cycle is mainly composed of lavas and pyroclastic rocks. Its composition is generally hornblende-bearing basaltic andesite to andesite and locally trachyandesite. The volcanic rocks of the Longwangshan cycle have K–Ar and Rb–Sr ages of between 136 and 125.3 Ma (Ningwu Research Group, 1978, Wang and McDougall, 1980; Yue and Ding, 1999) and a zircon U–Pb age of 131 ± 4 Ma (Zhang et al., 2003). The Dawangshan cycle is exposed at the northern and central part of the volcano-sedimentary basin, and consists of andesitic volcanic rock, tuff, and lava. The volcanic rocks of the Dawangshan cycle yield K–Ar ages of 120 Ma (Ningwu Research Group, 1978) and zircon U–Pb age of 127 ± 3 Ma (Zhang et al., 2003). The Gushan cycle is exposed in the southern part of the basin (e.g., around Zhongsang and Gushan), and is mainly composed of andesite, andesitic pyroclastic rocks. The volcanic rocks of the Gushan cycle yield K–Ar ages of between 110 and 116 Ma (Ningwu Research Group, 1978).

The Niangniangshan cycle forms the Niangniangshan caldera (Fig. 1), and consists of phonolite and phonolitic tuff (Chen et al., 1992). The volcanic rocks of the Niangniangshan cycle have whole-rock K–Ar ages between 91 and 106 Ma (Ningwu Research Group, 1978). Subvolcanic intrusions are widely distributed in the Ningwu district, were emplaced shortly after the Dawangshan cycle, and include gabbro–diorite porphyry and/or pyroxene diorite with K–Ar ages of between 90 and 137 Ma. These subvolcanic rocks with well-developed porphyritic textures occur as stocks emplaced less than 1 km from the paleosurface. They are characterized by high alkali contents and high Na/K values (Na2O + K2O = 4.8 to 9.1 wt.%; Na2O/K2O = 1.5 to 5.0; Ningwu Research Group, 1978).

Mineralization in the Ningwu district has a close spatial, temporal and genetic relationship with the subvolcanic intrusions. Most of volcanic and subvolcanic rocks in the Ningwu basin are Na- and K-rich (shoshonitic affinity) and were emplaced during the Cretaceous (K–Ar ages of between 90 and 137 Ma; Ningwu Research Group, 1978). They are enriched in LREE and large-ion lithophile elements, and depleted in Ti, and Nb and Ba (Wang et al., 2001). They exhibit relatively lower εNd (t) values ranging from −3.4 to −7.3 and relatively higher initial 87Sr/86Sr ratios varying between 0.7057 and 0.7062 (Ishihara et al., 1986; Tang et al., 1998; Wang et al., 2001; Wu et al., 1999; Xu and Xing, 1994; Yu, 2003). Geological data from the Ningwu basin suggest that the Cretaceous igneous rocks are distributed along NE-trending fault zones (e.g., Tang-Lu and Yangtze River Fault zones) in eastern China and were likely formed in an extensional setting within the Yangtze Craton of eastern China (Deng et al., 1992; Wang Q. et al., 2006; Wang Y.L. et al., 2001). Granite is also exposed in the volcano-sedimentary basin (Fig. 1). Its age and petrogenesis are unclear due to lack of data.

The Ningwu basin is bound by four fault zones: Fangshan–Xiaodayang Fault in the east, Yangtze River (Changjiang) fault in the west, Nanjing–Hushu Fault in the north, Sanshanjie–Xuanchong Fault in the south (outside of Fig. 1). In addition to the above-mentioned four faults, NE trending folds and NW to NWW trending faults are also extensively developed in the Ningwu basin (Fig. 1).

3. Iron oxide–apatite deposits

There are three areas with a dense distribution of magnetite or hematite deposits in the Ningwu NNE-elongated basin (Fig. 1): the Meishan deposit in the north; Washan and Taocun deposits in the center; and the Zhonggiiu and Gushan deposits in the south. This mineralization is closely associated with the subvolcanic plutons.

3.1. Meishan iron deposit

The Meishan iron deposit is located in the northern part of the Ningwu basin and is genetically related to the Meishan subvolcanic gabbro–diorite porphyry intrusion. The exposed rocks at the Meishan deposit are mainly biotite–pyroxene andesite of the Dawangshan cycle, which have been subjected to extensive late alteration along fractures and faults. The subvolcanic intrusion intruded into the volcanic rocks of the Dawangshan cycle (Chen et al., 1981; Ningwu Research Group, 1978).

The Meishan deposit comprises (1) the main orebody, and (2) disseminated and stockwork ores controlled by various alteration zones. The Meishan main orebody is approximately 1200 m-long, 850 m-wide, and 240 m-thick and is situated along the contact zone between the gabbro–diorite porphyry and biotite pyroxene andesite (Fig. 2a, b). It has a lenticular shape and sharp contacts between the main orebody and the country rocks. The main orebody includes massive and brecciated ores of magnetite, associated with gangue minerals including andradite, diopside, apatite, magnetite, calcite and quartz. The voids in the ores are filled by pyrite, anhydrite, calcite, siderite, dolomite, quartz, and chaledony.

3.2. Washan iron deposit

The Washan iron deposit is located in the central part of the Ningwu basin and is associated with the Washan subvolcanic intrusion. The exposed rocks are mainly trachyandesitic volcanic rocks of the Dawangshan cycle interpreted as a caldera succession intruded by subvolcanic gabbro–diorite porphyry (Chang et al., 1991; Zhai et al., 1992). The Washan subvolcanic intrusion is exposed over an area of 7.5 km² located at the intersection of the Bijiaoshan–Mashan Fault and the Yanghuatang–Washan Fault (Fig. 3a). It comprises a dominant gabbro–diorite porphyry intruded by albite porphyry and quartz–albite porphyry dykes (Zhai et al., 1992). All rocks have been subjected to extensive late-stage alteration along fractures and faults.

The main Washan orebody is approximately 600 to 800 m-long, 400 to 500 m-wide, and 250 to 300 m-thick. It occurs in the northern part of the gabbro–diorite porphyry body from where it extends into the volcanic exocontact (Fig. 3b; Chang et al., 1991). Most of the main Washan orebody is hosted by collapse breccia in its upper zone and cryptoexplosion breccia below (Fig. 3b). The iron ore is composed of high Ti- and V-bearing magnetite with fluorapatite, actinolite and albite. The ore averages 0.86 wt.% TiO₂ and 0.21 wt.% V₂O₅ (Zhai et al., 1992). The Washan orebody has a well developed lithologic, structural, mineralogical and alteration zoning. The following three zones can be distinguished from top to bottom (Fig. 3b):

(1) Upper zone of pegmatoidal and massive iron ores is hosted by the collapse breccia with local development of gabbro–diorite breccias. Several cm-long (exceptionally, up to 1 m-long) euhedral crystals of actinolite and fluorapatite are a component of the pegmatoidal and massive ores;

(2) Middle zone of brecciated ores is hosted by the cryptoexplosion breccia in gabbro–diorite porphyry. The breccia fragments are
in filled by actinolite, apatite and magnetite and the ore breccia is cut by massive magnetite vein;

(3) Lower zone of stockwork and disseminated iron ore is composed of apatite, magnetite, and scapolite.

There is a sharp contact between the upper zone of pegmatoidal and massive ore, and middle zone of brecciated ore, but there is no sharp boundary between the middle zone of ore breccia and the stockwork and disseminated ore beneath.

Five mineralization stages have been recognized, based on mineral assemblages and crosscutting relationships of ores (Zhai et al., 1992). The first stage includes fine-grained apatite–albite–magnetite disseminated iron ores associated with early sodic alteration. The second stage is dominated by the medium to fine-grained actinolite (after diopside) + apatite + magnetite assemblage, whereas the third stage has pegmatoidal actinolite (after diopside) + apatite + magnetite assemblage. Stages 2 and 3 coincide with the main period of iron mineralization at the Washan deposit.
The fourth stage is composed of medium to coarse-grained apatite–magnetite veins, veinlets and stockworks developed in the early sodic alteration zone, the middle diopside–albite–fluorapatite–magnetite zone, and in country rocks (Fig. 3b). The fifth stage is dominated by quartz, kaolinite and pyrite in an area of late silicic and argillic alteration and has locally associated small pyrite orebodies.

3.3. Taocun and Nanshan iron deposits

The Taocun and Nanshan deposits are also located in the central part of the Ningwu basin and hosted in subvolcanic gabbro–diorite porphyry. The exposed rocks at the Taocun and Nanshan deposits are mainly trachyandesitic volcanic rocks of the Dawangshan cycle interpreted to have formed in a caldera and they have been subjected to extensive late alteration along fractures and faults. The subvolcanic gabbro–diorite intrusion intrudes andesite and andesitic tuff of the Dawangshan cycle. The orebodies are 1000 to 1600 m-long, 500 m-wide and 10 to 150 m-thick. The ore varieties in the Taocun and Nanshan deposit mainly include disseminated ore (Fig. 4a, b) cut by veinlet, stockwork or pegmatoidal varieties. Ore minerals include vanadium-bearing magnetite and hematite in a gangue of albite, apatite and actinolite. The iron grade is 20 to 24%. The contents of other elements in the ore, such as V₂O₅, S and P are 0.04–0.3 wt.%, 0.01–3% and 0.01–1.95%, respectively.

3.4. Zhongjiu iron deposit

The Zhongjiu iron deposit is located along the contact of pyroxene diorite, albite diorite, quartz diorite porphyry, and sedimentary rocks. The latter include limestone of the Lower–Middle Triassic Qinglong Group, sandstone and shale of the Upper Triassic Huangmaqing Formation, and sandstone of Lower–Middle Jurassic Xiangshan Group. The southern orebody formed along the unconformity between limestone of the Qinglong Group and sandstone of the Xiangshan Group (Fig. 5a), and is stratiform. The northern orebody is also stratiform and it lies at the albite to albite–diorite endo-contact, adjacent to sandstone and shale of the Huangmaqing Formation (Fig. 5b). The Zhongjiu pyroxene diorite, partly altered to albite to albite diorite porphyry, is about 1 km-long, 600 m-wide with an outcrop area of about 1 km². The ores are disseminated and massive, with the former composed of magnetite and apatite, associated with diopside and phlogopite. Massive ore consists of magnetite with minor phlogopite, apatite, chaledony and calcite.

Based on mineral assemblages and crosscutting relationships of ores, three mineralization stages have been recognized (Joint...
Stage 1 has magnetite associated with diopside, apatite with minor phlogopite and titanite. Stage 2 is dominated by magnetite associated with diopside, apatite and phlogopite. Stage 3 resulted in a hematite + pyrite assemblage with minor chalcopyrite + bornite + galena + sphalerite.

Fig. 6. (a) Geology and (b) cross-section of the Gushan iron deposit (modified from Zhai et al., 1992).
\textbf{Table 1} Alteration patterns of iron oxide–apatite deposits in the Ningwu basin.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Lower light colored zone</th>
<th>Middle dark colored zone (from bottom to top)</th>
<th>Upper light colored zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meishan</td>
<td>Albite or diopside-bearing albitite</td>
<td>Magnetite–diopside–andradite rock</td>
<td>Wall rock andesite is also hydrothermally altered although distinct mineral zone are not well developed and the alteration comprises overlapping assemblage of pyrite–calcite–kaolinite–quartz. Pyrite–calcite–kaolinite–quartz rock is found only northwest of the main orebody (Fig. 2b). Elsewhere, andesite has been subjected to extensive silicification and kaolinization with local calcite and pyrite.</td>
</tr>
<tr>
<td>Taocun and Nanshan</td>
<td>Albite or diopside-bearing albitite</td>
<td>Apatite–diopside–scapolite rock</td>
<td>Andesite and andesitic tuff country rocks have been subjected to silicification, kaolinite, pyrite and carbonate alteration during the period of late hydrothermal activity. The upper light colored alteration is in the hanging wall of the disseminated orebodies, and it includes (1) silicified subzone of quartz + pyrite and (2) argillized subzone of kaolinite + quartz + pyrite (Fig. 4b).</td>
</tr>
<tr>
<td>Zhongjiu</td>
<td>Albitization, and/or sodic- and potassic feldsparization zone</td>
<td>Diopside–phlogopite–apatite–magnetite mineralization</td>
<td>Late hydrothermal quartz, chalcedony and calcite infill interstitial to apatite and magnetite, and disseminated pyrite in magnetite ores. These effects, however, are not very extensive.</td>
</tr>
<tr>
<td>Gushan</td>
<td>Late hydrothermal alteration zones from gabbro–diorite at depth towards the orebody (Fig. 6b) include: (1) carbonate alteration of the gabbro–diorite; and (2) silicification and kaolinization of the gabbro–diorite, as well as shale beds of the Huangmaqing Formation (Gu and Ruan, 1988).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washan</td>
<td>Sodic alteration including mainly albitite and marialitic scapolite</td>
<td>Diopside–albitite–fluorapatite–magnetite mineralization</td>
<td>Argillic, silicification, sulfide and carbonate alteration associated locally with some small pyrite orebodies.</td>
</tr>
</tbody>
</table>

3.5. Gushan iron deposit

The Gushan iron deposit is located near the south end of the Ningwu basin and is genetically associated with the Gushan gabbro–diorite intrusion. The rocks at the Gushan deposit include silty shale of the Huangmaqing Formation, sandstone of the Xiangshan Group, and andesite, andesitic tuffaceous breccia and tuff of the Gushan cycle. The Gushan intrusion occurs as a stock, and it intruded into silty shale of the Huangmaqing Formation. The gabbro–diorite is dark gray to gray green with a non-euigranular and pseudo-porphyrfig texture and 0.1 to 1.5 mm grain size, composed of 80% andesine, 5 to 10% albite, 3% pyroxene, 2 to 3% quartz with accessory magnetite, titanite and apatite. The tuffaceous claystone of base of the Gushan cycle sedimentary sequence lies on the gabbro–diorite intrusion, indicating that the gabbro–diorite predated the sediments (Zhai et al., 1992). The 700 m-long and 50 to 100 m-thick half-ring shaped orebodies are hosted by the gabbro–diorite and by breccia along the contact between the gabbro–diorite intrusion and the Huangmaqing Formation silty shale (Fig. 6a, b).

The Gushan iron orebodies include 40% massive ores and 40% brecciated ores, with the remainder being other styles comprising mottled, spherulitic and skeletal ores. Ore minerals include martite (after magnetite), with minor magnetite and hematite as 0.02 to 0.1 mm-sized grains, with apatite, quartz, and minor kaolinite and calcite gangue. Massive ore, except for minor apatite and quartz, has voids filled with quartz and minor kaolinite. Brecciated ore has fragments of silty shale and gabbro–diorite cemented by martite and minor magnetite with some quartz and minor kaolinite void fill as in the massive ore. In the mottled ore, 2 to 10 mm-sized martitized magnetite crystals, some arranged radially into 0.5 to 1 cm-sized spherules, rest in a groundmass of microcrystalline martite and hematite. The skeletal ore consists of randomly-oriented coarse martitized magnetite crystals in the microcrystalline groundmass of martite and hematite with occasional quartz and/or chalcedony infill. These mottled, spherulitic and skeletal ores have been interpreted to be of hydrothermal origin (Gu and Ruan, 1988). Martitized magnetite forms porphyroblasts and/or porphyroblastic aggregates.

Five mineralization stages have been recognized at the Gushan deposit on the basis of mineral assemblages and crosscutting relationships (Zhai et al., 1992). The first, main mineralization stage, formed magnetite later converted into fine-grained martite. The second stage produced platy magnetite, now martite (after magnetite), whereas the coarse-grained magnetite (now martite) was formed during the third stage, with minor apatite added in the fourth stage. The post-ore fifth stage is dominated by quartz, chalcedony and hematite.

4. Alteration patterns of iron oxide–apatite deposits

Alteration zoning of the iron oxide–apatite deposits is well developed in the Ningwu basin (Chang et al., 1991; Chen et al., 1981; Gu and Ruan, 1988; Joint Research Team of Institute of Geology, Eastern China, and Institute of Geology and Mineral Resources, 1975a,b; Ningwu Research Group, 1978; Zhai et al., 1992) and presented in Table 1 and Figs. 2b, 3b, 4a, b, 5a, 5b and 6b. It consists of (1) an upper light colored zone; (2) a middle dark colored zone; (3) a lower light colored zone. These zones are discussed below.

4.1. Lower light colored zone

Albitite or diopside-bearing albitite is composed of 5 to 20% granoblastic aggregate of diopside, 70 to 90% albite with minor actinolite, titanite, apatite, and magnetite. Diopside occurs as 0.05 to 0.1 mm anhedral to subhedral tabular grains in the Meishan deposit. Diopside displays megaphyric or glomeroporphyritic crystals generally in 2 to 3 cm long and 1 cm wide in the Taocun and Nanshan deposits. Albite occurs either as euhedral crystals ranging between 1 and 3 mm in diameter, or as irregular equigranular grains in the iron oxide–apatite deposits in the Ningwu basin. In addition, albite and K-feldspar metasomatism also affected the sandstone of the Lower–Middle Jurassic Xiangshan Group in the Zhongjiu deposit (Fig. 5a).

4.2. Middle dark colored zone

The middle dark colored zones consist mainly of diopside, apatite, and magnetite. Almost all economic iron ores in the Ningwu basin are distributed in these zones (Figs. 2b, 3b, 4a, b, and 5a). These zones can be divided into various sub-zones (Table 1) that are generally slightly...
variable for individual iron oxide–apatite deposits. For example, the middle dark colored zones at the Meishan deposit comprise, from bottom to top, diopside–andradite–marchellite,calcite–diopside,massive magnetite orebody and magnesite–diopside–andradite (Fig. 2b). The middle dark colored zones in the Zhongjiu deposit consist of actinolite-bearing albitite, diopside-bearing albitite, diopside-scapolite–albite rock and diopside–phlogopite–apatite–magnetite mineralization (Fig. 5a,b).

4.3. Upper light colored zone

The country rock here is overprinted by products of late hydrothermal activity although distinct mineral zones are not well developed. There is extensive argillic, kaolinite, silica, carbonate and pyrite alteration associated locally with some small pyrite orebodies (Figs. 3b and 4b).

Compared with other deposits in the Cretaceous Ningwu basin, the Gushan iron deposit lacks an albite-dominated lower light colored zone and a middle dark colored zone. The later hydrothermal alteration is zoned from the gabbro–diorite at depth towards the orebody (Fig. 6b), includes (1) carbonatization and (2) silicification and kaolinization of the gabbro–diorite, as well as of the Huangmaqing Formation shale (Gu and Ruan, 1988). These alteration types postdate Fe mineralization with which they are not associated (Zhai et al., 1992).

5. Origin of iron oxide–apatite deposits

Iron oxide–apatite deposits in the Cretaceous Ningwu basin are similar to the Kiruna-type Fe mineral system. The origin of the Kiruna-type deposits has been much debated and various formative processes have been suggested, ranging from magmatic origin due to liquid immiscibility (Frietsch, 1978; Kolker, 1982; Nyström and Henriquez, 1994; Philpotts, 1967) through exhalative-synsedimentary (Parak, 1991) to epigenetic–hydrothermal (Barton and Johnson, 1966; Bookstrom, 1977; Hilderband, 1986; Mark and Foster, 2000; Sillitoe and Burrows, 2002). Similarly, the Gushan deposit, major part of the Meishan deposit, and upper pegmatoidal ore at the Washan deposit have been interpreted to be magmatic origin (Chang et al., 1991; Chen et al., 1998; Zhai et al., 1992).

Other researchers, however, interpreted the iron oxide–apatite deposits in the Cretaceous Ningwu basin as hydrothermal replacements (Gu and Ruan, 1988; Institute of Geochemistry, Chinese Academy of Sciences, 1987; Lu et al., 1990). The main lines of evidence for 'magma ore' include (1) well-developed voids ('cavities') in massive high-grade iron ores in the main Meishan orebody and the Gushan orebodies; (2) high-temperature (up to 1080 °C) fluid inclusions in apatite, andradite and diopside (Li and Xie, 1984); and (3) sharp contacts between iron ore and country rock at the main Meishan and Gushan orebodies, and the upper zone of pegmatoidal and massive ore of the Washan orebody.

However, none of the above lines of evidence is unequivocal. Firstly, cryptoexplosion breccias and voids in iron ore resulted from a high proportion of volatiles in a caldera setting as in the Washan, Gushan, Taocun and Nanshan deposits. Secondly, melt inclusions in apatite, andradite and diopside possibly do not exist, as homogenization temperatures of inclusions in apatite vary between 330 °C and 500 °C (Li et al., 1979); this is indicative of a hydrothermal-metasomatic origin. Finally, there is also a sharp contact between iron ore and country rock for metasomatic skarn iron deposits in eastern China. A sharp contact between ore and country rock is probably present in the hydrothermal deposits, where the country rocks are pervasively replaced.

We consider these iron oxide–apatite deposits in the Ningwu basin as of postmagmatic metasomatic origin. The following observations support the hydrothermal replacement interpretation: (1) alteration zoning is well-developed for individual deposits in the Ningwu basin and almost all economic iron ores in the basin are in the middle dark colored zones; (2) the common occurrence of albitized rocks, interpreted partly as originally subvolcanic intrusions in footwalls of individual deposits, suggests sodic metasomatism associated with subsolidus melt evolution as the cause of albitit; and (3) deposits in the Ningwu basin tend to occur in the roof of the subvolcanic intrusions that ruling out an origin by iron phosphate–silicate melt immiscibility because iron phosphate melts are much denser than silicate melts. Instead, we interpret these deposits in the Ningwu basin as the products of high-temperature fluids generated during volatile exsolution.

6. Comparison with Kiruna-type deposit, Sweden

Kiruna-type deposits contain variable quantities of magnetite–fluorapatite–actinolite ores in volcano-plutonic terrains that range in age from Proterozoic to Cenozoic. The best known, and one of the largest deposits is in the Kiruna region of northern Sweden (Frietsch, 1978; Frietsch and Perdahl, 1995), but other well-known deposits of similar type occur in Missouri, U.S.A., in the Great Bear magmatic zone of Canada (Hilderband, 1986), in the Bafq mining district of central Iran (Förster and Jafarzadeh, 1994; Torab and Lehmann, 2007), in the Avnik region of southeastern Turkey (Helvaci, 1984), and in the Circum-Pacific belt of Chile and Peru (Frietsch and Perdahl, 1995) and elsewhere (Williams et al., 2005).

Iron oxide–apatite deposits of the Ningwu Cretaceous basin share many similarities to the Kiruna-type deposits, particularly with respect to mineral assemblages, fabric and structure of the iron ores, occurrence of the orebodies and wall rock alteration zones. For example, the iron ores are mainly composed of magnetite or hematite, diopside or actinolite and apatite. These deposits are interpreted as having formed in a rift or extensional environment and mineralization is associated with alkaline magmatism. Geochronological data (see Mao et al., 2010; Xie et al., this issue; Zhou et al., 2011-this issue) indicate that the time interval between the magmatism and associated mineralization is very short. Alteration, especially albitization, is very pronounced in footwall rocks under the orebodies. These Kiruna-type characteristics and how they compare with the Ningwu deposits are detailed below.

6.1. Mineralogical composition and mode of ore occurrence

Ores of the Kiruna-type consist of magnetite and less commonly hematite. Fluorapatite is also a characteristic mineral. Other gangue minerals such as actinolite and occasionally diopside or calcite, occur in variable amounts. The orebodies range in size from many hundreds of millions of tons of high-grade iron ore to small veins and veinlets (Hilderband, 1986; Nyström and Henriquez, 1994). Elongate, tabular, or lens-like massive bodies mostly occur in the roof of the parent intrusions. In many deposits a portion of, or whole orebodies, have the form of stockworks of anastomosing or intersecting Fe oxide veinlets, often with diffuse boundaries against the barren rock. Some orebodies have the form of breccia of altered rock fragments cemented by Fe-oxides.

6.2. Geodynamic setting of orebodies

The geodynamic setting of the Kiruna-type is generally attributed to extensional sub-domains such as rifts and/or back-arcs in convergent (Andean-type) continental margins, and to intracontinental (intracratonic) rifts within a subaerial to shallow marine basinal sequences floored by crystalline basement. A recently quoted example includes the Bafq Fe-(Cu, U, Au) mining district in central Iran interpreted as a product of a Neoproterozoic to Triassic-Pan-African tectono-thermal event that took place in an active continental margin magnetic arc (Torab and Lehmann, 2007) or, alternatively, within a rifted consolidated Gondwana basement (Daliran, 2002). The former puts emphasis on the presumed similarity with the Cretaceous Fe and Fe–Cu–Au–Ag metallogeny in the Coastal Cordillera of north-central Chile partly controlled by the Atacama Fault system (Williams et al., 2005). The Kiruna-type region in northern Sweden is attributed to
Paleo- to Mesoproterozoic rifting within the Laurentian basement (Frietsch and Perdahl, 1995).

The shoshonitic magmatism in the Ningwu region originated mainly from an enriched mantle metasomatized by subducted oceanic sediments (Wang Q., et al., 2006; Wang Y.L. et al., 2001). These shoshonitic rocks appear to be linked to an intra-continental extensional setting where partial melting of enriched mantle was probably controlled by lithospheric thinning and upwelling of hot asthenosphere along NE fault zones (e.g., Tanlu and Yangtze River Fault zones, Mao et al., 2006; Wang et al., 2006) in eastern China. Recently, Mao et al. (2008, 2010) suggested that metallic deposits in volcanic-filled fault basins in eastern China, within the age range of between 135 and 80 Ma, were related to lithospheric thinning, asthenospheric upwelling and partial melting of the lower crust. This was controlled by change in motion of the Iazagi Plate parallel to the continental margin. The mineralization comprises deposits of iron oxides–apatite, skarn Fe–(Cu), epithermal gold–copper, vein-type gold and volcanic to subvolcanic–hydrothermal Pb–Zn–Ag.

6.3. Magmatism

The volcano–plutonic association that hosts the Kiruna-type deposits ranges from calc-alkaline to alkaline, predominantly andesite to rhyolite. The Fe ores-affiliated volcanics in northern Sweden and in the Missouri Mesoproterozoic have alkali contents (Na2O+K2O) of between 6 and 11 wt.%. In general, sodic-rich volcanics are predominant but there are also highly potassic varieties (Fritsch, 1978). In the Ningwu basin the apatite-bearing iron ores are associated with Cretaceous volcanics and subvolcanic intrusions of intermediate to mafic composition. The subvolcanic intrusions have a high alkali contents and high Na/K values (Na2O+K2O = 4.8 to 9.1 wt.%; Na2O/K2O = 1.5 to 5.0) (Ningwu Research Group, 1978).

6.4. The role of calderas

Many Kiruna-type occurrences, especially those rich in ore breccias, are attributed to subaerial caldera settings, in particular to resurgent calderas intruded by felsic to intermediate stocks (Förster and Jafarzadeh, 1994; Hilderband, 1986). In the Oligocene Chupadero caldera on the outskirts of Durango City, Mexico, magnetite and hematite mineralization has a number of forms that include presumed magnetite (apatite) lavas, dikes, ore-fragments bearing tuff and tuff breccias, and bedded hematite (Lyons, 1988). We attribute the Washan, Gushan, Taocun and Nanshan Fe deposits in the Cretaceous Ningwu basin to a similar setting.

6.5. Time interval between mineralization and associated magmatism

In the Kiruna area the volcano–plutonic event, formation of the iron oxide–apatite ores and a major part of subsequent deformation and alteration occurred within a brief period of time between 1.90 and 1.88 Ga (Cliff et al., 1990). In the Ningwu basin the volcanic rocks of the Dawangshan cycle yield zircon U–Pb age of 127 ± 3 Ma (Zhang et al., 2003) and they were shortly followed by emplacement of subvolcanic intrusions. 40Ar/39Ar dates of albite in the apatite-bearing iron deposits range from 123 to 125 Ma (Mao et al., 2006; Yu and Mao, 2004). Both rock- and ore-forming ages closely correlate and this confirms spatial, temporal and genetic relationship.

6.6. Hydrothermal alteration

Magnetite–apatite–actinolite accumulations associated with granitoid plutons in the Great Bear magmatic zone, northwestern Canada, have been described by Hilderband (1986). These plutons have km-wide alteration halos comprising an inner zone of nearly complete wall-rock albitionization, an intermediate zone of magnetite–apatite–actinolite veins, pods, breccias, and an outer zone of disseminated Fe–(Cu) sulfides. Extensive Na metasomatism also occurs in the footwall of the Kiruna-vaara deposit in northern Sweden and Fennoscandia (Frietsch and Perdahl, 1995; Frietsch et al., 1997). In the Baq mining district, central Iran (Torab and Lehmann, 2007), there is a general trend from sodic alteration at deep levels, to actinolitic (Ca–Mg) and potassic alteration at intermediate levels, to sericitic alteration and silicification at shallow levels. These features are comparable with the alteration zoning in the iron oxide–apatite deposits in the Cretaceous Ningwu basin, indicating a post-magmatic hydrothermal origin.

Current understanding tends to group the ‘Kiruna-type’ deposits as an end-member of the hydrothermal Iron oxide–Copper–Gold IOCG family (Groves et al., 2010; Hitzman, 2000; Hitzman et al., 1992; Williams et al., 2005). This is supported by similarity of tectonic setting, abundance of early-stage magnetite, occurrence of minor late stage pyrite, chalcopyrite + gold ± REE in or near massive magnetite deposits, and certain shared secondary and gangue minerals, especially actinolite and apatite.

7. Conclusions

(1) The iron oxide–apatite deposits in the NNE-elongated Cretaceous Ningwu basin, traditionally designated as ‘porphyry iron deposit’ in the Chinese literature, are associated in time and space with continental volcanic and subvolcanic rocks of intermediate to mafic composition. The subvolcanic intrusions are characterized by high alkali contents and high Na/K values (Na2O+K2O = 4.8 to 9.1 wt.%; Na2O/K2O = 1.5 to 5.0).

(2) Alteration zoning of these deposits is pronounced, and includes (1) an upper light colored zone of argillation, kaolination silicification and pyritization; (2) a middle dark colored zone of diopside, fluorapatite–magnetite mineralization, phlogopite, and garnet; (3) a lower light colored zone of albitionization. However, the Gushan iron deposit lacks the lower light colored zone (i.e., albite) and the middle dark colored zone. The main alterations at Gushan comprises silicification, kaolization, and carbonatization.

(3) The Ningwu Fe oxide–apatite deposits are interpreted as of magmatic–metasomatic origin and are comparable with the Kiruna Fe–P type with which they share similarity in mineral composition, setting, form of orebodies, and alteration zoning. The orebodies are genetically related to Na and K–alkaline magmatism, there was a very short interval between magmatism and associated mineralization, and there was a rift or extensional control.

Acknowledgements

We thank Huang Jianping, Xu Zhigang, Wang Lihua, Sheng Jifu, He Jurui, Ye Shuqian for their kind support and help during the field investigation. This study was financially supported by the Major State Basic Research Program (2007CB411405), National Natural Science Fund of China (No. 40472055).

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