The major Gushan iron oxide deposit, typical of the Middle-Lower Yangtze River Valley, is located in the eastern Yangtze craton. Such deposits are generally considered to be genetically related to Yanshanian subvolcanic-volcanic rocks and are temporally-spatially associated with ca. 129.3–137.5 Ma dioritic porphyries. The latter have a very narrow $^{87}\text{Sr}^{86}\text{Sr}$ range of 0.7064 to 0.7066 and low $\varepsilon_{\text{Nd}}(t)$ values of $-5.8$ to $-5.7$, suggesting that the porphyries were produced by mantle-derived magmas that were crustally contaminated during magma ascent. The ore bodies occur mainly along the contact zone between dioritic porphyries and the sedimentary country rocks. The most important ore types are massive and brecciated ores which together make up 90 vol.% of the deposit. The massive type generally occurs as large veins consisting predominantly of magnetite (hematite) with minor apatite. The brecciated type is characterized by angular fragments of wall-rocks that are cemented by fine-grained magnetite. Stockwork iron ores occur as irregular veins and networks, especially with pectinate structure; they are composed of low-temperature minerals (e.g. calcite), which indicate a hydrothermal process. The similar rare earth element patterns of apatite from the massive ores, brecciated ores and the porphyries, coupled with high-temperature fluids (1000°C) suggest that they are magmatic in origin. Furthermore, melt flow structure commonly developed in massive ores and the absence of silicate minerals and cumulate textures suggest that the iron ores formed by the separation of an immiscible oxide melt from the silicate melt rather than by crystal fractionation. Combined with theoretical and experimental studies, we propose that the introduction of phosphorus due to crustal contamination during mantle-derived magma ascent could have been a crucial factor that led to the formation of an immiscible oxide melt from the silicate magma.

**Keywords**: iron oxide ore deposit; dioritic porphyries; apatite; immiscibility; Yangtze craton

**Introduction**

The Gushan apatite-magnetite (hematite) deposit is situated in Dangtu County, Anhui Province, in the south part of the Ningwu (Nanjing-Wuhu) basin in the Lower Yangtze River Valley, which is an important Cu–Au–Fe–S ore belt (including more than 200 ore deposits) associated with Mesozoic magmatic rocks.
in China (Jiang et al. 2006). It is one of the P-richest magnetite-apatite deposits in the area. Production from the Gushan iron mine has developed a total 128 million tonnes of iron since it was mined by the Ma’anshan Iron & Steel Company in the 1950s.

Among the iron ores in the world, there is a specific mineral assemblage, i.e. magnetite-hematite-apatite, called ‘Kiruna’-type iron deposits, which are characterized by sulphide-poor low-Ti magnetite-fluorapatite-actinolite assemblage, and ore types containing many hundreds of millions of tonnes of high-grade massive iron ore, to small vein and veinlet ores (Hildebrand 1986; Nyström and Henriquez 1994). The few occurrences reported in the literature are all confined to continental rifted margins (back arcs) and intracontinental rifts (anorogenic) within a subaerial to shallow marine basin, accompanied by volcano-plutonic activity and large scale fluid overprint, as indicated by sodic alteration (Hitzman 2000). The Gushan deposit is considered to be an example of a Kiruna-type deposit (Song 1981). ‘Kiruna’-type deposits are generally believed to be formed in post-Archean tectonic regimes characterized by magmatism in response to mantle underplating, high heat flow, and oxidized source rocks that commonly contain evaporates (Hitzman 2000).

The Gushan and other P–Fe-oxide deposits in the Lower Yangtze River Valley have various mineralogical and geochemical characteristics that are typical of the Kiruna-type magnetite-apatite end member.

The origin of magnetite-apatite deposits is uncertain and remains a controversial topic, particularly the Kiruna deposit itself (Ripa 1988; Nyström and Henriquez 1994; Frietsch 1991; Frietsch and Perdahl 1995; Martinsson 1997; Martinsson and Weihe 1999). The Kiruna-type deposits have been interpreted by magmatic origin (liquid immiscibility) (e.g. Frietsch 1978; Nyström and Henriquez 1994; Naslund et al. 2000), exhalative-synsedimentary (Parák 1973), or epigenetic-hydrothermal (e.g. Hildebrand 1986; Bookstrom 1977; Gleason et al. 2000; Sillitoe and Burrows 2002). For the Gushan hematite-apatite deposit, an immiscible liquid model has been proposed, similar to that suggested for Kiruna-type deposits (Chang et al. 1991; Zhai et al. 1996), whereas other workers preferred to emphasize the effect of hydrothermal fluid in the metallogenic processes (Gu and Ruan 1988; Lin et al. 1983). Although the Gushan iron deposit has been previously studied, most publications are in Chinese (e.g. Zhang 1986; Cui 1991; Zhu et al. 1991; Pei and Hong 1995; Zhao et al. 1999; Zhai et al. 1992; Chang et al. 1991; Research Group of the Porphyry Iron Ore 1977; Institute of Geochemistry, China Academy of Science 1987; Song 1981), and none has been published in a prominent international journal.

In this paper, we describe detailed geological and geochemical characteristics of the ore-bearing dioritic porphyries and economically important, high-grade iron ores from the Gushan deposit, and then discuss the ore-forming conditions and the possible genetic link between the dioritic porphyries and the iron deposit. Finally, we propose a genetic and exploration model of the Gushan iron deposit, which will be helpful for further exploration for the same type of the iron deposits in the region and around the world.

Regional geology

The Gushan oxide iron deposit is tectonically located in an uplifted region of the basement, in the southeast margin of the Ningwu volcanic basin, formed in the Late Jurassic to Early Cretaceous, close to the Yangtze deep fault, in the eastern margin
of the Yangtze Craton, the borders of which are marked by several large strike-slip fault systems (Figure 1).

The metamorphic basement rocks in the Yangtze craton include amphibolite and granulite facies of biotite–hornblende gneisses, tonalites, trondjhemites, granodiorites and supracrustal rocks, and pervasive migmatization (Chang et al. 1991; Zhai et al. 1992). Zircon U–Pb and whole-rock Sm–Nd geochronological data reveal that these basement rocks are Palaeo-Proterozoic to Archean in age, 1895 to 2900 Ma (Chang et al. 1991). The basement is overlain by a 2000-m-thick Palaeo- to Neo-Proterozoic (990 to 1850 Ma) (Chang et al. 1991) volcano-sedimentary suite of calc–alkaline basalts, rhyolitic rocks, and shallow marine carbonate and clastic sedimentary rocks that have been moderately metamorphosed to schists and gneisses (Pan and Dong 1999). A recent biostratigraphic and stratigraphic investigation has shown that, starting in the Cambrian, thick (>1 km) carbonate and clastic sequences were deposited in the Palaeotethys ocean, and a large number of organ-rich black shales and chert nodules as well as phosphorous layers and nodules were formed in response to several anoxic events during the Palaeozoic time (Lü et al. 2004).

There are two tectono-magmatic records, i.e. Late Jurassic and Early Cretaceous, which might be related to the collision between the Yangtze Craton and the North China Craton and to the westward subduction of the Pacific Plate (Guo et al. 1980; Chang et al. 1991). Following these tectonic activities, large-scale folding and deep faults occurred, and numerous basement faults were reactivated and became favourable for the channels for magma ascent. Therefore, the extensive felsic intrusions and extrusive rocks are distributed along the deep faults, while two different trending fault intersects are commonly favourable for the locations of

Figure 1. Regional geological map of porphyry iron ore deposits in the Ningwu Basin, SE China (modified from Ningwu Research Group 1978). The sizes of the filled circles represent the areal extent of the iron oxide deposits.
many ore fields (Zhai et al. 1996), e.g. the Gushan iron deposit, which is located in the intersect of the NNE-striking fault and WNW-striking fault.

**Mine geology**

The Gushan deposit occurs in a poorly exposed area, where a north-northeast-plunging anticline is truncated by a west-northwest-striking fault. The stratigraphic sequence outcropped in the Gushan mine consists of Upper Triassic sandstone and shale of the Huangmaqing Formation (Fm.) and the Jurassic sandstone of the Xiangshan Group, overlain by Cretaceous andesite of the Longwangshan Fm. and Dawangshan Fm. The sandstone and shale of the Huangmaqing Fm. and the quartz sandstone and feldspar sandstone of the Xiangshan Group are intruded by the dioritic porphries in the Gushan mine (Figure 2(a)).

In the mine, only one dioritic porphyritic intrusion as well as minor syenite dikes have been recognized. The syenite dikes formed much later than the dioritic porphyritic intrusion and mineralization because the dioritic porphyritic intrusion and orebodies have been partly cut by the syenite dikes. The dioritic porphyry outcrops has an outcrop area of ~5 km². The south and west part of the porphyry has been exposed at the surface, but most of the porphyries have been covered by ~100-m-thick Quaternary sediments.

The porphyries are dark grey to greyish-green and changed to be grey white where kaolinite alteration occurs. The hypocrystalline texture of dioritic porphyry can commonly be recognized. Dioritic porphyry far from the orebody consists predominately of plagioclase (60–65%), dark minerals (25–30%), consisting mainly of augite and magnetite, and quartz (5%). The plagioclases, 0.5 to 1 mm in diameter, are chiefly andesine with An contents of 46–49%. The rhythmic zoning is common in plagioclase. The anhedral augite and magnetite fill the spaces between the randomly-arranged plagioclase crystals. In addition, there are some accessory minerals, such as fluorapatite, chlorite and titanite. Quartz and plagioclase contents in the dioritic porphyritic rocks near the orebody increased. The earliest K–Ar dating on whole-rock dioritic porphyry yielded an age of 137.5 Ma (Song 1981), while Xu and Xing (1994) obtained an age of 129.33 ± 0.19 Ma by the whole-rock and mineral Rb–Sr isochron method. In such a case, we believe that ~130 Ma could be the best age estimate of the Gushan dioritic porphyry.

Whole-rock analyses of major and trace elements, including rare earth elements (REE), for the Gushan dioritic porphyries have been reported by Li (2007) (Tables 1 and 2). They are of weakly alkaline to calc-alkalic affinities. Their SiO₂ contents vary considerably, ranging from 52.72 to 60.68%, and K₂O + Na₂O contents range from 2.07 to >6.3%. In general, the K₂O + Na₂O contents are higher than those of normal diorites (K₂O + Na₂O = 4.7; Clark 1989). However, caution is advised because some mobile elements, such as K, Na, Rb, Sr, Ba, etc., have been dramatically altered by post-magmatic hydrothermal alteration. Therefore, relatively immobile trace elements (e.g. Y, Tb, Nb, and V versus TiO₂) were utilized for tracing their petrogenesis. The dioritic porphyries have a very narrow initial ⁸⁷Sr/⁸⁶Sr range, from 0.7064 to 0.7066 (Li 2007), close to those of the volcanic and subvolcanic rocks in the area, but significantly higher than those typical mantle-derived magmatic rocks. Two porphyry samples have a εNd(T) value of −5.8 to −5.7 (Xing 1998; Chen et al. 2001), much higher than those of the crustal materials in the region (about −20, Qiu et al. 2000). Hence, their Sr and Nd isotopic compositions suggest that the magmas that produced the dioritic porphyries could be derived from the upper mantle, but
Figure 2. (a) Geologic map of the Gushan iron oxide deposit. (b) Approximately N-S cross-section of the Gushan iron oxide deposit looking east (modified from Zhai et al. 1992).
Table 1. Major element compositions of the Gushan dioritic porphyritic rocks.

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<tr>
<th></th>
<th>SiO₂</th>
<th>TiO₂</th>
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<th>Fe₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>H₂O</th>
<th>P₂O₅</th>
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<td>6.85</td>
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<td>5.52</td>
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Note: Data for 1–2 are from the Geologic Survey Report of Gushan Pit Mine (unpublished); for 3 are from Song (1981); for 4 are from the Research Group of the Porphyry Iron Ore (1977); for 5 are from Lin (1975); for 6 are from the Institute of Geochemistry of Chinese Academy of Sciences (1987); for 7–8 are from Li (2007).

Table 2. Bulk-rock trace elements analyses of the Gushan dioritic porphyry intrusion.

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<th></th>
<th>La</th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Tb</th>
<th>Dy</th>
<th>Ho</th>
<th>Er</th>
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<th>Lu</th>
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<td>3.728</td>
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<td>Cu</td>
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<td>Zr</td>
<td>Nb</td>
<td>Ba</td>
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</table>

Data are from Li (2007).
contaminated by crustal materials. This conclusion is also supported by their primitive mantle normalized trace element patterns with significantly negative Nb, Ta and Ti anomalies (Figure 3).

The chondrite-normalized REE patterns for the Gushan dioritic porphyry samples are characterized by remarkable light REE-enrichment relative to middle REE (MREE) and heavy REE (HREE), and no significant MREE enrichment relative to HREE, with slightly positive Eu anomalies (Figure 4). The absence of a negative Eu anomaly is commonly attributed to high magmatic oxidation states (Lang and Titley 1998).

Mineralization

Orebodies

The orebodies have mainly been recognized at the contact zone between the dioritic porphyry rocks and the sedimentary country rocks, consisting of the muddy siltstone and shale of the Huangmaqing Fm. and quartz sandstone and feldspar sandstone of the Xiangshan Group. The Gushan deposit is composed of variable orebody shapes which occur as a ring in the east and an irregular shape in the west. There are also NE-trending veined orebodies at the southwest side (Figure 2(a)). As a whole, the orebodies constitute a dome shape (Figure 2(b)). However, the border of the orebodies in the southeast has not been marked. The east and south parts of the orebodies trace discontinuously and are much less thick than those of the west part. The complicated shapes of the orebodies are likely controlled by the shape of the dioritic porphyritic intrusion and the combined fracture system: the emplacement of the intrusion led to the ring shape orebodies, and the intensive fractures resulted in the regular linear and veined orebodies.

Ore types and mineralogy

Four types of ores have been recognized (Figure 5). The most important types are massive ores and brecciated ores which make up 90% of the iron ores in volume.
Almost all massive ores and part of the brecciated ores have a high Fe grade of 45 wt-%. A few ores of stockwork, disseminated, banded and skeleton ores are also common, but are not as important as the two above types economically. Most brecciated ores and disseminated ores belong to low grade ore (30–45%Fe) and all stockwork ores and minor disseminated ores are subeconmic (TFe<30%). An important distinctive feature of the orebody in the Gushan deposit is the sharp contact between the massive orebodies and the country-rcoks or dioritic porphyry rocks and gradual contact between massive ores and the brecciated ores. The brecciated ores are mostly located between the massive ore and the country rocks and also occur between the massive ore and sedimentary country rocks. However, in some localities, the brecciated ores are absent. Another feature is that the iron orebodies usually show mineralogical and textural zonation from centre to margin. The massive ores in the centre are characterized by fine-grained magnetite interlocking with fine-grained apatite, whereas the marginal zones consist mostly of brecciated ores. In some localities, irregular massive ore bodies are surrounded by a stockwork of magnetite-quartz-apatite veins.

Massive and banded ore

The massive ore is the most important ore type in the Gushan iron deposit (Figure 5(a)), and makes up 40 vol.-% of the deposit. Massive ores occur as lenses, veins or irregular shapes. The massive ores consist predominantly of magnetite and martite, with minor accessory minerals such as apatite, quartz, and a few titanates. As usual, there are miarolitic cavities, amygdaloidal structures, and holes, which are usually filled by quartz crystals. At the lower part of the orebodies, holes, tubes, and amygdale are absent in the massive ores, but melt flow structures are commonly

Figure 4. Chondrite-normalized REE patterns of three Gushan dioritic porphyritic rocks. (Data are from Xing 1998 and Li 2007). Normalized values are from Sun and McDoung (1989).
Figure 5. Photographs of some representative ore structures and ore types: (a) massive ore; (b) massive ore displaying melt flow structure; (c) brecciated ore; (d) brecciated ore, with bleached zone in the fragments; (e) massive ore and brecciated ore, exhibiting gradual contact relation; (f) disseminated ore; (g) stockwork ore; (h) stockwork ore with pectinate structure.
observed instead (Figure 5(b)). This means that the iron oxide ores are formed by magmas. The banded ores are always found in the deepest part of the orebodies (Zhai et al. 1992)

*Brecciated ore*

Brecciated ore is also an important type, and makes up 50% of the iron ores by volume. It consists of angular brecciated fragments of the country rocks or the dioritic porphyries cemented by Fe-bearing minerals which are also observed in the massive ores (Figure 5(c) and (e)). The fragments of brecciated ores vary in granularity and quantity (Figure 5(d)), and in the ores the martite is fine grained. There are many holes in the brecciated ores. This is also a distinctive feature of the deposit, suggesting a large number of gases in the ore-forming magmas and fluids.

*Disseminated ore*

Disseminated iron ore (Figure 5) is commonly observed in the dioritic porphyry and the metavolcanic rocks of Dawangshan Fm. The ore minerals in disseminated ores consist of martite. They are usually in euhedral to subhedral grains, which locally formed in irregular aggregates. The gangue minerals include quartz, ferruginous dolomite, calcite and kaolinite. In some places, almost all of gangue minerals are ferruginous dolomite, locally interlocking with each other. The euhedral magnetite or martite grains are randomly disseminated in gangue minerals. A large amount of hematite has been replaced by dolomite, and only skeleton hematite is preserved, suggesting that the dolomite formed later than martite.

*Stockwork iron ore*

Stockwork iron ore (Figure 5(f)) occurs as irregular vein networks, especially with the pectinate structure (Figure 5(h)), composed of magnetite or hematite. The veins vary in thickness, from a few millimetres to at least 3 m, and in some places different striking-fine veins intersect each other, form trellises-shape patterns, and locally cut other types of ores, such as massive ores and brecciated ores. The stockwork veins generally consist of large magnetite, hematite, apatite, and quartz crystals. In addition, there are some other types of ores, including skeleton ore and slag ore; however, these types of ores are economically valueless.

A vertical zonation, from the top downward, vesicular ore or slag ore, brecciated ore, massive ore, disseminated ore, and banded ore, has been recognized in the mine. The ore minerals are very simple, i.e. hematite (martite) at the upper and magnetite at depth, and the main gangue minerals are made up of apatite, quartz, calcite, jasper, opal, and kaolinite, with a few biotite, diopside, albite, barite, and celestite. Pyrite and chalcopyrite are scarce.

The chemical compositions of the main ore types are listed in Table 3. Based on their chemical compositions, we can conclude that martitization has occurred in most magnetite ore, thus the average FeO/Fe₂O₃ ratio in magnetite ore is 1:3.2, and not 1:2.2 in the fresh magnetite ore. The sulphur content in all ores is low (<0.07%), which is readily reconciled with the absence of pyrite in the ores. One distinctive feature of the Gushan iron deposit is that the content of V₂O₅ and P₂O₅ is relatively high, ranging 0.025–0.14% and 0.039–0.31% respectively. Another one is that the content of TiO₂ decreases gradually from the magnetite ore, martite ore to hematite ore.
Table 3. Analyses of oxide minerals from the Gushan iron deposit.

<table>
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<th></th>
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<td>Martite</td>
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<td>0.005</td>
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<tr>
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<td>0.0025</td>
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<td>90.469</td>
<td>95.5</td>
<td>90.925</td>
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<td>94.726</td>
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Note: Data for 1 and 5–9 are from Song (1981), and for 2–4 and 10–11 are from the Geologic Survey Report of Gushan Pit Mine. All data are determined by wet-chemical analysis.
**Main minerals**

Magnetite is the dominant iron mineral in all types of ores in the deposit, although some magnetites have been replaced by martite. It occurs as euhedral to subhedral grains (Figure 6(a)), and was probably poor in Ti before alteration. The fine-grained magnetite was mainly formed by rapid cooling, especially for those with spherulitic texture (Figure 6(b)). In the near-surface of the deposit, the magnetite commonly has...
been altered by martite along grain boundaries, fractures, crystal faces, and octahedral cleavage faces (Figure 6(c) and (d)). Sheet magnetites form a skeleton filled by quartz or chalcedony (Figure 6(e)), and some of sheet magnetites and martites exhibit an oriented arrangement which displays a branching structure. The pectinate structures are commonly observed in ores that consist of coarse-grained magnetite which coexists with apatite and quartz. Due to the effect of oxidation and the activities of hydrothermal fluid, most magnetite has been changed into martite, so the magnetite is only preserved in the lower part of the orebodies. The martite is not only present near the surface, but also occurs at 200-m depths below the surface.

There are two types of hematite. One is in sheet crystal, coexisting with quartz and apatite; another is hydrothermal origin-hematite (specularite), coexisting with quartz. In the veins of stockwork ore, some vertical fractures are filled by hematite ‘oolites’ (Figure 6(f)). The V₂O₅ and TiO₂ contents of magnetite and hematite are quite low, 0.025–0.14% and 0.26–0.39% respectively. Comparably, the V₂O₅ and TiO₂ contents of the magnetites in the gabbros associated with iron oxide deposits are much higher, e.g. an average content of 0.28 wt-%V₂O₅ and 12.6 wt-%TiO₂ for those from the Panzhihua gabbro intrusion hosting a super-large V–Ti magnetite deposit, SW China (Zhou 2005). The slightly magnetic nature of the hematite ores could be attributed to the presence of some magnetite in addition to the predominant hematite.

Apatite is the second most common mineral, although there are not many apatites in the ores. The apatite is fluorapatite, which usually contains small amounts of hydroxyl rather than chlorine or CO₂. Fine- and coarse-grained apatite is associated with magnetite. The apatite in the massive and stockwork ores is subhedral to euhedral grains, mostly 0.02 to 0.5 mm long. The content of Y, Ce, and La in apatites from the dioritic porphyry rock and stockwork ore is very close (Table 4).

Calcite and quartz are the dominant gangue minerals through all mineralization stages. Kaolinite and jasper formed at mesogenetic stages.

**Stages of mineralization**

Based on the relationships of ore veins, mineral assemblages, paragenetic sequence (Figure 7), and ore fabrics, four mineralization stages can be recognized:

1. **Magmatic stage**, represented by the intensive magnetite, which is fine-grained, coexisting with a few euhedral to subhedral apatite, martite, and

Table 4. Average Y, Ce, and La content of apatites from stockwork ore and dioritic porphyritic rocks.

<table>
<thead>
<tr>
<th></th>
<th>Y</th>
<th>Ce</th>
<th>La</th>
<th>Y + Ce + La</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Content</td>
<td>Value of</td>
<td>Content</td>
<td>Value of</td>
</tr>
<tr>
<td>Stockwork</td>
<td>wt-%</td>
<td>distribution</td>
<td>wt-%</td>
<td>distribution</td>
</tr>
<tr>
<td>ore</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0642</td>
<td>10.49</td>
<td>0.3648</td>
<td>59.63</td>
<td>0.1828</td>
</tr>
<tr>
<td>Dioritic</td>
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<td></td>
</tr>
<tr>
<td>porphyry</td>
<td>0.0600</td>
<td>13.10</td>
<td>0.2711</td>
<td>59.18</td>
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</tbody>
</table>

Note: Data are from Song (1981).
hematite – most massive ore and brecciated ore were formed during this stage;

(2) hydrothermal stage I, mainly characterized by the extensive replacement of martite, which mainly occurred along grain boundaries, fractures, crystal faces, and octahedral cleavage faces of magnetite in the magmatic stage, and hematite (sheet crystal), coexisting with calcite, apatite, and quartz, whereas coarse-grained magnetite is found in the veins of stockwork ore;

(3) hydrothermal stage II, represented by the presence of apatite-magnetite-hematite-quartz association. In this association, sheet magnetites and martites or magnetites form a skeleton filled by quartz or chert;

(4) supergene stage, represented by the silicates replaced by kaolinite, which is the main alteration minerals, developed in most rocks and ores. Magmatic stage and hydrothermal stages are the main stages of mineralization.

Wall-rock alteration

The wall-rock alteration in the Gushan iron deposit mainly occurs along the mineralized fractured zones. However, as a whole, the alteration is quite weak. The main alteration types include kaolinization and silicatization. The extent of alteration depends on the composition of the original rocks and the distance from the mineralized zone.

Weak silicatization and kaolinization occurred in the dolomite limestone of the Qinglong Group and the mud shale and siltstone of Huangmaqing Fm., but representative skarn minerals have not been recognized. Due to the thermodynamic effect of the magma, metamorphism occurred in the country rocks, which led to recrystallization of limestone and formation of quartzite changed from quartz sandstone.

The dioritic porphyry has undertaken intensive hydrothermal alteration, which comprises a light-colour alteration zone and a dark alteration zone. The former includes silicatization and kaolinization, which occurs at near orebodies. The
silicatization led to elevated SiO2 contents of dioritic porphyry, up to 68.32% (Zhai et al. 1992) and subordinary quartz in the porphyry. The kaolinization is characterized by the feldspars replaced by kaolinite and dramatically varied chemical compositions. The dark-colour alteration zone is characterized by the replacement of chlorite and carbonate minerals. Of those alteration types, silicatization and kaolinization is the most important, because they are the indicator of mineralization.

Discussion

Magmatic origin or hydrothermal origin?

The origin of the Gushan deposit remains controversial. Two contrasting inferences have been proposed. Some workers proposed that the ores are of magmatic origin (e.g. Chang et al. 1991; Zhai 1996), whereas other workers argued against this model, but prefer the hydrothermal model instead (Gu and Ruan 1988; Lin et al. 1983).

Based on the field observation and the textures of the ores, we proposed that the main economic ores (e.g. massive ores, banded ores, and brecciated ores) are of magmatic origin, whereas the stockwork ores are of hydrothermal origin. The arguments are mainly based on the following evidence:

1. The brecciated ore with angular fragments of the wall-rock and dioritic porphyry cemented by magnetite can be plausibly interpreted as an explosion of the magmas caused by a sudden, volatile release in response to decreasing pressure during their ascent to near the surface, but cannot readily be reconciled with the hydrothermal activities. The density of the diorite is about 2.87 g/cm³ (Olhoeft and Johnson 1989), much heavier than the NaCl solution (Potter and Brown 1977). This means that the hydrothermal fluid (NaCl solution) cannot load the heavy fragments. In addition, melt flow structure, a typical magma feature, is common in the massive ores. The elongated stomata and the spherulitic matite aggregation also indicate a magmatic origin.

2. The high Ce₂O₃, La₂O₃, Nd₂O₃, and Y₂O₃ contents in the apatite indicate a high temperature (Song 1981) and the similar chondrite-normalized REE patterns of apatites from the massive ores and dioritic phryrites suggest they were fractionated by a common parental magma. Although the apatites from the iron ores in the Gushan deposit and ‘Kiruna’-type iron ores are characterized by enrichment in LREE and negative Eu anomalies, the apatites from the Gushan iron ores appear to have much higher LREE concentrations and much higher LREE fractionation from HREE (Yu and Mao 2002), which could have resulted from the alkali-rich feature of porphyries (Frietsch and Perdahl 1995) because the Gushan dioritic porphyries have alkaline affinity as described above. In addition, the apatites from the Gushan ores have much higher total REE concentrations, ranging from 3031 × 10⁻⁶ to 12080 × 10⁻⁶ than the hydrothermal-origin apatites (1919 × 10⁻⁶; Yu and Mao 2002), which also reflects a magmatic origin.

3. The exploding temperature of inclusion in magnetite and martite ranges from 350 to 1040°C (Li and Xie 1984), and Lu et al. (1990) found that their homogeneous temperature shows a peak at 1000°C, which undoubtedly indicates a magmatic origin. However, the homogeneous temperature of
magnetite from the stockwork ore is lower than 400°C (Institute of Geochemistry, Chinese Academy of Sciences 1987), indicating a hydrothermal origin.

4. The previous experimental studies have provided more evidence for magmatic origin (Philpotts 1967). Taking into account the Fe$_3$O$_4$–Ca(PO$_4$)$_3$–NaAlSiO$_4$–CaMgSi$_2$O$_6$ quaternary system, Su (1984) concluded that at a certain temperature and pressure, given enough mineralizing agent (P, F, Cl), the iron- and phosphorus-rich melt can separate from the silicate melt. By using the ore minerals and the gangue minerals similar to the mineralogy observed in the Gushan deposit in the experiment, Yu (1984) observed an immiscible iron oxide-enriched phase from the silicate melt.

5. The stockwork iron ore occurs as irregular vein networks, especially with the pectinate structure, composed of magnetite or hematite. In the veins of stockwork ore, some vertical fractures are filled by hematite ‘oolites’, a typical characteristic of hydrothermal fluid.

In summary, there is little doubt that the massive ores, brecciated ores and banded ores in the Gushan iron deposit are magmatic in origin and crystallized from iron oxide melts, and the subeconomic ores such as stockwork ores were formed by hydrothermal fluid.

Immiscibility or fractional crystallization?

A model of fractional crystallization has been proposed to interpret the generation of the other magmatic iron oxide deposits, e.g. Hongge V–Ti–Fe deposit in west Sichuan province (Pang et al. 2008). Abundant Fe–Ti oxide inclusions in cumulus olivine from the Hongge intrusions show evidence for early crystallization of Fe–Ti oxides in ferrobasaltic magma, which is consistent with the interpretation that the stratiform oxide ores in the Hongge intrusions formed by accumulation of Fe–Ti oxide crystals which are formed by fractional crystallization rather than immiscible oxide melt.

Unlike the Gushan intrusion, those in the Pan-Xi region occurring as iron beds associated with the gabbros are generally concentrated in the lower parts of the intrusion (Hu and Zhou 2001) while the orebodies in the Gushan deposit occurred at the top of the intrusion due to low density of ore-bearing magma with enormous volatile contents, as indicated by many holes in the massive ores and brecciated ores. The typical melt flow structure in the massive ores is good evidence for magma flow. In addition, the absence of magnetite and hematite associated with silicates and accumulation-texture precludes the possibility of fractional crystallization. Alternately, all indicate that the massive ores formed from a cooling magma phase.

The formation of an immiscible oxide melt from the silicate magma may have resulted from crystal fractionation, magma mixing, an abrupt change in oxygen fugacity, and/or an introduction of fluids or P. There is no evidence of magma mixing or significant mineral fractionation for the Gushan dioritic porphyries given only a single lithologic unit and few varied chemical compositions, therefore it is unlikely that magma mixing or mineral fractionation led to the formation of an immiscible oxide melt. Consequently, we propose that the formation of an immiscible oxide melt in the Gushan deposit could be related to the following three possible factors. The first one is an abrupt elevated oxygen fugacity due to the opening structure environment for the ascending magmas from a relative reductive
environment. Secondly, the presence of minor apatite in the Gushan ores suggests that P may have acted as fluxing agents that facilitated development of the immiscible liquids. The theoretical and experimental studies have shown that the introduction of P could cause the formation of an immiscible oxide melt from the silicate magma due to the change of melt structure (Philpotts 1967; Su 1984; Yu 1984). In the eastern Yangtze craton, there are phosphorite layers and nodules in Cambrian, Ordovician, Silurian, Carboniferous, and Permian strata (Lü et al. 2004). As stated above, the magmas that produced the Gushan dioritic porphyries have been crustally contaminated. Thus, it can be inferred that the magmas could inevitably be contaminated by phosphorous materials during their ascent. The third one is an introduction of CO$_2$-rich fluids as indicated by the presence of calcite in the ores. This process can be reached by magma–wall-rock interaction (mantle-derived magmas contaminated by carbonate) during the magma ascent rather than crystallization because no hydrous minerals in the dioritic porphyries have been recognized.

Based on the above and a previous regional geologic setting, we proposed a metallogenetic model for interpreting the formation of the Gushan iron deposit, and the cartoon model is shown in Figure 8.

The middle–lower Yangtze River valley, including the Gushan deposit, developed on Precambrian basement and remained quite stable during the Palaeozoic as a wide open trough with vertical movements. From the Cambrian to the Early Triassic, the Middle-Lower Yangtze River Valley represented a stable trough filled by carbonate and clastic rocks of shallow marine facies. Phosphorite layers and nodules formed during this period. Collision between the Yangtze and North China cratons took place at 238–218 Ma (Ames et al. 1996; Chavagnac and Jahn 1996; Rowley et al. 1997). From the Middle Triassic to the Middle Jurassic, this belt was a foreland basin located south of the Dabie orogen, and geodynamics are characterized by extension and thinning of the lithosphere and mantle uplift (Deng et al. 1992). From 160 to 135 Ma, due to the convergence of the Palaeo-Pacific and Euroasian plates, the NS-trending principal stress field changed progressively to an EW-trending principal stress field in the eastern China continent. The Cu–Mo–Au–(Fe) metallogenic system in the Middle-Lower Yangtze River Valley formed at the end of this period of geodynamic adjustment (Zhai et al. 1996). After geodynamic adjustment, an extensional regime developed in the EW-trending principal stress field, possibly caused by lithospheric delamination (Xiao et al. 2006). Rapid extension and dramatic thinning of the lithosphere led to development of a series of parallel NNE-trending fault basins, and thereafter decompressional melting of diapiric mantle at 130–115 Ma (Zhai et al. 1996). The latter caused formation of the dioritic (andesitic) porphyry systems associated with Cretaceous subvolcanic rocks in the Ningwu volcanic fault basins including the Gushan deposit.

The Gushan dioritic magmas possibly formed by fractionation of mantle-derived magmas and enrichment of volatiles in the dioritic magmas have been reached by fractionation of anhydrous minerals (e.g. olivine and clino-pyroxene). During the magma ascent, the magmas have been contaminated by the phosphorite layers and nodules and the carbonate layers (CO$_2$). When the ore-forming magma emplaced near the surface, the fluxing agents, mainly the phosphor and CO$_2$, facilitated development of the immiscible oxide melt. Fluid exsolution developed by decompression during ore-forming magma ascent, and the growth of bubbles constitutes the driving force behind rising magmas. Boiling occurred due to
suddenly decreasing pressure, and the internal fluid pressures became suddenly larger than the lithostatic load. Eventually, new bubble formation led to an explosion near the surface, resulting in the immediate fragmentation of the roof of the intrusion and sedimentary wall-rocks. These fragments were then cemented by Fe oxide melts, forming brecciated ores. The residual oxide melts filled in the small faults and fissures, leading to the formation of massive ores. The hydrothermal fluids were possibly formed by the mixture of magmatic fluids and meteoric water.

**Concluding remarks**

The Gushan iron oxide deposit is temporally and spatially associated with the dioritic porphyries which formed in the early Cretaceous and can be classified into an example of a ‘Kiruna’-type deposit. The dioritic porphyries have been produced by fractionation of the mantle-derived magma and the later crustal contamination. The Gushan iron oxide deposit is characterized by predominant massive ores and
brecciated ores with minor stockwork, disseminated, banded and skeleton ores. The massive orebodies were formed by immiscible oxide melt separated from the silicate melt, and the brecciated ores, characterized by angular fragments of the wall-rock and dioritic porphyry cemented by magnetite, could be attributed to an explosion of the magmas at the near surface responsible for fluid exsolution developed by decompression. The introduction of P and CO$_2$ to the magmatic system following crustal contamination during magma ascent could be a crucial factor for the formation of immiscible oxide melt. In contrast, the stockwork iron ores are characterized by irregular vein networks, especially pectinate structures formed by the later hydrothermal processes. Consequently, Early Cretaceous dioritic porphyries, which developed in a Mesozoic basin filled by a suite of carbonate and clastic rocks including phosphorite layers and nodules of shallow marine facies, could be the prerequisite for future exploration, and the associated breccias characterized by angular fragments of the wall rock and dioritic porphyry cemented by magnetite is a direct indicator of mineralization.

Acknowledgements
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