Genesis of the Xinqiao Gold-Sulfide Orefield, Anhui Province, China

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Abstract  The Xinqiao S-Fe-Cu-Au orefield is located in the Tongling ore cluster in the middle and lower reaches of the Yangtze River in East China. There have been many researches regarding the genesis of the Xinqiao orefield in recent years, showing that it belongs to various types, such as sedimentary-reformed type, stratabound-skarn type, sedimentary submarine rocks-hosted exhalative type. We propose that it was formed in two periods of mineralization base on systematic field observation and Pb and S isotopic analyses in nearly ten years. The first period was formed during a syngenetic sedimentary process, whereas the massive sulphide orebodies are mainly related to the Yanshanian granitic magmatism. Sulfide metallic mineral associations show zoning around a granite intrusion, i.e. magnetite and pyrite → pyrite, chalcopyrite and native gold → pyrite, sphalerite and galena. Gold orebodies occur outside the contact zone of the granite intrusion.

Key words: Xinqiao orefield, geological characteristics, ore-forming process, massive sulphide orebody

1 Introduction

The Tongling area is an important copper, iron, and sulfur-producing district in East China, where the Tongguanshan, Shizishan, Xinqiao and Fenghuangshan orefields are located. Researches have been done by previous researchers on the geological characteristics of the ore district, ore-forming process, mineralization and ore-controlling structures of the Cu-Au-Fe deposits. Some researchers consider these deposits to be of the skarn-hydrothermal type (or sedimentary-hydrothermal reformed deposits) related to granitic rocks (Liu et al., 1988; Chang et al., 1991; Huangbin, 1991; Zhai et al., 1992; Huang et al., 1993; Yu et al., 1995; Tang et al., 1998; Wu et al., 2003, 2004). Pan and Dong (1999) have summarized them as porphyry-skarn-manto deposits related to granite. Meng et al. (1996a, 1996b) thought that the Xinqiao and the Dongguashan deposits are intrusive massive sulfides. Since the 1980s, some researchers (Fu et al., 1977; Gu et al., 1983, 1984; Xu et al., 1986; Ji et al., 1990; Yue et al., 1993; Zhou et al., 2000; Xu et al., 2001; Zeng, Xiao et al., 2002) argued that stratiform orebodies hosted in Devonian and Carboniferous systems were formed by submarine sedimentation-exhalation.

The Xinqiao orefield consisting of the Xinqiao, Niushan, and Shaojiliao deposits 26 km east of Tongling City, is a large orefield dominated by pyrite with proven reserves of 0.33 million tons of Cu with an average grade of 0.9%, 83 million tons of S, averaging 31% and 29 million tons of 43% Fe. In recent years, local geologists found economic gold orebodies (reserves of 25.9 tons of Au with an averaging grade of 4.70 g/t) in the stratiform sulfide deposits. The discovery of primary gold in the Xinqiao deposit has provided new incentives for prospecting for gold in massive sulfide deposits in the Middle and Lower reaches of the Yangtze River. Here, we try to document the metallogenic process in the area based on the geological characteristics revealed during years of mining, in combination with the Pb and S isotopic compositions of the deposits.

2 Geological Setting and Orefield Geology

Geotectonically, the Tongling area belongs to the middle section of the Ma'anshan-Guichi uplift southeast of the Indosinian lower Yangtze uplift (Chang et al., 1991; Liu et al., 1996; Tang et al., 1998). The geological evolution of the study area underwent three main stages, i.e., the formation of the Pre-Sinian basement, the deposition of Sinian-Middle Triassic cover, and late Triassic-Cenozoic intraplate deformation. The Paleozoic sedimentary rocks especially carbonates, are the major strata exposed in the area. They are the major country rock of copper, sulfur and gold deposits. Indosinian deformation resulted in NE-trending S-shaped folds and different levels of interlayer gliding structures. The main magmatic rocks in this area are Yanshanian-intermediate-acidic rocks with a high alkali content. The adamellite and granodiorite are closely
associated with metallogeneses.

The Xinqiao orefield is located at the intersection of the Shujiadian anticline, Dachengshan anticline and Shengchong syncline (Fig. 1). The sedimentary strata in the Xinqiao orefield are Silurian, Upper Devonian, Carboniferous, Permian, Triassic and Quaternary in age. The orebodies mainly occur in stratabound detachment horizons within the Upper Devonian Wutong Formation sandstone and siltstone, the Middle Upper Huanglong Formation and Chuanshan Formation carbonate rock, and the thick-bedded limestone of the lower Permian Qixia Formation. Igneous rocks in the study area are mainly intermediate-acid stocks, apophyses and small dikes of varying lithology, among which the Jitou and Niushan stocks are the large ones (Fig. 1). The Jitou magmatic rocks in the middle of the Xinqiao orefield are predominantly quartz monzonitic diorite with an ellipsoidal surface area of 0.5 km².

3 Geological Characteristics of the Xinqiao Deposit

There are two types of mineralization. One is represented by siderite ore occurring at the bottom of the Permian Qixia Formation and formed due to sedimentation, as well as minor pyritogelite at the bottom of the Middle Carboniferous Huanglong Formation and the other is represented by sulfide orebodies related to the Jitou stock, which include stratiform, skarn and hydrothermal vein-like orebodies (Fig. 2). The stratiform massive sulfide orebody is the major one of the Xinqiao deposit and accounts for 90% of the total reserves.

3.1 Geological characteristics of siderite orebody

The siderite orebody occurs mainly at the bottom of the Lower Permian Qixia Formation, namely a transitional zone from sandstone to carbonate rock. The orebody is stratiform and stratoid with a thickness of 3–31 m, which extends 700 m along its strike and 50–200 m along its dip. The ore displays ooidic and microcrystalline and micritic textures. Carbonaceous cement fills voids. The grains are fine in size. The siderite ores show both laminated and porous structures and contain minor pyrite and sphalerite.

3.2 Geological characteristics of sulfide orebody

The Xinqiao deposit is dominated by stratiform, skarn and hydrothermal vein-like sulfide orebodies. However, significant economic reserves are presented only by stratiform orebodies. The main orebody is 2650 m long, extending 1810 m along its dip with an average thickness of

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*Fig. 1. Geological map of the Xinqiao orefield (revised after Liu, 1996).*

Fig. 2. Composite cross sections of the Xinqiao deposit.

21 m. The orebody is mainly distributed along the unconformable interface between the Wutong Formation sandstone and the Huanglong Formation dolomitic limestone (Fig. 2). The major ore minerals are pyrite, minor pyrrhotite, magnetite and chalcopyrite; minor lead-zinc ore and pyritogelite are also present. The major nonmetallic minerals are calcite and dolomite. Massive and marialitic structures are the most common, whereas disseminated ore and network structures are secondary. Specifically, the ore textures include euhedral-subhedral granular texture, granular mosaic texture, metasomatic relict texture, blastocolloform texture and cataclastic texture. The massive structure, the main structure of the ore, is composed generally of euhedral-subhedral pyrite grains. The mialitic structure, which is characteristic of the stratiform orebody, is also generally developed. Vugs formed by pyrite are commonly seen in dense massive pyrite orebodies (Plate I). The network structure shows net-veined pyrite of different widths, filling in early formed cracks (Plate I). The disseminated structure is adjacent to the top and pinching position of the orebody. The major vein minerals are calcite and dolomite. Footwall alteration of the stratiform orebody is weak, mostly pyritization, silicification and formation of talc. Talc is mainly developed in sandstone and adjacent to the orebody. Marblization and chloritization are only seen in the roof country rock of the orebody with weak pyrite mineralization locally developed. Marble breccia can be seen in orebodies, but alteration is not seen in marble. The orebody and its country rock has a sharp contact (Plate I).

Skarn-type orebodies: Contact metasomatic skarn-type orebodies are developed in the contact zone between limestone of the Qixia, Huanglong and Chuanshan Formations and the Jitou stock. There are more than 40 orebodies, which account for 10% of the total reserves. The orebodies pinch out far away from the intrusion. Orebody 5 is the largest, and probably accounts for 8% of the total reserves. It is lenticular and irregular in shape (Fig. 2). The skarns include mainly garnet skarn, although there are diopside and actinolite skarns. Metallic minerals are mainly magnetite, pyrite and chalcopyrite; in addition to garnet and diopside, the minor nonmetallic minerals include quartz and calcite. Magmatite is predominant while pyrite is secondary, characterized by massive, disseminated and veined textures and metasomatic dissolution and filling textures. The skarn-type orebodies display a circular zoning pattern surrounding the intrusion. Magnetite is mainly adjacent to the intrusion and pyrite at a distance.

Hydrothermal vein-like orebodies are composed mainly of lode groups filled in fractures, such as veined lenticular orebodies filled in the Wutong Formation strata and the faults in skarn and intrusions. The industrial value of this type of orebodies is not significant in terms of the whole orefield. Such ore displays euhedral-subhedral crystal texture and massive, disseminated structure. The ore mineral is mainly pyrite, while predominant gangue minerals are quartz and calcite.

Relationships between stratiform, skarn-type and hydrothermal vein-like orebodies are as follows. The skarn-type orebody is mainly developed above the stratiform orebody; and skarn mineralization is locally developed along the intrusive contact with stratiform orebody; whereas hydrothermal ore veins are formed in the late stage of magmatic hydrothermal fluid activity, and are found in faults of the country rock, skarns and intrusions. Mineralization therefore evolves in a sequence of skarn→stratiform→vein, and all are products of the same magmatic metallogenic system.

Ore-controlling structures are as follows. NE-NNE-trending interlayer detachment faults are the major ore-hosted structures. The sliding (detachment) plane between the Wutong and Huanglong Formations was the major channel along which magmatic hydrothermal fluids flowed and metallic sulfide was precipitated. As a consequence, the main orebody appears stratiform or stratoïd on the whole although it crosscuts stratigraphic units locally (Fig.
Ore is also distributed along both the intraformational gliding planes and faults. For example, massive sulfide orebodies occur along the gliding plane in the Wutong Formation (Plate 1), and along faults in both intrusion (Fig. 4) and skarn (Plate 1). The best locations for mineralization are between the intrusion contact zone and the interlayer (Wutong/Huanglong) faults where the main orebodies have fairly large thicknesses. For example, the orebody is 68 m thick in borehole ZK133 on line 23, 91 m thick in borehole ZK2407 on line 24, and 107 m thick in borehole ZK330 on line 25.

3.3 Distribution characteristics of primary copper and gold orebodies

Primary gold and silver ore mostly occur in stratiform copper-sulfur orebodies. In recent years, over 40 copper and gold orebodies have been defined in exploration. Copper and gold orebodies are circularly distributed around the intrusion either on plan or cross section (Fig. 5). Although distributed around the intrusion, they are not in the contact zone, but lie at certain distances from the intrusion margin (Fig. 5). The gold-enriched zone, whose major mineral assemblages are chalcopyrite-pyrite-native gold and pyrite-pyrrhotite-native gold, is within the range of 100–500 m from the intrusion margin. The gold-depleted zone, whose major mineral assemblage is magnetite-pyrite, lies within 50–100 m from the pluton margin. The gold content in the depleted zone is lower than the average content of associated gold in the whole deposit, i.e. Au<0.5 g/t. It can be seen from Fig. 5 that horizontal zoning of mineral assemblages was formed during mineralization associated with the intrusion, as is shown by this spatial distribution: intrusion → magnetite, pyrite → pyrite, chalcopyrite and native gold → pyrite lead and zinc. This distribution pattern of gold shows that the gold has magmatic sources. In positions near the intrusion, the temperature is relatively high, which is not favorable for

![Diagram](image)

Fig. 3. Sketch showing the massive sulfide orebody filled in faults in quartz monzonodiorite.
1. Orebody; 2. Chuanzhe Formation marble; 3. quartz diorite porphyry; 4. strike and dip.

![Diagram](image)

Fig. 4. Sketch showing the local stratiform orebody cutting the hanging wall.
1. Quartz monzonodiorite; 2. orebody; 3. strike and dip; 4. sampling location.

![Diagram](image)

Fig. 5. Symmetrical gold bodies in the Xinqiao deposit (A); primary zoning in the Xinqiao deposit (B).
(Exploration data from the No. 803 Geological Team, 1995).
gold precipitation. Gold usually migrates at relatively high temperatures and precipitates at relatively low temperatures and under favorable structural conditions to form gold orebodies. The range of 50–100 m is an activation and migration zone for gold mineralization, whereas the range of 100–500 m is a gold-enrichment zone.

4 S and Pb Isotopic Compositions of sulfide orebodies

4.1 Sampling site

The authors systematically collected samples from stratiform sulfide orebodies, skarn-type orebodies (Figs. 7, 8), vein-like orebodies and quartz monzodiorite at different levels (Plate I; Fig. 3). Sampling locations are shown on Figs. 3, 4, 6, 7 and 8, and on Plate I. All samples were fresh and have no alteration.

4.2 Analytical method and measured results

Sulfur and lead isotopes in sulfides of different genetic types, and lead isotopes of K-feldspar in quartz monzodiorite were measured at the isotope laboratory of the Institute of Mineral Resources, Chinese Academy of Geological Sciences.

**Sulfur isotopes** Pyrite was measured with the MAT25E mass spectrometer using $\text{Cu}_2\text{O}$ as the oxidation agent and silver sulfide of the first-class national standard as the standard sample based on the international standard VCDT. The analytical precision is 0.2% and the results are shown in Table 1.

**Lead isotopes** HCl was used to dissolve pyrite, dense HF and HNO$_3$ were used to dissolve K-feldspar, and lead was extracted by anion-exchange resin. The mass spectrum was measured by using the MAT262 mass spectrometer, and the apparatus was calibrated by the NBS981 standard. The measuring conditions are the same as for NBS981. Each set of data is composed of ten scans and calculated after correction for ion-current intensity against time. The isotopic fractionation is better than 1‰, and the NBS 981 precision is 0.1‰. The measured results are shown in Table 2 (the error is 2σ absolute one).

It can be seen from Tables 1 and 2 that the $\delta^{34}\text{S}$ values of pyrite in orebodies of different genetic types in this study are similar, and that they are in a range of 1.3‰–5.3‰. The lead isotope values of orebodies of different genetic types are also similar. Moreover, the lead isotopic compositions of the sulfide deposits are similar to those of K-feldspar in quartz monzodiorite, but different from those of the country rocks.

5 Discussion

**Metallogenic tectonic setting** Xu et al (1985) in a comprehensive analysis pointed out that the middle and lower reaches of the Yangtze River were relatively stable from Cambrian to Early Triassic. This area is a continuously developed down-warped basin where shallow marine carbonate rocks and clastic rocks were deposited. Huang et al (1999) studied Carboniferous sequence strata in the lower reaches of the Yangtze River. They concluded that Carboniferous strata in this area was deposited in a shallow cratonic sea instead of a fault depression zone. The Carboniferous crust in Jiangsu and Anhui provinces along the Yangtze River including the Tongling area is a stable craton, featuring slow elevating and subsiding, whose sedimentation is dominated by medium- and fine-grained littoral clastic sediments and carbonate sediments of the shallow epicontinental sea platform. Li et al (1989)

Fig. 6. Sampling locations in stratiform orebodies.
1. Stratiform orebody; 2. Qixia Formation limestone; 3. cataclastic zone; 4. Wuqong Formation sandstone; 5. sample.

Fig. 7. Sampling locations for skarn ore in the Xinqiao deposit (at a level of –24 m).

Fig. 8. Sampling locations for skarn ore in the Xinqiao deposit (at a level of –27 m).
demonstrated that the metallogensis of the hydrothermal brine formed by volcanic eruption and exhalation beneath the sea floor did not take place in the Carboniferous period. After years of work at Xinqiao, Fu et al. (1977) recognized a "volcanic rock range" in Niushan. However, mining proved that it is a subvolcanic stock instead of volcanic rocks. As discussed above, the Xinqiao orebody occurs primarily along the unconformable contact between the Upper Devonian Wuutong Formation and the Middle Carboniferous Huanglong Formation. The Lower Carboniferous Gaolishan Formation is absent. This indicates that the slowly elevating and subsequent subsiding took place in this area in the Early Carboniferous. The thickness of the Huanglong Formation in the Xinqiao area is only 30 m, and the lithological characteristics of its dolomite and limestone indicate a deposition environment of a shallow-water tidal flat.

Sources of substance All deposits having commercial value in the Tongling-Daijianghai area are located in a WEtrending magmatic structural-metallogenic belt. The copper, iron, sulfur, gold and silver orebodies in the area are spatially and genetically associated with Yanshanian monzodiorite. The Xinqiao deposit has good metallic mineral zonation, and the copper-gold orebodies are distributed around the intrusion. High-temperature mineral assemblages are close to the intrusion; low-temperature mineral assemblages are far away from it, suggesting that the source of copper and gold is the intrusion, from which ore fluids were released. The systematic sampling of sulfides from orebodies of different genetic types in the Xinqiao orefield and the measurement of sulfur and lead isotopes done by the authors revealed that the sulfides from the orebodies of different genetic types have different ranges of $\delta^{34}$S isotope values (Table 1). In the mining area, pyrite formed by sedimentation has relatively large negative values, which is characteristic of S isotopes in sedimentary pyrite and indicates that organisms took part in mineralization during the course of sedimentation. The ranges of $\delta^{34}$S values of pyrite in sulfide orebodies, including stratiform sulfide ore, skarn-type ore and vein-like ore, are relatively small, and the $\delta^{34}$S values are close to each other. The values are also close to those of sulfides in igneous pluton intrusions and skarns, which suggests that all have sulfur isotope sources related to magmatism. Lead isotopes of stratiform sulfide ore, skarn-type ore and vein-like ore are consistent with those of K-feldspar in magmatic rocks (Table 2), and are different from those of the country rocks, suggesting that the lead of the sulfide deposits was derived from the granitic magmatic system, and the lead of country rocks from the crust.

In the Tongling ore cluster, stratiform sulfide orebodies were formed in the discordant boundary between Carboniferous and Middle Carboniferous, just like that in the Mashan, Dongguashan, Taoyuan and Tongguanshan orefields. Many geologists have done researches on the Tongguanshan orefield for many years, and believed that this is a typical deposit related to magmatic mineralization. In this orefield, stratiform orebodies overlying the Wutong Formation show horizontal mineralization zoning around the intrusion and gold mineralization is also exhibited (Yuan et al., 2002). Wan (1989) conducted a research on the Taoyuan rich sulfide deposit lying in the same intraformational sliding fault zone as the Xinqiao deposit and drew a conclusion that the Taoyuan deposit, like those at Xinqiao and Tongguanshan, shows zoning of mineral assemblages. He believed that the orebody was the product of middle and low-temperature hydrothermal fluids, and that the ore solutions originated from a deep granodiorite intrusion. The characteristics of such mineral zoning in these deposits show that magma is not only a thermal center, but also a source of metallogenic hydrothermal activity for metallogenes.

Based on the copper isotopes of the Dongguashan deposit, Lu Jianjun (Mao et al., 2004) demonstrated that copper primarily originated from a granitic magmatic system, but thought that part of the sulfur from the ore was deposited syngenetically with the country rocks. Tang et al. (1998) and Zhai et al. (1996) also proposed that in the course of mineralization dominated by magmatic fluids in the Yanshanian epoch syndepositional sulfides were involved in the metallogenic system. Some researchers found that at the bottom of the Xinqiao stratiform orebody melnikovite ore was traversed by late-stage pyrite veins (Xu et al., 2001). However, this type of ore is scarcely seen. The discovery of early sedimentary melnikovite reveals that sedimentary sulfide can be formed in the course of diagenesis. However, it is almost impossible to form relatively large-scale and industrial-grade orebodies.

The Xinqiao deposit is characterized by a S-Fe-Cu-Au assemblage, whereas a typical sedimentary exhalative (SEDEX) deposit is characterized by a Pb-Zn-Ag assemblage (Goodfellow et al., 1993; Cooke et al., 2000). The SEDEX deposits, whose host rocks are generally sedimentary rocks, are enriched in Pb and Zn, but poor in Cu. They are associated with Ag and Ba and have almost no Au (Han et al., 1999). Compared to the typical SEDEX deposit, the Xinqiao deposit is enriched in S, poor in Pb-Zn, and uneven in Cu mineralization. Its reserves is $1.75\times10^5$t, but the metal reserves of lead and zinc is only $4.09\times10^5$t. Banded structure of a SEDEX deposit is rarely seen in the Xinqiao deposit, and sedimentary structures of SEDEX deposits, such as graded bedding and rhythmic bedding, are not present in the Xinqiao deposit, either. A typical SEDEX deposit has a common "binary"-structural pattern, i.e. ore
layers in the upper while ore lodes in the lower. The joints of different orientations in the Wutong Formation sandstone at the bottom of the stratiform sulfide were filled up with pyrite stringers (Plate I), whose distribution pattern is dense → sparse → sporadic → wedging out from the orebody outwards within a 10 m zone around the footwall. Mineralization or strong alteration is not found outside this 10 m zone. It is observed that the sandstone of the Wutong Formation was hydrothermally metamorphosed to quartzite, which is not the feature of the fluid pathway of a typical SEDEX. A SEDEX deposit looks like a sedimentary deposit, accompanied by intense alteration, but alteration is not well developed in the Xinqiao deposit. Specifically, alteration minerals of typical SEDEX, such as tourmaline, biotite, albite and muscovite, are not present in the Xinqiao deposit. Studies of modern oceanic deposits have showed that all submarine sedimentation-exhalation mineralizations are related to underlying magmatic activity. However, there is no Hercynian intrusion in this area, even in the whole middle and lower Yangtze River reaches.

**Metallogenic epoch** In light of recent Re-Os age dating of some copper and gold deposits in the Tongling ore cluster area, Mao et al. (2004) proposed that both stratiform and porphyry-skarn orebodies were formed between 134.7±2.2 Ma and 143.7±1.6 Ma. They hold that both types of orebodies are products of a metallogenic system related to granitic rocks of the Yanshanian age. By comparing a number of ore deposits in North America including the Bingham superlarge copper deposit with those of the middle and lower reaches of the Yangtze River, Pan and Dong (1999) reached a similar conclusion for the genesis of the Chinese porphyry-skarn-type stratiform orebodies. The age (with the amphibole Ar-Ar method) of the Jitou intrusion related to the mineralization of the Xinqiao orefield is 137 Ma (Zhou et al., 2000), which is consistent with the metallogenic epoch. This shows that the Xinqiao deposit, which lies in the same ore cluster and metallogenic
setting, is also a product of the Yanshanian magmatism.

**Metallogenic model** The Xinqiao deposit is thought to have experienced two main periods of mineralization, i.e., the earlier sedimentary mineralization and the later mineralization related to magmatic activity. Regionally, a 1.0 m-thick sandstone layer is developed at the bottom of the Qixia Formation, which indicates that from the terminal Carboniferous to the early Permian, slow subsidence of the crust resulted in the deposition of clastic rock, followed by marine transgression and deposition of limestone of the Qixia Formation. In the basin area, soluble colloidal substance of metals (mainly Fe) originating from the ancient land were accumulated and an ore-grade siderite bed was precipitated through biological-chemical processes.

In the early stage of the late Carboniferous-Early Permian period, the lower and middle reaches of the Yangtze River had a shallow-sea tidal-flat reduction environment. In some depression segments only a few pyritiferous layers are associated with carbonate rocks. They have low grade and poor industrial significance. Regional NS-trending Indosinian compression brought about several intrastratal detachment planes, so that the syndepositional sulfide and siderite layers were disrupted and brecciated. However, such sliding planes supplied space for the later magmatic orebodies.

In the Yanshanian, due to rapid thinning of lithosphere, the interaction between the crust and mantle and related large-scale mineralization took place in the lower Yangtze area (Deng et al. 1999, 2001). Granitic magma related to mineralization mainly originated from partial melting of the lower crust and upper mantle. The interaction between the crust and mantle was quite intense, as demonstrated by a large number of pyroclastic enclaves and amphibole megacrysts in intrusions (Qin et al., 2002). The intrusions and their magmas related to mineralization were along the junction between WE-trending and NNE-trending faults. Intermediate-acid melts were also along interlayer detachment surfaces, leading to migration and precipitation of hydrothermal ore-forming solutions. Early sedimentary sulfide was interacted with the metallogenic system, and formed a series of massive sulfide orebodies largely related to magmas.

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**References**


**Explanation of Plate I**

1. Miaringitic structure of stratiform orebody
2. Network structure
3. Relationship between sulfide orebodies
4. Sulfide orebody filled in bedding fault
5. Sulfide orebody filled in fault in skarn
6. Network pyrite in soleplate of orebody