Session 10
Mesozoic to recent geodynamics and metallogeny of eastern Asia
Abstract. The Erdenet porphyry copper-molybdenum deposit in central Mongolia is hosted in the Selenge Intrusive Complex and is genetically related to the Late Triassic and Early Jurassic volcanic units in the complex. The deposit is part of a porphyry association that consists of two main stages: granodiorite porphyry and dacite; and granite porphyry and leucogranite. The main chalcopyrite and molybdenite mineralization is associated with both of the main stages of this association. Three main types of alteration occur: sericitic (quartz-sericite) and late siliceous, intermediate argillic (chlorite-sericite), and propylitic (chlorite and epidote-chlorite). These three alteration types occur in zones in the Erdenet deposit. Geochemical and supporting petrographic data show that leaching of Na and deposition of SiO₂ occurred during quartz-sericite alteration. The distribution of trace elements reflects relative mobility during alteration, with HFSE (Zr and Ti) being the most immobile and the lithophile and chalcophile elements being the most mobile.

Keywords. Cu-Mo porphyry deposit, alteration, geochemistry, Mongolia

1 Introduction

The largest deposit in Mongolia is the Erdenet porphyry copper-molybdenum deposit. The annual production from the deposit which has been exploited since 1978, is 20 million metric tons of copper and 3,500 metric tons of molybdenum. The geology and mineralization of the deposit have been studied by Khasin et al. (1977), Koval et al. (1985), Sotnikov et al. (1984, 1995), Sotnikov and Berzina (1989), Koval and Gerel (1986), Gavrilova and Maksimyuk (1990), and others. However, the magmatic history of the deposit remains controversial (Gerel and Munkhtsengel, in print).

The Erdenet deposit occurs in the Orkhon-Selenge trough that is filled by Permian volcanic rock that is intruded by the Permian and Early Triassic Selenge Intrusive Complex. The trough is overlain by Late Triassic and Early Jurassic volcanic rock and is a part of the extensive Mongol-Okhotsk belt that stretches over 3,000 km from central Mongolia to the Pacific Ocean.

Geochemistry of granitoids and altered rocks of the Erdenet porphyry copper-molybdenum deposit, central Mongolia

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Copper-molybdenum mineralization is associated with a granodiorite porphyry stock that intruded the late Paleozoic Selenge Intrusive Complex. The granodiorite porphyry is part of a porphyry association (Koval et al. 1984; Gerel 1990) that forms shallow bodies ranging from quartz diorite porphyry and granodiorite porphyry to granite and leucogranite porphyry. This porphyry association is genetically related to an early Mesozoic volcanic rock sequence containing basalt and basaltic andesite (Koval and Gerel 1986).

This study contributes and interprets mineralogical and geochemical data on the Erdenet open pit mine in order to better understand the relation between the porphyries and hydrothermal alteration that is genetically linked to copper-molybdenum mineralization.

2 Geology

The host for mineralization is the Erdenet pluton which consists of an early-phase gabbro, diorite and the main-phase granodiorite that has an isotopic age of 226-245 Ma. The granodiorite is coarse- to medium-grained and slightly porphyritic, and contains plagioclase, quartz, K-feldspar, and biotite, and accessory magnetite, apatite, and zircon. The copper-molybdenum mineralization is associated with the porphyry. Gavrilova and Maksimyuk (1990) recognized five stages in the porphyry. Based on mapping and detailed observation, we distinguish early and late stage porphyries, consisting of granodiorite, dacite, and granite. The granodiorite porphyry forms the main mass of the mineralized, early-stage intrusive stock, along with associated apophyses, satellites, and dikes (Fig. 1). The granodiorite porphyry contains phenocrysts of plagioclase with a composition of An₃₇₋₃₅ and up to 4.4 by 2.5 mm in size, quartz up to 2.7 by 0.17 mm, chloritized biotite, hornblende up to 2.4 by 0.17 mm, and very rare K-feldspar. The phenocrysts occur in a holocrystalline groundmass composed of plagioclase laths up to 0.2 by 0.06 mm in size, K-feldspar, quartz, amphibole, and bi-
otite, accessoryapatite, magnetite, and secondarychlorite, sericite, leucoxene, pyrite, limonite, and carbonate. Plagioclase occurs as twinned subhedral clusters. Quartzsericite and quartz alterations assemblages sometimes obscure primary texture that can still be clearly recognized. Locally, plagioclase-phyric and dacite with plagioclase and minor hornblende phenocrysts occur in a cryptocrystalline groundmass. The granite porphyries contain plagioclase, hornblende, and rounded quartz phenocrysts. Plagioclase is the dominant mineral.

The late stages porphyries form a group of biotite and plagioclase-phyric granodiorites, granite porphyries, and leucogranite porphyries, along with rare rhyolite and minor subvolcanic andesite. Propylitic chlorite-epidote alteration is associated with some of late stage porphyries.

Post-ore dikes (with an isotopic age of 185 Ma) are very common and cut all porphyries and host granodiorites. The dikes consist of basalt, andesite, and subvolcanic rock and trend north-south (Fig. 1).

A structural study shows that syn-ore veins and fractures are irregularly distributed with a dominant vertical orientation. Post-ore fractures are filled by widespread veinlets and dikes of intermediate and mafic rock and carbonate. Post-ore faults are both normal and shear types and trend northeast-southwest. Clay minerals occur along these faults.

3 Alteration and mineralization

This study investigates the altered zones, utilizing thinsection and whole-rock chemical analyses of altered and unaltered granite and granodiorite porphyries. Three principal alteration zonations occur in the Erdenet deposit (Kominek et al., 1977, Khasin et al., 1977). From the core to the periphery, the alterations are: sericitic (quartz-sericite) and late siliceous; intermediate argillic (chlorite-sericite); and propylitic (chlorite and epidote-chlorite). K-feldsparization has occurred but is minor and consists of a K-feldspar-biotite-magnetite assemblage.

The quartz-sericite alteration is pervasive and commonly consists of replacement of feldspar by white mica with minimal dissolution of quartz. Feldspar hydrolysis and alkali metasomatism caused sericitization. Siliceous alteration, along with residual and secondary quartz, is interpreted as the result of changes in the acidity and salinity of hydrothermal fluid and is possibly the result of boiling. Hydrothermal muscovite is produced by hydrogen metasomatism, causing the release of alkali and silica. ASD analysis reveals the occurrence of smectite, kaolinite, and illite in quartz-sericite altered rocks.

Khasin et al (1977) distinguished six stages of alteration and mineralization: (1) pre-ore quartz-sericite; (2) quartz-pyrite; (3) quartz-pyrite-molybdenite; (4) quartz-pyrite-chalcopyrite; (5) quartz-pyrite-galena-sphalerite; and (6) post-ore gypsum-calcite with pyrite. Hypogene mineralization contains bornite, chalcocite, and covellite, whereas oxidation produced Cu carbonate, oxide, phosphate, and sulfate minerals, and native Cu and ferromolybdenite. Mineralization and alteration age is determined by a Re-Os molybdenite isotopic age of 240.7+/-0.8 Ma (Watanabe and Stein 2000), and a 40Ar/39Ar sericite isotopic age of 207 Ma (Lamb and Cox 1999).
The early Mesozoic volcanic host rock consists of a high alumina K-Na and basalt-andesite series (Koval and Gerel 1986). The porphyry association consists of a calc-alkaline, medium K granitoids, I-type, and magnetite series. Fresh granite has intermediate SiO$_2$ and K$_2$O (Fig. 2).

Granite and granodiorite from the open pit mine exhibit a fractionation of LREE relative to HREE and a low negative Eu anomaly, and constitute a characteristic I-type granite. The granites and granodiorite in the open pit mine are depleted in Nb, Sr, Eu, U, and light REE. During alteration, Na was removed and Si was added. Light REE was also removed with relative enrichment of HREE (Fig. 3).

### Figure 2: Chemical composition of fresh (a-top) and altered (b-bottom) granodiorites, granites and porphyries in the Erdenet open pit mine (Gerel and Munkhtsengel, in press)

### 4 Geochemistry

The early Mesozoic volcanic host rock consists of a high alumina K-Na and basalt-andesite series (Koval and Gerel 1986). The porphyry association consists of a calc-alkaline, medium K granitoids, I-type, and magnetite series. Fresh granite has intermediate SiO$_2$ and K$_2$O (Fig. 2).

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### 5 Conclusions

The ore-bearing porphyries are genetically associated with early Mesozoic volcanic rock and consist of shallow bodies and dikes. They consist of a medium-high potassium calc-alkaline, I-type, and magnetite series. They are depleted in Nb, Ti, and P, and formed in an active continental margin environment.

A quartz-sericite alteration dominates the ore field and open pit mine. Besides quartz and sericite, the altered rocks contain smectite, illite, and hydrogibbsite, and rare kaolinite. This alteration was succeeded by K enrichment. The altered granites and porphyries are related to high potassium rocks. During alteration Na, light REE were removed and Mo was added.

There are three main stages of alteration: quartz-sericite with siliceous; intermediate argillic (chlorite-sericite); and propylitic (chlorite and epidote-chlorite). An early stage, potassic alteration is very limited and consists of K-feldspar and biotite and contains ore minerals of disseminated and veinlet-style pyrite. Quartz-molybdenite and quartz-chalcopyrite veins are related to the main stages.

The altered rocks in the ore field consist mainly of quartz-sericite metasomatite that also contains smectite, illite, and hydrogibbsite, and rare kaolinite. The altered rocks form a high potassium series in which also Na was removed. Khasin et al (1977) distinguished six stages of alteration and mineralization: (1) pre-ore quartz-sericite; (2) quartz-pyrite; (3) quartz-pyrite-molybdenite; (4) quartz-pyrite-chalcopyrite; (5) quartz-pyrite-galena-sphalerite; and (6) post-ore gypsum-calcite with pyrite. Hypogene mineralization contains bornite, chalcocite, and covellite, whereas oxidation produced Cu carbonate, oxide, phosphate, and sulfate minerals, along with native Cu and ferromolybdenite.
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Gold content and distribution in hydrothermal alteration zones of the Haenam area, southwestern Korea

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Abstract. Hydrothermal alteration zones are extensively developed within the Haenam area of southwestern Korea. The geology of the area consists of granitic rocks, quartz porphyry, andesite, rhyolite, tuff and sedimentary rocks. The rhyolites and tuffs around the clay mines are variably and locally intensely hydrothermally altered. Gold contents range from less than 2 ppb to 5930 ppb in the minerals and rocks. Gold is enriched in alunite and altered rhyolite and tuff, and in particular, gold is enriched around fractures developed in silicified alteration zones. Variation trends of gold are similar to silver and arsenic. Gold might be transported and concentrated by acid sulfate solutions along fractures and faults. Silver and arsenic are considered to be useful pathfinders to explore for gold deposits in the study area.

Keywords. Hydrothermal alteration, gold contents, acid-sulfate, pathfinder elements, Korea

1 Introduction

Many workers have studied gold mineralization associated with acid alteration and acid leached residual silica in volcanic rocks distributed in the Circum-Pacific belt (Hayba et al. 1985; Heald et al. 1987; Hedenquist 1987; Izawa 1990; Rytuba and Miller 1990; White 1990). The included deposits are variably termed Carlin-type, Nansatsu type, acid-sulfate type or high sulfidation (Heald et al. 1987), adularia-sericite type or low sulfidation (Heddenquist 1987) and alunite-kaolinite-pyrophyllite and adularia-sericite (illite) types (Berger and Henley 1989). Most deposits were formed in Tertiary.

Most Korean gold production was derived from metamorphic or igneous rock-hosted gold bearing quartz veins of Jurassic or Cretaceous ages. Kim et al. (1990) reported that the Ogmaesan deposit that formed in the Cretaceous formed from acid sulfate solutions, based on the occurrence and assemblages of minerals, and results of geochemical study. Although it was known that hydrothermal alteration zones were extensively covered, a number of hydrothermally altered clay deposits were historically developed in this area. Research on gold geochemistry has been published since the 1990s (Kim et al. 2002; Yoon 1993, 1995; Yoon and Chang 2003; Yoon and Kim 2004). Recently, an exploration company has discovered a gold deposit in this area and it is currently being exploited. The purpose of this study is to make basic data available for the application of geochemical exploration of gold deposit in areas of hydrothermal.

2 Summary of geology and alteration

In the southern part of the Korean Peninsula, four distinct geological provinces are recognized from northwest to southeast such as Gyeonggi massif, Ogcheon belt, Ryeongnam massif and the Gyeongsang basin. The Gyeonggi and Ryeongnam massifs are developed in NE to SW directions, and composed mainly of Precambrian schist, gneiss and gneissose granite. The Ogcheon belt is located between Gyeonggi and Ryeongnam massifs, and is composed of Precambrian to Paleozoic sedimentary rocks. The Gyeongsang basin is located in the southeastern part of the Peninsula, and underlain by thick accumulations of Cretaceous sedimentary rocks.

The Youngdong-Gwangju depression zone is located between the Ogcheon belt and the Ryeongnam massif in the southwestern part of the Peninsula as shown Figure 1. The geology of the Youngdong-Gwangju depression zone consists of Precambrian metamorphic rocks intruded by Jurassic and Cretaceous granitic rocks, and Cretaceous volcanic and sedimentary rocks. The study area is in the southwestern-most part of Youngdong-Gwangju depression zone (Fig. 1).

The geology of the study area consists of Precambrian metamorphic rocks, Jurassic granite and Cretaceous granitic and volcanic rocks. The metamorphic rocks are composed mainly of biotite gneiss and mica schist, which are intruded by Jurassic and Cretaceous granitic rocks, and are unconformably overlain by Cretaceous volcanic rocks. Jurassic granitic rocks are unconformably covered by Cretaceous volcanic rocks, and are intruded by Cretaceous granitic rocks. They are composed of hornblende, biotite and two-mica granites. The Cretaceous granitic rocks are divided several plutonic suites named after their local place names. Volcanic rocks are widely distributed, but have extensive hydrothermal alteration, and produced many clay deposits.

In the clay mines of this study area, the Seongsan, Ogmae, Gusi and Haenam mines are targets of the present study. They can be classified into two types; pyrophyllite and kaolin types (Kim 1992). Pyrophyllite types include the Gusi and Haenam mines, and kaolin types include Seongsan and Ogmaesan. The most important minerals are alunite and kaolinite in the kaolin type mines, while they are absent or rare in the pyrophyllite type mines.
Alunites formed by acid solutions occur predominantly as veins or irregular types at the Seongsan and the Ogmaesan deposits. The host rocks are acidic tuffs and rhyolites, which are hydrothermally altered by acidic solution related to volcanism (Moon et al. 1990; Koh and Chang 1997). Advanced argillic alteration zones, sericite alteration zones and propylitic alteration zones are developed from upper to lower, or center to marginal parts in the Seongsan and Ogmaesan deposits. Silicification zones are developed in the central and marginal parts of the mines, and vuggy silica is developed in the silicification zone and advanced argillic alteration zones. The alteration boundaries are gradational. On the other hand, the alteration types in the Haenam and Gusi deposits are different from those in the Seongsan and the Ogmaesan deposits. The characteristic alteration zones can be classified as illite zone-kaolinite zone-pyrophyllite zone, and quartz zone-pyrophyllite zone-kaolinite zone from upper to lower part, respectively.

3 Sampling and experimental

About 150 rock and mineral samples were sampled in the alteration zones. For this study, 138 mineral and rock samples were analyzed. The samples were crushed and ground by disc-mill made of tungsten-carbide, and powdered to under 200 mesh. Trace elements including gold and rare earth elements (REE) were analyzed by inductively-coupled plasma source mass spectrometer (ICP-MS) and neutron activation analysis (NA) at ACTLABS, Canada. Analytical error for most elements is less than 2%.

4 Results and discussion

The result of the geochemical analysis of the samples by ICP-MS and NA are shown in Table 1. Detection limits of Au were 2 ppb. Au contents of the samples from the Seongsan and the Ogmaesan deposits ranged from less than detection limit to 5930 ppb with an average of 129 ppb. Those from the Gusi deposits ranged from the less than detection limit to 59 ppb with an average of 5.1 ppb, and those from the Haenam deposit are not shown (Table 1). In particular, Au contents tend to show high values in the areas where advanced argillic alteration is developed, however, they are low or not shown in the areas without well-developed advanced argillic alteration (for example in the Gusi and Haenam mines). Gold contents are higher in the alunites than in the pyrophyllites. Gold contents of the quartz-alunite-pyrite veins (Yoon 1995) from the Seongsan mine were also higher than those of quartz veins from in the Ogmaesan mine area. Gold concentrations in the altered rocks are much higher than those in the fresh rocks which are less than 4 ppb. Gold concentrations are the highest in the altered tuffs which have fine cracks which are filled by fine pyrites or Mn-Fe oxides. A gold-silver mine is currently being exploited near the site showing the highest Au concentrations. It indicates that the fractures are responsible for transporting the auriferous hydrothermal solutions. The hydrothermal solution might be an acid-sulfate solution that mixed with magmatic fluids and meteoric waters at the shallow depths, which was enriched in Au HS, based on the occurrence of minerals and results of geochemical analysis (Gammons and Williams-Jones 1997). Gold distribution patterns are similar to Ag and As patterns. Thus, Ag and As contents are considered to be useful elements to explore gold deposits in this area of the Seongsan and the Ogmaesan.

5 Summary

Au contents are high in the advanced argillic alteration zone and altered rhyolite and tuff. In particular, they are the highest concentrated (5930 ppb Au) near faults and fractures filled by fine-grained pyrite and Mn-Fe oxides, although there are many samples with less than 2 ppb Au. However, Au contents are very low in the fresh volcanic and plutonic rocks distributed in the study areas (less than 4 ppb Au). Silver and As elements are considered to be useful elements to explore for gold deposits in the study area based on the similar distribution patterns with gold.

Acknowledgements

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Table 1: Range and average of major and trace elements from the studied area.

<table>
<thead>
<tr>
<th>Element</th>
<th>Gusi mine area (30)</th>
<th>Haenam mine area ($)</th>
<th>Seongsan and Ogmae mine area (70)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (ppb)</td>
<td>nd - 59</td>
<td>5.1</td>
<td>nd - nd</td>
</tr>
<tr>
<td>Ag (ppm)</td>
<td>nd - 0.4</td>
<td>0.0</td>
<td>nd - nd</td>
</tr>
<tr>
<td>As (ppm)</td>
<td>nd - 30</td>
<td>6.9</td>
<td>nd - 1.9</td>
</tr>
<tr>
<td>Ba (ppm)</td>
<td>nd - 6600</td>
<td>1187.7</td>
<td>nd - 1200</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>1.2 - 31.1</td>
<td>6.0</td>
<td>2.0 - 17</td>
</tr>
<tr>
<td>Mn (ppm)</td>
<td>2.8 - 1668.2</td>
<td>205.1</td>
<td>17.8 - 1140.5</td>
</tr>
<tr>
<td>Mo (ppm)</td>
<td>nd - 10</td>
<td>3.5</td>
<td>nd - 3</td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>nd - 161.9</td>
<td>28.3</td>
<td>3.5 - 59.8</td>
</tr>
<tr>
<td>Rb (ppm)</td>
<td>nd - 184</td>
<td>46.2</td>
<td>90.0 - 160</td>
</tr>
<tr>
<td>Sb (ppm)</td>
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<td>1.5</td>
<td>nd - 0.2</td>
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<tr>
<td>Sr (ppm)</td>
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<td>285.7</td>
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<tr>
<td>Y (ppm)</td>
<td>1.1 - 44.6</td>
<td>13.5</td>
<td>7.0 - 16.4</td>
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<tr>
<td>Zn (ppm)</td>
<td>6.0 - 225.9</td>
<td>42.0</td>
<td>0.3 - 88.1</td>
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<td>Al (%)</td>
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<td>6.7</td>
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<tr>
<td>Ca (%)</td>
<td>nd - 0.9</td>
<td>0.1</td>
<td>nd - 0.4</td>
</tr>
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<td>Fe (%)</td>
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<td>1.8</td>
<td>0.1 - 1.6</td>
</tr>
<tr>
<td>K (%)</td>
<td>nd - 3.9</td>
<td>1.2</td>
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<tr>
<td>Mg (%)</td>
<td>nd - 2.5</td>
<td>0.3</td>
<td>nd - 0.3</td>
</tr>
<tr>
<td>Na (%)</td>
<td>nd - 2.8</td>
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<td>0.1 - 2.8</td>
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<tr>
<td>P (%)</td>
<td>nd - 0.1</td>
<td>nd</td>
<td>nd - nd</td>
</tr>
<tr>
<td>S (%)</td>
<td>nd - 0.1</td>
<td>nd</td>
<td>nd - 0.2</td>
</tr>
<tr>
<td>Ti (%)</td>
<td>0.1 - 0.6</td>
<td>0.2</td>
<td>nd - 0.2</td>
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Geochronology of ore-forming fluids and the enrichment of copper-gold in the Shizishan ore-field, Tongling, Anhui Province, China

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Abstract. The Shizishan copper (gold) ore-field is the largest in the Tongling ore district. The field is characterized by complex metallogenetic processes as indicated by its dominantly skarn-type and stratabound skarn-type deposits. These deposits are rich in fluid inclusions with homogenization temperatures that range from 140 to 570°C and salinities that range from 1.07 to 60.72 wt% NaCl equiv. The ore-forming fluids were magma-derived and behaved in a supercritical state in the early stage, and experienced an evolution from high-temperature and high-salinity to moderate-temperature and low-moderate-salinity. There was an addition of meteoric water during the fluid evolution. Temperature decrease, and decompression and boiling of the fluids were the main factors that led to the large enrichments of copper and gold.

Keywords. Ore-forming fluid, fluid inclusions, geochemistry, copper, Shizishan, Tongling

1 Introduction

The Shizishan Cu (Au) ore-field, is among the largest within the Tongling mineral district in the middle-lower Yangtze River metallogenic belt. This ore-field has a complex metallogenic history and contains numerous ore deposit styles. Considerable exploration and various research projects on the geology, mineral resources and metallogeny have been carried out with a goal towards understanding ore genesis, the development of a mineralization model, such as that for stratabound skarn-type deposits (Chang et al. 1983), and a multilayer ore-forming model (Huang et al. 1993). Several geologists have studied the features of the ore-forming fluids from single ore deposits, but if we consider ore-field as a whole, a study on the evolution of ore-forming fluids is possible. Based on studies of the geochemistry of the fluid inclusions, this paper reveals the composition, source and evolution of the ore fluids that resulted in accumulation of copper and gold, and provides valuable information for the interpretations of ore-forming mechanisms.

2 Metallogeny and geological setting

The region is located near the northern margin of Yangtze Plate with the North China Plate. The strata in this region, whose lithologies include carbonate and clastic strata, mainly consists of rocks of late Paleozoic and Triassic ages. Sedimentary beds containing primary ore sources were formed in the late Carboniferous (Liu et al. 1984), and these provided the ground preparation for the stratabound skarn-type deposits. The intense late Jurassic to early Cretaceous magmatic products that were enriched in potassium and alkalis (such as quartz monzodiorite and granodiorite) were key factors in ore formation. The main basal structures are deeply-buried faults striking easterly and northerly, among which the fault zone from Tongling to Shatanjiao is considered to be the most important. The shallow structures, Indosinian folds striking north-east and forming in an “S” shape, controlled the occurrence of magmatic bodies and associated ore deposits.

The skarn-type and the stratabound skarn-type deposits are the most important ore types in the ore-field. The mineralization process includes the skarn stage, quartz-sulfide stage and carbonate-quartz-sulfide stage, of which the quartz-sulfide stage is the main ore-formation stage.

3 Fluid inclusion petrography and microthermometry

The studied samples include ore-bearing quartz veins, ore-bearing garnet-endoskarn and quartz-bearing or calcite-bearing primary ores. They were formed during different parts of the ore-forming stage. Vein quartz, lumpy quartz and medium-coarse calcite have trapped abundant fluid inclusions, with rare inclusions also occurring in garnet. Fluid inclusions were classified into three main types based on their proportions of phases at room temperature: gas-rich, liquid-rich and daughter-bearing multiphase inclusions. Liquid-rich inclusions account for 50 to 80 % of all inclusions. Daughter minerals are dominated by halite and include minor sylvite and rare unidentified transparent minerals. Melt temperatures of unidentified transparent minerals are usually high (>320°C), some daughter minerals can not be melted even at 530°C. They are difficult to distinguish from sylvite but are probably “trapped minerals” (i.e. granules of wall rock or sedimentary new crystals, Li et al. 1988) trapped together with fluid.
Homogenization temperatures of all inclusions mostly concentrate from 140 to >570°C, with salinities ranging from 1.07 to 60.72 wt% NaCl equiv. Inclusions in garnet do not homogenize even at 570°C, and salinities for some multi-phase inclusions range from 44.32 to 54.51 wt% NaCl equiv. The homogenization temperatures of inclusions in diopside are mostly between 450 and 550°C, and a few gas-rich inclusions in garnet in the Dongshizishan deposit reach between 670 and 750°C; Li (1988) also measured the homogenization temperatures of the inclusions in garnet from the Lamo deposit (Guangxi province), which are > 630°C. The results indicated that ore fluids existed in a supercritical state in the early ore-forming stage. The results of thermometry of inclusions in quartz show that the homogenization temperature of gas-rich inclusions are between 274 and 470°C (avg. 351.6 to 417.5°C), and the salinities are between 18.04 and 18.55 wt% NaCl equiv; the homogenization temperatures of liquid-rich inclusions are between 191 and 487°C (avg. 292.3 to 360.9°C), and the salinities are between 6.88 and 23.18 (avg 12.63 to 18.27) wt% NaCl equiv; the homogenization temperatures of daughter-bearing multiphase inclusions is from 192 to 545°C (avg. 236 to 348.3°C), and the salinities range from 30.27 to 60.72 (avg. 32.13 to 51.03) wt% NaCl equiv. The homogenization temperature of gas-rich inclusions in medium-coarse calcite is from 280 to 285°C (avg. 282.7°C); liquid-rich inclusions is from 131 to 366°C (avg 196.1°C), and the salinities range from 1.07 to 23.11 (avg. 15.20) wt% NaCl equiv; daughter-bearing multiphase inclusions are from 128 to 191°C, and the salinities are from 31.87 to 34.56 wt% NaCl equiv.

Temperatures of homogenization and salinities of the same type of inclusions gradually decrease in the order of garnet, to quartz, and to medium-coarse calcite, indicating that from the early to late stages the ore fluids experienced an evolution from high temperature and high salinity to moderate-temperature and low-moderate-salinity, which corresponds with the mineralization stages. Therefore, the decrease of temperature is a main factor controlling ore precipitation. Three kinds of common inclusions in quartz frequently coexist and their similar homogenization temperatures indicate that boiling may have been taken place (Roedder 1984; Shepherd et al. 1985). Boiling also possibly brought heterogeneity to the fluids and trapped minerals. Usually, boiling in fluids occurs in the main mineralization stage, which is in agreement with the characteristics of the ore fluids of Chinese skarn-type deposits (Zhao et al. 1990). The boiling of fluids does not occur in the skarn stage, showing that the system is at a relatively closed state and the pressure of fluids is relatively high. The ore-forming fluids in the Dongshizishan deposit has apparently boiled four times (Xiao et al. 2002), which relates to special structural conditions. The daughter minerals are mainly halite, less syltive and so on, such that it is nearly a pure NaCl-H2O system. The ore-forming fluids mainly fall into unsaturated NaCl-type according to the correlations between homogeni-zation temperatures and salinity. Evidently, the quartz contains two kinds of inclusions: high-salinity (>30 wt% NaCl equiv) and low-moderate-salinity (=23.18 wt% NaCl equiv), whose characteristics are consistent with that of porphyry copper deposits (Nash 1976).

4 Fluid composition, source and evolution

The fluid inclusion gases mainly consist of H2O, CO2 and N2, with minor amounts of CH4, He, Ar, O2, C2H6, and H2S etc.. Average values for H2S content in the inclusions are 0.071 mol% in garnet -magnetite pairs, 0.124 mol% in quartz and 0.002 mol% in medium-coarse calcites, respectively, CO2 content is 16.705, 3.125, 5.5004 mol% in these host-minerals, respectively; ratios of CO2/H2O are 0.247, 0.033 and 0.059, respectively.

 Ionic elements detected are mainly Na+, K+,Ca2+, SO42- and Cl-, with minor amount of Mg2+, and F- occurs in a few samples. The Ca2+ contents of inclusions are larger than Mg2+. The inclusions average values for K+ content in garnet, quartz and medium-coarse calcites are 4.00, 2.28 and 1.17 ppm, respectively. The inclusions’ K+/Na+ ratios for garnet are generally > 1, and mostly for quartz and calcite < 1.

The δ18O_H2O values range from 0.38 to 10.7 per mil (avg. 5.49‰) in quartz, and 8.74 to 9.64 per mil (avg. 9.24‰) in garnet. The δD values range from -94.3 to -58.64 per mil (avg. -71.50‰) in quartz, -95.77 to -75.82 per mil (avg. -85.25‰) in garnet. The range of the δ18O_H2O values of garnet is narrow, but the average value is larger than quartz; as well as the narrow range of the δD values of garnet, and its average value is similarly lower than quartz. This suggests that the δ18O_H2O values of ore-forming fluids decreased, and that the δD values increased gradually along with the ore-forming progression. Oxygen and hydrogen isotope compositions of water in equilibrium with garnet fall into the range of primary magmatic water or nearby; those of water in equilibrium with quartz samples fall mostly in the range of magmatic water, and some fall into the range between magmatic water and meteoric water line or the range of contemporary surface water.

Carbon isotope analyses were performed on samples of hydrothermal calcite. Combining the former data, most δ13C values of hydrothermal calcite are clustered between -6.9 and -4.3 per mil which differ from those (0.1 to 5‰) of local marble, limestone and dolostone. These indicate that carbon in the ore fluids has approximately identical sources, apparently it is impossible to come from the stratum directly. Compared with δ13C values (-5‰ ± 2‰; Ohmoto 1979) for magmatic carbon from the partial melting of pyrolite, hydrothermal calcite can be interpreted as having a magmatic origin.
Carbon and oxygen isotope compositions of calcite from some ores are concentrated in a narrow range near granitoid compositions, implying that ore-forming fluids are not from single source, as both magmatic water (as main source) and some meteoric water could be included. Although the carbon in sedimentary carbonates was involved in the formation of hydrothermal carbonate minerals, it offered little CO₂ for the ore-forming fluids. This was mainly related to two factors: (1) possibly being combined with SiO₂ from magmatic fluid, Ca and Mg of sedimentary carbonates mainly formed skarn minerals during the replacement, and carbon rarely entering new carbonate minerals mostly escaping with CO₂; (2) carbon from sedimentary carbonates might form hydrothermal carbonate minerals but were not identified using carbon isotopes due to various alterations (Zhang et al. 2003).

In the late Jurassic and early Cretaceous, large-scale intermediate-acid magma intruded and provided abundant fluids which are the most important carrier for Cu-Au in the intrusive rocks, dated on biotite by 40Ar/39Ar method, the Shizishan ore-field while the regional tectonic setting fluids which are the most important carrier for Cu-Au in intermediate-acid magma intruded and provided abundant δ fluids changes from low, high to low, the CO₂ changes from high, low to high, CO₂/H₂O and K+/Na+ ratios and the K+ contents decreases. The Cl⁻ content reaches their peak in the early stage, the H₂S content in the ore fluids indicates that copper (gold) mainly migrated as chloride complex.

5 Conclusions

1. The fluid inclusions of the Shizishan ore-field yield homogenization temperatures that are concentrated from 140 to >570°C, and have salinities from 1.07 to 60.72 wt% NaCl equiv. The ore-forming fluid is mainly of an unsaturated NaCl-type, that experienced a continuous evolution from high temperature and high salinity to moderate-temperature and low-moderate-salinity which corresponds to the various mineralization stages. It is considered that the temperature decrease of the system is an important factor resulting in the precipitation of ore-forming material.

2. The ore-forming fluids are magma-derived fluids in the early stage, and possibly mixed with meteoric water during their evolution. The redox of the ore-forming fluids greatly changed during fluid evolution. Moreover, a great deal of metallic sulfides were deposited in a relatively reductive condition. High Cl⁻ contents in the ore fluids indicates that copper (gold) mainly migrated as chloride complexes.

3. The ore-forming fluids behaved in a supercritical state in the early stage, and subsequently underwent boiling which resulted in considerable copper (gold) deposition and enrichments from ore-forming fluids in the main ore-forming stage due to decompression.

References

Chapter 10-4

Distribution, metallogenic epochs and mineral resource potential of the North China Block

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Abstract. This paper discusses the present situation of mineral resources in the North China Block, dealing mainly with the distribution of the main types of mineral resources and metallogenic epochs of ferrous metals, non-ferrous metals, and noble metals, and non-metal resources. There is great potential for the discovery of additional mineral resources in North China Block. We analyze the existing problems of mineral endowments and suggest the next exploration prospects of mineral resources in North China Block.

Keywords. Distribution, ore classification, mineral deposits, metallogenic epoch, north China

1 Introduction

The North China Block (NCB) lies between two major tectonic domains of the marginal Pacific and Paleo-Asian, and has undergone a complex geologic-tectonic history. The NCB is a rare paleo-continental block, also called the North China craton. Unlike most cratonic blocks, the NCB has unique characteristics of a complicated multi-episodic history of tectonic reworking extending back to the Archean. Owing to its particular tectonic evolution, there are rich endowments of mineral resources, such as the large and super-large Haicheng, Dongshengmiao, Jiaoja, Caijiaying, Jinchuan, Tongkuangyu, Baiyunebo and Anshan deposits. There are more types of mineral resources and richer endowments than in other important metallogenetic areas of China, but there exist problems with shortages in resources and reserves in certain materials. There are plenty of REE resources, but there are shortages of some major metal mineral resources (e.g. iron, manganese, aluminum and copper). There also exist problems in that the region is rich with medium and small scale ore deposits but hosts few large and super large ore deposits. There also exist multiplicity, universality and dispersion of mineral resources in NCB. Discovery of future ore resources is dependent upon the geological, tectonic and metallogenetic history of NCB which must be better understood.

2 Ferrous metal resources

Ferrous metal resources of NCB contain five kinds of mineral resources: iron, manganese, chrome, vanadium and titanium. Iron resources are most abundant with the NCB representing the most important iron producing area in China hosting almost 60% of national reserves. More than 646 iron occurrences have been discovered. Most of the iron deposits are distributed in the area of Jinjiluyu and along the northern margin of the NCB. Most of the major iron deposits are concentrated in Liaoning, Hebei, Shanxi and Inner Mongolia. The main types of iron deposits are sedimentary-metasomatic and contact metasomatic. The main metallogenetic epochs were the early Precambrian and Mesozoic. Although it is difficult to find high-grade iron deposits in NCB, there are broad prospects for a next level of exploration with more limited grades.
NCB and the Taihangshan region. Furthermore it is necessary to recognise the possibility of discovering the copper mine in the peripheral and deeper parts within the existing large scale lead-zinc deposits.

**Lead deposits:** Currently there are three large scale lead deposits and ten medium scale lead deposits within a total of 121 discoveries. Lead deposits are mainly distributed in Inner Mongolia, Henan, Hebei and Liaoning provinces. Most of lead reserves are concentrated in Inner Mongolia and Liaoning Province. The main types of lead deposits are sedex and hydrothermal-type. The main metallogenic epochs are middle Proterozoic and Mesozoic. Lead mineralization is related to rifting and zones of Mesozoic tectonic and magmatic activity.

**Zinc deposits:** There are 9 large scale zinc deposits and 20 medium scale zinc deposits among the 118 discovered deposits. Zinc deposits are mainly in Inner Mongolia, Hebei, Henan, Liaoning, Jilin and Shandong provinces. The extant reserve is about 21% of the national total. The main types of zinc deposits are sedex and hydrothermal-type. The main large and medium scale zinc deposits occur in the Langshan - Zhaertaishan and, Yanshan - Taihangshan rifts, in Archean greenstone belts and along the northern margin of NCB. Currently the amount of the national lead-zinc resources output are balanced with consumption. Some zinc resources are exported. The consumption of lead and zinc resources will increase steadily until 2020, and these commodities will face a resource crisis. The areas with the most potential resources in NCB are the northern margin of NCB, the north Taihangshan, Liaodong, Jibei and Yuxinan areas. In recent years, there have been discoveries of large scale lead-zinc-silver deposits in the Yuxinan and Taihangshan areas.

**Bauxite deposits:** NCB hosts the most abundant of China's aluminum resources, with 155 discovered bauxite deposits, among them are 39 large scale deposits and 99 medium scale deposits. Bauxite deposits are mainly distributed in Shanxi and Henan provinces. The extant reserve of bauxite deposits is 61% among the total discovered reserves of China. Along with the rapid development of China's aluminum industry, the need for aluminum resources has also increased quickly. Exploration will mainly be emphasized on blind and deeper ores in the existing Jiaodong and Taihangshan regions. Furthermore it is necessary to recognize the possibility of discovering the copper mine in the peripheral and deeper parts within the existing large scale lead-zinc deposits.

**Molybdenum deposits:** Approximately 50 molybdenum deposits have been discovered, of which includes 3 super-large scale deposits and 7 large scale deposits. Molybdenum deposits are widespread in all of the provinces especially in Henan, Jilin, Hebei and Shandong. The extant reserve of molybdenum is 66% in th total discovered reserves of China. The main types of molybdenum deposits are porphyry type and contact metasomatic type which include all the large and super-large scale deposits such as the Nannihu, Yangjiazhangzi deposits. Molybdenum resources can guarantee China's consumption for twenty years.

### 4 Noble metal resources

The NCB is the most important area of noble metal resources in China. 652 noble metal deposits have been discovered, including 487 gold deposits, 153 silver deposits and 5 platinum deposits. There are 48 large scale deposits and 71 medium scale gold deposits, and 12 large scale and 13 medium scale silver deposits. The extant reserve of gold, silver is 36% and 21% in the total discovered reserves of China, respectively.

**Gold deposits:** Approximately 374 lode gold deposits have been discovered in the NCB. The main rock type hosting gold deposits are the inner and outer contact zones of plutons, with secondary greenstone belt types. The main metallogenic epoch was Mesozoic, secondarily in the Precambrian. Mesoproterozoic clastic rock- carbonate-hosted gold deposits have been discovered in the NCB in recent years, such as the Xiaodongjiapuzi and Zhulazhaga gold deposits. The main gold deposits are concentrated in Jiaodong, Jidong, Taihongshan, Zhangjiakou, Liaodong, Xiaozi, Chifeng and Wulashan areas. The area with greatest additional potential for increased gold resources are Jidong, Yuxi, Liaoqiong, Xiaozi, Jidong, Zhangxuan, Taihangshan, Daqingshan -Wulashan and Alashan areas. Recently, there have been prospecting breakthroughs for blind and deeper ores in the existing Jiaodong and Xianqingling gold deposits.

**Silver deposits:** 58 silver deposits have been discovered, including 6 large scale and 2 medium scale deposits in NCB. The main hosts of silver deposits are volcanic-cryptovolcanic rock type. The main metallogenic epoch was Mesozoic. The discovered reserves of silver resources are concentrated in Inner Mongolia, Hebei, Henan, Shanxi and Liaoning provinces, listed in decreasing order. The greatest potential lies in the Liaodong area, northern margin of NCB, Yuxi area and north Taihangshan. Recent discoveries of large scale lead-zinc-silver and silver deposits have been made in the Liaodong area, Yuxinan area and north Taihangshan.

### 5 Non-metal resources

There are widespread and abundant non-metal deposits in NCB which are characteristic of many varieties of considerable economic value. About 80 non-metal resources and 1567 non-metal deposits have been discovered, which include 26 super-large scale, 272 large scale and 595 medium scale deposits. Considerable non-metal resources rank highly to the advantage of China, such as magnesite, diamond, talc, boron, jade, rivaite, graphite, sulphur, phosphorus, gyps, pearlite, bentonite, cement limestone and glauber salt. Liaoning, Hebei, Shandong provinces and Tianjin City are the predominant producing areas of ocean salt producing areas in north China. The main type of non-metal deposits are the sedimentary type, including...
the partly sedimentary-metamorphic type, and the main metallogenic epoch was the Palaeozoic.

**Magnesite** deposits are in Liaoning and Shandong provinces. Liaoning province is the dominate magnesite producing area in China. The discovered reserve is more than 94% of the total reserve of China. Magnesite deposits occur in Palaeoproterozoic Desiqiao formation rocks of the Liaohe group. There are 7 large scale deposits with > 100 million tons of discovered reserves, the largest is the Huiziyu deposit with 783 million tons of reserve.

**Diamonds** are concentrated in Liaoning and Shandong provinces. The extant reserve is 97% of the total in China. The diamonds occurred in early Caledonian kimberlites near the Tanlu fault. The diamonds are dominated by colorless and transparent ones, and yield excellent industrial and gem grades. Residue and alluvial materials near the kimberlites contain diamond sands in which the 31.76 g Changlin diamond was found in 1977.

**Talc** deposits are concentrated in Liaoning and Shandong provinces and occur in dolomite and dolomitic marble of Palaeoproterozoic Dashiqiao formation of Liaohe and Fenzishan groups. The extant reserve is about 36% in the national total.

**Boron** deposits include the metamorphic type in the east Liaoning peninsula and the sedimentary type in the north Tianjin-Liaoning peninsula which is the dominate boron producing area in China. The boron output in the east Liaoning peninsula is more than 90% in the total amount of China. The main boron deposits occur in metamorphic volcanic rocks of Palaeoproterozoic Liaohe group. Typical deposits include the Houxiangyu boron deposit, Woguqiangou boron-iron deposit. The Jixian boron deposit in Tianjin occurs in manganeous-bearing marine shales.

**Graphite** deposits are distributed in Shandong, Henan, Shandong provinces and Inner Mongolia. The main type of graphite deposits are metamorphic and lesser contract metamorphic. The deposits mainly occur in the Neorchean Jining, Taihua, Wulashan groups and the Palaeoproterozoic Jingshan group, and consist of about 18% of China’s total.

**Gypsum** deposits can be classified into marine and continental sedimentary types. Marine sedimentary gypsum deposits are in Shansi, Hebei, Shandong and Henan provinces, and occur in the Fengfeng, Majiagou and Cixian formations. Continental sedimentary gypsum deposits are in Shandong, Hebei provinces and Inner Mongolia, and occur in Paleogene-Neogene gypsum-bearing clastic rocks. The Suji gypsum deposit in west Etuoke county of Inner Mongolia is the largest in China.

Natural **sulfur** ores are in Mesozoic and Neozoic depressions of Taian-Sishui in Shandong province. The discovered reserves make up 99% of total in China. The ore body occurs in the upper part of clastic rock-carbonate rock-evaporate formation. Natural sulfur deposits are dominated by cryptocrystal aggregation, and are accompanied by salt, gypsum and industrial oil.

The main types of **pyrite** deposits are stratabound and sedimentary and are often accompanied by multi-element enrichments. Stratabound pyrryite ores are generally distributed in Inner Mongolia, Liaoning and Hebei provinces. Sedimentary pyrite ores are concentrated in Shanxi province. Total NCB reserves are 24% of China's total.

**Phosphorus** deposits are dominated by magmatic types, with lesser metamorphic and sedimentary types. Magmatic phosphorus deposits are widespread in Shandong, Hebei and Liaoning provinces, and occur in Proterozoic and Variscan basic-ultrabasic rock and alkali rocks. Metamorphic phosphorus deposits are in Inner Mongolia and Liaoning province where phosphorus occurs in apatite. Sedimentary phosphorus deposits are mainly in Shanxi, Henan provinces and Inner Mongolia. NCB's phosphorous reserves are 14%.

Glauber **salt** forms in recent continental lakes in Inner Mongolia and Shanxi province. The Dalate glauber salt deposit in Inner Mengolia is one of the the largest and best quality in the world. The ores can be divided into glauber salt rock and clay-bearing glauber salt rock, in which 99% of the soluble salt is glauber salt.

**Bentonite** ores predominantly occurred in Neo-Mesozoic acidic volcanic clastic rock and tuff in Shanxi, Hebei, Faku, Liaoning, Shandong provinces and Inner Mongolia. The deposits are usually in Jurassic and Cretaceous strata.

**Cement limestone** is distributed in all provinces and major cities in NCB and consist of 29.3% of the country’s reserves.

**Fluorite** ores are in Inner Mongolia, Hebei, Shandong and Liaoning provinces. The main metallogenic epoch is the Yanshan period. The Sizhiwangqi of Inner Mongolia is a vast fluorite ore-forming district. The deposits occur in the lower Permian Xilimiao formation.

There are good prospects for exploration of limestone, dolomite, fluorite, gypsum, pyrite and various rock materials, but excellent kaolinite, porcelain clay and rich phosphorus deposits are difficult to find.
Abstract. There are four metallogenic belts in China consisting of mid-low temperature hydrothermal deposits. They are commonly accompanied by oil, gas or/and coal-bearing basins. Systematic geochemical research of representative mid-low temperature hydrothermal deposits with super-large or large tonnages, such as the Xikuangshan Sb deposit and the Woxi Au-Sb deposit in the Hunan Province, reveal that ore-forming materials were mostly derived from the Proterozoic basement and that large-scale fluid flow in ore-controlling strata was driven by the Yanshanian tectonic-magmatic event. The hydrothermal systems caused by large-scale fluid flow involved a large basin comprising at least three tectonic units (Jinningian, Caledonian and Yanshanian) with a thickness of thousands of meters. These deposits developed two types of primary geochemical anomalies, an external-source and an authigenous-source, depending on the source of ore-forming materials. Depleted zones of ore-forming elements in regions with negative anomalies near ore bodies characterize the authigenous-source geochemical anomaly around the deposits. The variation coefficient of ore-forming elements and cumulative probability plots are effective methods to recognize authigenous-source geochemical anomalies. The results show that since the Late Triassic, regional epeirogeny to subsequent widespread Yanshanian granitic magmatic plutonism in southern China, hydrothermal mineralization and large-scale geochemical zoning were generated in response to events and phenomena relating to thermal uplift driven by asthenospheric upwelling that resulted from the breakup of the Pangean supercontinent.

Keywords. Hydrothermal deposits, gold, stibnite, geochemistry, metallogenesis, South China

1 Introduction

Large numbers of hydrothermal ore deposits occur in South China such that it has become a most important area for Chinese nonferrous and rare metals resources. Most deposits were formed during the Yanshanian about from 180 to 80 Ma. In addition to the well-documented W-Sn deposits that are clearly related to the granites, the mid-low temperature hydrothermal deposits, such as Au, Sb, Hg mineralization in South China are also economically important. These deposits nearly all occur in the sedimentary rocks and their low-grade metamorphic counterparts, in regions with or without associated weak magmatic activity. They constitute the most important mid-low temperature metallogenic belt and are among the best studied deposits in China. One of the most outstanding characteristics of these occurrences is that the metallogenic belts are associated with oil, gas or/and coal basins, or with fossil oil-fields in region similar to as those of central Asian such as Kirghizia, Tajikistan, Uzbekistan, Kazakhstan and Turkmenistan (Ilyin et al. 1992). The mid-low temperature belt is located between the South China W-Sn Metallogenic Province of hypothermal deposits on the southeast, and the East Sichuan Oil-Gas-Coal Belt on the northwest. These three belts make up a large NE-trending mineralization zonation district with high temperature granite massif centers in the southeast to the low temperature features in the northwest (Ma 1999).

There are three other metallogenic belts of mid-low temperature hydrothermal deposits in China. They are: (1) Qinling-Kunlunshan Metallogenic Belt; (2) Tianshan (-Changbaishan-Yinshan?) Metallogenic Belt; and (3) Yunnan -Sichuan-Tibet Metallogenic Belt. The Qinling-Kunlunshan belt is the second-most economically important in China, and the two other belts probably extend westward to mesh with the central Asian Metallogenic Belts but have received a comparatively lower amount of research. The present paper is a summary of some of our research since 1986 designed to understand the genesis of representative mid-low temperature hydrothermal deposits, mostly in Hunan Province. In addition, features of geochemical exploration for their primary halo are addressed.

2 Geochemical indications of ore sources

Data from geochemical measurements for related stratum formations and wallrocks of deposits, and hydrothermal experiments on the leaching of ore-forming elements show that the Proterozoic basement strata are important sources of ore-forming elements for the mid-low temperature deposits in the South China Metallogenic Belt (Ma and Pan 2002; Ma et al. 2002, 2003).

Gold and antimony distributions in 296 samples from sedimentary and metasedimentary rocks of various geologic ages reveals that these elements are concentrated in the Precambrian and have relative lower contents in the Paleozoic capping beds. For instance, the average contents of Sb in the Precambrian low-grade metasedimentary rocks in which many Au and Sb deposits and mineral occurrences occur, range from 1.1 to 4.7 ppm and show multi-model distributions; while the average content of Sb in the Devonian limestone and detrital rocks hosting the Xikuangshan stibnite deposit, the largest Sb deposit in the word, is only 0.4 ppm and 0.8 ppm respectively. We have recently found, using statistics, that the Sinian has
the overall highest average contents of Au and Sb. In the representative Au-Sb and Au deposits in Hunan, such as Woxi, Longshan and Mobin, geochemical investigations have revealed negative Au anomalies and regional Au depletion zones around the orebodies and the mine fields. Gold contents in bleached alteration zones (sericitization, carbonatization and some silicification) are lower than the regional background of ore-bearing formation. Gold contents increase usually only within several meters, or even several tens of centimeters, to the orebody.

The results of hydrothermal leaching experiments for Precambrian rocks with (NH₄)₂S and NaCl solutions under conditions of 100 to 300°C, and 200 to 400 bars, show that 45 % of Au and Sb and more than 90 % of Hg in the rocks can be mobilized into solution, and partial extraction experiments indicate that 56 % of Sb in the rocks exists as three types of easily mobilized ionic states, as carbonate or sulfide species.

### 3 Geochemical tracing of large-scale fluid movement

Conclusions as follows are drawn from geochemical research on the Xikuangshan Sb deposit in the Centre-Hunan Basin (Ma and Pan 2002; Ma et al. 2002, 2003).

#### 3.1 Paleofluid tracing by Sr, Hg and REE

Strontium and mercury are quite mobile in ground water such that their distribution patterns in regional rocks could indicate fluid movements in fossil fluid systems. Geochemical studies on the deposits and regional strata from the Mid-Proterozoic to the Carboniferous ages show that both Sr and Hg are relatively concentrated in the shallowly-buried Paleozoic sequences and in, or nearby Au-Sb deposits, whereas they are depleted in the deeper sequences, thus showing paleo-fluid flow trends. Moreover, the stibnite from Xikuangshan Sb deposit and the slate of the Proterozoic Madiyi Formation have the highest REE contents in region and have similar REE distribution pattern, suggesting a close relationship between the source of ore-forming materials and the Proterozoic basement.

#### 3.2 Stable isotope geochemistry

In the mid-Hunan Basin, integrated results form research on H, O and C isotopes, and the Sr and Hg distributions mentioned above, show that meteoric fluids played an important role in ore-forming process. All of the Sb and Au-Sb mining districts in the mid-Hunan Basin develop negative anomalies of ¹⁸O (<18.8 %). There is a notable spatial relationship in the distribution of C and O isotopic compositions between the deposits and the basin sedimentary formations, including the Cambrian black shale and the Carboniferous and Permian coal-bearing strata.

#### 3.3 Hydrothermal activity in coal-bearing strata

Geochemical investigations on trace elements in 13 coal mines around the Xikuangshan Sb deposit reveal that Sb, Ag and some other ore-forming elements are concentrated in some coal samples. For instance, Sb and Ag values in coal are up to 45 ppm at the Baishiling coal deposit, and 61 ppm at the Panqiao coal deposit. These deposits occur in the Carboniferous and Permian strata that form the roof wallrocks of the Xikuangshan Sb deposit which occurs in mid-Devonian strata. This therefore suggests that these overlying sequences were probably involved at a basin-scale as fluids related to the Yanshanian ore-forming process were mobilized.

#### 3.4 Relations between ore and basinal fluids

Studies on fluid inclusions in quartz and carbonate veins from Xikuangshan and deposits from the region, form a base to investigate sources for the ore-forming fluids. Basically, the ore-forming fluids were similar in composition to the basin paleofluid except the latter has appreciably lower contents of sulfur and potassium. However, salinity and homogenization temperatures of ore-bearing quartz veins (>5.5% and > 190°C respectively) are much higher than those of barren quartz veins in the region. As such, salinity and temperature can be used to evaluate ore-forming potential.

#### 3.5 Fluid modeling of the Xikuangshan Sb deposit

A numerical simulation of formation conditions determined from the results of the integration of geologic and geochemical research shows that: (1) buried granitic bodies under the deposit and basin edges supplied basin heat flow of about 0.2W/m² to drive fluid moving; (2) the average flow speed of basin and basemental paleofluid were 1.2 m/y and 0.6 m/y respectively; (3) the fluid from deep circulation of meteoric water reached 260-200°C and 49-69 MPa and became ore-bearing through leaching of Au, Sb and other metals from the Precambrian basement, (4) the flow speed of the ore-forming fluid, the ore-forming temperature and the geothermal gradient during ore deposit formed were respectively 0.5 m/y, 180-200°C and about 86 °C/km (Yang et al. 2003).

### 4 Geochemical exploration criteria

According to the interpreted source of ore-forming materials and their relations to ore-controlling sedimentary formations, we can distinguish between two kinds of primary geochemical anomalies, an external-source and an authigenous-source anomalies (Pan et al. 2002). The latter has a more complex anomaly structure in ore-forming element compositions and is more difficult to distin-
guish than the former. Our research of Au-Sb deposits occurring in the Jiangnan “Old-Land” such as the Woxi Au-Sb-W deposit and the Mobin Au deposit show that an authigenous-source anomaly is composed of a regional depleted zone, a negative anomaly near the orebody, and a positive anomaly close to the orebody. We have found that the authigenous-source anomalies could be revealed by three geochemical methods, (1) using variation coefficients as an anomalous criteria, (2) using probability plots to resolve multi-model distribution patterns for the determination of background and threshold values (Ma et al. 2000), and (3) using other pathfinder elements such as Sb, As and Hg. In addition, O isotopic compositions and fluid inclusion data, mentioned above, are also effective criteria for ore prospecting.

5 Relationships between mineralization and asthenospheric upwelling

To explain large and widespread mineralized zonations and metallogenic contemporaneity during the Yanshanian in South China, it would be straightforward to suggest a single, large-scale geothermal field generated by the Yanshanian granites governed distribution of these hydrothermal features and deposits. The S-wave seismic tomographic images of South China and adjacent areas show that there currently is a vertical plume-shaped low-velocity zone hiden under the deep mantle from 150 to 450km (Zhang et al. 1993). It is interpreted to reflect a remnant mantle plume. The area with the strongest magmatic activity of the Yanshanian granites is located directly above in projection. Five mantle cross-sections through the recent P-wave model of Kárason et al. (2000) illustrate the structural complexity in the upper-mantle transition zone and the regional variations in the fates of the subducted slabs. The findings of Kárason et al. (2000) show that the continental area of South China has a hot upper mantle compared with other areas in the world. Noticeably, also just under the active centre of granitic magma in South China, there is a mantle diapir puncturing the belt of transition from the lower mantle. Considering recent important reports of anomalous geological features such as Yanshanian basalts, A-type granites, alkali intrusive rocks and the bimodal magmatic activity in South China, combined with the fact that the Jurassic and Cretaceous sequences in South China are non-meta-morphic, weakly folded and controlled by fault basins, we suggest that the Late Triassic regional epeirogeny, subsequent Yanshanian large-scale granitic magmatic plutonism, hydrothermal mineralization and huge metal zoning, and related phenomena are related to thermal uplift driven by the asthenosphere upwelling in response to the breakup of the Pangean supercontinent.

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Chapter 10-6

Major products of the international collaborative project on mineral resources, metallogenesis, and tectonics of northeast Asia

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Keywords. Northeast Asia, metallogenesis, tectonics, regional geology

Abstract

A major international collaborative project on the mineral resources, metallogenesis, and tectonics of Northeast Asia is being concluded by the Russian Academy of Sciences, the Mongolian Academy of Sciences, Jilin University (China), the Korean Institute of Geoscience and Mineral Resources, the Geological Survey of Japan, and the U.S. Geological Survey. The project area includes eastern and southern Siberia, the Russian Far East, Mongolia, northern China, South Korea, and Japan. The project is a multi-national study at 5.0 m scale with over 50 international collaborators from six countries. The Northeast Asia project extends and builds on data and interpretations resulting from a similar previous project on the mineral resources, metallogenesis, and tectonics of the circum-north Pacific (Russian Far East, Alaska, and the Canadian cordillera). The Northeast Asia project is associated with a new project of the U.S. Geological Survey entitled a Global Mineral Resource Assessment.

The project has recently released several major products that provide major earth science data sets and interpretations. The products include: (1) a regional geodynamic map and detailed explanations that provide the geologic setting for tectonic and metallogenic interpretations; (2) comprehensive mineral resource tables and with data on about 1,700 lode deposits and 75 placer districts, based mostly on non-English publications; (3) regional mineral deposit location and metallogenic belt maps and detailed descriptions that provide the comprehensive interpretations of the geologic and tectonic origins of mineral deposits through geologic space and time; (4) a highly-integrated spatial data (GIS) compilation of these maps and descriptions; (5) descriptions of mineral deposit models for classification of mineral deposits, and (6) a four-dimensional time-space model depicting the regional tectonic history and metallogenic evolution for the origin and modification of mineral deposits and containing metallogenic belts. These publications provide enhanced, broad-scale metallogenic-tectonic reconstructions and interpretations to the industrial and scientific community. The publications are being released in paper, digital (CD-ROM), and Internet/Web formats, and are available for free downloading without copyright restriction.
Characteristics of ore deposit distribution in Northeast Asia, as derived from data compiled by the “Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia” project

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Abstract. The regional characteristics of ore deposit distribution in the Northeast Asia are obtained via examination of the mineral resources database prepared by the international project on the Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia. The spatial distribution of the mineral deposits indicates the differences between the eastern and the western sub-regions, suggesting distinct geological development of these regions. The temporal variation of the development of metallogenic belts indicates intense ore-forming events occurred in the Cenomanian-Campanian time. The importance of the regional geological and mineral resources information can be evaluated by examining the project data and interpretations.

Keywords. Northeast Asia, mineral resources, database, metallogenic belts

1 Introduction

Examination of regional distribution characteristics of ore deposits in a given region is useful for area selection for further exploration. The regional characteristics of ore deposit distribution in Northeast Asia are obtained with examination of the mineral resources database prepared by the international project on Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia (Nokleberg et al. 2003). The project recently presented various digital geoscience data for the Northeast Asia. The project area consists of Eastern and Southern Siberia, Mongolia, Northern China, South Korea, Japan, and adjacent offshore areas. This area is approximately bounded by 30 to 82° N. latitude and 75 to 144° E. longitude. The mineral resources database is one of the major publications resulting from this project. In this paper, we examine the regional distribution pattern of mineral deposits and temporal variation of numbers of metallogenic belts in the Northeast Asia, using data compiled by the project. Northeast Asia contains several stable cratons, Paleozoic and Mesozoic orogenic zones, and Mesozoic to Cenozoic Circum Pacific orogenic zones. The regional distribution pattern of the ore deposits is examined according to these geodynamic settings.

2 Characteristics of ore deposit distribution in northeast Asia

Ariunbileg et al. (2003) provided a mineral resources database with various computer formats. The lode deposit database that was used for this examination contains descriptions for 1674 deposits. Although the deposits were selected from large data set for each region, both major and significant deposits were included in the database and the database is representative for showing the regional distribution of ore deposits for the Northeast Asia. Figure 1 shows the location of these deposits in Northeast Asia. It is apparent that the deposits are clustered in specific zones probably related to geodynamic environments.
The numbers of deposits occur within 4 degree latitude are obtained from the mineral database, and plotted against the latitude (Fig. 2) that illustrates north-south variation of numbers of deposits. The maximum number of deposits occur at around 48° N. To the north of this point, the number of deposit decreases steeply. The northern area is covered by stable platform sediments, and the small number of the deposits could be the result of extensive sedimentary cover.

The difference in mineral deposit distribution between the eastern and western parts of the project area has been examined by grouping of the data for three sub-regions, western, central, and eastern regions. Those are bounded by 100 and 122° E (Fig. 1). Each region has an east-west width of 22 degrees. Numbers of deposits in the western, central, and eastern regions are 571, 491, and 612, respectively. Thus, each region contains almost the same number of ore deposits. However, the southern part of the western region is limited to between 40° and 52° N, and the actual sizes of the regions are different. The number of deposits in the central and western region normalized to the size of eastern region can be calculated, and are 614 and 1243, respectively. The figures indicate high concentration of deposits in the western region. Further more, the population of deposits obtained for every 10,000 km² in the eastern, central, and western regions are 0.82, 0.84, and 1.68, respectively. As the eastern region contains a large area covered by ocean, the actual population of deposits should be higher. In the case of the Japanese islands, 4.8 deposits per 10,000 km² are listed on the Northeast Asia database; this figure is much higher than for the western region.

Deposits with Au as major commodity were selected from the database. 331 deposits in the database list Au as major commodity. The data are also plotted on Figure 3. The Au deposit distribution pattern indicates large numbers of deposits occur between 36° N and 60° N, with two peaks at 40° N and 48° N. In the western region the maximum number of the Au deposits occur at around 52° N. The central region has a small peak at around 52° N, suggesting a continuation of the peak from the west. However, an additional higher peak occurs at around 40° N for central region. The eastern region has two peaks on the diagram, similar to the overall distribution pattern.
for Northeast Asia. The characteristics of Au deposits distribution can be understood by the regional tectonic history of the Northeast Asia as described as above.

3 Metallogenic belts of northeast Asia

The temporal variation of ore forming events is examined using the metallogenic belt data of Northeast Asia that were compiled by Rodionov et al. (2004). Although the estimated formation age of the deposits is listed in the mineral resources database, not all deposits have age data. Thus, the only metallogenic belts data which include timing of the metallogenic events were used. The metallogenic belts are characterized by a narrow age of formation and are defined with information from ore-forming events, tectonics, terranes and overlap assemblages, and mineral deposit models. The metallogenic belts were defined for 12 time slices (Rodionov, et al, 2004). The number of metallogenic belts for each time slice is summarized and plotted against time on Figure 4. It shows the variation of numbers of metallogenic belts in the Northeast Asia through geological time. As the time stages have different duration, the numbers of metallogenic belts normalized for the duration are also presented on Figure 4. This figure shows two major time stages of the metallogenic belts, Cambrian-Early Carboniferous and Cretaceous (Cenomanian-Campanian). The Cretaceous interval hosts the maximum number of metallogenic belts that occur mainly along the eastern margin of the Asian continent. The number of metallogenic belts peaks during the Middle Jurassic-Early Cretaceous interval. However, the Cenomanian-Campanian interval shows a higher normalized metallogenic belts number, suggesting more intense metallogenic events at this time. Those belts formed during subduction of the Pacific ocean plate under the Asian continent. The timing of development of metallogenic belts clearly shows a link of metallogeny to the geodynamic settings.

4 Conclusions

The regional characteristics of ore deposit distribution in the Northeast Asia are obtained via examination of the mineral resources database prepared by the international project on Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia. The spatial distribution of the mineral deposits highlight the difference between the eastern and the western sub-region, suggesting distinct geological development of these regions. The temporal variation of the development of metallogenic belts are analyzed. The results indicate timing of major ore forming events in the Northeast Asia. The tectonic environments for the ore forming events are considered. The importance of the regional geological and mineral resources information can be indicated with the preliminary evaluation of the data presented by the project.
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Tectonic structures of the Nezhdaninka gold deposit (northeastern Asia)

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Abstract. Data are presented on the structural geology of the Nezhdaninka gold deposit, one of the largest in northeast Asia. It is established that early thrust dislocations are represented by a large duplex in the hanging wall of a ramp anticline with easterly vergence. The roof thrust of the duplex is traced along the sandstones at the bottom of the Lower Permian Dyby Formation, while the lower-amplitude thrusts in the underlying Dzhuptaga Formation form horse-tail structures and asymptotically adjoin the roof thrust (detachment). Related to these deformations is a secondary foliation that is accompanied by transposition of primary layering. Z-shaped folds with sub-vertical hinges are accompanied by a crenulation cleavage, and orebodies with Au mineralization are associated with superimposed strike-slip faults of northeasterly and meridional strike.

Keywords. Nezhdaninka gold deposit, Northeast Asia, thrust, duplex, strike-slip, foliation, transposition

1 Introduction

The Nezhdaninka gold deposit is located in the northern part of the South Verkhoyansk synclinorium (rear part of the South Verkhoyansk sector of the Verkhoyansk fold-and-thrust belt). It is among the largest gold deposits in northeastern Asia. The deposit is well-explored and has been exploited for over 20 years. Its tectonic structure has been discussed by a number of researchers (e.g. Yanovskiy 1990; Gamyanin et al. 2000) but it was not until recently that systematic studies of the structural geology of the deposit have been undertaken using methods of structural and geometric analysis that are in widespread common practice. The deposit is located in the Lower Permian Dzhuptaga Formation (500 m) composed of mudstones and siltstones, which are exposed in the core of the 60 x 10 km Dyby anticline. The latter has a meridional strike and its axis dips gently (a few degrees) to the south. The overlying Lower-Upper Permian sandstones, siltstones and clay shales of the Dyby and Menkeche Formations (> 1000 m) are exposed on the limbs and the roof of the anticline. The structures of the deposits are difficult to study due to a widespread development of intense foliation in the ore-bearing strata. In spite of the low metamorphic grade (lower greenschist facies), an intense secondary foliation (or slaty cleavage) accompanied by bedding transposition over most of the deposit makes it difficult to identify bedding of the rocks in outcrops and pits.

This paper presents the results of structural studies performed in the central part of the deposit. The investigation techniques included detailed structural mapping and close observations of exposed deformational structures with a view towards developing a structural parageneses. Excellent exposures at the deposit make it possible to compile a series of detailed structural sections across the strike of major structures and to reconstruct the structure and deformation history of the deposit.

2 Structural paragenesis

2.1 First generation deformation

Early deformation phases are represented by low-amplitude asymmetric, similar close and tight folds (F1) of conic geometry and eastern vergence with a width of a few centimeters to several tens of meters. The eastern limbs of the anticlines are much steeper than the western ones. The folds are accompanied by a secondary continuous foliation (continuous cleavage) S1 of eastern vergence that is subparallel to the bedding, an intersection lineation Lox1 oriented subparallel to gentle submeridional and northeast-striking hinges of F1 folds, which forms at the intersection with the bedding, an intersection lineation Lox1 oriented subparallel to gentle submeridional and northeast-striking hinges of F1 folds. Foliation S1, steeply dips (60°-80°) mainly to the east and is accompanied by transposition of bedding and makes it difficult to observe the first generation folds. On the S1 foliation planes, chlorite and sericite are developed. Folds F1 are associated with thrusts of easterly vergence on which it is impossible to estimate the amplitude of motion due to the absence of convincing markers on the limbs of the faults.

The dislocations are widely manifested in the less competent clay rocks of the Lower Permian Dzhuptaga Formation, which compose the core of the Dyby anticline. In the overlying more competent rocks of the Dyby and Menkeche Formations on the limbs of the Dyby anticline, folds F1 become more extensive (up to a few hundreds of meters wide) and open, progressively dying out in the westward and eastward directions. In the roof of the anticline in the same strata, there are only spaced foliations (spaced cleavage or schistosity) with no folds but small thrusts. The asymmetric Dyby anticline of eastern vergence has a gently-dipping (10°-20°) eastern limb, a wide (up to 2 km) subhorizontal dome and a steep (up to 45°-
60°) eastern limb. Its morphology is similar to a classic ramp anticline. Spatial-geometric characteristics of the Dyby anticline permit us to consider it in the same structural paragenesis with the deformations of the first generation. It is supposed that at the base of the Dyby Formation, a gentle detachment is sub-parallel with the rock bedding. Earlier it was established that in the first stage of deformations metamorphic quartz veins were formed, bearing poor (less than 10%) sulfide mineralization, and background Au (up to 2 g/t) (Gamyanin et al. 1985).

2.2 Second generation deformation

The superimposed dislocations of the second generation include the northeast striking, first-order right-lateral strike-slip faults and the second-order splay strike-slip faults of meridional strike. The strike-slips are represented by crush and small-scale folding zones from a few decimeters to 1-5 meters wide. They are commonly localized on the steep limbs of the first-order folds at the sites where early foliation S_1 is subparallel to bedding S_0 and where the early transposition processes are most intense. Associated with them are F_2 folds (Z-shaped in plan) with suboval hinges into which foliation S_1 was draped. Crenulation cleavage S_3 is only observed in the curves of folds F_2. Major orebodies bearing Au mineralization are confined to the second-order splay strike-slip faults. Amplitude of motions along the strike-slip faults span a few tens to hundreds of meters.

We argue that it was during this deformation stage that the main orebodies of the deposit were formed, such as auriferous beresites and veins consisting of pyrite-arsenopyrite-quartz, productive chalcopyrite-galena-sphalerite and fahlore-sulfosalts, and post-productive berthierite-antimonite-carbonate assemblages. Post-ore rede-position consisted of the early minerals and separation of the electrum-pyrrargyrite-freibergite assemblage. Due to a complex genesis of the deposit, Au widely ranges in form, size, and composition. In some of the orebodies, Au content is 30% of the < 0.16 mm fraction volume. Au crystals as large as > 0.25 mm constitute up to 20% in the mineralized zones and up to 40% in the veins. Au is 560-900‰ fine, with most values falling into the 780-820‰ category (Parfenov and Kuz’min 2001).

3 Gold mineralization

The deposit consists of mineralized crush zones that persist along strike and down dip, as well as smaller veins. A total of 117 bodies with ore-bearing potential have been recognized at the deposit, of which only 12 have been thoroughly investigated. Crush zones are traced along second-order splays of the second generation strike-slip faults. The richest ore zones host two thirds of ore reserves. It is localized in a 15 km long and 1-40 m wide crush zone.

The thrust and strike-slip faults of both generations deform gabbro-diorite dikes that are dated at 154, 153 and 139 Ma (K-Ar, Nenashev and Zaitsev 1980). The \(^{40}\)Ar/\(^{39}\)Ar isotopic age of dislocation metamorphism and the first generation deformation is 119.4±0.5 Ma as determined on biotite developed on the plane of foliation S_1 in the central part of the South Verkhoyansk synclinorium (Prokopiev et al. 2003). The age coincides with that of the granite plutons: The Dyby – 122.5±0.6 Ma (\(^{40}\)Ar/\(^{39}\)Ar, biotite; Layer et al. 2001) located to the north of the deposit, the Tarbagannakh – 120±1 Ma (\(^{40}\)Ar/\(^{39}\)Ar, biotite; Prokopiev et al. 2003) and the Uemlyakh - 119-126 Ma (\(^{40}\)Ar/\(^{39}\)Ar, biotite; Layer et al. 2001) and 120.4±0.6 (U-Pb, zircon; unpublished date) located to the south of the deposit. The age of the first generation of deformation is estimated as Middle Aptian.

The main productive ore zones are related to the second generation of deformation and superposed on lamprophyre dikes (Bakharev et al. 2003) associated with granodiorites of the Kurum pluton (northern flank of the deposit, dated at 96.7±0.4 Ma (\(^{40}\)Ar/\(^{39}\)Ar, biotite; Layer et al. 2001). On the other hand, the Geldin stocks of diorites and quartz diorites, located on the south-west flank of the deposit, are dated at 92.1±0.6 Ma and 95.5±0.4 Ma (\(^{40}\)Ar/\(^{39}\)Ar, biotite; Layer et al. 2001) and intrude deformation structures. Thus, the age of the second generation deformations is Cenomanian-Turonian boundary.
5 Structural model for central Nezhdaninka

The early thrust dislocations are established to be represented by a large easterly vergin duplex in the ha anticline, where the vergin wall of the Dyby ramp anticline. The roof thrust of the duplex is traced along the bottom of the competent strata of the Lower Permian Dyby Formation. Low-amplitude thrusts make up horse-tail structures in the core of the most intense deformations (foliation and transposition) are manifested in the less competent Dzhuptaga Formation, and asymptotically adjoin the roof thrust (detachment) (Fig. 1). The footwall thrust of the duplex is unexposed. Thrust motions occurred in the direction from west to east. The superposed right-lateral strike-slip dislocations are represented by crush zones and orebodies with Au mineralization of meridional and eastern strike and zones of draping of early foliation into Z-shaped folds accompanied by crenulation cleavage.

6 Conclusions

Our studies show that in spite of a large volume of previous investigations into the structure of the Nezhdaninka deposit, the existing large-scale geological maps do not adequately reflect the geology and tectonic structure of the region. Furthermore they are commonly contrary to observations. In other words, only orebodies and quartz veins are correctly shown on the maps, but the structural and geological situation associated with the ores are lacking. The widespread development of the first generation foliation and transposition makes it difficult to discern the primary bedding attitudes. The economic gold mineralization preferentially occurs in the areas where strike-slip dislocations are superposed on the zones of intense first generation foliation.

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Metallogenesis of northeast Asia


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Abstract. These studies are part of a major international collaborative study of the ‘Mineral Resources, Metallogenesis, and Tectonics of Northeast Asia’ that was conducted from 1997 through 2004 by geologists from earth science agencies and universities in Russia, Mongolia, Northeastern China, South Korea, Japan, and the USA. The metallogenic analyses included several steps: metallogenic belts, mineral deposit models, relation between metallogenesis, tectonics, and geodynamic. Major results of the project are available by Internet at the following web site: http://minerals.usgs.gov/west/projects/minres.html

Keywords. Metallogenesis, North-East Asia, mineral deposit

1 Metallogenic belts of NE Asia

The metallogenic belts of Northeast Asia are herein synthesized, compiled, described, and interpreted with the use of modern concepts of plate tectonics, analysis of terranes and overlap assemblages, and synthesis of mineral deposit models. The data supporting the compilation are: (1) comprehensive descriptions of mineral deposits; (2) compilation and synthesis of a regional geodynamics map the region at 5 million scale with detailed explanations and cited references; and (3) compilation and synthesis of metallogenic belt maps at 10 million scale with detailed explanations and cited references.

Metallogenic belts are characterized by a narrow age of formation, and include districts, deposits, and occurrences. The metallogenic belts are synthesized and described for the main structural units of the North Asian Craton and Sino-Korean Craton, framing orogenic belts that consist of collage of accreted tectonostatigraphic terranes, younger overlap volcanic and sedimentary rock sequences, and younger stitching plutonic sequences. The major units in the region are the North Asian Craton, exterior passive continental margin units (Baikal-Patom, Enisey Ridge, Southern Taymir, and Verkhoyanski passive continental margin units), the early Paleozoic Central Asian orogenic belt, and various Mesozoic and Cenozoic continental margin arcs. Metallogenic belts are interpreted according to specific geodynamic environments including cratonic, active and passive continental margin, continental-margin arc, island arc, oceanic or continental rift, collisional, transform-continental margin, and impact.

The following concepts are employed for the synthesis of metallogenic belts.

- **Mineral Deposit Association.** Each metallogenic belt includes a single mineral deposit type or a group of coeval, closely-located and genetically-related mineral deposits types.

- **Geodynamic Event for Deposit Formation.** Each metallogenic belt contains a group of coeval and genetically related deposits that were formed in a specific geodynamic event. Examples are collision, continental-margin arc, accretion, rifting and others.

- **Favorable Geological Environment.** Each metallogenic belt is underlain by a geological host rock and (or) structure that is favorable for a particular suite of mineral deposit types.

- **Tectonic or Geological Boundaries.** Each metallogenic belt is usually bounded by favorable either stratigraphic or magmatic units, or by major faults (sutures) along which substantial translations have occurred.

- **Relation of Features of Metallogenic Belt to Host Unit.** The name, boundaries, and inner composition of each metallogenic belt corresponds to previously define characteristics of rocks or structures hosting the deposits, and to a suite of characteristics for the group of deposits and host rocks.

With these definitions and principles, the area defined for a metallogenic belt is predictive or prognostic for undiscovered deposits. Consequently, the synthesis and compilation of metallogenic belts is a powerful tool for mineral exploration, land-use planning, and environmental studies.

For modern metallogenic analysis, three interrelated problems exist.

1. What is the relation of geodynamics to regional or global metallogeny? As discussed by Zonenshain and others (1992) and Dobretsov and Kirdyashkin (1994), this problem includes the role of convective processes in mantle and mantle plumes, the global processes of formation of the continents and oceans, the dynamics of development of major tectonic units of the earth's crust,
metallogenic evolution of the earth, and the role mantle processes in the origin of major-belts of deposits.

2. What is relation of regional metallogeny to individual lithosphere blocks? As discussed by Guild (1978), Mitchell and Garson (1981), and Koroteev (1996), this problem includes the genesis of specific metallogenic belts as a function of specific geodynamic environments using the modern concepts of plate tectonics.

3. What is the relation of metallogeny to individual tectonostratigraphic terranes and overlap assemblages? As discussed by Nokleberg and others (1993, 1998) and Parfenov and others (1999), this problem includes the genesis of specific metallogenic belts in individual fault-bounded units of distinctive stratigraphy, defined as tectonostratigraphic terranes, and in younger overlapping assemblages often containing igneous rocks formed in continental margin or island arcs, along rift systems in continents, or along transform continental margins.

2 Methodology of metallogenic analysis

The compilation, synthesis, description, and interpretation of metallogenic belts of Northeast Asia is part of an intricate process to analyze the complex metallogenic and tectonic history of the region. The methodology for this type of analysis consists of the following steps. (1) The major lode deposits are described and classified according to defined mineral deposit models. (2) Metallogenic belts are delineated. (3) Tectonic environments for the cratons, craton margins, orogenic collages of terranes, overlap assemblages, and contained metallogenic belts are assigned from regional compilation and synthesis of stratigraphic, structural, metamorphic, isotopic, faunal, and provenance data. The tectonic environments include cratonal, passive continental margin, metamorphosed continental margin, continental-margin arc, island arc, transform continental-margin arc, oceanic crust, seamount, ophiolite, accretionary wedge, subduction zone, turbidite basin, and metamorphic. (4) Correlations are made between terranes, fragments of overlap assemblages, and fragments of contained metallogenic belts. (5) Coeval terranes and their contained metallogenic belts are grouped into a single metallogenic and tectonic origin, for instance, a single island arc or subduction zone. (6) Igneous-arc and subduction-zone terranes, which are interpreted as being tectonically linked, and their contained metallogenic belts, are grouped into coeval, curvilinear arc-subduction-zone-complexes. (7) By use of geologic, faunal, and paleomagnetic data, the original positions of terranes and their metallogenic belts are interpreted. (8) The paths of tectonic migration of terranes and contained metallogenic belts are constructed. (9) The timings and nature of accretions of terranes and contained metallogenic belts are determined from geologic, age, and structural data; (10) The nature of collision-related geologic units and their contained metallogenic belts are determined from geologic data. And (11) the nature and timing of post-accretionary overlap assemblages and contained metallogenic belts are determined from geologic and age data.

According to the main geodynamic events and the major deposit-forming and metallogenic belt-forming events for Northeast Asia, the following twelve time spans are used for groupings of metalogenic belts:

- Archean (> 2500 Ma).
- Paleoproterozoic (2500 to 1600 Ma).
- Mesoproterozoic (1600 to 1000 Ma).
- Neoproterozoic (1000 to 540 Ma).
- Cambrian through Silurian (540 to 410 Ma).
- Devonian through Early Carboniferous (Mississippian) (410 to 320 Ma).
- Late Carboniferous (Pennsylvanian) through Middle Triassic (320 to 230 Ma).
- Late Triassic through Early Jurassic (230 to 175 Ma).
- Middle Jurassic through Early Cretaceous (175 to 96 Ma).
- Cenomanian through Campanian (96 to 72 Ma).
- Maastrichtian through Oligocene (72 to 24 Ma).
- Miocene through Quaternary (24 to 0 Ma).

Paleogeodynamic and related metallogenic analyses were made separately for each time span. The example for Cenomanian-Campanian time span is shown below (Fig. 1).

![Figure 1: Paleogeodynamic and metallogenic reconstruction of North-East Asia for Cenomanian-Campanian time slice (87 Ma)](image-url)
3 Mineral deposit models

For descriptions of metallogenic belts, lode mineral deposits are classified into various models or types. The following three main principles are employed for synthesis of mineral deposit models for this study. (1) Deposit forming processes are close related to rock forming processes (Obruchev 1928) and mineral deposits originate as the result of mineral mass differentiation under their constant circulation in sedimentary, magmatic, and metamorphic circles of formation of rocks and geological structures (Smirnov 1969). (2) The classification must be as more comfortable and understandable for appropriate user as possible. And (3) the classification must be open so that new types of the deposits can be added in the future (Cox and Singer 1986).

In this classification for this study, lode deposits are grouped into the hierarchic levels of metallogenic taxons according to such their stable features as: (a) environment of formation of host and genetically-related rocks, (b) genetic features of the deposit, and (c) mineral and (or) elemental composition of the ore. The six hierarchial levels are as follows:

Group of deposits
Class of deposits
Clan of deposits
Family of deposits
Genus of deposits
Deposit types (models)

The deposit models are subdivided into the following four large groups according to major geological rock-forming processes: (1) deposits related to magmatic processes; (2) deposits related to hydrothermal-sedimentary processes; (3) deposits related to metamorphic processes; (4) deposits related to surficial processes and (6) exotic deposits. Each group includes several classes. For example, the group of deposits related to magmatic processes includes two classes: (1) those related to intrusive rocks; and (2) those related to extrusive rocks. Each class includes several clans, and so on. The most detailed subdivisions are for magmatic-related deposits because they are the most abundant in the project area. In the below classification, lode deposit types models that share a similar origin, such as magnesian and (or) calcic skarns, or porphyry deposits, are grouped together under a single genus with several types (or species) within the genus.

Some of the below deposit models differ from cited descriptions. For example, the Bayan Obo type was described previously as a carbonatite-related deposit. However, modern isotopic, mineralogical, and geological data recently obtained by Chinese geologists have resulted in a new interpretation of the deposit origin. These new data indicate that the deposit consists of ores that formed during Mesoproterozoic sedimentary-exhalative process, and along with coeval metasomatic activity, sedimentary diagenesis of dolomite, and alteration. The sedimentary-exhalative process consisted of both sedimentation and metasomatism. Later deformation, especially during the Caledonian orogeny, further enriched the ore. Consequently, the Bayan Obo deposit type is herein described as related to sedimentary-exhalative processes, not to magmatic processes. However, magmatic processes also played an important role in deposit formation. Consequently, this deposit model is part of the family of polygenetic carbonate-hosted deposits. Similar revisions are made for carbonate-hosted Hg-Sb and other deposit models.

Metalliferous and selected non-metalliferous lode and placer deposits for Northeast Asia are classified into various models or types described below. The mineral deposit types used in this study are based on both descriptive and genetic information that is systematically arranged to describe the essential properties of a class of mineral deposits. Some types are descriptive (empirical), in which instance the various attributes are recognized as essential, even though their relationships are unknown. An example of a descriptive mineral deposit type is the basaltic Cu type in which the empirical datum of a geologic association of Cu sulfide minerals with relatively Cu-rich metabasalt or greenstone is the essential attribute. Other types are genetic (theoretical), in which case the attributes are related through some fundamental concept. An example is the W skarn deposit type in which case the genetic process of contact metasomatism is the genetic attribute.

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The Kuranakh epithermal gold deposit (East Rusia)

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Abstract. The Kuranakh mine is one of the largest lode gold mines in Russia and has produced 7.1 million ounces of gold. Through 1997, the mine has extracted 74.1 million tonnes of ore grading 3.57 g/t gold (Benevolskiy 1985). The Kuranakh gold deposit is located within the Central Aldan Ore District on the Aldan shield, on the southern flank of the Siberian platform in the Russian Far East. Host rocks are composed of flat-lying Jurassic arkose and lower Cambrian limestone and dolomite overlying Precambrian metamorphic basement. The hydrothermal mineralizing event is associated with Jurassic - Lower Cretaceous igneous activity. In the mine area this igneous activity is manifest by three swarms of dikes with a few small plugs and sills composed of bostonite, microgabbro, and minette. The predominant trend of the dikes is N13°W. Gold mineralization is spatially related to the dikes, which may be both pre-mineral and post-mineral in age. The Kuranakh gold deposit is of the epithermal, quartz-adularia-sericite (illite)-type. Several sub-horizontal, blanket- or ribbon-like ore bodies up to 50 m thick occur mainly along and/or above, and in some places - under the contact between Cambrian calcareous footwall rocks and overlying Jurassic clastic rocks within a narrow zone, about 30 km long, bounded by several south-north trending faults. Originally, gold mineralization was associated with pyrite, arsenopyrite, sphalerite and galena; however, total sulfide content is only a few percent of the total rock mass. The deposit has been thoroughly oxidized and only traces of arsenopyrite and pyrite remain. Gold occurs primarily as mineral grains less than 5 microns in size and is usually contained within friable grains of porous goethite. Studies of fluid inclusions show homogenization temperatures from 80 to 220°C. Inclusions show homogenization temperatures from 80 to 220°C. Fluid inclusions show homogenization temperatures from 80 to 220°C but generally averaging from 110 to 160°C.

Keywords. Epithermal gold deposit, fluid inclusions, Russian Far East

1 Geologic setting

The Kuranakh gold deposit is located within the Central Aldan Ore District (CAD) that is situated within Aldan shield on the southern flank of Siberian Platform. The Aldan shield consists predominantly of Archean rock complexes that are metamorphosed to granulite and amphibolite facies. Mesozoic collision of the Siberian Platform and Bureya superterrane resulted in formation of sub-latitudinal systems of sedimentary basins of back-arc type that are filled with Jurassic and partly, Lower Cretaceous coal-bearing terrigenous deposits. The continued collision resulted in intensive folding of Mesozoic sedimentary rocks with development of complicated systems of gentle folds, isoclinal folds, and reverse folds (Mokrinskiy 1961), as well as numerous northward overthrusts. Widespread Mesozoic magmatic activity is also related to the collision processes.

Several different types of gold deposits occur within the Central Aldan Ore District (Vetluzhskikh, Kim 1997). Disseminated Au-U mineralization occurs within the Archean basement in the southeastern flank of the district. The deposit is related to feldspar-pyrite-carbonate and fluospar-carbonate-quartz altered rocks within breccia zones. Gold-bearing lens-shaped ore bodies are of hundreds meters long and of 10-30 meters thick. Gold content varies from 0.1 to 100.0 g/t.

Cambrian calcareous rocks on the south-west flank of the district host flat-lying gold-sulfide veins of very complicated morphology; they also host zones of disseminated gold-sulfide mineralization that occur at depths from 0-20 to 135-140 meters. The ore contains pyrite, pyrrhotite, galena, hematite, magnetite, sphalerite, native gold, rare cinnabar, native bismuth, silver, and tetrahedrite. Au/Ag ratios vary from 10/1 to 5/1. Gold content varies from 0.9 to 100.0 g/t and more.

Porphyry Au-Cu deposit occurs in the central part of the district. Stockwork gold-sulfide mineralization is related to alkaline syenite stock. Altered rocks consist of sericite, microcline, pyrite, ankerite. Disseminated and veinlet-controlled ore contains pyrite, chalcopyrite, bornite, and native gold.

Stratabound low-sulfide gold mineralization occurs at the contact of Jurassic sedimentary and Cambrian calcareous rocks in the northern part of CAD. This type of gold deposit is now the most economically important in the district. The Kuranakh deposit belongs to this type.

2 Geology of the Kuranakh deposit

The Kuranakh deposit (Fig. 1) is situated topographically lower and stratigraphically higher than most gold occurrences of the CAD. Jurassic clastic rocks, which are the predominant host rocks of the Kuranakh-type, are preserved in the uplift within a shallow synclinal basin which trends north-south and extends north onto the edge of the platform sedimentary rocks.

The stratigraphy of the Kuranakh deposit is composed of approximately 1,000 meters of Cambrian dolomite and
or karst cavity fillings; the thicknesses of material grading better than one gram per tonne gold may be up to 100 meters or more. The basal section of the sandstones has been altered (metasomatized) by hydrothermal fluids, and where intense enough, is distinguished by mine geologists as a separate rock unit – “metasomatite”. The metasomatite (a clay-potassic feldspar-quartz-bearing rock) is often reddish in color and usually displays myriad limestone unconformably overlain by 40 to 70 meters of Jurassic sandstone.

The upper contact of the Cambrian sequence is marked by the presence of a terra rosa of variable thickness. The unit generally varies from zero to 15 meters in thickness, but may be considerably thicker at some locales, and consists of clay and weathered limestone. It is mapped and logged by the mine geologists as “limestone weathering crust” and contains some gold.

Within the immediate vicinity of the mine, the igneous rocks present are Mesozoic (Early Cretaceous?) dikes and some plugs and sills of vogezeite, biotite-pyroxene porphyry, shonkinite, syenite-porphyry, trachyte, bostonite, microgabbro, and minette. The dikes have a close spatial relationship with the gold ores and may be related to the same thermal event that gave rise to the deposits.

3 Physical description of the Kuranakh ore field

In plan view, the ore bodies comprising the KOF form a shape resembling an inverted “Y”. The KOF extends from the south end of the Kanavnoye or body to the northern limits of the Severnoye ore body in the north - a distance of more than twenty kilometers; the field varies from one to eleven kilometers in width in an east west direction (Fig. 1). One of the longest stretches of continuous gold mineralization are the coalescing of Porphirovoye, Tsentralnoye, and Yakokutskoye ore bodies, which combine for a length exceeding ten kilometers. Although the terrain is only hilly, one of the striking features of the deposits is that the principal ore bodies tend to occur along topographic highs. This geomorphic phenomenon is perhaps due to the added resistance to weathering that the Jurassic sandstones have gained through the processes of metasomatic alteration and the fact that the sandstones themselves seem more resistant to weathering than the underlying carbonate rocks.

Morphologically the ore bodies have disjointed blanket-like shapes in their shortest dimension with thicknesses that rapidly increase in the areas of the most extreme faulting of calcareous rocks and karst development. Some disruptions in continuity perpendicular to the long axis of the ore bodies are due to gentle folding of the deposit and erosion of the limbs; other disruptions are due to the faulting and the considerable relief of the Cambrian-Jurassic contact which is now incised by erosion. Individual ore bodies (>1 g/t gold) have a lenticular shape, strongly oriented NNW-SSE and commonly coalesce or diverge along strike.

4 Mineralization and alteration

At Kuranakh mineralization is essentially restricted to the basal portion of the Jurassic sandstone, and the breccias

Figure 1: Geologic map of Kuranakh deposit (adopted from Kazarinov 1969).
According to the petrological and geological data, a depth of temperatures (Tf) and calculated using data of Potter (1977). The inclusions used as accessory material. The accuracy of temperature determination temperatures (Th) in order to determine the forming of the thermocamera. The equipment used allowed analysis of phases formation. The equipment used allowed analysis of phases.

The primary gold ore contains two generations of pyrite (3 to 20%), minor marcasite, chalcopyrite, pyrrhotite, sphalerite, arsenopyrite, and tellurides (Kazarinov 1969; Nesterov 1985). Gold is strongly associated with iron oxides and is represented by fine-grained native gold particles measuring from less than 50 to 250 μm, and rare - 4 mm, and by dispersed gold in the pyrite of first generation. Usually no visible gold is observed in the field. Gold fineness in pyrite is 900-970, native gold - 700-885.

5 Fluid inclusion studies

Thermometry and cryometry of individual inclusions in samples of Kuranakh mineralization have been studied to determine some physical and chemical factors of ore formation. The equipment used allowed analysis of phases and their changes in inclusions greater than 3-5 mc in diameter. The inclusions less than this diameter have been used as accessory material. The accuracy of temperature measurements was ±0.5°C for the cryocamera and 3-5°C for the thermocamera.

P-correction volumes were added to the homogenization temperatures (Th) in order to determine the forming temperatures (Tf) and calculated using data of Potter (1977). According to the petrological and geological data, a depth of formation of ore-bearing rocks in Kuranakh Ore Field was probably no more than 500 m. Because of the open character of the ore-forming hydrothermal fluid system, P-corrections were calculated in accordance with the hydrostatic model of fluid pressure. Estimations of the pressures were derived from fluid inclusions on the base of data (Potter and Brown 1977). In this case, the composition of inclusions is approximated by the system H₂O-NaCl.

We have studied quartz and calcite from Au-bearing ores of Severnoye, Porfirovoye, Tsentralnoye and Yuzhnoye ore bodies and found out that they contain two groups of inclusions of different origin. Gas-liquid and liquid inclusions of water solutions predominate. As follows from the obtained data, the temperatures increase southward from the Severnoye ore body towards the Yuzhnoye one. Apparently, the source of the ore-forming solutions was located nearer to the southern edge of the Kuranakh Ore Field.

Solution concentrations in inclusions for all deposits are nearly equal; the maximum values do not exceed 10% NaCl eq. There is no correlation between homogenization temperatures and solution concentrations, though, possibly, a tendency can be envisioned for a decrease in concentrations with increasing temperatures, especially in the “hottest” inclusions. At the same time, a drop in solution concentrations is distinct from primary to secondary inclusions in one same sample.

Fluid composition in inclusions from metasomatic quartz in all ore bodies are similar. They are essentially water solutions of chlorides of sodium and potassium, and rare calcium, magnesium and iron. Very low (-65, -78 and -79°C) eutectic temperatures hint at the presence of Li in one-phase liquid inclusions in quartz from the Severnoye and Yuzhnoye ore bodies.

Pressures of formation of Kuranakh ores did not exceed 100 bars, corresponding to a depth of no more than 1000 m according to the hydrostatic model and less than 500 m in terms of the lithostatic pressure.

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Tin metallogeny of Far East Russia

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Abstract. The northern part of the Eastern Asia Tin Belt occurs in the Russian Far East and contains five tin-bearing areas. The Russian Far East is one of the largest tin regions in the world. Numerous and well-known districts with tin lode deposits are known from Vladivostok in the south to the Chukchi Peninsula in the north. About 43,000 tonnes of tin concentrate were produced in the Russian Far East from 1991 to 1995. The geodynamic setting of the tin areas of Russian Far East is determined by their occurrence at the junction zones of various tectonic-stratigraphic units. The age of tin bearing intrusive rocks and associated Sn deposits of the Russian Far East ranges from Devonian to Miocene with a maximum in the Cretaceous.

Keywords. Tin, metallogeny, Russia, intrusive, geodynamic

1 Regional setting of tin districts

The Russian Far East is a part of the Eastern Asia Tin Belt that extends from Indonesia in the south to the Chukchi Peninsula in the north. The northern part of the Eastern Asia Tin Belt in the Russian Far East is represented by five tin districts – Chukotka, Kolyma, Yana-Indigirka, Khingan-Okhotsk, and Sikhote-Alin (Fig. 1).

The Russian Far East is one of the largest tin regions in the world. Numerous well-known districts with tin lode deposits were discovered from Vladivostok in the south to the Chukchi Peninsula in the north from 1937 to 1980. About 43,000 tonnes of tin concentrate were produced in the Russian Far East from 1991 to 1995. Previous studies of tin metallogeny of the Russian Far East were mainly based on the geosynclinal concept and did consider the correlation between geodynamics and tin metallogeny. Various modern publications interpret the tin metallogeny of the Far East Russia from a plate tectonic point of view (Rodionov 1988, 2000; Gonevchuk 2002; Mitrofanov 2002).

According to Rodionov (1998, 2000), the geodynamic setting of the tin districts of the Russian Far East is determined by their location at the junction zones of different tectonic-stratigraphic units of the following types: (1) cratonic and (or) metamorphosed continental margin terranes composed of Paleozoic and older metamorphic rocks; (2) accretionary wedge or subduction zone terranes composed predominantly of Paleozoic and early Mesozoic chert-volcanic-terrigenous rocks; (3) turbidite basin terranes composed predominantly of Mesozoic continental slope terrigenous rocks with local tectonic lenses and inclusions of deep-water oceanic calcareous, sandy-argillaceous, and chert-volcanic rocks of Paleozoic and early Mesozoic age; and (4) overlapping and stitching assemblages of calc-alkaline volcanic-plutonic belts of predominantly late Mesozoic and Cenozoic age.

The geodynamic settings are illustrated by the relation of tin deposits to corresponding structural elements (Fig. 2) and by composition features of tin magmatic complexes (Fig. 3).

2 Associated intrusive rocks

The age of tin-bearing intrusive rocks and associated Sn deposits of the Russian Far East varies from Devonian to Miocene with a maximum in the Cretaceous. The intrusive rocks are characterized by a wide range of composition, ranging from diorite, granodiorite, adammellite, biotite and (or) hornblende-biotite granite, to leucogranite and granite porphyry. These granitoids form two types of multiple intrusive complexes that were first recognised by Govorov (1973) and Rub et al. (1982).

The intrusive complex of the first type named as granodiorite-granite complex, typically consists of granodiorite and granite that form large batholiths. Spatially and temporarily related are rare gabbro, gabbro-diorite, and diorite that occur as dikes, or in the outer parts of granodiorite-granite massifs, or as xenoliths in granite. These more mafic rocks are interpreted as the earliest phase of the complex. The late, immediately pre-ore phase of the complex consists of dikes and stocks of leucocratic granite, granite porphyry, and aplite that occur in or near the granodiorite-granite batholiths. Mafic dikes, either symineral or postmineral, also locally occur. The rocks of the granodiorite-granite complexes belong to the ilmenite series with Fe2O3/FeO < 0.5 (Ishihara 1977), and are I-type (Chappell and White, 1974) mostly with a molecular ratio of Al2O3/(Na2O+K2O+CaO) of less than 1.1.

The granodiorite-granite complexes host tin quartz vein, tin greisen, and rare tin pegmatite deposits. The ore-magmatic systems including the granodiorite-granite complex and associated tin deposits occur mainly mainly in the inner parts of tin-bearing areas. The formation of these ore-magmatic systems proceeded in a relatively stable tectonic environment. The intrusive bodies and related deposits occur either at the margins of cratonic terranes or in close proximity. Tin deposits occur close to small intrusive bodies formed in the final magmatic stages of ore-magmatic systems. Mineralised fractures occur in folded rocks and in the margins of magmatic bodies. The fractures are interpreted as having formed during either folding, or intrusion and cooling of the magmatic bodies.
The second type of tin-bearing magmatic complex, i.e., the diorite-granodiorite complex, comprises abundant mafic and intermediate rocks. Although the sequence of intrusive rocks is the same as in the first type of magmatic complex, diorite and granodiorite are predominant. Gabbro and diorite of the first phases are of I-type ac-
According to the classification of Chappell and White (1974) with a molecular ratio of Al\textsubscript{2}O\textsubscript{3}/(CaO+Na\textsubscript{2}O+K\textsubscript{2}O) less than 1.1. Quartz diorite, granodiorite, and granite of the second phases have Al\textsubscript{2}O\textsubscript{3}/(Na\textsubscript{2}O+K\textsubscript{2}O+CaO) molecular ratio of about 1.1 and less. The rocks of the third, immediately pre-ore phases are mostly S-type with a molecular ratio of Al\textsubscript{2}O\textsubscript{3}/(Na\textsubscript{2}O+K\textsubscript{2}O+CaO) \textgeq 1.1.

The diorite-granodiorite intrusive complexes occur mainly in the peripheral parts of tin-bearing areas, and are usually accompanied by comagmatic volcanic sequences. This type of complex is associated with tin polymetallic veins and porphyry tin deposits. The final stages of the ore-magmatic systems occurred in areas that were tectonically active. Mineralized fractures are localized far from the intrusive bodies and are associated with regional structures.

The rocks of both intrusive complexes belong mainly to ilmenite series (Ishihara 1977) with small variations.

To understand the differences and similarities of above two tin magmatic complexes, the author studied geochemical evolution because the style of geochemical evolution is one of the important features of tin granites (Lehmann 1990). Figure 4 shows contrasting tin contents in different phases of the two tin magmatic complexes of the Russian Far East. The granodiorite-granite complex is characterized by a gradual increase in tin content in consecutive order from early to late magmatic phases (Fig. 4a). The evolution of the diorite-granodiorite complex corresponds to tin enrichment of the interim phases as well, but the last magmatic phase shows a relative decrease of tin content (Fig. 4b).

This assumption is confirmed by employing the Rittmann method (Rittmann 1973). The fields of early, interim, and late phases of both magmatic complexes occupy the corresponding close positions in a Streckeisen AQP diagram. The differentiation trends are also close (Fig. 6).

Figure 5 illustrates a gradual increase of initial Sr isotope ratio for tin magmatic complexes of the Russian Far East. The value of initial Sr isotope ratio almost for all isochrons corresponds to the field of mixed mantle-crustal material.

The two complexes were compared by the degree of fractionating using the ratio of 1/K\textsubscript{2}O (according to Togashi 1985), and Sr differentiation for the example of the South-Sikhote-Alin belt. A relatively low degree of fractionation was discovered for the rocks of the granodiorite-granite complex in contrast to the diorite-granodiorite complex. The Sr differentiation is comparable in both complexes. The fractionating trend of the rocks of the main phase of granodiorite-granite complex (low value of 1/K\textsubscript{2}O ratio and low Sr value) continues for the same phase of diorite-granodiorite complex (relatively high value of 1/K\textsubscript{2}O ratio and Sr). Based on that comparison, it is possible to assume the propinquity of the initial magmatic melt of both magmatic complexes.
The correlation of K and Rb contents in host rocks can be a confirmation of the assumption of the propinquity of the initial magmatic melt for both complexes. As shown by Kovalenko et al. (1981) and Rub et al. (1983), the Rb content in initially mantle magma is about 80 ppm or less, and the K/Rb ratio is about 500 or more. Palingenic crustal magmas contain Rb of about 150 ppm or more, and the K/Rb ratio is about 200 or less. The analysis of K-Rb correlation shows that rocks of the two tin magmatic complexes occupy the same intermediate area between mantle and crustal magmas.

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Figure 6: AQPF diagrams for two tin magmatic complexes of South Sikhe-te-Alin
Abstract. Granitoids and related mineralization in the circum-Japan Sea region and its environs in Northeast Asia were reviewed from the viewpoint of the evolution of the crust. Redox state of granitoid magmas, linked strongly with metallogeny, is influenced by sedimentary materials under various tectonic settings in the eastern margin of Eurasian continent during the Mesozoic to Early Tertiary time. The style of magmatism and mineralization contrasts with that of western North America which was situated in a relatively monotonous convergent margin. Magmatism in a given area tends to be of the oxidized-type with time due to the depletion of crustal carbon by previous magmatism. Stress conditions may also play an important role for the genesis of granitoid types; the oxidized-type granitoids may form even in a sedimentary-dominated crust under specific extensional environments without significant crustal input.

Keywords. Felsic magmatism, granitoid types, metallogeny, tin, accretionary complex, Jurassic, Cretaceous, Japan, Korea, Sikhote-Alin, Khingan-Okhotsk, Vorkhynsk-Kolyma

1 Introduction

Eurasia is a collage of continents of various origins, which were amalgamated in the Paleozoic and early Mesozoic. Since the Jurassic, East Asia has been an active continental margin with the subduction of the paleo-Pacific plate generating extensive magmatism and mineralization. The Jurassic, Cretaceous and Neogene to Quaternary felsic magmatic events provided major mineral resources to East Asia.

Jurassic magmatism widely occurred in east China and the Korean Peninsula, but it is not recognized in Sikhote-Alin and the Japanese Islands except for the Hida Belt in the northeastern Inner Zone of SW Japan (Sato et al. 1992). Sikhote-Alin and the Japanese Islands were situated in an accretionary terrane during Jurassic to earliest Cretaceous time, and changed to a magmatic arc in the Cretaceous (Sato et al. 2004a). The Cretaceous granitoids and related volcanic rocks in this region are dominated by the reduced-type granitoids and are often accompanied by Sn and W mineralization (Ishihara et al. 1992; Sato et al. 1992, 1993a,b; Khanchuk et al. 1996; Romanovsky et al. 1996), but they are of the oxidized-type (magnetite-series) and associated with Au or Mo mineralization in the following three areas: (1) Gyeongsang Basin in the southern Korean Peninsula, (2) southwestern Sikhote-Alin, and (3) Kitakami Belt in NE Japan (Fig. 1).

Cretaceous reduced-type magmatism occurs in the Jurassic accretionary terrane, while the Cretaceous oxidized-type magmatism occurs mainly in the older magmatic belts; the Jurassic belt in Korea and the Paleozoic belt in the Khanka massif within southwestern Sikhote-Alin (Fig. 2). The Kitakami Belt, particularly its northern half, is an exceptional case, where Early Cretaceous granitoids of the oxidized-type were emplaced in the Jurassic accretory complexes (Sato et al. 1992). Paleogene magmatism of the oxidized-type occurs in the Cretaceous magmatic belts (Sato et al. 2004a).

Regional distribution of the two types of granitoids and mineralization, corroborated with O, S and Sr isotope data suggest that the reduced-type granitoids are characterized by the association of Sn mineralization were generated in carbon-bearing sedimentary crust which was composed mainly of accretionary complexes. On the other hand, oxidized-type granitoids characterized by the association of Au or Mo mineralization were generated in...
igneous crusts which were depleted in reducing reagents by older magmatism (Sato et al. 2004a). Therefore, granitoid magmatism in a given area tends to be increasingly more of the oxidized-type with time. Geology of the Early Cretaceous Kitakami belt suggests that a specific extensional environment provided a site for oxidized-type granitoids and felsic volcanic rocks that are accompanied by Sn mineralization (Sato et al. 2004b).

3 Khingan-Okhotsk region

The Khingan-Okhotsk volcano-plutonic belt extends from the southeastern margin of the Bureya massif to the coastal area of the Okhotsk Sea, where Jurassic accretionary complexes are widely distributed. The belt consists mostly of the reduced-type granitoids and felsic volcanic rocks that are accompanied by Sn mineralization. The mid-Cretaceous episodic magmatism is thought to have been caused by the subduction of a young back-arc basin like the Andaman Basin in the Sunda arc (Sato et al. 2002).

4 Northeast Russia

Mesozoic magmatism and mineralization occurred in two belts: the Verkhoyansk-Kolyma region and the Okhotsk-Chukotka volcanic belt (e.g., Zonenshain et al. 1990; Parfenov et al. 1993). Late Jurassic to Early Cretaceous collision-related granitoids are distributed around the Kolyma-Omolon block. They are characterized by the S-type features and association of Sn deposits (Parfenov et al. 1999), suggesting reduced nature. Subduction-related volcanic rocks and granitoids are widely distributed in the Okhotsk-Chukotka belt, which are accompanied by rugged magnetic anomaly patterns (USSR Ministry of Geology, 1977), suggesting that the oxidized-type rocks are dominated.
In the Magadan area where the two belts intersect, granitoid plutons, probably of the southern end of the Verkhnyansk-Kolyma collisional belt, consist of the reduced type characterized by Sn and Au mineralization with negative $\delta^{34}S$ values, while those in the Okhotsk-Chukotka belt are of the oxidized type characterized by Au and Mo mineralization and positive $\delta^{34}S$ values (Ishihara et al. 1995; Goryachev and Goncharov 1995).

5 Summary

In Northeast Asia, diverse geodynamic settings provided many favorable sites for the generation of the reduced-type granitoids by the involvement of carbonaceous materials (Sasaki and Ishihara, 1979; Sato, 2003). Jurassic accretionary complexes may have been largely displaced from the original place of accretion to the northeastern margin to form a wide region of sedimentary crust in Sikhote-Alin and Khingan. These regions were subsequently subjected to intense Cretaceous felsic magmatism (Fig. 3) and converted to a large province of reduced-type granitoids accompanied by Sn mineralization (Sato et al. 2004a). In northeast Russia, collision of the Kolyma-Omolon block with the Siberian craton generated Late Jurassic to Cretaceous granitoids magmatism of the reduced-type. In western North America, repeated arc magmatism in the monotonous geodynamic setting during the Mesozoic formed granitoids of the oxidized-type which are practically free of Sn. The difference in the geodynamic regime between the east and west of the Pacific rim may have resulted in the remarkable contrast in the style of granitoids magmatism and mineralization.

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Tectonic and metallogenic evolution of northeast Asia: Key to regional understanding

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Abstract

The vast, mountainous terranes of Northeast Asia hold the key to the tectonic and metallogenic evolution of a major and geologically complicated region of the world. This region stretches from the Ural Mountains and the Arctic Islands of central Russia to the Kamchatka volcanic arc in the Russian Far East. The region also includes northern Kazakhstan, China, Mongolia, the Korean Peninsula, and Japan. The tectonic development of the region is recorded in a series of cratons, craton margins, oceanic plates, terranes, and overlap assemblages is complex due to extensional dispersion and translation during strike-slip faulting that occurred subparallel to continental margins.

This talk presents a series of regional tectonic time-slice maps and a computer animation that dynamically illustrate the tectonic assembly and major metallogenic events of Northeast Asia since the late Precambrian. The key events in the tectonic history of Northeast Asia are: (1) the formation of the Siberian craton during the breakup of a late Precambrian supercontinent (Pannotia); (2) the establishment, during the late Precambrian and early Paleozoic, of an active subduction zone along the present-day, southern margin of Siberia (Mongolian subduction zone); (3) closure of oceans between Siberia and Baltica (Ural Mountains), Kazakhstan and Siberia (Tien Shan Mountains), and North China and Amuria (Solonker zone) during the late Paleozoic; (4) the progressive closure of the Amurian seaway between northern China and Siberia during the Triassic and Jurassic to form the core of present-day Northeast Asia; (5) the Late Jurassic through early Cenozoic arrival of
allochtonous terranes in northern Siberia and the Russian Far East; (6) in the early Cretaceous, for the first time formation of a continuous continental complex between the Russian Northeast northwestern North America; and finally (7) in the Cenozoic, the formation of continental-margin arcs and back-arc basins along the entire Pacific-facing margin of Northeast Asia. We hope that this preliminary tectonic and metallogenic model of Northeast Asia, through incomplete and speculative, will provide new insights into the geologic, tectonic, and metallogenic evolution of this complex region, and will provide a basis for further study and investigation.
Mafic granulite xenoliths and their implications for mineralization at the Chaihulanzi gold deposit, Inner Mongolia, north China

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Abstract. Xenoliths within augite diorite at the Chaihulanzi gold deposit are grouped into mafic and amphibolite compositions; the mafic ones have experienced granulite metamorphism. Geochemistry, P-T conditions and isotopes of the mafic xenoliths indicate that they were derived from the lower continental crust and resulted from magmatic underplating during the early Mesozoic. The similarity in geochemistry and isotopic composition between host rock and mafic granulite xenoliths indicate that both were products that evolved from the same magmatic sources. Underplating is considered to have played an important role in the formation and migration of ore-forming fluids as well as the precipitation and enrichment of in Chaihulanzi gold deposit. H$_2$O and CO$_2$ are key constituents that controlled the formation and evolution of ore-forming fluids.

Keywords. Mafic granulite xenoliths, gold deposit, ore-forming fluids

1 Introduction

The Chaihulanzi gold deposit is a small deposit located at the northeastern end of the Mingshan uplift in the Chifeng-Chaoyang gold district on the northern margin of North China Plate. The gold deposit belongs to the alteration type, with ores hosted in the Late Archaean metamorphic rocks of the Jianping Formation. Ores are mainly in the No.1 mineralized alteration zone in augite diorite which is controlled by a NW-trending fault (Fig. 1). Alteration related to gold mineralization includes sericitization, silification and graphitization.

Studies on the genesis of the Chaihulanzi deposit by former researchers indicated that it is related to the augite diorite in the northern area of the gold deposit and has a magmatic mesothermal origin although the ore-forming fluids and materials were derived from depth (Wang, et al. 1994; She, et al. 2000). Recently, we have discovered a large numbers of xenoliths in the augite diorite (Fig. 1), some are mafic granulite xenoliths derived from the lower crust. Because the formation of the gold deposit is closely related to the augite diorite, studying the characteristics of the augite diorite and associated xenoliths may assist in determining the genesis of the gold deposit and its geologic setting. Sixteen xenoliths and eight host rocks were sampled for study of their geochemistry and isotopic compositions.

2 Mineralogy and geochemistry of xenoliths and host rocks

The augite diorite host to the xenoliths is mainly composed of calcic plagioclase (50-60%, An 59.2-77.5) and hornblende (30-35%) with minor augite (5%) and biotite (3-10%). SiO$_2$ contents of whole rocks range from 49.5-53.9 wt% with average of 52.4 wt%, it belongs to the calc-alkaline rock series. Using the K-Ar geochronologic method, an early Mesozoic age of 206 Ma has been determined (She et al. 2000).

Xenoliths in the augite diorite are of elliptical shape and about 5-20cm long with dark green or black structural banding and dark and light layering. The xenoliths can be classified into two groups: mafic and amphibolitic.

Mafic xenoliths are usually fine-grained with granoblastic, relict gabbroic or mosaic microstructures. Their mineralogies are dominated by clinopyroxene (15-80 % augite or diopside), hypersthene (30-35%) with minor augite (5%) and biotite (3-10%). SiO$_2$ contents of whole rocks range from 49.5-53.9 wt% with average of 52.4 wt%, it belongs to the calc-alkaline rock series. Using the K-Ar geochronologic method, an early Mesozoic age of 206 Ma has been determined (She et al. 2000).
Amphibolitic xenoliths are fine-medium grained, usually have granoblastic microstructure, and mainly consist of amphibole (25–50 %), plagioclase (30–55 %, An48–84.6), contain less augite (5–10 %), biotite (5–10 %) and quartz (0–10 %). Apatite is a common accessory mineral. Rock types include plagioclase amphibolite, amphibolite and quartz-bearing amphibolite.

The major element compositions of mafic granulite xenoliths are very consistent, SiO₂ contents are between 51.10 and 51.75 wt%, average of 51.3 wt%, all are mafic. SiO₂ contents of amphibolite xenoliths range from 50.0–58.1 wt% with an average of 54.0 wt%, and belongs to a mafic and intermediate rock class.

In general, the REE and trace element patterns of the xenoliths and host augite diorite are similar. Total REE contents of all samples are from 42.8 to 115.6 ppm, most are below 100 ppm. Intermediate amphibolite xenoliths and augite diorite have slightly higher total REE contents than mafic granulite xenoliths. The normalized (to primary mantle) REE patterns of all samples show LREE enrichment with LREE/HREE ratios at 2.89 to 9.55 and positive Eu anomalies (except one sample) with (n)Eu of 1.02–1.63, indicating that xenoliths’ source rocks have experienced partial melts.

All xenoliths and augite diorite samples have Cs, Ba, Nb, Sr, K enrichments, P, Th, U, Ta, Hf, Zr, Ti depletions. The trace element patterns of all rocks are similar to continental margin arc volcanic rocks.

3 P-T conditions

Temperatures and pressures for xenoliths were calculated using the major element compositions of mineral phases determined by an electronic microprobe. The thermometers employed are the two-pyroxene system of Wells (1977), and the plagioclase-amphibole system of (Holland, et al. 1994). The plagioclase-amphibole thermometer yield temperatures of 771°C for mafic amphibole-bearing granulite xenoliths and 667–889°C for amphibolite xenoliths, but may represent temperatures of retrograde metamorphism. The temperatures for mafic granulite xenoliths given by the thermometer of Wells (1977) provides temperatures as high as 1019–1320°C and as such may not be reliable, as they indicate that mafic granulite metamorphism equilibrium may not be well preserved. But it is reasonable to suppose that the temperatures should be greater than that (667–889°C) of retrograde metamorphism; 800–1000°C would be an acceptable temperature range for mafic granulite xenoliths according to estimated temperature for other granulite xenoliths in the world (Rudnick 1987, 1995). The amphibole barometer by Schmidt (1992) and the plagioclase-clinopyroxene-quartz barometer of McMarthy et al. (1998) has given pressures of 6.0–11.2 kbar (21.0–41.2 km) for the mafic granulite xenoliths and pressures of 2.2–6.5 kbar (7.8–23.2 km) for the amphibolite xenoliths. These data imply that the mafic xenoliths were derived from the lower crust and have experienced granulite facies metamorphism (T>650°C, P>4kbar), amphibolite xenoliths were entrained at mid-crust or upper lower crustal levels. It can be concluded that a complex metamorphic history has been endured by the xenoliths suites.

Compared with mafic granulite xenoliths in other areas of world, the xenoliths in Chaihulanzi gold deposit have similar geochemistry and microstructures, but are distinguished by their abundant contents of hydrous minerals (amphibole and mica) and lack of garnet (Rudnick et al. 1987, 1995, and references therein).

4 Isotopes

The δ¹⁸O values of host augite diorite, mafic granulite and amphibolite xenoliths range from 5.0–7.6 ‰, 6.6–7.0 ‰ and 8.1‰, respectively, indicating that they are all igneous origin. The δ¹⁸O of host rocks and the mafic granulite xenoliths are higher than that of mantle values, implying that they may be contaminated by the crust.

The lead isotope compositions of xenoliths and host rocks are quite consistent with ratios of 206Pb/204Pb, 207Pb/204Pb, 208Pb/204Pb from 18.108–18.634, 15.507–15.608, 38.212–38.836 with averages of 18.338, 15.562, 38.509, respectively. All model ages of lead isotope data are negative, suggesting that there was an addition of radioactive lead, or that the lead was from an enriched source. The lead isotopic compositions mainly fall within the range of the lower continental crust on the 207Pb/204Pb diagram (Fig. 2). The ratios of 206Pb/204Pb, 207Pb/204Pb, 208Pb/204Pb of the pyrite from gold ores ranges from 18.696–20.048, 15.701–15.851, 37.889–41.785, respectively, and also have negative model ages, but with a larger variation than the xenoliths and host rocks. This suggests that the ore-forming leads have a complex source, maybe from the augite diorite and influenced by the high radioactive materials in the continental upper crust (Fig. 2).
5 Petrogenesis of xenoliths

Heat provided only from an assumed geothermal gradient cannot provide the high temperature > 800°C required for granulite metamorphism at the lower continental crust, so an extraneous heat source is needed. Due to the absence of deformation structures in the xenoliths, frictional heat by tectonic movement is excluded as a source. The most probable source for additional heat would be from underplating basaltic magmas at the lower continent crust (Rudnick 1992). It is suggested that the mafic granulite xenoliths and host augite diorite resulted from basaltic underplating during the early Mesozoic. The similarity in the geochemistry and isotopic composition between the host rocks and the mafic granulite xenoliths indicate that they evolved from the same magma sources. The cumulates deposited from early basalt magmas were heated by later basalt magmas, experienced granulite facies metamorphism, and then were entrained and transported to shallow crustal levels as mafic granulite xenoliths by the more evolved diorite magma. Retrograde metamorphism (amphibolite facies) most likely occurred during ascent to the upper lower crust or middle crust. The positive Eu abnormality also indicates that the source rocks for the mafic granulite xenoliths were cumulates and experience plagioclase enrichment. The conformable geochemical and isotopic features for xenoliths and host rocks imply that underplated magma equilibrated at depth, and homogenization was achieved. The Pb, Sr, and Nd isotope data indicate that magma has been strongly affected by continental lower crust. All of this suggests that the underplated magma was evolved in AFC (Assimilation-Fractionation-Crystallization) model (Hildreth et al. 1988).

6 Implications for gold mineralization

The above discussion indicates that there was underplating beneath the Chaihulanzi gold deposit during the early Mesozoic, and that mafic granulite xenoliths and its host rocks were the product of underplating. It is reasonable to conclude from the close relationship between the host augite diorite and the gold orebody that the formation of the gold deposit could be related to magma underplating too. Base on current references and the features of the Chaihulanzi gold deposit, underplating may have influenced the formation of the gold deposit in following ways:

1. The underplating magma from the mantle would release enormous volumes of CO₂, releasing water from the magma, which will promote the formation of CO₂-rich aqueous fluids and promote granulite facies metamorphism (Wells 1979; Newton et al. 1980). The dehydration during partial melting as induced by underplating would also provide additional sources for fluids. The formation of CO₂-rich fluids would accelerate the decomposition of the sulfide minerals in wall-rocks or magmas, because as gold is a sulfophile element, sulfide decomposition would benefit the exsolution of gold into the melt and fluids, resulting in the formation of ore-forming fluids (Cameron 1988; 1989). The abundant CO₂-rich fluid inclusions in the Chaihulanzi gold orebody and graphite alteration in wall-rock around augite diorite may be related with such the CO₂-rich fluids.

2. At later stages of underplating, magmas would be H₂O-rich after CO₂ was released, and result in the formation of aqueous magma (Ronald et al. 1987). The H₂O-rich magma would cause the retrograde metamorphism of mafic granulite xenoliths and the formation of hydrous minerals (hornblende and mica). After the magma intruded the shallow crust, it would release a large amount of fluids at late magmatic stages. This is favorable for the migration and precipitation of gold and causes the alteration of wall rocks.

3. The underplating of the lower crust would cause extension of crust, and form a permeable zone down to several kilometers in the shallow crust (Groves et al. 1988; Wickman 1992). In addition to the high geothermal gradient induced by underplating, it would promote the formation of a hydrothermal convection system that would provide a favorable conduit for fluids and host structures for ore precipitation and enrichment.

Based on the above study, we can conclude that underplating has played an important role in the ore sources, formation and migration of ore-forming fluids, the precipitation and enrichment of ore. H₂O and CO₂ are key factors that control the formation and evolution of ore-forming fluids.

Acknowledgements

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Gold deposits of Transbaikalia, Russia

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Abstract. This paper considers gold deposits of Transbaikalia generated during Middle-Late Jurassic collisional and Early Cretaceous rifting stages. These deposits are clustered around the Mongolia-Okhotsk suture zone along which the Siberia and Mongolia-China continents had joined during collision. The distribution area of Mesozoic mineralization coincides with the occurrence of collisional and rift-related magmatism. The latite and high-potash calc-alkaline magmas are considered to be ore-generating. Gold deposits related to the collisional stage are divided into low-sulfide mesothermal (gold-quartz formation), moderate-sulfide mesothermal (gold-sulfide-quartz formation) and high-sulfide mesothermal (gold-quartz-sulfide formation) deposits of moderate depth. Deposits related to the rift stage are attributed to the formation of low-sulfide epithermal type of gold-silver formation. Relative resources of different types of mineral deposits have been estimated.

Keywords. Gold deposits, mineralization types, magmatism, collision, suture zone, rifting

1 Introduction

Transbaikalia (Trans-Baikal Region) is one of the largest gold provinces in Russia. Gold mineralization was generated within a significant span of time, from the Early Paleozoic to the Late Mesozoic. However, a major part of the Transbaikalia gold district, including those deposits that possess economic concentrations, formed in the Middle-Late Jurassic and Early Cretaceous. This paper presents the characteristics of these deposits.

2 Geodynamic setting and distribution of gold mineralization

The Siberian and Mongolia-China continental blocks, as well as the Onon island-arc terrane situated between them, collided during the Early/Middle Jurassic. These three crustal blocks are divided by two branches of the Mongolia-Onon suture which are the parts of the thrust systems having south-eastern vergence. The main branch of the suture, according to a new interpretation given in Zorin et al. (1998, 2001) is found along the Shilka River, and then turns to the south where it coincides with the Onon-Tura fault, and goes further to Mongolia where it is continued by the Bolnan fault (Fig. 1). In Transbaikalia, the suture has an additional Onon branch, limiting the Onon terrane from the east and the south. In the Early Cretaceous, the neighboring areas of Siberia and Mongolia-China were involved in rifting giving rise to concentric-depression structures.

We compared the gold deposit positions and the gold mineralization density (number of gold occurrences per 100 km²) with the location of the Mongol-Okhotsk suture zone given in the context of a revised interpretation (Fig. 1). This comparison shows that the major part of maximum gold concentrations and deposits cluster in a 60-80 km band along two branches of the suture. Moreover, these bands contain both Middle-Late Jurassic deposits related to the collisional stage and Early Cretaceous deposits related to the rifting stage. The richest deposits (Darasun and Balei) show relation to the conjunction of the branches of the Mongolia-Okhotsk suture.

The clustering of gold mineralization sites in the branches of the Mongolia-Okhotsk suture zone can be explained by their relatively higher fault permeability for transport of ore-forming magmatic melts and gold-bearing fluids. The blocks which participated in the collision were of different geometries. Therefore, some time after the collision the permeability of the suture zones was likely greater than that of faults newly formed in the continental crust after accretion. Clustering of gold occurrences in rather wide (60-80 km) bands can be due to the thrust character of the suture branches. Ore-forming magmas, could create intermediate chambers beneath the allochthonous and penetrated into them along some smaller faults, thus forming concentric features. In this scenario, ore occurrences should be located in the allochthonous somewhat apart from the thrust front. If the allochthonous served as a screen during the formation of magma chambers, then ore deposition could have taken place inside the autochthon as well. The mineral-bearing zones of the autochthonous could have been exposed by its partial denudation and (or) by tectonic unroofing during the Early Cretaceous rifting.
3 Magmatism

The ore-forming intrusions associated with the gold systems mainly include rocks of the shoshonite-latite and high-potassium calc-alkaline geochemical series. This suggests involvement of mantle sources for the magmatic melts. This is verified by Sr isotope studies where $\text{Sr}^{87}/\text{Sr}^{86}$ ratios in primary melts vary from 0.7050 to 0.7080. A comparison of Sr isotope values in pre-ore propylites (0.7044), syn-ore carbonates (0.7046) and latites (0.7050) verifies that mantle melts of latite compositions could serve as the source of fluids capable of carrying ore components (Plyusnin et al. 1988). The mantle-related origin for gold mineralization is confirmed by Pb isotope data from galena in the gold deposits and isotopic compositions of sulfur in associated sulfide minerals ($\delta^{34} \text{S} = +0.7 \text{ to } +7.8 \text{ } \%$; $S^{32}/S^{34} = 22.22$), which are similar to that of sulfur from meteorites (Plyusnin et al. 1988; Prokó‘ev et al. 2000). However, along with shoshonite-latite and high potash-calc-alkaline magmatic rocks, Middle-Late Jurassic calc-alkaline (Sr$^{87}/$Sr$^{86} = 0.7130$) magmatic rocks also occur.

The combination of mantle-related and crust-related melts can be explained by the overlapping of the mantle plume by the continental lithosphere during the collision (Zorin et al. 1998). Along with it, the broad occurrence of crust and mantle-related magmatism can result from the detachment of the lithospheric mantle and the formation of the astenospheric upwarp under a wide zone adjoining the suture (Zorin et al. 2001). Magmas are con-

sidered to have been generated due to decompression within the upwarp. Under these conditions, the lowermost crust also may have become partially molten. Mantle-related magmas partially mixed with the crust-related ones and penetrated jointly with fluids into the upper crust mainly along zones in the suture branches. The mantle-related source of melts provided the subalkaline character of the collisional magmatism, while a thick screen of the continental lithosphere (40-45 km) gave rise to a wide magmatic area. There is an approximate coincidence of collisional and rifting magmatic areas. Early Cretaceous continental rifting may have been driven both by the collapse of the collision-produced uplift after compression had ceased and by mantle convection related to the hotspot activity, overlapped by the continental lithosphere.

4 Types of deposits

According to formation conditions, deposits of the collisional stage are divided into low-sulfide mesothermal (1-5% sulfides), moderate-sulfide mesothermal (5-15% sulfides) and high-sulfide (>15% sulfides) mesothermal of moderate depth. The first group is attributed to gold-quartz formation with general temperature range of mineral formation from 450º to 120ºC. The productive mineralization stages include gold-low-sulfide (T=350-280ºC), feldspar-quartz (T=350-280ºC), quartz-bismuth-telluride with gold (T=400-270ºC), and pyrite-pyrrhotite-quartz (T=450-340ºC). The second type belongs to gold-sulfide-quartz formation with a general temperature range of 520-85ºC. The productive stages comprise quartz-actinolite-magnetite (T=400-295ºC), quartz-tourmaline with pyrite and chalcopyrite (T= 450-330ºC). The third group is attributed to gold-quartz-sulfide with general temperature range of 430-50ºC. The productive stages include mercury-barite-antimonite, called also as sulfoantimonite (T=270-150ºC), tetraedrite-chalcopyrite-fahlerz i.e. sulfosalt (T=300-200ºC), quartz-pyrite-galena-sphalerite, i.e. polymetallic (T=315-230ºC), quartz-pyrite-arsenopyrite-i.e.pyrite (T=390-275ºC). These deposits are controlled by concentric dome structures.

Deposits generated during the rift stage can be characterized as low-sulfide epithermal types of gold-silver that formed within a temperature range of 355-80ºC. The productive stages include quartz arsenopyrite-antimonite, gold-pyrrargyrite-miargyrite-carbonate-quartz (T=250-200ºC), adularia-carbonate-quartz with gold (T=250-200ºC), quartz-carbonate with chalcedony ones. The deposits are controlled by concentric depression structures.

5 Resources

Ore deposits and occurrences differentiated by resources are united into local ore-magmatic systems and are related to common metal sources. A new approach to resource estimation and prognosis of the ore-magmatic systems is proposed. It considers the total ore potential for all ore occurrences of each separate ore-magmatic system, which, in turn, considers such systems as large districts. The actual resources of deposits from concentric-dome structures related to the collisional stage make up 68% of the total gold resources, predictable resources amount to 83%; resources of deposits from concentric depression structures related to the rifting stage make up 32%, with predictable resources amounting to 17%.

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Unique ore complexes of sulfide dissemination zones
in northeastern Asia

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Abstract. Sulfide dissemination zones make up unique ore complexes. The genesis of large zones of fine-grained sulfide disseminations in terrigenous-volcanogenic sequences is presumably related to different processes ranging from hydrothermal-sedimentary to epigenetic processes related to deep-seated fluids. These zones have been insufficiently explored, although they serve as essential sources of ore materials for porphyry and vein deposits. The finely-disseminated sulfide minerals are enriched in various trace elements and are associated with inclusions of native metals (rare, noble, and other varieties). Therefore, systematic investigations of the mineral compositions of such zones for their geochemical characteristics are required. This is essential for solving questions of inherited mineralization and for identifying different sources of ore materials.

Keywords. Sulfide dissemination, genesis, sources, gold deposits, trace elements

1 Introduction

It has become increasingly evident that large ore-bearing zones are independent geological structures that have a prolonged evolutionary history that occasionally exceeds the duration of magmatic and tectonic cycles. The work of many investigators has revealed that metallocerous sedimentary and volcano-sedimentary sequences play an essential role in the formation of ore deposits. It is highly probable that gold mineralization in sedimentary sequences of the Verkhoyansk Complex is related to zones of finely-disseminated sulfide mineralization. Such zones are widespread in the Earth’s crust and genetically diverse, but they have been poorly studied because of their low commercial significance. Zones with finely-disseminated sulfidization and nanoscale mineralization serve as a missing link in the concept of basic ore formations (Tomson et al. 1984; Sidorov 1998). Previously, researchers could not explain the relationship of separate ore-bearing (particularly, epithermal rootless) veins with other ore-bearing structures. Therefore, they believed that ore materials in veins were derived from a proximal intrusion or some deep-seated (subcrustal) fluids. Based on the method of hierarchical ore-formation analysis, we demonstrate that the mineral composition of zones with finely-disseminated mineralization in several districts mimics mineralogical types of poly- and monochronous ore-formation series (hereafter, ore complexes). At the same time, all members of a specific series are characterized by certain features of mineralogical-geochemical interrelations.

2 Types of ore-bearing zones

In the northwestern Pacific, one can distinguish at least four types of sulfidization zones and corresponding ore complexes (Table 1). Zones of finely-disseminated sulfidization zones in Mesozoic sandy-clayey terrigenous sequences, which are widespread at the base of volcanogenic belts and in perivolcanic districts, are best studied. For example, ore-bearing zones of the Okhotsk-Chukot volcanogenic belt (OCVB) are accompanied by an assemblage of large volcanogenic depressions (tectonomagmatic zones). These structures are occasionally confined to hidden fractures and are spatially associated with volcanic structures. Gold-sulfide zones with disseminated ores are confined to shear (dynamometamorphism) zones composed of dark gray siltstones with finely-disseminated pyrite and arsenopyrite. Within the ore bodies (or fields), one can also recognize veins and veinlets with base metal sulfide mineralization of the gold-rare metal, gold-silver, antimony, and mercury assemblages. At the same time, these assemblages make up independent deposits beyond the disseminated ore zones. Therefore, we include all ore associations mentioned above into a single ore complex type, with disseminated gold-sulfide deposits as the major member (Sidorov 1998).

The mineralogical-geochemical analysis of ore zones and sulfide concentrates revealed inhomogeneous concentrations of Au, Ag, Pb, Sn, Zn, Sb, and other elements in fine-disseminated sulfides. Weakly differentiated ore material is an efficient intermediate source for the more differentiated vein deposits in the ore complex considered above. Disseminated sulfidization zones of the hydrothermal-sedimentary pyritic ore type are not scrutinized in the present communication. Results of the study of the Goldstrike deposit (Embsbo et al. 2003) - one of the largest Carlin-type deposits in the world, where the Paleozoic sequence includes pre-ore disseminated mineralization that was probably remobilized at the ore stage - support our genetic model (Volkov and Sidorov 2001).

Vein-dissemination zones with pre-porphyry silver mineralization in the superimposed riftogenic Omsukchan Depression at the southern OCBV branch are of special interest. Consideration of data on the Ag-bearing province of the western Verkhoyansk region (Kostin et al. 1997) suggests the following conclusion: Like respective rocks in the western Verkhoyansk region, Permian sequences
of the Verkhoyansk Complex at the base of the Omsukchan Depression have been characterized by abundant disseminated silver-sulfide mineralization that probably served as the primary source of ore material for the Late Cretaceous volcanogenic Dukat deposit. In other words, based on certain genetic features of mineral assemblages in ores of the Mangazei and Dukat deposits, we have every reason to include the Mangazei-type deposits into the basic silver-sulfide formation of the regional polychronous ore complex. Lead isotope data also do not contradict our assumption (Sidorov et al. 2003). The rhodonite-rhodochrosite mineralization in the Dukat deposit can easily be explained by the regeneration of stratiform deposits in the Permian manganiferous siliceous-terrigenous-carbonate sequences that are widespread in the adjacent Kolyma region (Shpikerman 1998).

Tin-bearing sulfide zones in the Kavalerov ore district (Primorye) are restricted to perivolcanic structures of the East Sikhote Alin Volcanic Belt (ESVB) and are also very interesting. According to Tomson et al. (1984), sulfide and carbonaceous metasomatite zones are developed in Mesozoic terrigenous sequences of the folded ESVB base strata. Carbonaceous metasomatites are composed of black and dark gray fine-grained rocks including graphite stringers and low-crystalline carbonate material with rutile, ilmenite, sulfides, native metals, carbides and spinels. The ilmenite-carbonaceous metasomatite contains several native metals, such as iron, lead—tin alloy, aluminum, tin, iron-zinc alloy, wustite, cohenite (?), and osmiridium. Native metals and their alloys are also found as accessories in volcanic rocks of Primorye (Filimonova 1981). The study region incorporates several porphyry- and vein- type tin ore deposits coupled with numerous anomalies of tin and associated metals. Gold and mercury aureoles outline boundaries of the ore region.

The study of the porphyry Cu and related ore complexes revealed that they are occasionally related to preporphyry sulfidization zones or massive sulfide deposits. According to Sidorov (1998), V.S. Popov assigned such porphyry Cu deposits to the massive sulfide ore complex that serves as the transitional member between the massive sulfide and porphyry ore types (Sidorov 1998). Similarities in the ore-metasomatic columns of massive sulfide and porphyry Cu deposits have also been noted in Meyer (1981). New data on the possible source of material for the porphyry Cu deposits have been reported from the P'yagin Peninsula (northern Okhotsk region). The Lora deposit is confined to the domal Srednii Pluton in the internal zone of the OCVB. Rocks of the pluton are superimposed on Triassic-Late Jurassic island-arc rock complexes (Sidorov 1998). Xenoliths of these rocks were found in diorites of the Srednii Pluton located approximately 15 km south of the Lora porphyry Cu-Mo deposit. Based on an abundance of bornite and chalcopyrite disseminations (up to 50%) in these rocks, we suggest that such copper mineralization in volcanosedimentary basaltic rocks could serve as the source of material for the younger porphyry mineralization. The primary source could be represented by both cupriferous basalts and massive sulfide Cu deposits in island-arc rocks that subsequently served as the basis and source of Cu for the Cretaceous volcanoplutonic structures. The geochemical specialization of porphyry Cu ores also testifies to their genetic relationship with basaltic rocks, because Cu displays the highest positive correlation with Cr in stringer-disseminated ores from the granitoids. The Mo input is probably related to volcanoplutonic complexes of the granitoid series. At the same time, Sn- and W-bearing magmatic rocks also contributed some specific features to the porphyry Cu deposits.

### Table 1: Major ore complexes, giant gold ore (Au-bearing) deposits, and their satellites in the northwestern sector of the Pacific ore belt.

<table>
<thead>
<tr>
<th>Type of ore-bearing zone</th>
<th>Major ore complex</th>
<th>Examples of giant gold ore (Au-bearing) deposits</th>
<th>Types of gold deposits and their satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disseminated As-bearing sulfides in terrigenous-carbonate sequences</td>
<td>Disseminated gold-sulfide</td>
<td>Maisk (Chukotka), Natalka (Magadan district), Nezhdaninsk (Yakutia)</td>
<td>Disseminated gold-sulfide, epithermal gold-silver, gold-quartz, and silver-base metal</td>
</tr>
<tr>
<td>Disseminated sulfide deposits in green tuffs and basalts</td>
<td>Massive sulfide porphyry copper</td>
<td>Peschanka (Chukotka), Lora (Magadan region)</td>
<td>Porphyry Cu, porphyry Cu-Mo, epithermal gold-silver, disseminated gold-rare metal, and skarn base metal</td>
</tr>
<tr>
<td>Disseminated base metal sulfide deposits in terrigenous-carbonate sequences</td>
<td>Disseminated silver-sulfide</td>
<td>Dukat (Magadan district), Prognoz, and Mangazei (Yakutia)</td>
<td>Epithermal gold-silver, silver-base metal, gold-rare metal, and tin-sulfide</td>
</tr>
</tbody>
</table>

### 3 Conclusions

The genesis of large zones of fine sulfide disseminations in terrigenous-volcanogenic sequences is presumably related to different processes ranging from hydrothermal-sedimentary to epigenetic (deep-seated fluid). These zones have been insufficiently explored, although they serve as essential sources of ore material for porphyry and vein deposits. Coupled with monochronous deposits of the porphyry Cu-Au-Sn series and other numerous satellite bodies, the sulfide dissemination zones make up unique...
ore complexes (polychronous ore-formation series). The finely-disseminated sulfides are enriched in various trace elements and associated with inclusions of native metals (rare, noble, and other varieties). Therefore, they should be systematically investigated for the mineral compositions of such zones for their geochemical character. This is essential for both solving the question of inherited mineralization and identifying different sources of ore materials.

Acknowledgements

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Kostin AV, Zaitsev AI, Shoshin VV (1997) The Silver-Bearing Province of Western Verkhoyansk Region, Yakutsk. (in Russian)
Sidorov AA (1998) Ore Formations and Evolutionary-Historical Analysis of the Noble Metal Mineralization, Magadan (in Russian)
Abstract. Based on an analysis and summary of available age data from gold deposits in the Xiaoqinling and other relevant areas, combined with a study of the tectonic evolution of east China, the authors suggest that the major ages of gold mineralization in the Xiaoqinling area range from ca. 130 to 120 Ma. These ages coincide with the age range of metamorphic core complex formation at shallow crustal levels and with widespread removal of the deep lithosphere.

Keywords. Ore-forming age, gold deposits, metamorphic core complexes, delamination

1 Introduction

The Xiaoqinling area is located on the southern margin of the North China craton and represents the second largest gold-producing area in China. Quartz vein-type deposits are the major gold resource. Much research around the lode gold deposits in this area has been carried out in order to better understand the gold mineralizing processes. However, knowledge of the timing of gold mineralization highly varies. Based on an analysis and summary of the available age data, we attempt to describe accurately the timing of quartz vein-type gold deposits in the Xiaoqinling area.

2 Available age data

The earliest ages of gold mineralization in the Xiaoqinling area are 108-76 Ma (Cao 1989). These ages were indirectly determined based on cross-cutting relationships between gold-bearing quartz veins and diabase and minette dykes. The ages of the latter were determined by K-Ar. Liu (1992) analyzed metallic minerals from quartz veins and obtained total-fusion $^{40}$Ar-$^{39}$Ar ages of 85 and 673 Ma for galena and pyrite, respectively, which he interpreted as two mineralization stages. Li et al. (1993) analyzed quartz of both the quartz-pyrite stage and quartz-polymetallic sulfide stage of quartz veins and obtained an Rb-Sr isochron age of 161.5±17.9 Ma. These authors suggested that the main mineralizing event occurred between 160 and 170 Ma. Shen et al. (1994) and Li (1997) suggested that gold mineralization occurred earlier than 1800 Ma in light of lead isotopic compositions and a comparison with gold deposits occurring elsewhere on the north margin of the North China craton. Xu et al. (1998) analyzed sericite from altered rocks in quartz veins by $^{40}$Ar-$^{39}$Ar and obtained a plateau age of 132.16±2.64 Ma. These authors suggested that gold mineralization took place after 132 Ma. When analyzing vein quartz, Xue et al. (1999) gained Rb-Sr isochron ages of 2382-2234 Ma and $^{40}$Ar-$^{39}$Ar ages of 2046 Ma (plateau age) and 2005 Ma (isochoine age), which led these authors to argue that the main gold mineralization occurred in the Paleoproterozoic. Lu et al. (1998) suggested that the mineralizing event occurred during the Indosinian orogeny according to an integrated analysis.

We have used the $^{40}$Ar-$^{39}$Ar dating method to analyze auriferous altered rocks from quartz veins in the middle-deep section of the deposit. Our results show that the main gold deposition occurred at ca. 128-126 Ma (YT Wang et al. 2002) (Table 1).
3 Discussions and conclusions

The age data obtained for mineralization from deposits in the Xiaoqinling area range from Paleoproterozoic to Late Cretaceous. The data obtained originally were mainly K-Ar ages (Cao 1989), and the geological implications of these dates is uncertain because the dating method cannot provide information on excess argon or argon loss. 40Ar-39Ar total release ages (Liu 1992) provide an average value of apparent ages so that these data actually agree well with those gained by the K-Ar method, but their uncertainty is the same as that of the K-Ar age. Li et al. (1993) put quartz samples of different mineralization stages together for Rb-Sr analysis and the isochron age obtained is possibly also a mixed age. Based on ore-forming temperatures, the homogenization temperatures of fluid inclusions in the quartz are generally lower than 350°C, which is far lower than the metamorphic temperature of the Paleoproterozoic amphibolite facies. Thus, it is improbable that the main gold mineralizing event occurred in the Paleoproterozoic (Shen et al. 1994; Li 1997; Xue et al. 1999). All of the different age data (Table 1) directly influence the recognition of the source of ore-forming materials and fluids, as well as metallogenic mechanisms.

Several integrated studies (Chen et al. 1998; Mao and Wang 2000; Zai et al. 2001; Mao et al. 2003) show that large-scale gold mineralization in the North China craton occurred in the Mesozoic. More and more reliable age data with good precision have been obtained from gold deposits at the peripheries of the North China craton in recent years, which are helpful to interpreting the mineralization ages in the Xiaoqinling area, where there similar geological settings and metallogenic features exist. There are many gold deposits in the Xiaoqinling area recorded the orogenic evolution as a marginal component of the Qinling orogen. In the collision process, the Xiaoqinling incorporated the Taihua nappe as an overthrust basement in a compressional tectonic regime (QC Wang et al. 1989; YT Wang and Hu 1999). In the post-collisional intracratonic process, the Xiaoqinling developed as a metamorphic core complex in an extension-dominated tectonic regime (Hu et al. 1994; JJ Zhang et al. 1998). The synorogenic (intracratonic orogeny) detachment parallel to the orogen developed in the Xiaoqinling metamorphic core complex at 135-123 Ma (JJ Zhang et al. 1998). Therefore, gold mineralization in the Xiaoqinling area mainly occurred at ca. 130-120 Ma, which coincides with the time range of formation of metamorphic core complexes in the shallow level and lithosphere delamination at deep levels.

### Table 1: Available age data of gold mineralization in the Xiaoqinling area, central China.

<table>
<thead>
<tr>
<th>No.</th>
<th>Gold-bearing quartz vein</th>
<th>Dating method</th>
<th>Age (Ma)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>K-Ar</td>
<td>108-76</td>
<td>Cao 1989</td>
</tr>
<tr>
<td>2</td>
<td>Q505</td>
<td>40Ar-39Ar</td>
<td>85 (glenite), 673 (pyrite)</td>
<td>Liu 1992</td>
</tr>
<tr>
<td>3</td>
<td>Q60</td>
<td>Rb-Sr</td>
<td>161.5±17.9</td>
<td>Li et al. 1993</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>Pb-Pb</td>
<td>&gt;1800</td>
<td>Shen et al. 1994; Li 1997</td>
</tr>
<tr>
<td>5</td>
<td>Q507</td>
<td>40Ar-39Ar</td>
<td>132.16±2.64</td>
<td>Xu et al. 1998</td>
</tr>
<tr>
<td>6</td>
<td>Q303</td>
<td>40Ar-39Ar</td>
<td>2046</td>
<td>Xue et al. 1999</td>
</tr>
<tr>
<td>7</td>
<td>Q875</td>
<td>40Ar-39Ar</td>
<td>128.5±0.2, 126.7±0.2</td>
<td>Wang et al. 2002</td>
</tr>
</tbody>
</table>

In eastern China, the lithosphere thinned rapidly to <80 km in the Mesozoic (Fan and Menzies 1992; Menzies et al. 1993; Deng et al. 1996), which may have resulted from lithosphere delamination (Gao et al. 1998) or lithosphere derooting (Deng et al. 1996). The timing of extensive lithospheric thinning is constrained to the Mid-Late Cretaceous although it lasted into the Cenozoic. During this period, volcanic activity, magmatic intrusions and metamorphism were extensive, and granitoids related to mineralization were mainly emplaced at 130-110 Ma (Mao et al. 2003). This tectonic regime originated during the peak time of crust-mantle interaction when deep-seated fluids, including magmatic fluids and metamorphic dehydration fluids, were produced, migrated and accumulated (Mao et al. 2000, 2003).

Numerous studies (SG Li et al. 1989; Ames et al., 1993; GW Zhang et al. 1996) show that the Qinling orogen resulted from collision between the North China plate and the Yangtze plate in the Indosinian period. In the Qinling area, the presence of both widespread collisional granites (GW Zhang et al. 1996) and rapakivi granites (Lu et al. 1996) in the Shangxian-Danfeng suture indicate that the two plates finally converged in the late Indosinian period, and that the area underwent intracontinental evolution or intracontinental orogenesis. During this process, the Xiaoqinling area recorded the orogenic evolution as a marginal component of the Qinling orogen. In the collision process, the Xiaoqinling incorporated the Taihua nappe as an overthrust basement in a compressional tectonic regime (Q.C Wang et al. 1989; YT Wang and Hu 1999). In the post-collisional intracratonic process, the Xiaoqinling developed as a metamorphic core complex in an extension-dominated tectonic regime (Hu et al. 1994; JJ Zhang et al. 1998). The synorogenic (intracratonic orogeny) detachment parallel to the orogen developed in the Xiaoqinling metamorphic core complex at 135-123 Ma (JJ Zhang et al. 1998). Therefore, gold mineralization in the Xiaoqinling area mainly occurred at ca. 130-120 Ma, which coincides with the time range of formation of metamorphic core complexes in the shallow level and lithosphere delamination at deep levels.
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Mineralizing pulses and geodynamic setting of Cu-Fe-Au polymetallic deposits in the Lower Yangtze valley, east-central China

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Abstract. Seven ore districts comprising more than 200 polymetallic deposits along the Lower Yangtze valley (LYV) from west to east are Edong, Jiurui, Anqing-Guichi, Tongling, Luzong, Ningwu and Ningzhen. These districts include Fe-Cu (Au), Cu-Au (Mo), Cu-Fe-Mo (Au), Fe-Cu-Pb-Zn, Cu-Au, Fe-Cu (Mo) and Fe-Pb-Zn deposits. According to available highly-precise isotopic ages for Cu-Fe-Au polymetallic deposits and related rocks in the LYV, large-scale mineralizing processes took place during the Late Mesozoic, with two pulses occurring at ~140 Ma and ~125 Ma. These ages are in agreement with the emplacement ages (135-140 and ~125 Ma) of voluminous igneous rocks in this region. Two stages of Late Mesozoic polymetallic mineralization occurred in this lithospheric extensional regime, and are probably related to lower crustal delamination and lithospheric thinning in East China.

Keywords. Mineralizing pulses, geodynamic setting, Cu-Fe-Au polymetallic deposits, China

1 Introduction

The Lower Yangtze valley (LYV), covering an area of about 30,000 km² and extending about 450 km from southeastern Hubei eastward to Zhenjiang provinces (Fig. 1), is the most important Cu-Fe-Au polymetallic metallogenic belt in East China. It has attracted considerable interest among the international exploration and mining communities. Systematic exploration and study of the LYV metallogenic belt started in the 1950s and focused on skarn-type copper and iron deposits. During the 1970s, several subvolcanic iron deposits were discovered in the Ningwu-Luzhong basins and exploration was undertaken (Fig. 1) (Ningwu Research Group 1978). In the past few decades, large Au (Cu) skarn deposits have been found, total gold reserves in this belt have been estimated at more than 600 tons Au (Zhao et al. 1999). Over the past 50 years, many studies on the sedimentation, magmatic activity, tectonic setting and metallogeny in the region have been undertaken and a wealth of geological and geochemical data for the Cu-Fe-Au polymetallic deposits have been accumulated (Chang et al. 1991; Zhai et al. 1996; Pan and Dong 1999; Zhao et al. 1999; Mao et al. 2004). More than 200 Cu-Au-Mo-Fe deposits have been discovered to date. From west to east, there occur the Edong Fe-Cu (Au), Jiurui Cu-Au (Mo), Anqing-Guichi Cu-Fe-Mo (Au), Tongling Cu-Au, Luzong Fe-Cu-Pb-Zn, Ningwu Fe-Cu (Mo) and Ningzhen Fe-Pb-Zn districts (Fig. 1). Ore deposits in this region are controlled by structure, sedimentation and magmatism (Zhai et al. 1996).

Recent, highly precise isotopic ages for the timing of formation of the Cu-Fe-Au polymetallic deposits and related rocks in the LYV, such as molybdenite Re-Os ages, mica ⁴⁰Ar-³⁹Ar ages, Rb-Sr isochron ages and zircon SHRIMP U-Pb ages, have been determined. Herein, we compile precise isotopic ages of Cu-Fe-Au polymetallic deposits and igneous rocks in the LYV to resolve the ages and stages of Mesozoic mineralizing processes and the nature of their corresponding tectonic settings.

2 Geological setting

The LYV metallogenic belt is situated on the northern margin of the Yangtze craton, and on the Sino-Korean craton and Qinling-Dabie orogenic belt (Fig. 1). The dominant regional structures are several large strike-slip systems. The metallogenic belt is bounded by the Xiangfan-Guangji Fault (XGF) on the northwest, the Tangcheng-Lijiang Fault (TLF) on the northeast, and the Yangxing-Changzhou Fault (YCF) on the south (Fig. 1). The LYV has a complex tectonic history with Proterozoic metamorphic basement rocks throughout. A thick sequence of Palaeozoic marine sediments unconformably overlies the basement rocks. From the Jurassic to Cretaceous, the LYV was affected by Late Mesozoic intensive magmatism which occurred extensively throughout eastern China. Among the igneous rocks, intermediate-acid intrusive rocks are dominant, consisting of calc-alkaline adakitic rocks (Xu et al. 2002; Wang et al. 2003), followed by extensive deposition of Cretaceous volcanic rocks and volcanic-sedimentary rocks.

According to Zhai et al. (1996), the LYV ore deposits conform to three associations - skarn and porphyry Cu-Mo-Au deposits related to calc-alkaline potassic intrusive rocks; skarn and ore magma type Fe-Cu-Au deposits related to sodium-rich calc-alkaline intrusive rocks; and Kiruna-type Fe deposits related to andesitic rocks in volcanic basins. The first and second groups are porphyry/skarn/strata-bound Cu-Au-Mo-(Fe) deposits (Pan and Dong 1999) formed in the Late Jurassic to Early Creta-
ceous, and thus earlier than the Fe deposits which formed in the Early Cretaceous (Zhai et al. 1996; Mao et al. 2004). The Mesozoic magmatic event consisted of Late Jurassic-Early Cretaceous mainly calc-alkaline plutonism and Early Cretaceous subalkaline to alkaline volcanism (Pei and Hong 1995; this study). According to their geochemical characteristics, magmatism related to mineralization processes in this region is divisible into two series: a high-K calc-alkaline granodiorite series and a sodium-rich calc-alkaline diorite series. The former consists of I-type gabbro, diorite, quartz diorite and granodiorite related to Cu-Au-Mo-(Fe) polymetallic mineralization in all ore districts (Pei and Hong 1995). Pei and Hong (1995) further related the occurrence of these granitoids to mantle-crust interactions and confined them to extensional and subsiding regions. The latter is composed of pyroxene diorite porphyry and diorite porphyry and their eruptive equivalents which are probably related to Kiruna-type Fe deposits in some ore districts, such as the Ningwu basin (Ningwu Research Group 1978). This volcanic sequence probably formed in an extensional tectonic regime (Chang et al. 1991).

3 Timing of Cu-Fe-Au polymetallic mineralization

The precise ages of metallic deposits in the LYV metallogenic belt are shown in Figure 2. The data in this figure apparently indicate that extensive Cu-Fe-Au polymetallic mineralization occurred in the Late Jurassic and Cretaceous. These events record an important metallogenic event, which is consistent with previous observations (Zhai et al. 1996; Mao et al., 2004), and that two mineralizing pulses took place at ~140 and ~125 Ma (Fig. 2). There occurred an important mineralization episode in Late Jurassic to Early Cretaceous (~140 Ma) in the LYV. On the eastern margin of the Jiurui ore district, the Chengmenshan deposit is one of the most important porphyry Cu, Mo skarn, and stratabound Cu-Au deposits, which has reserves of 3.07 million tons of copper ore with an average grade of 0.77%, 43.6 tons of gold ores with an average grade of 0.24 g/t and a molybdenum grade of 0.047% (Pan and Dong 1999). Molybdenite Re-Os model ages of this deposit range from 139±3 to 144±2 Ma (Wu et al. 1997; Mao et al. 2004).

The Yueshan Cu-Mo deposit is the most important deposit on the eastern margin of the Anqing-Guichi ore district, and contains 34 million tons of copper ore with an average grade of 1.03% (Pan and Dong 1999). Mao et al. (2004) used Re-Os dating to determine mineralization ages from 137.9±1.5 to 142.6±1.7 Ma with an average of 140.3 Ma, similar to the Os-Os model age of 136.1±2.0 Ma obtained by Sun et al. (2003). The Tongling ore district is the largest polymetallic area in the LYV, where dozens of Cu-Mo deposits have been found and mined. The molybdenite Re-Os isochron ages of the Datuanshanadn and Jinkouling Cu-Mo deposits are 139.1±2.7 Ma and 137±0.2 Ma respectively (Mao et al., 2004; Meng et al., 2004). Chromium sericite in ores from Xiaodongguashan and Laomiaojishan Cu deposits gave 40Ar/39Ar plateau ages of 135.48±0.45 and 144.93±0.44 Ma (Meng et al. 2004). Zeng et al. (2004) obtained a phlogopite 40Ar/39Ar plateau age of 144.9±0.4 Ma for ore-bearing skarn in the Shizishan Cu deposit. In addition, Kiruna-type deposits have been discovered in the Ningwu volcanic basin in the east of the LYV. 40Ar/39Ar plateau and isochron age dating of potassium-bearing minerals from orebodies and related altered rocks in these Fe deposits have been determined in recent years. Albite from the Meishan and Taocun Fe deposits yielded 40Ar/39Ar plateau ages of 122.90±0.16 Ma and 124.89±0.30 Ma and phlogopite from the Zhongshan-Gushan ore field gave a plateau age of 126.7±0.17 Ma (Yu and Mao 2004). These features indicate that these Kiruna type deposits related to volcanic rocks formed later than the porphyry and skarn type Cu-Au-Mo(-Fe) deposits related to in-
trusive rocks. Based on the geological setting, it may be inferred that extensive Late Mesozoic intrusive and volcanic rocks in the region are genetically associated with Cu-Fe-Au polymetallic mineralization in the LYV (Chang et al. 1991; Zhai et al., 1996). For comparison, the precise ages of the intrusive and volcanic rocks are also shown in Fig. 2. It can be seen that LYV magmatic activity took place in the Late Jurassic to Cretaceous, with two peak activities at 140–135 Ma and ~125 Ma, corresponding to two coeval mineralizing episodes (Fig. 2). The intrusive rocks emplaced during 140–135 Ma are related to the porphyry and skarn-type Cu-Au-Mo (-Fe) deposits, while the volcanic rocks formed at ~125 Ma and are related to Kiruna type deposits.

4 Geodynamic mechanisms controlling Cu-Fe-Au deposits in the LYV

Large-scale mineralization processes in East China occurred in response to certain tectonic processes. Most of the Late Mesozoic intrusive rocks related to mineralization in the LYV have recently been proposed to be adakite-like, and their geochemical characteristics suggest that asthenospheric upwelling and lithospheric thinning occurred in the LYV (Wang et al. 2001).

In comparison with other parts of the Asian circum-Pacific metallogenic belt, these polymetallic deposits formed in an aborted continental rift setting (Zhai et al. 1996). Based on precise molybdenite Re-Os dating of LYV Cu-Au-Mo deposits, Late Jurassic-Early Cretaceous (144–134 Ma) polymetallic deposits formed during the tectonic transformation from a N-S compressional regime to E-W extension (Mao et al. 2004). The porphyry iron deposits formed as a result of large-scale lithospheric delamination and sinistral strike-slip movement along the Tanlu fault zone (Yu and Mao, 2004). Accordingly, the mineralizing pulses and their relationship to magmatism and the geodynamic framework, widespread Cu-Fe-Au deposition occurred in an extensional setting that probably occurred in response to lower crustal delamination and lithospheric thinning. However, the geodynamic setting of the large-scale mineralization processes in the LYV remains to be further studied.

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Mesozoic Mo-W-Ag-Pb-Zn mineralization in the Nannihu area, western Henan Province, China

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Abstract. There are many Mesozoic hydrothermal Mo-W-Ag-Pb-Zn deposits in the Nannihu area, west Henan Province, which is located in the eastern part of the Jinduicheng-Nannihu Mo-W polymetallic metallogenic belt of the southern margin of the North China Craton. Deposit types in the Nannihu area include porphyry-skarn Mo-W deposits, skarn polymetallic pyrite deposits, and structurally-hosted, altered-rock Ag-Pb-Zn deposits. These deposits show a consistent spatial-temporal association with Late Jurassic magmatism. Sulfur and lead isotopic compositions indicate that ore was mainly derived from the lower crust. Hydrogen-oxygen isotope compositions indicate that ore fluids were derived from primary magmatic water in the early stages, and a mixture of magmatic and meteoric water in the later stage. During a period of tectonic regime transitions in eastern China in the Late Jurassic, underplating of mafic magma, partly remelting of the lower crust, and intrusion of acid magmas developed successively, resulting in extensive mineralization in the area.

Keywords. Deposit type, mineralization characteristics, mineralization model, Nannihu, Henan

1 Introduction

The Nannihu area is located in the eastern part of the world’s second largest, Jingduicheng-Nannihu Mo-W polymetallic metallogenic belt. Since the 1970s, several large Mo-W and Ag-Pb-Zn deposits have been discovered in this region. Most research publications have concentrated on the geological features, geochemistry, and mineralogy of the deposits and the petrogenesis of porphyries associated with Mo-W-Pb-Zn-Ag mineralization of the area (Luo et al. 1991; Yan et al. 2002; Xu et al. 2003).

This paper presents a metallogenic model based on new data associated with magmatism, mineralization ages and S, Pb, H and O isotopic compositions.

2 Geological setting

The Nannihu area is located on the southern margin of the North China Craton, sandwiched between the Luanchuan fault on the south and Machaoying fault on the north. Outcrops include banded chert-bearing carbonate rocks of the Neoproterozoic Guangdaokou Group, carbonates rocks and trachyte of the Neoproterozoic Luanhu Group and terrigenous clastic-carbonate rocks of the Neoproterozoic Taowan Group. The nearly W-trending faults formed in the Late Triassic and Early Jurassic (Ren et al. 1998) and the NE-trending faults formed during the Mid-Late Jurassic transition of the tectonic regime in eastern China (Mao et al. 2003), and constitute a grid-like structural framework. In addition, the Late Jurassic Nannihu and Sanfanggou granite porphyries also occur. These intrusions were derived from partial remelting of the lower crust that gave rise to I-type granitoids (Wang et al. 1986). Mo-W-Ag-Pb-Zn deposits occur around the granite porphyries.

3 Types of Mo-W-Ag-Pb-Zn deposits

Hydrothermal mineralization in the Nannihu area includes porphyry-skarn type deposits (e.g. Nannihu-Sandaozhuang Mo-W, Sanfanggou Mo-Fe), skarn deposits (e.g. Luotuoshan polymetallic pyrite), and structural altered-rock type deposits (e.g. Lengshuibeigou Ag-Pb-Zn). The location of various main deposits is shown in Figure 1 and their characteristics are given in Table 1.

4 Metallogeny of Mesozoic Mo-W-Ag-Pb-Zn deposits

4.1 Spatial distribution of deposits

There is a regular zonation surrounding the porphyries, i.e. porphyry-skarn Mo-W deposits occur within the contact zone of porphyries and wall rocks; skarn polymetallic pyrite deposits occur within skarned marbles around the intrusions; and structurally controlled altered-rock Ag-Pb-Zn deposits occur within faults around the intrusions. The regular distribution of deposits around the porphyries exhibit zoned features of hypothermal, mesothermal and leptothermal mineralization.

4.2 Metallogenic ages

The Nannihu and Sanfanggou granite porphyries have SHRIMP zircon U-Pb ages of 157.1±2.9 Ma and 157.6±2.7
Ma respectively (Mao et al. 2005), the Nannihu-Sandao-zhuang and Sanfanggou deposits have a Re-Os isochron age of 141.5±7.8 Ma (Li et al. 2004), the Lengshuibeigou Ag-Pb-Zn deposit has an 40Ar-39Ar plateau age of 137.87±0.39 Ma. These ages show that the granitic porphyries are slightly older than the deposits, and that the porphyries and deposits exhibit different evolution stages of the same tectonic-magmatic-ore fluids system in the same geodynamic setting.

4.3 Features of ore fluids

Mineralization of porphyry-skarn Mo-W deposits can be divided into three stages: early skarnization stage, late skarnization stage and hydrothermal stage. The average temperatures of each stage are as follows: 447°C in the early skarnization stage (Hu 1988); 410°C in the late skarnization stage; 345°C of the K-feldspar-quartz assemblage (substage I), 310°C of the sulphide-quartz assemblage (substage II) and 250°C of the zeolite-carbonate assemblage (substage III) in the hydrothermal stage (Zhou et al. 1993). The mineralization of skarn deposit can also be divided into three stages as the porphyry-skarn deposits, but only the data of the late skarnization stage and hydrothermal stage are available. The average temperatures of the late skarnization stage are 370-520°C and that of hydrothermal stage are 160-230°C respectively. The mineralization of the structural altered-rock deposits can be divided into three stages: pyrite-quartz stage, quartz-polymetallic sulphide stage and quartz-carbonate stage. The average temperatures of every stage is 330°C, 220°C, and 140°C respectively. Hydrogen-oxygen isotope characteristics of the porphyry-skarn and structural alteration type deposits indicate that the ore fluids feature a mixture of magmatic water and meteoric water. As shown in

Table 1: Main types and characteristics of hydrothermal deposits in Nannihu area.

<table>
<thead>
<tr>
<th>Type</th>
<th>Deposit</th>
<th>Host rock</th>
<th>Spatially associated intrusions</th>
<th>Ore-controlling structure</th>
<th>Ore mineral assemblage</th>
<th>Wall-rock alteration</th>
<th>Mineralization ages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porphyry-skarn type</td>
<td>Nannihu-Sandao-zhuang Mo-W deposit</td>
<td>Skarnification marble, biotite halleflinta, skarn of Neoproterozoic Luanchuan Group</td>
<td>Nannihu granitic porphyry (157.1Ma, Mao et al. 2005)</td>
<td>Contact zone of granitic porphyry body and wall rock</td>
<td>Pyrite, pyrrhotite, molybdenite, chalcopyrite, galena, sphalerite, scheelite</td>
<td>Skarnification, k-feldsparization, silicification, carbonatization, fluoritization, zeolitization</td>
<td>141.5Ma (Li et al. 2004)</td>
</tr>
<tr>
<td></td>
<td>Sanfanggou Mo-Fe deposit</td>
<td>Dolomite, marble, halleflinta, skarn of Neoproterozoic Luanchuan Group</td>
<td>Sanfanggou granitic porphyry (157.6Ma, Mao et al. 2005)</td>
<td>Contact zone of granitic porphyry body and wall rock</td>
<td>Pyrite, magnetite, scheelite, pyrrhotite, sphalerite, molybdenite</td>
<td>Skarnification, silification, k-feldsparization, sericitization, fluoritization, carbonatization</td>
<td></td>
</tr>
<tr>
<td>Skarn type polymetallic pyrite</td>
<td>Luotushan polymetallic pyrite deposit</td>
<td>Quartzite, quartz, mica schist, marble, halleflinta, skarn of Neoproterozoic Luanchuan Group</td>
<td>Late Jurassic granitic porphyry dike</td>
<td>Nearly EW trending fault</td>
<td>Pyrrhotite, pyrite, sphalerite, galena, chalcopyrite, scheelite</td>
<td>Skarnification, k-feldsparization, silification, chloritization, carbonatization, actinolitization</td>
<td></td>
</tr>
<tr>
<td>Structural altered-rock type</td>
<td>Lengshuobei Ag-Pb-Zn deposit</td>
<td>Quartzite, quartz, mica schist, marble, halleflinta, skarn of Neoproterozoic Luanchuan Group</td>
<td>Late Jurassic granitic porphyry dike</td>
<td>NE trending fault</td>
<td>Galena, sphalerite, Pyrite, chalcopyrite, Native silver</td>
<td>Pyritization, silicification, sericitization, carbonatization</td>
<td>137.87Ma (this study)</td>
</tr>
</tbody>
</table>
Figure 2, the δD values (–72.00‰ to –75.10‰) and δ18O values (7.95‰ to 8.61‰) (Xu et al. 1999) of the fluid inclusions of strongly silicified quartz in the late skarnization stage of Sanfanggou porphyry-skarn deposit plot in the magmatic water region. In the hydrothermal stage, the δD and δ18O of the fluids have the values of δD = –66.3‰ and δ18O = +4.95‰ (substage I), δD = –81.4‰ and δ18O = +3.7‰ (substage II), and δD = –77.7‰ and δ18O = +0.24‰ (substage III), showing their deviation from primary magmatic water but mixing towards the meteoric water line from early to late substages. In the Lengshuibeigou structural altered-rock type Ag-Pb-Zn deposit, the δD values (–80‰ to –83‰) and the δ18O values (–0.03‰ to 1.93‰) of the fluids indicate a mixture of magmatic water and meteoric water. The ore fluids exhibit low salinity features of the H2O-CO2-NaCl system with salinities ranging from 3.2% to 10.3% (Zhou et al.1993).

4.4 Sulfur-lead isotope geochemistry

The δ34S values of 93 samples of metallic minerals from the Nannihu-Sandaozhuan and Sanfanggou deposits range between +0.37‰ and +5.44‰, with an average of +2.93‰; the δ34S values of 9 samples of metallic minerals from Luotuoshan deposit range between +1.29‰ and +4.2‰, with an average of +2.57‰. The δ34S values of 7 samples of metallic minerals from the Lengshuibeigou deposit range between +0.70‰ and +3.80‰, with an average of +2.3‰. The δ34S values of 2 pyrite samples from Neoproterozoic Baishugou Formation of the Luanchuan Group are +18.63‰ and +12.43‰ respectively. The δ34S values of 7 pyrite samples from Neoproterozoic Meiyaogou Formation of the Luanchuan Group are divided into two groups, i.e. –12.4‰ to –8.1‰ and +6.6‰ to +10.5‰. The δ34S values of metallic minerals from various types of deposits exhibit a narrow range, which is notably different from the wide range of the δ34S values of metallic minerals in strata. It indicates that various types of deposits have almost the same sulphur source, which mainly came from the deep level rather than the cover.

The 206Pb/204Pb, 207Pb/204Pb and 208Pb/204Pb values of K-feldspar from porphyries, pyrite and galena from ores are of 17.12-17.894, 15.23-15.705 and 37.57-39.095 respectively. Most values (Fig. 3) plot near the mantle evolution curve, and some between the mantle and orogenic lead evolution curves and near the lower crust lead evolution curve. This suggests that the lead and associated metals in the porphyries and the deposits were mainly derived from the lower crust.

5 Hydrothermal mineralization model

In the Triassic, the Yangtze and North China plates collided to form the Qinling orogenic belt, and then both the south margin of the North China Craton and Qinling orogenic belt entered a new stage of intracontinental tectonic evolution. During the Middle-Late Jurassic, under the influence of transition of the tectonic regime in eastern China, underplating of basic magma took place near the crust-mantle boundary resulting in the rise of mafic magma and emplacement into the crystalline basement of the Neoarchean Taihua Group. The diabase dykes formed at 182–142 Ma (K-Ar, Hu et al. 1988). In this thermal regime, the lower crust partially remelted and formed granitic magmas. The intrusion of magmas at the intersection of the W- and NE-trending faults resulted in the formation of hypabyssal I-type granitic porphyries (e.g. Nannihu, Sanfanggou porphyries) and hydrothermal ore-forming fluids.
Various types of deposits formed during the hydrothermal evolution: porphyry-skarn type Mo-W deposits formed near the contact zone of the intrusions and wall rocks in the earlier stage, resulted by the precipitation of ore substance from the post magma hydrothermal fluids; skarn polymetallic pyrite deposits formed in the skarned carbonate wall rocks of the intrusion; structural altered-rock Ag-Pb-Zn type deposits formed in faults around the intrusions in the late stage resulted by the precipitation of ores from mixing magmatic and meteoric waters.

Acknowledgements

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References


Abstract. The outer part of the western belt of the Circum-Pacific ore-forming belt in eastern China underwent widespread tectono-magmatic-metallogenic processes in the Mesozoic. Well-developed superimposed metallogenic systems constitute one of the main regional metallogenic features of eastern China. Through the study of these metallogenic systems in the middle and lower reaches of the Yangtze River, and of the Yuebei basin (northern Guangdong province), the authors suggest basic patterns of sedimentary-magmatic superimposed metallogenic processes and summarize their controlling factors and conditions of formation.

Keywords. Metallogenic systems, superimposition, Yangtze River, Yuebei basin

1 Examples of superimposed metallogenic systems

Eastern China belongs to the outer part of the western belt of the Cenozoic Circum-Pacific ore-forming belt. The timing of the metallogenic peak in eastern China occurred in the Mesozoic due to tectonic transition and widespread magmatism at that time (Hua 1999). Eastern China underwent repeated crust-mantle interactions, polycyclic tectonization, sedimentation and magmatism. As a result, there were good conditions for the superimposition of metallogenic systems. Superimposition of metallogenic systems constitutes one of regional ore-forming features of eastern China (Zhai et al. 1999a; Zhai 2002).

China has an extremely complex tectonic setting, with multiple stages of tectonic, magmatic, and metallogenic histories as well as tectonic-related sedimentary-metallogenic histories. As a result of this complexity, superimposition of metallogenic systems is a common feature of many of the ore districts. Among them, superimposition between early sedimentary or hydrothermal-sedimentary metallogenic system and late magmatic-hydrothermal metallogenic systems is the most common. Typical examples of superimposed metallogenic systems in China are shown in Table 1.

1.1 Yangtze River Fe, Cu, Au, S, Pb, Zn metallogenic province

The Early Paleozoic sedimentary metallogenic system occurred in the Cambrian black siliceous mudstone formations; ore-forming elements contain U, W, Sn, Mo, Cu, Au, V and P, etc., and mainly constitute the ore-source bed. Some moderate and small ore deposits formed locally. This system is distributed in the southern and northern belt of a faulted depression ore-forming belt on the periphery of an ancient crystalline basement.

The Late Paleozoic hydrothermal sedimentary metallogenic system is mainly distributed in early and middle Carboniferous submarine secondary depressions. Siderite-pyrite is the typical mineral association. Its formation may be due to hydrothermal sedimentation induced by ancient earthquakes and relative uplift. Both ore-source bed and ore formation occurred along the regional and contemporaneous faults. Contemporaneous faults controlled both the formation of ore-bearing secondary basins and the migration and deposition of early stage ore-forming materials. It also controlled the intrusion of the Yanshanian (middle and late Mesozoic) late stage ore-bearing intrusions.

The Yanshanian granite-diorite magmatic metallogenic system turned into an extensional structural mechanism in late Yanshanian time. The crust is stretched and thinned, and the mantle uplifted. Upper mantle fluids, alkali materials and a large amount of metals migrated mantle uplifted areas due to decompression associated melting. The fluids assimilated the lower-crustal rocks and formed melts. Abundant metals and fluids, high heat flow and structural activities constituted favorable ore-forming conditions. Deep-seated high-temperature magmas and ore-magmas are dominant in the main mantle uplift belt, where they formed Fe, Cu, Au, S deposits of ore-magma type and skarn type and porphyritic Fe deposits. While in the two lateral uplift-depression transitional belts, well-differentiated intermediate-acidic magmatic-hydrothermal ore-formation are prevalent and Cu, Mo, Au, Pb, Zn deposits of porphyritic type and porphyritic-skarn compound type formed.

Weathering metallogenic system: This is related to Cenozoic weathering action and modification of above-mentioned ore deposits and ore-source beds of different genesis, including iron caps, gold-bearing iron caps, supergene-enriched copper deposits, sedimentary and drift-bed depositional gold deposits and lateritic gold deposits.
Superimposition is striking between metallogenic systems in this area, namely, the late-stage formed Yanshanian magmatic (-hydrothermal) metallogenic systems that overlap early-formed Paleozoic hydrothermal-sedimentary metallogenic systems. The superimposition of two major ore-forming events produced important large Cu, Fe, Au deposit in this area, such as Wushan, Chengmengshan, Dongguashan, and Xinqiao.

1.2 Polymetallic sulfide ore districts of the Yuebei Basin

Many kinds of ore deposits in the Yuebei basin in the northern Guangdong Province are the products of tectonic movement, magmatism and evolution of sedimentation-diagenesis-related mineralization of the basin. Very thick accumulations of volcanic and sedimentary rocks were deposited in a pre-Darvonian interarc ocean trough in this area. These metal-rich rocks are the material source for later mineralizing events. The superimposition of two major ore-forming events produced important large Cu, Fe, Au deposit in this area, such as Wushan, Chengmengshan, Dongguashan, and Xinqiao.

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### Table 1: Some superimposed metallogenic systems in Eastern China.

<table>
<thead>
<tr>
<th>Regional tectonic setting</th>
<th>Superimposition between different metallogenic system</th>
<th>Ore deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault depression of the middle and lower reaches of the Yangtze River</td>
<td>Hercynian hydrothermal sedimentary ore-formation-Yanshanian (middle and late Mesozoic) magmatic-hydrothermal ore-formation</td>
<td>Wushan, Dongguashan</td>
</tr>
<tr>
<td>Fault depression of the middle and lower reaches of the Yangtze River</td>
<td>Ore-formation of Triassic evaporates-Yanshanian magmatic-hydrothermal ore-formation</td>
<td>Echung</td>
</tr>
<tr>
<td>Fault depression between Zhejiang and Jiangxi provinces</td>
<td>Late Carboniferous(C1,C2) hydrothermal sedimentary ore-formation-Yanshanian magmatic-hydrothermal ore-formation</td>
<td>Linghouch copper ore deposit of Jiande</td>
</tr>
<tr>
<td>Palaeozoic basin in the northern Guangdong province</td>
<td>Hydrothermal-sedimentary and volcanic-sedimentary ore-formation of the Donggangling stage of the Middle Devonian-Yanshanian magmatic-hydrothermal ore-formation</td>
<td>Dabaoshan</td>
</tr>
<tr>
<td>The Danchi fault depression of the northwestern Guangxi province</td>
<td>Hydrothermal-sedimentary ore-formation of the Donggangling stage of the Middle Devonian-Yanshanian magmatic-hydrothermal ore-formation</td>
<td>Dachang</td>
</tr>
<tr>
<td>Tidal flat area in basins of the margins of the Yangtze Craton</td>
<td>Sedimentary Mn ore deposit of the Datangpo stage of early Sinian-Indosinian (early Mesozoic) magmatic-hydrothermal ore-formation</td>
<td>Tangnanshan magnesian ore deposit in Ningxian area</td>
</tr>
<tr>
<td>Epicontinental sedimentary area of South China</td>
<td>Sedimentary Mn ore deposit of the Chuanxian stage of late Carboniferous-Yanshanian magmatic-hydrothermal ore-formations</td>
<td>Lianchenshaoqian Mn ore deposit</td>
</tr>
<tr>
<td>Fault depression belt in the southwestern Fujian province</td>
<td>Sedimentary Mn ore deposit of the late stage of middle Devonian-Yanshanian magmatic-hydrothermal ore-formations</td>
<td>Mimaoshan Mn ore deposit</td>
</tr>
<tr>
<td>Hercynian-Yanshanian ore-forming belt in Hunan province</td>
<td>Upper Permian coal formation-Yanshanian granitic contact hydrothermal metasomatic graphite ore deposit</td>
<td>Lutang graphite ore deposit in Chengzhou</td>
</tr>
</tbody>
</table>

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**Middle-Late Devonian (D2-D3) pyrite metallogenic epoch:** In the early Devonian, the basement of Southern China was reactivated and rifted, forming Hercynian-Indosinian (early Mesozoic) sedimentary basins. In early stages of Middle-Late Devonian (D2-D3), the Yuebei basin formed as a result of rapid transtension. The northern margin of the basin uplifts locally, and syn-depositional faults are common. Ore-forming fluids migrated along these faults. When FeS2 migrating in the form of chlorine complex or organic complexes met with H2S barriers in the strata, beddinglevel pyrite ore bodies formed. This type of pyrite ore deposit (Hongyan type) is widely distributed in the Yingde area in the southern part of the basin. These deposits formed in the contemporaneous faults or in the hanging wall of the Middle Devonian series and the lower part of the Upper Devonian series. At this stage, submarine volcanism occurred at the junction of the Dabaoshan-Yingde contemporaneous fault and a WNW-striking contemporaneous fault, causing the formation of submarine volcanic exhalative-sedimentary Cu-Pb-Zn deposits and siderite deposits (Dabaoshan type)(Ge et al. 1987).

**Late stage of early to middle Carboniferous (C1-C2) Pb, Zn and pyrite ore-forming epoch:** Affected by the strong extension of the western Pacific rift and associated large scale volcanism, the Fankou area of the Yuebei basin uplifted in the late stages of the early Carboniferous era. Micro-riffs (the Hutian trench) occurred and basic magmas intruded in the middle Carboniferous, forming hydrothermal circulation systems (seawater and deep fluid) in submarine zones. Deep-seated high temperature fluids rich in CO2, Pb, and Zn upwelled along contemporaneous faults. Shallow seawater rich in HCO3 oozed downward along contemporaneous faults and extracted Pb, Zn etc. These two kinds of fluids converged in extensional syn-depositional zones within the Hutian formation. Large scale sulfide ore bodies of Pb, Zn and pyrite with complex shapes occurred due to the H2S geochemical barriers. They also overlap on the pyrite ore beds of the first ore-forming epoch.
Yanshanian (J-K₁) magmatic-hydrothermal W, Sn, Mo, Pb, Zn ore-forming epoch: Mineralization of this epoch mainly occurred in certain areas of the Yuebei basin. Accompanying the Yanshanian orogenic process were large amounts of S-type granites that intruded causing the formation of granite-related W, Sn, Mo, Pb, Zn metallogenic systems such as the Dabaoshan phorphyritic Mo-W(Cu) deposit, the Yiliu Pb-Zn deposit and the Hongling W deposit. The Dabaoshan intrusive bodies also superimposed on the early bedding ore bodies, forming the complex superimposed metallogenic system.

2 Combination patterns of sedimentary-magmatic superimposed metallogenic systems

Superimposition between sedimentary ore-forming and magmatic ore-forming systems is the most common superimposition metallogeny. There are many combination patterns (Fig. 1) of superimposition metallogeny in the geological evolution. Based on research in eastern China, superimposition between Paleozoic sedimentary (hydrothermal, volcanic) metallogenic systems and Mesozoic (Indosinian, Yanshanian) magmatic-hydrothermal metallogenic systems is the most common one. Other combination patterns require more attention and further research.

3 Formation conditions of superimposed metallogenic systems

Superimposition of metallogenic systems is one of the most important mechanisms for forming large ore deposits and many strata-bound ore deposits are formed through this mechanism.

What factors control the superimposing of metallogenic systems? Through the study on superimposed metallogenic system of the middle and lower reaches of the Yangtze River, the Yuebei basin (basin in the northern Guangdong province) the Nanling area and other areas, the following reasons are put forward.

- Stable geochemical field. A long-stable geochemical field can supply ore-forming elements many times. They can concentrate and form ores several times throughout their history, thus providing basement material for the superimposition between two or more metallogenic systems. For example, the Nanling W-Sn geochemical province is considered as the source material for W-Sn mineralization.
- Overlap of ore-forming structural belts. Overlapping of ore-forming structural belts can cause the superimposition between two metallogenic systems. For example, sedimentary (or hydrothermal sedimentary) metallogenic systems in rifts or rifting basins of extensional structural mechanisms can be superimposed by deep-seated magmatic hydrothermal metallogenic systems in orogenic process.
- Persistent structurally-focused hotspots. These can provide necessary heat for several metallogenic systems.
- Repeated activity of contemporaneous faults. Research on the Tongling, Dabaoshan and other syngenetic deposits in China, and comparative research on multi-genetic and compound ore deposits abroad, show that syn-basin-forming faults can serve as passageways of ore-bearing fluids and depositional space for part of the ores associated with marine hydrothermal sedimentary ore deposits (SEDEX type)(Zhai, et al. 1998). When reactivated due to later tectonic stresses, the fault can reactivate to act as passageways for later magmatic fluids and host related ore deposits. So syn-basin faults are the hinge and bridge to link early and late ore formation. They play a very important role in the formation of sedimentary-revised ore deposits.
- Ore minerals of some bedded ore deposits that formed in the early metallogenic systems can provide geochemical barriers for later ore-bearing fluids and favor the superimposition of two metallogenic systems. The formation of strata-bound Cu-polymetallic ore deposits in the middle and lower reaches of the Yangtze River may be caused by this ore-forming mechanism.

<table>
<thead>
<tr>
<th>Sedimentary-volcanic sedimentary</th>
<th>Magmatic-hydrothermal</th>
<th>1 Archean</th>
<th>2 Proterozoic</th>
<th>3 Paleozoic</th>
<th>4 Mesozoic</th>
<th>5 Cenozoic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Archean</td>
<td></td>
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<tr>
<td>B Proterozoic</td>
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<tr>
<td>C Paleozoic</td>
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<tr>
<td>D Mesozoic</td>
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<tr>
<td>E Cenozoic</td>
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</tbody>
</table>

Figure 1: Basic types of sedimentary-magmatic superimposed metallogenic systems. Examples: A4-greenstone type gold deposit; B3-Bayan Obo; C4-Wushan, Tongguanshan, Dabaoshan, Dachan, Linghou; D4-Shizishan; D5-Yalong. Possible: A2-Ancient weathered crust of BIF; A5, B5, C5-weathered crust type ore deposit of early formed ore deposit.
Favorable preserving conditions. This has two meanings, namely, the early formed metallogenic system are favorable preserved and occurred at suitable depth; also there are preferential preserving conditions after it is superimposed by late metallogenic system.

Acknowledgements

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Li PL (1989) Ore-forming process evolutionary regularities of the Fankou Pb deposit. Geology and prospecting 25: 9-16
Abstract. The South Qinling orogenic belt is well-known for its Pb-Zn polymetallic ore deposits. Most are regarded as SEDEX deposits that formed during the Devonian. Recently however, some advances in exploration have shown that not only are there sedimentary exhalative types of mineralization, but also epigenetic hydrothermal mineralization that are also very important. There are two types of epigenetic mineralization according to recent research on two typical deposits in the Zhashan polymetallic district: fluid metasomatism and fluid metasomatic-reformed mineralization based on hydrothermal exhalation-sedimentary ores or rocks. Ore bodies of the Mujiazhuang copper deposit are controlled by fractures, and rich ore bodies of the Tongmugou zinc deposit are similarly controlled. Lead isotopes from ore minerals in the Mujiazhuang have highly radiogenic compositions as do altered rocks near the ore body, indicating that they formed from the same lead isotope reservoir. On the basis of fluid inclusion evaluations from the Mujiazhuang copper deposit, it is shown that the deposit formed from moderate to high salinity ore-forming fluids.

Keywords. Epigenetic mineralization, Carboniferous, Mujiazhuang copper, Tongmugou zinc, South Qinling Lead-Zinc polymetallic belts

1 Introduction

The South Qinling orogenic belt, is widely known for its Pb-Zn polymetallic ore deposits (Fig. 1). Most of these deposits are regarded as SEDEX deposits that formed during the Devonian (Wang Junfa et. al. 1991; Qi Sijin et. al. 1993a, 1993b, 1999; Wang Xiang et. al. 1996; Wang Jilei et. al. 1996; Xue Chunji 1997; Fang WeiXuan 1998). Recent exploration advances have shown that, as well as the sedimentary exhalative styles of mineralization, there are also important deposits of epigenetic mineralization. It is very clear that the Mujiazhuang copper deposit, located in the Zhashan polymetallic district, is an epigenetic deposit that formed by fluid metasomatism during the Carboniferous. In addition, the Tongmugou zinc deposit, also located in the Zhashan polymetallic district, is a fluid metasomatic-reformed ore deposit based on hydrothermal sedimentary exhalative-ores or rocks, on the basis of research on geological characteristics of isotope geochemistry, fluid inclusions geochemistry, mineralization dating and event geology.

2 Geologic setting of epigenetic mineralization

The South Qinling Devonian Pb-Zn metallogenic belt extends from Tanchang County of Gansu Province eastwards to Shanyang County of Shaanxi Province and is bounded by the Lixian-Baiyun-Shanyang deep fault on the north and by the Minxian-Liangdang-Zhenan deep fault on the south. The belt is 560 km in length from east to west and 17-58 km in width, with a total area of 23,000 km². This metallogenic belt can be divided into three Pb-Zn ore fields from east to west: the Xichen Pb-Zn ore field, the Fengtai ore field and Shanzha ore field.

Three key magmatic-hydrothermal and associated mineralizing events have been recognized based on research of the regional magmatism, metamorphism and geochronology. These include the hydrothermal sedimentary event during 360-340 Ma, the structurally-focused magmatic associated mineralization formed by deeply magmatic activity and linked hydrothermal activity during 320-280 Ma, and the shear zone associated alteration at the brittle-ductile transition by late-stage crustal hydrothermal fluids that were active during 190-170 Ma. It is widely recognized that the 320-280 Ma fluid metasomatic event (Carboniferous) is the most important among the regional hydrothermal events (Zhu 2004).

An important feature in causing these regional hydrothermal events, is the collision between the Qinling Block with the North China Plate during Carboniferous begins forming the granite in the deep interior of the Zhashan area to generate a region of high geothermal background, which resulted in the formation of fluid metasomatic metallogenic districts (Zhu 2004).
3 Mineralization and ores

There are two kinds of epigenetic mineralization based on research of two typical ore deposits in the Zhashan polymetallic concentration area: fluid metasomatism and fluid metasomatic-reformed mineralization based on hydrothermal exhalation-sedimentary ores or rocks.

The Mujiazhuang copper deposit is located nearly in axial planar fractures of the Jinjinghe-Hujiamiao inverted anticline which is in south limb of Hongyansi-Heishan composite syncline in the Zhashan area. The axial planar fracture is a complicated structure, as it forms in an inverted limb, has two stages of activity: early detachment and later left-lateral strike-slip faulting. The structures are filled by Cu-bearing ankerite-quartz veins, but the main ore bodies are located in late-stage fractures. Most of the ores in-filled dilatant zone of fracture, are mass and network forming mineralization. The scale of ore bodies depends on the properties of the host-rocks: network veins form ore bodies in brittle rocks and massive ore bodies form in softer, less-brittle rocks. Biotite alteration forms in relation to copper mineralization.

The Tongmugou zinc deposit, located in the inverted north limb fractures of the Maluping inverted syncline, is a rich zinc deposit of the fluid metasomatic-reformed type. The main ore-bearing rock is albite slate or albite-scapolite slate of the Qingshiya group which is Devonian aged. There are multi-layer lamella and minute sphalerite grains in low-grade ores that it are intergrown with pelite, composed of minute lamellar and relic layering. Wall-rock alteration (albite, silication, scapolite etc …) is single-sided or asymmetric. It is clear that they formed by hydrothermal exhalation-sedimentary during the Devonian. Ore shoots, are located in subsidiary fractures (F3) derived from F2 structures, and are larger and thickness near points of F2-F3 intersections, and are en echelon arranged down dip. Wall-rock alteration (greenstone-coloured, mainly composed of hoepfnerite, epidote, diopside, biotite, quartz, and chlorite) is symmetrical about ore shoots indicating that the massive and brecciated ores of the Tongmugou zinc deposit are of the fluid metasomatic-reformed deposit type.

4 Lead isotopes

Ore mineral lead isotope values of the Mujiazhuang area are highly radiogenic and anomalous, as are the altered rocks near the ore body (Fig. 2). Some analyses of copper minerals have Pb isotope compositions that are distinctly more radiogenic: \( ^{206}\text{Pb}/^{204}\text{Pb} \) varies from 21.496 to 23.533, and \( ^{207}\text{Pb}/^{204}\text{Pb} \) varies from 15.775 to 15.972, \( ^{208}\text{Pb}/^{204}\text{Pb} \) varies from 40.221 to 41.426, which show that lead was derived from U and Th. The Pb isotope compositions of the wall rocks have a very restricted range of compositions: \( ^{206}\text{Pb}/^{204}\text{Pb} \) varies from 17.933 to 18.598, and \( ^{207}\text{Pb}/^{204}\text{Pb} \) 204Pb varies from 15.469 to 15.527, \( ^{208}\text{Pb}/^{204}\text{Pb} \) varies from 37.693 to 37.859; and show that the Pb isotope compositions of altered rocks near the ore body have distinctly more radiogenic compositions: \( ^{206}\text{Pb}/^{204}\text{Pb} \) varies from 20.125 to 22.299, \( ^{207}\text{Pb}/^{204}\text{Pb} \) varies from 15.671 to 15.770, \( ^{208}\text{Pb}/^{204}\text{Pb} \) varies from 38.580 to 39.054. Abnormal Pb ratios are restricted to the ore body and altered rocks near the ore body, and indicates derivation from the same lead reservoir.

In contrast, both the Mujiazhuang and Cambrian ores and rock lead isotopes compositions are homoplasy, and it is suggested that the abnormal Pb isotopes reservoir of the Mujiazhuang are from Cambrian. It is put forward that lead of the Tongmugou zinc deposit are also abnormal which are from the basis rocks like hydrothermal deposit rocks.

5 Fluid inclusions

On the basis of fluid inclusions for the Mujiazhuang copper deposit, it is shown that there were two stages of fluid evolution: the first stage is magmatic-hydrothermal with moderate temperatures, moderate and high salinity (CO₂)-H₂O+NaCl fluid, its homogenization temperatures range
from 190 to 265°C and salinity 12.5-35.34 wt% eqNaCl, pressure 12.8-21.3 Mpa. Due to the co-existence of hyper-saline fluid inclusions and vapour inclusions in the Mujiazhuang copper deposit, it is suggested that the mineralizing fluid was over-saturated and that boiling occurred.

The second stage is characterized by a moderate-high temperature, moderate to high salinity H2O+NaCl fluid, with homogenization temperatures of 300-350°C and salinities of 7.4-41.59 wt% eqNaCl, at pressures of 10.8-19.3 Mpa (Zhu 2004). On the basis of fluid inclusions for the Tongmugou zinc deposit, it seems that only the first stage of fluid evolution occurred there.

On the basis of the geochemistry of the fluid inclusions (tracing of indifferent gas and REE), it is suggested that the mineralized fluid derived from formational and magmatic water in the Tongmugou deposit, and from formational and magmatic water in the Mujiazhuang deposit. Hydrogen and oxygen isotopic data from the Mujiazhuang copper deposit also support this notion (Zhu et al. 2003, 2004).

6 Dating of mineralization

Biotite associated with chalcopyrite in the Mujiazhuang copper deposit returned an Ar-Ar age date of 323.7 Ma (Zhu Huaping 2004), which represents the age of mineralization. The formation age of hoepfnerite minerals was close to the timing of deposition of the Pb-Zn deposit, and a less accurate K-Ar age is 293 Ma (Zhu Huaping 2004). The main ore-forming age of Cu-Pb-Zn deposits in the Zhashan area is therefore about 323-293 Ma. It is inferred that Carboniferous mineralization was a very important metallogenic period in the Zhashan area. The mineralization model of epigenetic fluid matomatism, is founded according to geological and geochemistry characteristics, and suggests a new direction for ore deposits exploration.

References

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