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Fluid inclusion and H–O–S–Pb isotopic evidence for the Dongxiang Manto-type copper deposit, South China

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ABSTRACT

The Dongxiang copper deposit is located in northeastern Jiangxi Province, South China. Ore bodies in the Zishan Formation of this province are primarily stratoid and lentiform and show a close spatial association with Jurassic intrusive rocks. The current debates generally concentrate on whether the Dongxiang copper deposit is a Carboniferous sedimentary deposit or, alternatively, a Jurassic porphyry–skarn deposit. Three stages of mineralization can be observed in this deposit: the pre-ore, main ore, and post-ore stages. The massive sulfide ore bodies are identified as the main ore stage, whereas the pyrite-quartz veins and barren quartz veins are identified as pre-ore and post-ore stages, respectively. Three fluid inclusion types were recognized: two-phase vapor-rich fluid inclusions (type 1), two-phase liquid-rich fluid inclusions (type 2), and halite-bearing fluid inclusions (type 3). All three of these types of inclusions are present in the main copper mineralization stage, but only type 2 inclusions occur in both the pre-ore and post-ore stages. Type 2 inclusions in the pre-ore stage display homogenization temperatures (Th) of 349–392 °C, with salinities of 1.4–8.1 wt.% NaCl equivalent. In the main ore stage, types 1 and 3 inclusions show similar Th at 289–346 °C and 273–348 °C but contrasting salinities of 0.4–4.5 and 29.4–41.9 wt.% NaCl equivalent, respectively. In the post-ore stage, type 2 inclusions have Th of 144–228 °C and salinities of 0.4–6.0 wt.% NaCl equivalent. The coexisting types 1 and 3 inclusions in the main ore stage have similar Th ranges but contrasting salinities, which indicates that fluid boiling occurred. The determined hydrogen and oxygen isotopic values for these fluids (δD from −42‰ to −69‰; $\delta^{18}O_{H2O}$ 5.04‰ to 9.01‰), based on analysis of fluid inclusions and host quartz, imply that the inferred ore fluids were principally derived from magmatic water. The lead isotopic compositions of sulfides from the ores and plagioclases from the adjacent porphyry indicate that they share a common origin. The sulfides from the ores show $\delta^{34}S$ values of 0.3–3.2‰, also suggests a magmatic source. As the fluid inclusions and isotopic compositions strongly suggest a magmatic origin, this argues against a SEDEX origin for this deposit. In addition, the presence of stratoid and lentiform ore bodies and the absence of skarn alteration minerals suggest that the Dongxiang copper deposit is best described as a Manto-type rather than a porphyry–skarn deposit.

1. Introduction

The most important base metal reserves in South China are represented by more than 20 major deposits; examples include Mashan, Wushan, Chengmenshan, Dongguashan, Xinqiao, Dongxiang, Yongping, Dabaoshan and Fankou. These deposits occur within the sequences of Hercynian–Indosinian marine basins and consist primarily of stratiform and/or stratoid ore bodies. The genesis of these deposits is controversial. Submarine sedimentary exhalative genesis was first proposed by Xu and Zhu (1978) and has been widely accepted by numerous authors (Gu and Xu 1984; Gu and Xu 1986; Gu et al., 2003; Hou and Zaw 2008; Liu et al. 1979; Wang et al. 1986; Xu and Zhu 1978; Zaw et al. 2007; Zhao et al. 2013; Zhu and Zhang 1981; Zhu 2005). Alternatively, other authors have reported that these deposits have a genetic association with Late Mesozoic intrusions and can be classified as porphyry–skarn type deposits (Mao et al. 2008).

The Dongxiang copper deposit (E116°36′34′-116°39′41″, N28°17′15″-28°17′55) is located 43 km northeast of Fuzhou City, Jiangxi Province, South China. It was discovered in the 1950s due to the presence of a gossan. Subsequent geological prospecting and exploration demonstrated that it is a Cu–Fe–W deposit. The Dongxiang deposit contains 0.31 Mt of Cu metal at an average grade of 1.1 wt.% Cu and a cutoff grade of 0.3 wt.% Cu, 1.09 Mt. of iron with an average grade of 46 wt.% Fe, 19,000 t of W with an average grade of 0.65 wt.% W, and 3.59 Mt S with an average grade of 22 wt.% (JGEB 1983). Various aspects of geological setting, mineralization and exploration of the Dongxiang copper deposit have previously been reported by many researchers (Xu 1997;

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Xue et al. 2000; Zhang 2001; Zhang and Huang 1979; Zhu 2005, CSU 1997; JGEB 1983). Nevertheless, the characteristics of ore-forming fluids and the source of ore-forming materials are still poorly constrained.

In this paper, we present new data obtained from a combined fluid inclusion microthermometric and Raman analytical study, together with the results of detailed H–O–S–Pb isotope analysis, on representative samples obtained from the three stages of mineralization associated with the deposits. These data provide important constraints on the PVTX properties and origin of fluids associated with these different stages of mineralization, including ore-forming fluids and materials. The results are discussed in the light of previously proposed ore genetic models and fluid sources for the deposit and a new model (Manto-type) is proposed and discussed.

2. Geological setting

South China consists of the Yangtze Block to the northwest and the Cathaysia Block to the southeast, separated by the Qinzhou–Hangzhou belt (Fig. 1A), of which the eastern part is well known as the Jiangshan–Shaoxing (simplified as Jiang-shao) fault zone. The Jiang-shao fault zone is considered to be a Neoproterozoic suture zone, along which the two tectonic units amalgamated at ~1.1 Ga to 0.9 Ga (Li et al. 1999; Mao et al., 2011a, b; Yang and Mei 1997; Zhang and He 2002). The NE Jiangxi Province in the Qinzhou–Hangzhou belt is one of the most important locales for Cu (Au) polymetallic deposits in South China, where many large and super-large Cu (Au) polymetallic deposits are present, such as the Dexing copper deposit, the Yongping copper deposit, the Yinshan Cu–Pb–Zn polymetallic deposit and the Dongxiang copper deposit (Cai et al. 2011; Mao et al., 2011a; Wang et al. 2012, 2015a; Zhao et al. 2013; Li et al. 2015). In this belt, magmatic activities were frequent and intensive from the Jurassic to the Cretaceous, particularly during the Mid-Late Jurassic, with principally intermediate-acid rocks. The intermediate-acid granodiorite porphyries of the Mid-Late Jurassic are widely accepted to have a close relationship with copper mineralization in this area (Hsu et al. 1990; Wang et al. 2012, 2013, 2015a; Zhou and Yue 1998).

The Dongxiang copper deposit is located at the junction of the NE Jiangxi deep fault and Pinxiang-Guangfeng deep fault (Fig. 1B). The stratigraphy sequence in the ore district comprises the Neoproterozoic Shuangqiaoshan Group, Upper Devonian-Lower Carboniferous Zhongpeng Formation, Upper-Lower Carboniferous Zishan Formation, Upper Carboniferous Hutian Group and Cretaceous sedimentary rocks. Neoproterozoic rocks, which occur in the northwestern part of this area, consist of phyllite-based, epi-metamorphic rocks. The Upper Devonian-Lower Carboniferous Zhongpeng Formations, comprising clasolite and shale, are present in the middle of this deposit. They are in unconformable contact with the underlying Neoproterozoic epi-metamorphic rocks. The Upper–Lower Carboniferous Zishan Formation comprises gray quartz sandstone, sandstone, shale and conglomerate intercalated with marl. The Upper Carboniferous Hutian Group is composed of marine carbonate rocks. Cretaceous sedimentary rocks comprise silicious clasolite-conglomerate and sandstone with thick-layered siltstone, which occur in the southeast of this deposit (Fig. 1C).

The main intrusions are the Jurassic granodiorite porphyries. The granodiorite porphyry extends underground from southwest to northeast in this district. It contains 50–60% plagioclase, 10–30% quartz, and 2–10% biotite with accessory zircon, apatite and titanite and is basically controlled by NE-trending faults and cut by NNE- or WNW-trending faults. Pyritic phyllic alterations of these intrusions are commonly observed near the copper mineralization (Fig. 3K–L). The intrusive rocks also have a close spatial relationship with the ore bodies (Fig. 2).

The copper ore bodies occur in the sandstone and shale of the upper section of the Zishan Formation occur as stratoid bodies and lenses. Ore minerals include chalcopyrite, pyrite, bornite and chalcocite. The three main ore bodies are designated I, V and VII, of which V is the largest (Fig. 1C). These ore bodies are controlled by the same NE–NNE trending faults as the intrusive rocks (Fig. 2). Therefore, the ore bodies, faults and intrusive rocks are closely spatially associated and perhaps genetically related. Phyllic alteration and sericitic alteration are generally associated with copper mineralization and commonly observed along the copper ore bodies (Fig. 3M–O). Spatially, from ore bodies to wall rocks and distant from ore bodies, the alteration becomes less extensive (Fig. 3P).

3. Description of samples

Samples for fluid inclusion and isotope studies were collected from underground mining levels (−275 and −125.5 m). The samples for fluid inclusion and H–O isotope studies were collected from massive ores (Fig. 3A–B). The primary minerals in the massive ores are pyrite, chalcopyrite and quartz (Fig. 3C–D). The ore stage quartz is mainly distributed around chalcopyrite and pyrite and often coexists with metal sulfide (Fig. 3E–F), which strongly indicates that quartz and chalcopyrite were coeval. Some pre-ore stage pyrite-quartz veins were parallel to the host sedimentary rock bedding and had been folded with it (Fig. 3G–H). In these pre-ore stage quartz veins, only pyrite can be found, and chalcopyrite is absent (Fig. 3I–J).

Twenty-one samples were selected for fluid inclusion studies and Raman spectroscopic analysis, and ten samples were chosen for H–O isotope analysis. The sulfides used for S and Pb isotope analysis are pyrite and were collected from the massive ores. Eighteen and thirteen samples were prepared for the sulfur isotope and lead isotope analyses, respectively.

Plagioclases in intrusive rocks were also selected for Pb isotope analysis. In the Dongxiang copper deposit, granodioritic porphyry is a common intrusive rock. The samples for analysis were collected from drill cores ZK6702 and ZK6701. The rock masses in the sampling areas intruded into the sandstone of the Zishan Formation in Carboniferous strata. The samples vary in color from off-white to pinkish-gray and appear in both massive structures and porphyritic textures, and the phenocrysts include plagioclase, quartz, amphibole and some K-feldspar. The matrix has the same mineral components as the phenocrysts but is different in mineral content. The accessory minerals are primarily zircon and sphene. Feldspar phenocrysts have generally undergone sericitization, with sericite grown in the rims of the plagioclase phenocrysts.

4. Analytical methods

Double polished thin sections were prepared, and microthermometric measurements were performed with a Linkam THMS600 heating–freezing stage with a temperature range of −195 to +600 °C. The stage was calibrated by measuring the melting points of pure water inclusions (0 °C), pure CO_2 inclusions (−56.6 °C), and potassium bichromate (+398.0 °C). The accuracy of the measured temperatures is approximately ±0.2 °C during cooling and approximately ±2 °C between 100 and 600 °C. The salinities of $NaCl–H_2O$ inclusions were calculated using the final melting temperatures of ice (Bodnar 1993). The salinities of halite-bearing fluid inclusions were calculated using the dissolution temperatures of the daughter minerals (Hall et al., 1988). All fluid inclusion studies were conducted in the State Key Laboratory for Mineral Deposit Research, Nanjing University.

Quartz samples were handpicked and/or separated using a magnetic separator. Oxygen was liberated from quartz by reaction with BrF_5 (Clayton and Mayeda 1963) and converted to CO_2 on a platinum-coated carbon rod. The $\delta^{18}O$ determinations were made on a MAT-252 mass spectrometer at the State Key Laboratory for Mineral Deposit Research, Nanjing University. The reproducibility for isotopically homogeneous pure quartz is approximately ±0.1‰ (1σ).

Analyses of the hydrogen isotopic compositions of fluid inclusions were made on the same quartz samples measured for oxygen isotopes.