Genesis of Xinzhai Sandstone-Type Copper Deposit in Northern Laos: Geological and Geochemical Evidences

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ABSTRACT: Xinzhai sandstone-type copper deposit located in northern Laos lies in the Jiangcheng-Phongsaly-Phrae Mesozoic basin (JPMB), which is regarded as southern extension of the Lanping-Simao Mesozoic basin in China. The copper deposit belt is bounded by the Ailaoshan-Heishui River fault and the Dian Bien Phu-Luang Prabang fault at the east and Lancang River-Bannankan faults at the west. Two types of orebodies are identified in the Xinzhai area based on geological investigation. One is lamellar copper orebody hosted by the fine lithic feldspar sandstones and feldspar lithic sandstones; another is vein-type orebody. The sulfur isotopic compositions of the chalcopyrite and tetrahedrite are from -11.6‰ to -1.8‰, indicating that sulfur is derived from bacterial sulfate reduction (BSR). δD values of fluid inclusions in ore-bearing quartz samples are from -99‰ to -78‰. The calculated δ18O-water values of ore-forming fluid vary from -2.3‰ to 0.4‰ using the quartz-water fractionation equation and the mineralization temperature. Oxygen and hydrogen isotopic compositions show that the ore-forming fluid was derived from basin fluid. Rock-mineral identifications show that both of the mineral grain maturity and the structural maturity are high in the Jurassic Huakaizuo Formation, reflecting a far-source accumulation and lake facies sedimentary environment. Based on tectonic determination diagram of the Al2O3/SiO2-TFe+MgO, the sandstone samples collected from the Huakaizuo Formation were plotted in the passive continental margin. The collision of the Indian and Eurasian blocks during the Cenozoic formed large-scale strike-slip and thrust nappe structures in margin of the basin. With the tectonic movement, Cu-rich basin fluid from the basement of basin migrated upward along the contemporaneous fault and into the high porosity strata. At the same time, in organic matter-riched condition, bacterial sulfate reduction (BSR) has been triggered, forming a large number of $S^2_2$ ions, and then precipitation of sulfide started. This mechanism describes the process of copper mineral deposition in the Xinzhai deposit.

KEY WORDS: Laos, sandstone-type copper deposit, geology, geochemistry, genesis.

0 INTRODUCTION

The Jiangcheng-Phongsaly-Phrae Mesozoic basin (JPMB) in northern Laos is linked with the Lanping-Simao Basin in southern China. The JPMB is an important component of the Southeast Asian metallogenic belt (Fig. 1a), extending to the southern part of the “Sanjiang” metallogenic belt in China (Liu et al., 2015; Fan and Zhang, 1994). Meanwhile, the Lanping-Simao Basin (microplate) is an important component of the Tethyan tectonic domain. The microplate is constrained by the Lancang River-Bannankan fault, Ailaoshan-Heishui River fault, and Dian Bien Phu-Luang Prabang fault, which are shown in Fig. 1b (Li et al., 1995). Several deposits are found in the Lancang-Simao Basin, including the world class Jinding Pb-Zn deposit (Fig. 1b; Table 1; Gao et al., 2008), the medium-sized Baiyangping Ag-Pb-Zn-Cu deposit (Fig. 1b; Table 1; Zou et al., 2014), the medium-sized Jinman Cu deposit (Fig. 1b; Table 1; Liu et al., 2003, 2001, 2000), small-sized Bailongchang, Yaojiazhai, Wunu, Nanyong and Shangyong Cu deposits (Fig. 1b; Table 1; Yuan et al., 2015; Zheng et al., 2014; Gao et al., 2013; Miao et al., 2013; Cui and Yang, 1998; Yan, 1997).

In recent years, studies on fresh rocks, alteration rock, ore-controlled structure sequence, mineral assemblage, fluid properties and ore geochemistry have been conducted on Cu-Pb-Zn deposits from Lanping-Simao Basin (Xue et al., 2007, 2002; Zhao, 2006; Li et al., 1997, 1995). A great number of geochemical and geochronological data have been obtained (Tang et al., 2013; Zheng et al., 2012; Wang X H et al., 2011; Liu et al., 2003; Wu et al., 2003). Ages mainly vary from 23 to 68 Ma, showing that the mineralization is related to Himalayan Movement. The Cu isotopes in the Jinman Cu deposit (Jiang et al., 2001), Zn isotopes (Deng et al., 2017) and in situ S isotopes (Deng et al., 2017; Xue et al., 2015; Tang et al., 2014) in the Jinding Pb-Zn deposit have been measured. These new...
results show that the deposit in the Lanping-Simao Basin could have many metal sources and the ore-forming process is more complex (Deng et al., 2017; Xue et al., 2015). Concerning the source and the drive force of ore-forming fluid, there are three opinions: (1) deep source fluid or basin fluid are driven by magma derived heat (Xue et al., 2002; Li et al., 1997, 1995); (2) mantle derived heat drove the basin fluid migration (Wang et al., 2009; Zhao, 2006; Xu et al., 2005); (3) tectonic movement drove the basin fluid (He et al., 2009; Hou et al., 2008a; Gu et al., 2007; Li and Song, 2006; Xu and Zhou, 2004; Xu and Li, 2003).

However, the study of the ore deposits in the southern part of the metallogenic belt is relatively rare, and not many geological, geochemical and chronological studies have been carried out in a number of ore deposits, which has seriously influenced the study of basin fluid ore-forming system and exploration of this type of deposit. This study can provide more information for the geological scientists to understand the metallogenic mechanism and background of the ore deposits in the region. In this study, a detailed field geological investigation in the Xinzhai deposit is presented. The mineral grain size and composition, major and trace elements of sandstones from the ore-hosted strata, sulfur isotopic composition of sulfide, oxygen and hydrogen isotopic value of sulfide-bearing quartz are carried out.
Based on newly acquired data, the sedimentary facies and background of wall rocks, fluid-driving mechanism, the source of sulfur and metals and the ore genesis of the Xinzhai Cu deposit have been discussed.

1 REGIONAL GEOLOGY

Three major blocks occur in Laos, namely the Indochina, the South China, and the Simao-Lampang, which are separated by Dian Bien Phu, the Luang Prabang-Nanfu and the Majiang suture zones. The northeastern Heishui River rift (VII) belongs to South China Block (Fig. 1c; Li F X et al., 1995). To the east, the Indochina Block is bounded by three northwest-trending faults (Majiang, Lanjiang, and Changshan) and includes the Xam Nua Hercynian–Early Indosinian Island Arc (VI), the Xiang Khoang-Changshan Hercynian fold zone (V), the Luang Prabang-Loei Hercynian-Indosinian fold zone (III), and the Vientiane-Kon Tum Block (IV). The Simao-Lampang Block includes the Jinghong-Houayxay Hercynian–Indosinian Island Arc (I) and the JPMB (II). Therefore, seven tectonic units are identified in Laos (Fig. 1c; Li F X et al., 1995).

The Proterozoic metamorphic rocks consist of gneiss, schist, and amphibolite. The Paleozoic metamorphic rock series are schist, sandstone, mudstone and limestone. The Mesozoic strata consist of sandstone, clay, mudstone, and limestone. And Cenozoic strata consist of conglomerate, sandstone, shale, siltstone, and a few basaltic lava, cinerite and lignite. Magmatism in Laos mainly erupts or emplaces in the Jinningian and Himalayan orogenic belts. The Jinningian belt distributes in the eastern region of Laos, and magmatic rocks include mainly gneissic biotite granite and gneissic muscovite-granite. The Himalayan belt distributes in the northwestern, north-central, and some southern regions. It contains granodiorite, monzonitic granite, two mica monzonitic granite and biotite granite and alkali basalt.

The study area lies in the southern part of the Lanping-Simao Basin (Fig. 1b). In Laos, the JPMB is a north-northeast-trending strip belt. The Luang-Prabang arc belt and the Jinghong-Houayxay arc belt are located in the east and west sides with F3 and F1 as their boundary faults respectively (Fig. 1c). The JPMB is covered by a thick large-scale Mesozoic and Cenozoic red bed and scattered by the Late Paleozoic geological bodies. The microplate experienced a series of the strong tectonic movements.

2 GEOLOGY OF ORE DEPOSIT

2.1 Strata

The outcropped Mesozoic Jurassic and Cretaceous strata in the deposit area are shown in Figs. 2 and 3a. The Mesozoic sedimentary model and rock facies are consistent with the geological features in the Jiangcheng-Jinghong region (Yuan et al., 2015; Yang et al., 2013). Therefore, stratigraphic sequences and strata in the research area can be reassessed or renamed by Jiangcheng and Mengla sheets (1 : 200 000 regional geological data; Feng et al., 2017; Guo et al., 2017; Du et al., 2016; Zhang et al., 2016; Hu et al., 2015; Lü et al., 2015). According to the lithostratigraphy data of Yunnan Province, the strata in the mining and surrounding areas can be divided from the bottom upward as follows: Jurassic Huakaizuo Formation, Bazhulu Formation, Cretaceous Jingxing Formation, Nanxin Formation and Hutousi Formation.
2.1 Jurassic

The Middle and Upper Jurassic rocks distribute in the central and northern part of the deposit (Fig. 3a). Huakaizuo Formation (J₂h) is 2014 m thick, which can be divided into two sections according to the rocks assemblage. The first section (J₂h₁) outcrops in the northern part of the mining area, with thickness of 803 m. The lower part consists of maroon thin to middle-stratified siltstone and calc-argillaceous siltstone, interbedded with thin-stratified mudstone. The upper part consists of purplish red and maroon thin to middle-stratified microfine-grained lithic sandstone, siltstone and mudstone. The second section (J₂h₂) also exposes in northern part of the mining area. The lower part consists of grayish yellow and maroon middle-stratified feldspar lithic sandstone and thin-stratified limestone. The upper part consists of brownish red and grayish yellow thin-stratified fine-grained calcareous quartz sandstone and fine-grained feldspar quartz sandstone.

The Bazhulu Formation (J₃b) lies in the central part of the mining area and is 578 m thick (Fig. 3a). Purplish red and maroon thin to middle-stratified calcareous lithic sandstone, siltstone and mudstone. The upper part consists of maroon thick-stratified gravel-bearing sandstone with 10 to 20 m thick. The gravel includes siliceous and carbonate rocks with sizes of 0.5 to 3 cm.

2.1.2 Cretaceous

The Jingxing Formation (K₁j) exposes in the central and southern parts of the mining area (Fig. 3a). The lower part contains grayish middle to thick-stratified meso and fine-grained feldspar quartz sandstone and calcareous lithic quartz sandstone. The bottom part consists of maroon thick-stratified silty sandstone and gravel-bearing quartz sandstone. It is parallel unconformity contact with the underlying Upper Jurassic Bazhulu Formation.

The Nanxin Formation (K₁n) exposes in the southwestern part of the mining area (Fig. 3a) and is 609 m thick. It consists of maroon and amaranth middle-stratified siltstone, calcareous siltstone, mudstone, and silty calcium mudstones.

The Hutousi Formation (K₁h) exposes in the southern part of the mining area (Fig. 3a). It consists of ashen and grayish yellow middle to thick-stratified meso to coarse-grained lithic quartz sandstone and meso to fine-grained greywacke.

2.2 Structure

The main structure in the deposit is the Gongjishan syncline (Figs. 3a and 3b). Faults are widely developed in the northwest wing of the syncline. The northwest-trending faults are all across the mining area, including eight faults (F₁, F₂, F₃, F₄, F₅, F₆, F₇, F₈, and F₉). Ore-controlling faults are represented by F₂ and F₇ (Fig. 3b). The northeast-trending faults have experienced from an early extension to late compression. Lenticle and carbonization are common in the schistosity zone, reflecting a brittle tectonic deformation.
2.3 Orebody Features

2.3.1 Lamellar copper orebodies

Orebodies host in the transition zone between the grayish white sandstone belt and the purplish sandstone belt (Chen et al., 2000; Li F X et al., 1995). The transition between the grayish white sandstone and the purplish sandstone appears as in the shape of a wave line (Figs. 4 and 5a), which indicates that the greyish white sandstone was formed by hydrothermal alteration. When the transition zone is stable, industrial orebodies occur in the greyish white sandstone (Figs. 4 and 5a; Wu et al., 2008; Zeng et al., 2008; Zhu et al., 2008). Large-scale orebodies exist in the second section of the Huakaizuo Formation in the 3# oreblock. Orebodies occur as layered or stratoid (Figs. 4 and 5a). Locally multi-layered industrial orebodies have been explored. The controlled length, slope depth, and attitude of the orebodies are 1 900 m, 50 m and 264° ∞ 34°, respectively. The orebody thickness ranges from 1.39 to 6.58 m (average of 3.63 m). The main copper minerals in the deposit are chalcopyrite and tetrahedrite and the second largest amount of copper minerals include malachite and azurite (Fig. 6). Copper grade ranges from 0.53% to 2.40% (average of 1.19%). Mineralization mainly occurs in the light grayish yellow middle to thick-stratified feldspar quartz sandstone, fine-grained feldspar sandstone, and quartz sandstone (Qi et al., 2012).

2.3.2 Vein-type orebody

Vein-type orebodies distribute along the faults (Figs. 4 and 5b; Liu and Liu, 2013). The altitude of orebodies is steep and consistent with the fault occurrence. Malachite and azurite, supergene products from primary Cu-sulfides, appear as vein, veinlets, or spots usually around the tectonic breccia or as cements binding the debris particles or filling mineral fissures (Fig. 6e; Wang et al., 2011). Geological observation indicates that the vein-type and lamellar ore should form in the same stage (Fig. 4). Ore-bearing fluid migrated along inner layer fault or fissure and then form lamellar orebodies and also can

Figure 3. Simplified geological map (a) and cross-section (b) of the Xinzhai deposit
Figure 4. Geological sketch map of twelfth exploration profile in the Xinzhai deposit.

Figure 5. Geological sketch map of No. 3 oreblock illustrating the lamellar type orebody (a) and No. 13 gallery illustrating the vein-type orebody (b) in the Xinzhai copper deposit.
Figure 6. (a) (b) (c) microscopic characteristics of the feldspar quartz sandstone from Huakai Formation; (d) lamellar orebody spreads along the stratum; (e) vein type orebody fills in the fault; (f) disseminated and spotted chalcopyrite distribute in gray-white sandstone; (g) disseminated fine-grained chalcopyrite aggregate distribute along bedding of sandstone, forming the banded structure; (h) fine-grained pyrite inlay in the cement of sandstone; (i) spotted azurite occur in cements around quartz or feldspar particles; (j) irregular spotted azurite and malachite are distribution in the cements of sandstone; (k) irregular chalcopyrite vein distribute in the fissure; (l) fine-grained chalcopyrite inclusions are enwrapped in the tetrahedrite. Azu. Azurite; Mal. malachite; Cp. chalcopyrite; Py. pyrite; Te. tetrahedrite.

fill into fractures and form vein-type orebodies.

2.4 Ore Structure and Mineral Paragenetic Sequences

In Xinzhai deposit, copper minerals mainly include chalcopyrite, tetrahedrite, malachite and azurite (Fig. 6), and gangue minerals are mostly quartz and calcite. Based on the previous studies and field observation, two metallogenetic stages in Xinzhai deposit are identified in this paper. Those are quartz-sulfide stage (stage 1) and supergene stage (stage 2) from early to late stage (Fig. 7). The chalcopyrite and tetrahedrite hosted in the grey siliceous sandstone or faults formed at quartz-sulfide stage. Disseminated chalcopyrite appeared as irregular particles with sizes of 0.03 to 0.052 mm filled in the cement of sandstone (Fig. 6d) and chalcopyrite inclusions were wrapped by tetrahedrite (Fig. 6l). Fine-grained chalcopyrite occurs as veinlet scattered in the sandstone bedding, forming banded structure (Fig. 6g). In the vein-type ore, chalcopyrite occurred as irregular vein or spotted filled in cataclasite or cement (Figs. 6e, 6f and 6k). At supergene oxidation stage, sulfides reacted with water and air in surface or faults development area. Physical destruction caused by biology should speed up the reaction process. The new copper minerals (malachite and azurite) were formed at supergene oxidation stage (Figs. 6i and 6j). Disseminated malachite is found in sandstone surfaces (Fig. 6i). Azurite and malachite appears as irregular particulates or stalactite usually around the tectonic breccia or as cements binding the debris particles or filling mineral fissures (Fig. 6j). Few globular pyrite aggregations are found in the cement of
sandstone (Fig. 6h), in combination with the characteristics of hand specimens, the paragenetic sequence of metal minerals in Xinzhai deposit can be concluded in Fig. 7.

3 ANALYTICAL METHODS

3.1 Major and Trace Elements

The major element and trace element analyses are conducted at the State Key Laboratory of Ore Deposit Geochemistry, Chinese Academy of Science. The standard X-ray fluorescence (XRF) and the AXIOS XRF are applied, and the analysis accuracy is better than 5%. The inductively coupled plasma mass spectrometer is used, and the analysis accuracy is also better than the designated 5%. The experimental procedures are conducted from Qi et al. (2000).

3.2 Sulfur Isotope

The sulfur isotopic analysis is conducted using the MAT-251EM mass spectrometer in the State Key Laboratory of Ore Deposit Geochemistry. The test data is calibrated in accordance with the National Sulfur Isotope Standard GBW-4414 ($\delta^{34}S= -0.07\%$) and GBW-4415 ($\delta^{34}S=22.15\%$). The sulfur isotope values are reported using $\delta$ notation in permil ($\%$) relative to the CDT. The measurement precisions are within ±0.2‰.

3.3 Hydrogen and Oxygen Isotopes

The fresh ore samples were crushed with grain size of 40–60 meshes, to select quartz. At low temperature, water was adsorbed and secondary fluid inclusions were dried. And then the H$_2$O in the primary fluid inclusions from the quartz samples were extracted by heating and blasting. H was prepared by reaction of extracted H$_2$O and Zn and the value of $\delta^D$ was measured. The oxygen isotope of quartz is determined by BrF$_5$ analysis. The analysis and testing of hydrogen and oxygen isotopes were performed on the MAT253 mass spectrometer of the Beijing Institute of Geology of the Nuclear Industry. The data were V-SMOW as the standard, the accuracy of oxygen isotope analysis was 0.2‰ and the accuracy of hydrogen isotopes was 2‰.

4 RESULTS AND DISCUSSIONS

4.1 Geological and Geochemical Characteristic of Sandstone

In this study, 34 sandstone samples are collected from the mine for petrographic observation. For each thin section, more than 200 detrital components are observed under microscope. Statistical results are plotted in sandstone classification diagram, as shown in Fig. 8a. The Huakaizu Formation mainly consists of feldspar lithic and lithic feldspar sandstones. The mineral grain maturity and the structural maturity are relatively high, reflecting the sedimentary environment of far-source accumulation.

Feldspar lithic sandstone: It is mainly mauve and celadon in color, and appears as a middle and thick layer. Based on microscopic observation, the fragment content is from 75% to 95% while the interstitial material content is from 1% to 23%. The fragments include quartz and feldspar. In addition, the quartz content is from 35% to 65% while the feldspar content is from 14% to 49% (Fig. 6a).

Lithic feldspar sandstone: This type is mainly mauve and celadon in color, and appears as a middle and thick stratified. Based on microscopic observation, the fragment content is from 35% to 65% while the feldspar content is from 14% to 49% (Fig. 6a). The rock debris content ranges from 16% to 41%, and various types of debris, such as igneous and metamorphic rocks are observed.

Lithic feldspar sandstone: This type is mainly mauve and celadon in color, and appears as a middle and thick stratified. Based on microscopic observation, the fragment content is 71% to 96% while the interstitial material content is between 2% to 29%. The quartz and the feldspar contents are 32% to 70% and
15% to 34%, respectively (Figs. 6b and 6c).

The major and trace element compositions of sandstones are listed in Table 2. The SiO$_2$ content variation in mineralized fine sandstone is from 79.5% to 92.2%. The CaO content is of large variation from 0.01% to 10.2%. The content of Al$_2$O$_3$ varies from 3.69% to 4.83%. In addition, Fe$_2$O$_3$ and TiO$_2$ content variations are 0.71% to 3.24% and 0.08% to 0.25%, respectively.

In the Al$_2$O$_3$/SiO$_2$ vs. TFe+MgO tectonic determination diagram (Fig. 8b), all samples are plotted in the passive continental margin field. This result is consistent with the continental rift setting (Shi et al., 2014). In the chondrite-normalized REE patterns (Fig. 9), sandstone is enriched in light rare earth elements, and depleted in heavy rare earth elements. This pattern is similar to Jinman Cu deposits in Lanping County of China (Cheng et al., 2015). The Eu negative anomaly in the sandstone should represent the REE feature of original rock.

4.2 Possible Source of Sulfur

Results of sulfur isotopes of the Xinzhai deposit are listed in Table 3. $\delta^{34}$S values range from -11.6‰ to -1.8‰. The sulfur isotope histogram is presented in Fig. 10. Which shows that sulfides from lamellar ore have $\delta^{34}$S values of -9.8‰ to -1.8‰, and sulfides from vein ore have $\delta^{34}$S values of -11.6‰ to -4.3‰. Sulfur isotopic compositions of chalcopyrite vary from -10.8‰ to -3.2‰, and tetrahedrite vary from -11.6‰ to -1.8‰. The $\delta^{34}$S values of super large Jinding Pb-Zn deposits, medium-sized Baiyangping Ag-Pb-Zn-Cu deposit, medium-sized Jinman Cu deposit and small-sized Bailongchang Cu deposit are from -19.8‰ to 16.0‰, -7.3‰ to 18.1‰, -10.6‰ to 11.0‰, and -14.3‰ to -4.9‰, respectively (Fig. 11; Zheng et al., 2012; Xue et al., 2010; Wei, 2003; Wu et al., 2003; Yan, 1997; Li F X et al., 1995). The $\delta^{34}$S values of Xinzhai deposit are plotted in sulfur isotopic range of summarized various deposits in the Lanping-Simao Basin (Fig. 11), shows that the sulfur could derive the same source. These sulfur isotopic values show similar variation range between the lamellar and vein ore (Fig. 11). The widely variable depleted $\delta^{34}$S values imply that bacterial sulfate reduction (BSR) produced reduced sulfur for the Cu mineralization.

The widely distributed evaporate sulfates in the Lanping-Simao Basin, whose $\delta^{34}$S values are from 10% to 26‰ (Xue et al., 2007). Thermal decomposition of the organic matters will generate considerable strong reducing materials which functions as catalyster and can make sulfate reduced to S$^2$.

4.3 Source of Metals

Oxygen and hydrogen isotopic compositions for ten sulfide-bearing quartzs from the Xinzhai deposit are listed in Table 4 and Fig. 12. The measured $\delta^{18}$O values of quartzes are from 9.4‰ to 12.1‰. The $\delta^{18}$O values of the ore-forming fluid are calculated by the quartz-water fractionation equations and the mineralization temperature referenced by the homogenization temperature of fluid inclusions. The $\delta^{18}$O of super large Jinding Pb-Zn deposits, medium-sized Baiyangping Ag-Pb-Zn-Cu deposit, medium-sized Jinman Cu deposit and small-sized Bailongchang Cu deposit are from -19.8‰ to 16.0‰, -7.3‰ to 18.1‰, -10.6‰ to 11.0‰, and -14.3‰ to -4.9‰, respectively (Fig. 11; Zheng et al., 2012; Xue et al., 2010; Wei, 2003; Wu et al., 2003; Yan, 1997; Li F X et al., 1995). The $\delta^{18}$O values of Xinzhai deposit are plotted in sulfur isotopic range of summarized various deposits in the Lanping-Simao Basin (Fig. 11; Cheng et al., 2015), shows that the sulfur could derive the same source. These sulfur isotopic values show similar variation range between the lamellar and vein ore (Fig. 11). The widely variable depleted $\delta^{34}$S values imply that bacterial sulfate reduction (BSR) produced reduced sulfur for the Cu mineralization.

Table 2

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<th>Sample No.</th>
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Figure 9. Chondrite-normalized REE patterns of sandstone. The normalizing values of chondrite are from Sun and McDonough (1989).
temperatures (average value of 200 °C) of fluid inclusions from Jinding Pb-Zn deposit. The calculated δ¹⁸O_H₂O values are from -2.3‰ to 0.4‰. The δD values of fluid inclusion water in quartz are from -99‰ to -78‰. In Fig. 12, all samples are plotted in the Lanping-Simao, Youjiang and Alberta Basin fluid field. Therefore, hydrogen and oxygen isotopic compositions in Xinzhai deposit indicate that the ore-forming fluid is basin fluid, which occupied and flowed through the pores of sediments in the basin (Zhang et al., 2015). It includes fluids from the interior of the basin (formation water or hydrocarbons) and fluids from the exterior of the basin (meteoric water or metamorphic fluid in the basement of the basin). Thus, basin fluid is usually mixed fluid. Identification of a large amount of organic matter in Jinding, Jinman and Baiyangping deposit further indicates that the ore-forming fluid in Lanping-Simao Basin may be mainly of the basin fluid.

![Figure 10. Frequency histogram of δ³⁴S values for sulfide minerals from the Xinzhai deposit.](image)

![Figure 11. Summary of the δ³⁴S values for sulfide for sandstone-hosted Cu-Zn-Pb deposits in Lanping-Simao Basin.](image)

![Figure 12. Hydrogen and oxygen isotope diagrams of ore-forming fluid in Xinzhai deposit. The basin fluid values of Youjiang and Alberta Basin are from Wang et al., 2002; and basin fluid values of Lanping-Simao Basin are from Zhang et al., 2015.](image)

<table>
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<th>Deposit</th>
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<th>δ³⁴S (‰)</th>
<th>Sample</th>
<th>Orebody</th>
<th>Mineral</th>
<th>δ³⁴S (‰)</th>
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Table 3. Sulfur isotope compositions in the Xinzhai copper deposit.
Simao Basin were derived from magma (He et al., 2005; Wang, 2004; Wang and He, 2003; Xue et al., 2003). In addition, Nanyong deposit in Laos, about 45 km southeast of the Xinzhai deposit is hosted in sandstones of the Lower Paleogene Mengyejing Formation; the metallogenic age should be slightly younger than Mengyejing Formation (57 Ma). This indicates that basin fluid is ore-forming fluid. These geological features support sulfate reduction model. The hypothesis is also reinforced by the organic matter-riched stratum and sulfur isotopic evidences. The Cu-rich basin fluid from deep reservoir migrated upward along the contemporaneous fault and into the high-permeability sandstone (Huang et al., 2015). Organic matter acted as a reducing barrier mediating the metal accumulation from upwards migrating metal-bearing brines. And bacterial sulfate reduction was realized at the same time. \( \delta^{34}S \) is one of the products in this chemical reaction, which is essential anion for sulfide. This metallic supersaturated fluid was triggered and the precipitation of sulfides started. The Lamellar orebodies formed when the ore-forming fluid migrated along with inner layer faults or fissures. The vein-type orebodies formed when the ore-forming fluid migrated along tensile faults.

### 5 CONCLUSIONS

(1) The copper minerals of the Xinzhai sandstone-type copper deposit in the northern region of Laos include tetrahedrite, chalcopyrite, azurite and malachite. The mineral grain maturity and the structural maturity of sandstone from the Huakaizuo Formation are concluded as the lacustrine facies that is identified as a passive continental margin setting by its diagenesis and reworking model (Qiu et al., 2017; Wang et al., 2017; Hu et al., 2013). Orebody-hosting sandstone is gray in color from Xinzhai deposit, indicating that an intense alteration caused by reducing fluid present in the mineralization process. The relatively small sulfide crystals and surrounding minerals close cemented with sulfide also indicate the characteristics of the rapid deposition. These geological features support sulfate reduction model. The hypothesis is also reinforced by the organic matter-riched stratum and sulfur isotopic evidences. The Cu-rich basin fluid from deep reservoir migrated upward along the contemporaneous fault and into the high-permeability sandstone (Huang et al., 2015). Organic matter acted as a reducing barrier mediating the metal accumulation from upwards migrating metal-bearing brines. And bacterial sulfate reduction was realized at the same time. \( \delta^{34}S \) is one of the products in this chemical reaction, which is essential anion for sulfide. This metallic supersaturated fluid was triggered and the precipitation of sulfides started. The Lamellar orebodies formed when the ore-forming fluid migrated along with inner layer faults or fissures. The vein-type orebodies formed when the ore-forming fluid migrated along tensile faults.

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REFERENCES CITED


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Abstract


