Geochemistry and S, Pb isotope of the Yangla copper deposit, western Yunnan, China: Implication for ore genesis

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ABSTRACT: The Yangla copper deposit, situated in the middle section of Jinshajiang tectonic belt between Zhongza-Zhongdian block and Changdu-Simao block, is a representative and giant copper deposit that has been discovered in Jinshajiang-Lancangjiang-Nujiang region in recent years. There are coupled relationship between Yangla granodiorite and copper mineralization in the Yangla copper deposit. Five molybdenite samples yielded a well-constrained ^{187}Re-^{187}Os isochron age of 233.3±3 Ma, the metallogenesis is therefore slightly younger than the crystallization age of the granodiorite. S, Pb isotopic compositions of the Yangla copper deposit indicate that the ore-forming materials were derived from the mixture of upper crust and mantle, also with the magmatic contributions. In the late Early Permian, the Jinshajiang Oceanic plate was subducted to the west, resulting in the formation of a series of gently dipping thrust faults in the Jinshajiang tectonic belt，meanwhile, accompanied magmatic activities. In the early Late Triassic, which was a time of transition from collision-related compression to extension in the Jinshajiang tectonic belt, the thrust faults were tensional; it would have been a favorable environment for forming ore fluids. The ascending magma provided a channel for the ore-forming fluid from the mantle wedge. After the magma arrived at the base of the early-stage Yangla granodiorite, the platy granodiorite at the base of the body would have shielded the late-stage magma from the fluid. The magma would have cooled slowly, and some of the ore-forming fluid in the magma would have entered the gently dipping thrust faults near the Yangla granodiorite, resulting in mineralization.

Key words: Western Yunnan; Yangla copper deposit; Geochemistry；S, Pb isotope

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1. Introduction

The Yangla copper deposit is located in the Yangla area of the Henduan Mountains in Deqin County, Yunnan Province, southern Tibet. A team from the Yunnan Geology and Exploration Bureau discovered the deposit in 1965 in the course of mapping and exploring the area, mining of the Yangla copper deposit started in November 2007. The deposit was investigated by the third Regional Geological Survey Team of Sichuan Province, the third Team of Yunnan Geology and Exploration Bureau, the China University of Geosciences, the Yichang Institute of Geology and Mineral Resources, and the Chengdu Institute of Geology and Mineral Resources, among others (Qu et al., 2004). The deposit has copper reserves of 1.2 Mt (Yang, 2009), and given its location in the Jinshajiang tectonic zone (Pan et al., 2001), this region has great potential for further exploration. Previous studies have reported the structural characteristics (Lin and Wang, 2004), geochemical characteristics of the ores and the rocks in the Yangla copper deposit (Wei et al., 1997; Pan et al., 2000), however, the ore genesis of the deposit is still debated. Wei et al. (1999) suggested that the deposit is a VMS type, a conclusion later supported by Pan et al. (2003). Based on geochemical evidence of ore-bearing skarns, Lu et al. (1999) and Wei et al. (2000) concluded that the deposit is a skarn-type deposit related to the Yangla granodiorite. Lin et al. (2004), Hu et al. (2008), Li et al. (2008) and Liu et al. (2009) suggested that the deposit is structurally controlled.

Recent mining exposures at the Yangla copper deposit provided an ideal opportunity for detail underground investigation and systematic sampling. In this paper, we present a comparison of the REE and trace element compositions of the ores with those of the Yangla granodiorite, S, Pb isotopic composition, and molybdenite Re–Os isotopic dating of the Yangla copper deposit. We discuss the origin of ore-forming materials and the ore genesis of the Yangla copper deposit. The results contribute to our understanding of the genesis of the Yangla copper deposit and will guide further exploration in the region.

2. Economic geology of the Yangla copper deposit

The Jinshajiang–Lancangjiang–Nujiang region in southwestern China is located in the eastern part of the Tethyan–Himalayan tectonic belt, and also in the tectonic junction between Gondwanaland and Eurasia (Hou et al., 2003). Several of the Paleozoic sutures in the region provide a record of the history of the Paleo-Tethys Ocean, which consists of four paleooceanic basins: the Ganzi–Litang, Jinshajiang, Lancangjiang and Changning–Menglian oceans from east to west (Jian et al., 2009). The birth and final closure of the Paleo-Tethys Ocean are associated with the breakup and assembly of Gondwanaland (Xiao et al., 2008). It has been commonly accepted that the Changning-Menglian Suture Zone is the main boundary that separates the Yangtze Block from Gondwanaland (Jian et al., 2009), and that the Changdu-Simao and Zhongza micro-continental Blocks were marginal terranes of the Yangtze Block (Wang et al., 2000; Metcalfe, 2002; Zhu et al., 2011).

The Yangla copper deposit is located in the middle part of the Jinshajiang tectonic belt (Fig. 1). The Jinshajiang tectonic belt, regionally situated between Zhongza block to the east and Changdu-Simao block to the west, which developed in the late Paleozoic due to subduction of the Jinshajiang Oceanic block, and has experienced multiple tectonic processes (e.g., rifting, extension, subduction, and continent–continent collision) during the latest Permian to latest Middle Triassic.

2.1. Stratigraphy

The Jinshajiang tectonic belt has been subjected to intense compression during the geological evolution of the Jinshajiang–Lancangjiang–Nujiang region; consequently, the rocks are fragmented and faults are widely developed. No stratigraphy is preserved: the various rock types occur as fragments (Feng et al., 1999) that show no common stratigraphy, occurring instead as mélange (Qu et al., 2004). Previous studies proposed various stratigraphic schemes for the Yangla area (He et al., 1998; Qu et al., 2004; Zhu et al., 2009). Surface rocks are dominated by the Gajinxueshan Group, which is a suite of sediments, including quartz schist, biotite plagioclase gneiss, metasandstone, quartzite, marble, slate, volcanoclastics, and andesite, with ages ranging from the Neoproterozoic to the Carboniferous. The ore deposit at Yangla is hosted in the Devonian Jiangbian suite (marble interlayered with sericite quartz schist and amphibole-bearing andesite), Devonian Linong suite (sericite slate, metasandstone, and marble), and Early Carboniferous Beiwu suite (compact massive basalt, tuff, and interlayered sericite-bearing slate and marble) (Fig. 1).

2.2. Structure

The Yangla copper deposit is located between the N–S- trending Jinshajiang and Yangla faults. These faults were active beginning in Early Paleozoic, were subducted and subjected to compression during the Indosinian (Triassic Period), and were reactivated as sinistral strike-slip faults during the Himalayan Tectonic Period. Second-order faults (dipping to the NW) formed during the Himalayan, with lengths of several kilometers and widths of tens of meters. The second-order faults intersect each other, with most being thrust faults or strike-slip faults. (Gan et al., 1998; Zhan et al., 1998).

2.3. Intrusive Magmatism

In the Yangla region, a granitic intrusion is exposed in the northern Jiaren granite belt, which trends

N–S in the western part of the Jinshajiang tectonic zone. Most of the granite occurs as stocks. The main granitic intrusion is the Linong granodiorite (Fig. 2), which is located in the middle of the Yangla ore district and is offset by the F4 fault, with 2 km long (N–S) and 1.5 km wide (E–W) at the surface, covering an area of 2.64 km^2. Most of the intrusion is overlain by Quaternary sediment, meaning it has an irregular distribution at the surface. The wall rock is the Devonian Linong suite and the Jiangbian suite, which both occur as xenoliths in the Linong granodiorite. The granodiorite can be divided into a marginal facies (40% of the total surface area) and a center facies (60%), separated by a transition zone. The grainsize of the granodiorite varies from medium-fine to medium-coarse, and it varies in composition from intermediate at the center to acid at the margin. The granitic belt intruded the Gajinxueshan Group. Alteration of the wall rock has produced hornfels and skarn, as well as fine veins of copper mineralization and disseminated copper deposits.

The granodiorite is off-white in color, hypautomorphic and medium-coarse grained, with both compact massive and banded structure. The mineral assemblage is plagioclase (40%), K-feldspar (15%), quartz (25%), hornblende (15%), and biotite (5%), with minor zircon and apatite. The plagioclase is mainly zoned andesine, and alteration is dominated by sericitization, amphibolization, biotitization, and locally chloritization and prehnitization.

2.4. Geological characteristics of the deposit

The Yangla copper deposit is divided into five ore blocks: Jiangbian, Linong, Lunong, Jiaren, and Beiwu. The Linong ore block is the largest, and the KT2 and KT5 orebodies of the Linong ore block are the only parts of the Yangla copper deposit mined today. KT2 and KT5 is bordered by a series of gently dipping imbricate thrust faults. The orebodies dip 20°–40° to the west, although the dip increases to 50° at deeper levels (Fig. 3), and the average grade of copper in the ore is 1.03%. The hanging wall and the footwall of the orebodies consist of sandstone, marble, sericitic slate, and granodiorite. The alteration minerals include pyrite, chalcopyrite, galena, sphalerite, magnetite, limonite, and malachite. The most abundant ore minerals are chalcopyrite, pyrite, bornite, chalcosine, pyrrhotite, galena, sphalerite, and magnetite. The chalcopyrite, bornite, chalcosine are associated with Pb, Zn, Ag, Au, Bi, Sn, As, and Sb. Oxidized ore consists of malachite, azurite, tenorite, and limonite, and gangue minerals are diopside, actinolite, garnet, quartz, calcite, mica, and feldspar. The ore show hypidiomorphic, mist-like texture, filled-sponge, striped, cracked and porphyroid textures. The ore body includes compact massive structure, disseminated structure, and fine veiny structure.

3. Samples and analytical methods

We analyzed samples of ores and the Yangla granodiorite of the Yangla copper deposit. Samples of copper ore and the granodiorite were collected from the Lunong and Linong ore block in the Yangla copper deposit. The samples were analyzed for major elements, trace elements, and rare earth elements (REEs) at the Institute of Geophysics and Geochemistry Exploration, Chinese Academy of Geoscience, Langfang, China. The major elements, trace elements and REEs were analyzed by ICP–MS, for details of the analytical procedure, see Zhu et al. (2009).

The sulfur isotopic compositions of 9 sulfide samples were analyzed on a MAT 251E gas mass spectrometer by using Cu_2O to oxidize the sulfides at the Geological Analysis Laboratory under the Ministry of Nuclear Industry, Beijing, China. The analytical procedure usually yielded an in-run precision of 0.2‰. The calibrations were performed with regular analyses of internal $\delta^{34}S$ standard samples.

The lead isotopic compositions of 9 sulfide samples were analyzed on a MAT 261 mass spectrometer using the thermal ionization crosssection analytical technique at the Stable Isotope Laboratory of the

Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China. The precision of the $^{208}Pb/^{206}Pb$ measurements (1μg of Pb) is ≤0.005%, and the measured ratios (2σ) of international standard sample NBS981 are $^{208}Pb/^{206}Pb$ =2.16736±0.00066, $^{207}Pb/^{206}Pb$ = $^{207}Pb/^{206}Pb$ =0.91488±0.00028, and $^{206}Pb/^{204}Pb$= 16.9386±0.0131.

Five molybdenite samples were collected from quartz and sulfide veins in the orebody of the Yangla copper deposit. The molybdenite was separated by heavy liquid separation and handpicked under a binocular microscope. ^{187}Re and ^{187}Os contents were measured using a TJA PQ ExCell ICP–MS housed in the Re–Os Laboratory, China Testing Center of Geology Experimentation, Beijing, China. For details of the analytical procedure, see Smoliar et al. (1996).

4. Analytical results

4.1. Geochemical characteristics of copper ores

Table 1 lists the trace element and REE contents of copper ores from the Lunong and Linong ore blocks. The ores contain low concentrations of trace elements (∑REE=11.5 μg/g–59.2 μg/g), and the chondrite-normalized REE patterns show that LREEs slope gently to the right and HREEs are relatively flat with low concentrations (Fig. 4a). LREEs and HREEs are not obviously fractionated, with LREE/HREE = 2.1–6.3 (average, 3.4) and $(La/Yb)_N$ = 0.9–7.5. Most of the samples show a negative Ce anomaly (δCe=0.6–0.8) and possess a positive or negative Eu anomaly (δEu=0.6–1.4). Primitive-mantle-normalized trace element patterns for the copper ores (Fig. 4b) show an enrichment in large ion lithophile elements (Rb and Pb) and a strong depletion in Ba and Sr.

4.2. Geochemistry of the Yangla granodiorite

Table 2 lists the major element, trace element, and REE composition of the Linong granodiorite. The granodiorite shows little chemical variation, being characterized by high contents of Si (SiO_2 = 58.3 wt.%–69.8 wt.%, with the average at 63.8 wt.%) and Al_2O_3 (13.4 wt.%–19.8 wt.%; average, 15.9 wt.%), low contents of Ti (TiO_2 = 0.4 wt.%–0.5 wt.%; average, 0.4 wt.%) and MgO (1.5 wt.%–1.7 wt.%; average, 1.6 wt.%), and high $Mg^{\#}$ ($Mg^{\#} = Mg^{2+}/(Mg^{2+} + TFe^{3+}) \times 100$) ($Mg^{\#}$ = 38–64; average, 49). The granitoids has a high alkali content (K_2O+Na_2O = 6.0wt.%–8.3wt.%; average, 6.8wt.%) with a δ ratio ($\delta = [(K_2O+Na_2O)^2]/[(SiO_2 - 43)]$(wt.% ratio)) of 1.7–2.6 (average, 2.3).

The granodiorite is enriched in light REEs (LREEs), has a slightly negative Eu anomaly, and low contents of Y and Yb. Chondrite-normalized REE patterns show that LREEs slope to the right and that heavy REEs (HREEs) are relatively flat, with low HREE contents (Fig. 5a). The granodiorite contains medium to low REE contents (∑REE = 85.0 μg/g–119.2 μg/g; average, 104.5×10^{-6} μg/g), of which LREEs and HREEs are highly fractionated ($(La/Yb)_N$ = 8.9–12.4; average, 10.7; $(La/Sm)_N$ = 4.7–5.8; average, 5.3).

Primitive-mantle-normalized trace element patterns for the granodiorite (Fig. 5b) show enrichment in large ion lithophile elements (Rb, K, Pb), strong depletion in Ba, Nb, P, and Ti, and flat Dy–Lu.

4.3. S and Pb isotopic composition

The data listed in Table 3 show that the $\delta^{34}S$ values of sulfides from the Yangla copper deposit vary from -9.8‰ to -0.9‰, but are mainly within the range of -4.2‰ – -0.9‰.

The data listed in Table 4 show that the sulfides are very homogeneous in their Pb isotopic composition, $^{208}Pb/^{204}Pb$= 38.655–38.732, $^{207}Pb/^{204}Pb$=15.703–15.735, $^{206}Pb/^{204}Pb$=18.326–19.038.

4.4. Molybdenite Re–Os isotopic dating

Analyses of 5 molybdenite samples from the Yangla copper deposit are reported in Table 5. Five molybdenite samples yield model ages ranging from 229.7±3.3 to 233.0±3.4 Ma. The data, processed using the ISOPLOT/Ex program ISOPLOT 3.00 program (Ludwig, 2003), yielded a well-constrained ^{187}Re-^{187}Os isochron age of 233.3±3 Ma, with MSWD=0.31 and an initial ^{187}Os of $-0.77 \pm 0.93 \times 10^{-9}$ (Fig. 6). The nearly identical model age and isochron age suggest that the analytical results are reliable.

5. Discussion

5.1. Origin of ore-forming materials

Yangla copper deposit is hosted mainly by the gently dipping thrust faults near the Yangla granodiorite. Five molybdenite samples yielded a well-constrained ^{187}Re-^{187}Os isochron age of 233.3±3 Ma, and the Yangla granodiorite formed at 234.1±1.2 to 235.6±1.2 Ma (Indosinian) (Yang et al., 2011), the metallogenesis is therefore slightly younger than the crystallization age of the granodiorite, indicating a temporal and spatial link between the deposit and the granodiorite.

Besides the ∑REE contents, the patterns of REEs also differ between the copper ores and the granodiorite. The chondrite-normalized REE patterns of the granodiorite shows that LREEs slope to the right, with a weak negative Eu anomaly. The ores contain low REE contents, as well as LREEs and HREEs are not obviously fractionated; most of the samples possess a negative Ce anomaly and a positive or negative Eu anomaly. Comparing figure 5a with 4a reveals that the hydrothermal overprinted ore body is lower in REE, probably because the hydrothermal fluid was rich in complex REE ligands that were leached them from the rock fragments to the ore body. Europium occurred as Eu^{3+} dominantly at more oxidizing condition and lower temperature, resulting in the form of negative Eu anomaly. Whereas Eu^{3+} can be reduced to Eu^{2+} under reducing conditions and increased temperature, resulting in positive Eu anomaly. Eu anomaly of the copper ores in the Yangla copper deposit have a following regularity: obvious positive Eu anomaly→slightly positive Eu anomaly→obvious negative Eu anomaly from the deep ore bodies to the shallow bodies, indicating the ore-forming fluids experienced a process from reducing conditions to oxidizing conditions. Under oxidizing conditions, unlike other trivalent REE ions, Ce^{3+} can be readily oxidized to Ce^{4+}, and then precipitated in the form of CeO_2 or absorpted onto the surface of secondary minerals, thus the ore-forming fluids were depleted in Ce, resulting in negative Ce anomalies in the ores (Kerrich and Said, 2011).

The $\delta^{34}S$ values of sulfides from the Yangla copper deposit vary from -9.8‰ to -0.9‰ (Fig. 7), a difference of 10.7‰. This range of isotopic values from the Yangla copper deposit indicate simultaneous incorporation of heavy and light sulfur in the hydrothermal fluids from which the ores were deposited. The most abundant ore minerals in the Yangla copper deposit are pyrrhotite, pyrite, chalcopyrite, the variation range and average of S isotopic composition from the sulfides represent S isotopic composition of the ore-forming fluids. Of the 9 sulfides analysed from the deposit, 8 have $\delta^{34}S$ values between -4.2‰ to -0.9‰ with the average at -2.2‰, indicating a much greater contribution from the mantle to the ore-forming fluids (Harris et al., 2005; Li et al., 2006).

The data of sulfide minerals from the deposit straddle above the supracrustal lead evolution curve (Fig. 8a), and cross the orogenic evolution curve to the supracrustal lead evolution curve (Fig. 8b). The data reflects Pb mobilization from an only granulite and contributions of typical upper crustal Pb. Note that the granulites may be in an upper crustal position at the time of Pb mobilization. The Pb isotopic values of all samples from the Yangla copper deposit were calculated according to the equations $\Delta\gamma = (\gamma - \gamma_M)\times1000/\gamma_M$ and $\Delta\beta = (\beta - \beta_M)\times1000/\beta_M$ (γ: $^{208}Pb/^{204}Pb$ of sample, γ_M: $^{208}Pb/^{204}Pb$ of mantle = 37.47, β: $^{207}Pb/^{204}Pb$ of sample, β_M: $^{207}Pb/^{204}Pb$ of mantle = 15.33, Zhu, 1998),which can help in establishing the source of Pb through values of $\Delta\gamma$ and $\Delta\beta$ (Fig. 9). Sulfides from the Yangla copper deposit plot in the field of the upper crust and mantle, caused by subduction-related magmatism. These results suggest that the ore-forming materials in the sulfide stage of the deposit may be derived from the Yangla granodiorite (Zhou et al., 2011).

5.2. Ore genesis

The Jinshajiang Oceanic plate was subducted to the west, beneath the Changdu-Simao block, in the late Early Permian, resulting in the formation of a series of imbricate trust faults, dipping gently to the NW, which formed in a setting of E–W compression in the Jinshajiang tectonic belt (Macpherson and Hall, 2002; Love et al., 2004).

Shallow subduction of the Jinshajiang Ocean beneath the continent interior (Burchfiel et al., 1992) resulted in a temperature gradient near the subducting plate, with the maximum temperature near the site where the subducting plate was close to the overriding plate. The subducting plate was subjected to metamorphism and partial melting, and the overriding crust was thickened by the addition of subducting plate and stacking of the upper plate (Mo et al., 2007). The resulting rise in isotherms led to partial melting of the lower crust over the subducting plate (Li et al., 2011), producing magma that ascended to the upper crust to form granite (Hezarkhani, 2006; Karsli et al., 2010). The zircon U–Pb age of the Yangla granodiorite (Yang et al., 2011), combined with its geochemical characteristics, indicates this rock is collisional, resulting from the partial melting of thickened lower crust (Wei et al., 1997). Gao et al. (2010)

recognized the geochemistry of the granodiorite is in keeping with that of C-type adakites, which was triggered by westward subduction of the Jinshajiang Oceanic plate under a tectonic setting of compression.

Subduction of the Jinshajiang oceanic plate resulted in channel flow within the mantle wedge over the subducting plate (Mcinnes and Cameron, 1994; Pearce, 1995), whereby low-density material ascended and high-density material descended (Cooke et al., 2005). This circulation resulted in the accumulation of large amounts of gas–liquid fluid in the mantle wedge (Du, 2009; Wei et al., 2010), derived from the mantle and containing ore-forming material (Drummond et al., 2006; Walshe et al., 2011).

In the early Late Triassic, which was a time of transition from collision-related compression to extension in the Jinshajiang tectonic belt (Mo et al., 1993; Wang et al., 1999, 2002; Li et al., 2003), the thrust faults were E-W tensional, it would have been a favorable environment for ore-forming fluids (Kühn and Gessne, 2006). The Jinshajiang Oceanic block was subducted westward at a low angle, resulting in partial melting of the lower crust (Sajona et al., 2000), and the ascent of the magma provided a channel for the ore-forming fluid in the mantle wedge (Mungall, 2002; Luo et al., 2008). After the magma arrived at the base of the early-stage Yangla granodiorite, the platy nature of the granodiorite body would have shielded late-stage magma from the fluid. The magma would have cooled slowly, and some of the ore-forming fluid in the magma would have entered the low-angle thrust faults near the Yangla granodiorite, resulting in mineralization (Fig. 10).

6. Conclusions

(1) S, Pb isotopic compositions of the Yangla copper deposit indicate that the ore–forming materials were derived from the mixture of lower crust and upper mantle, also with the magmatic contributions.

(2) Five molybdenite samples yielded a well-constrained ^{187}Re-^{187}Os isochron age of 233.3±3 Ma,

therefore, the age of metallogenesis is slightly younger than the crystallization age of the Yangla granodiorite.

(3) The Jinshajiang Oceanic block was subducted to the west, resulting in the formation of a series of gently dipping thrust faults in the Jinshajiang tectonic belt， meanwhile, accompanied magmatic activities. During a transition in geodynamic setting from collision-related compression to extension, the thrust faults were E-W tensional, it would have been a favorable environment for ore-forming fluids. The ascending magma provided a channel for the ore-forming fluid from the mantle wedge. After the magma arrived at the base of the early-stage Yangla granodiorite, the platy granodiorite at the base of the body would have shielded the late-stage magma from the fluid. The magma would have cooled slowly, and some of the ore-forming fluid in the magma would have entered the gently dipping thrust faults near the Yangla granodiorite, resulting in mineralization.

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Fig. 1. Geological map of the Yangla copper deposit (after Qu et al., 2004) .

1. Paleogene; 2. Upper Triassic; 3. Lower Triassic; 4. Upper Permian; 5. Lower Permian; 6. Gajinxueshan group; 7. Ultrabasic rock; 8. Carboniferous; 9. Devonian; 10. Silurian; 11. Ordovician; 12. Proterozoic; 13. Quartzdiorite; 14. Granitoids; 15. Copper deposit; 16. Fault; 17. Geological boundary; 18. Yangla mineral district; 19. Region of interest; Ⅰ. Yangtze block; □. Ganzi-Litang melange belt; □. Yidun arc belt; □. Zhongza-Zhongdian block; □. Jinshajiang melange belt; □. Jiangda-Weixi arc belt; □. Changdu-Simao block; □. Lancangjiang melange belt; □. Chayu block; □. Tuoba-Yanjing arc belt; Ⅺ. Nujiang melange belt.

Fig. 2. Geological sketch map of the Yangla copper deposit (after Yang, 2009).

1. Quaternary slope material; 2. Beiwu suite: massive basalt interlayered with sericite slate and marble; 3. Linong suite: sericite slate, metasandstone, and marble; 4. Jiangbian suite: marble, sericite slate, and metasandstone; 5. Plagiogranite; 6. Granodiorite; 7. Ore body and corresponding number; 8. Boundary between alteration zones; 9. Sericite-chlorite alteration zone; 10. Hornfels alteration zone; 11. Skarnization alteration zone; 12. Quartz–sericite alteration zone; 13. Chlorite–epidote alteration zone; 14. K-feldspar–quartz alteration zone; 15. Sericite–calcite alteration zone.

Fig. 3. No.13 prospecting line profile map in the Linong ore block of the Yangla copper deposit (after Yang, 2009).

1. Explosive breccia; 2. Metasandstone; 3. Marble; 4. Granodiorite; 5. Drilling and numbers; 6. Tunnel and numbers

Fig. 4. Chondrite-normalized REE patterns (a) and primitive-mantle-normalized trace element patterns (b) for copper ores of the Yangla copper deposit.

Fig. 5. Chondrite-normalized REE patterns (a) and primitive-mantle-normalized trace element patterns (b) for the Linong granodiorite (chondrite and primitive mantle data are from Sun and McDonough, 1989).

Fig. 6. Re–Os isochron diagrams for the molybdenite samples from the Yangla copper deposit

Fig. 7. Composite sulfur isotopic composition histogram of the Yangla copper deposit.

Fig. 8. Lead isotope compositions ($^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) of samples from the Yangla copper deposit plotted in the model lead evolution diagrams of Zartman and Doe(1981).

M. mantle-source lead; O. orogenic belt-source lead; U. supracrust-source lead; L. lower crust-source lead.

Fig. 9. $\Delta\gamma$-$\Delta\beta$ diagram of ore lead from the Yangla copper deposit (after Zhu, 1998).

Fig. 10. Schematic cross-section through the Yangla copper deposit (modified from Pearce, 1995).

1. Crust; 2. Mantle lithosphere; 3. Mantle asthenosphere; 4. Plate motion; 5. Mantle fluid advection.