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Formation of Au-polymetallic ore deposits in alkaline porphyries at Beiya, Yunnan, Southwest China

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ABSTRACT

The Beiya gold deposit is located in the central part of the Jinshajiang–Honghe strike–slip belt, at the junction zone of the Tethys-Himalaya orogenic belt and the Yangtze plate in SW China. This large-scale (125.6 million metric tonnes with a mean grade of 2.42 g/t) Au-rich polymetallic deposit is related to alkaline porphyry intrusions. Previous studies show that the Beiya alkaline porphyry intrusions are the fractionation product of a mantle-derived magma emplaced in an extension environment at the post-collision stage of the India–Eurasian plate collision; the Beiya deposit is considered to be skarn-related. Based on detailed field studies and previous work, we propose that the Beiya porphyry and associated Au-rich polymetallic ores were formed by the emplacement of magmas within the Jinshajiang–Honghe strike–slip fault during the late stage of the India–Eurasian plate collision at 45–25 Ma.

At Beiya, the mineralized zones in the Cu–Au-rich porphyries are surrounded by Au–Cu–Fe skarns and Au (Cu) veins. Pb–Zn–Ag-rich mineralization was derived from the inner porphyry, and is widely developed outside the central alkaline-rich porphyry.

The sulfur isotope signature of the sulfide mineralization in the Beiya and Qinhe deposits is −2.40‰–4.50‰ and 1.25–2.75‰, respectively. These values are close to 0‰, indicating that the sulfur may be mantle-derived. The $\delta^{18}O$ compositions of the ore-forming fluids responsible for the formation of calcites at Qinhe are 8.10‰–9.61‰, which is lower than that of Beiya ($\delta^{18}O = 10.5‰$) where the ores contain a larger contribution of oxygen from the mantle. The Beiya porphyry magmas provided fluids and the heat that drove the transport of the metals to the site of deposition.

Alkaline porphyries are widely distributed throughout the Jinshajiang–Honghe strike–slip fault belt, and they are potential hosts to future discoveries of Beiya-style mineralization.

1. Introduction

Porphyry Cu (Mo/Au) deposits are widely considered to be products of crust–mantle interaction at the collision margins of plates (Cooke et al., 2005; Sillitoe, 2010; Hou et al., 2011). Recent studies of porphyry Cu (Mo/Au) deposits have made significant contributions to the understanding of their environment of formation (Richards, 2003, 2009; Hou et al., 2003; Goldfarb et al., 2013; Lu et al., 2013; Richard et al., 2013). These studies have demonstrated that large-scale porphyry Cu (Mo/Au) deposits can form not only in island arc environments but also within orogenic belts. Orogenic porphyry deposits result from the emplacement of magma by upwelling of the asthenosphere after the delamination of intercontinental plate collision-generated thickened lithosphere (Hou et al., 2003, 2004; Meng et al., 2004; Luo et al., 2008). The emplacement of magma guided by mantle-penetrating strike–slip faults after oblique-collision can also result in the formation of porphyry deposits (Richards, 2003, 2009; Li et al., 2010; Lu et al., 2013) as well as other types of ore deposits (e.g., Lightfoot and Evans-Lamswood, 2015). Chernicoff et al. (2002) studied the intersections of major lineament zones in northwestern Argentina, and proposed that intersection zones form trans-lithospheric columns of low strength and high permeability during transpressional or transtensional tectonic strain, and may thereby serve as conduits for magma to ascend to shallow crustal levels. Large volumes of magma pooled in the shallow crust may devolatilize fluids, resulting in the formation of hydrothermal ore deposits. The alkaline-rich porphyries and related Au-rich polymetallic deposits at Beiya may have been formed by this mechanism. The "Sanjiang" (Nujiang River, Lancangjiang River and Jinshajiang River) region of China is located in the oblique-collision zone of the Indian and Eurasian plates (Fig. 1a), where numerous large-scale strike–slip faults converge due to motion between the Nansonggan, Lanping, Baoshan,

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and Tengchong blocks, and this nexus of faults was likely key to the formation of the Beiya deposits.

The Jinshajiang–Honghe alkaline-rich porphyry belt is an important Cu–Au polymetallic metallogenic zone that stretches north to south from Tungula, Yushu, and Mangkang, to Beiya, Machangqing, and Jinping in Yunnan, and south along the Honghe fault towards Vietnam (Fig. 1b). This belt constitutes a very large, tectonic–magmatic–hydrothermal metallogenic belt that stretches along the SE margin of the Qinghai–Tibet plateau (Hou et al., 2004). A number of alkaline-rich porphyries and Cu–Au deposits are distributed along this belt; these include the Yulong, Malasongduo, Duoxiasongduo, Bengge, Xifanping, Beiya, Machangqing, Habo, and Jinping deposits (Fig. 1b). The porphyries in this belt become younger in age (Fig. 1b) and more alkaline in composition from north to south (Bi, 2005; Xu et al., 2006a; Liang et al., 2009; He et al., 2013). Many deposits have been discovered in this region as a result of exploration work (Bi et al., 2006; Chen et al., 2009; Liang et al., 2009; Ge et al., 2010; Shu et al., 2012; Wang et al., 2012; Wu et al., 2013; Huang et al., 2013). The belt is further divided into the NW Jinshajiang porphyry domain and the SE Honghe porphyry domain (Fig. 1b). The mineralization is copper-rich in the northern domain and gold-rich in the southern domain. The Beiya Au-polymetallic deposit is located in the most northern portion of the SE domain. The porphyry-skarn mineralization occurs in association with the Beiya alkaline-rich porphyries. The environment of formation of the Beiya alkaline-rich porphyries remains incompletely understood. Although there are studies of the four types of mineralization in the Beiya deposit (Xu et al., 2006a,b; Xiao et al., 2009a,b, 2011; Wu et al., 2005, 2010; He et al., 2013), there is no study of the whole mineral system. The structural geochemical, and metallogenic results in this study indicate that the porphyries are genetically related to alkaline magma emplacement in the secondary fault system of the Jinshajiang–Honghe strike–slip belt (Fig. 1b). These alkaline porphyries provided the ore-forming metals and fluids, and the magma provided the heat-source required to form the Beiya deposit. The mineralization in the Beiya district can be grouped as a member of the "porphyry → contact zone → wall rock" type of Au-bearing polymetallic systems which comprise the Cu (Mo) and Cu–Au style of mineralization associated with the porphyry, the skarn Au–Cu–Fe mineralization in the contact zone of the porphyry

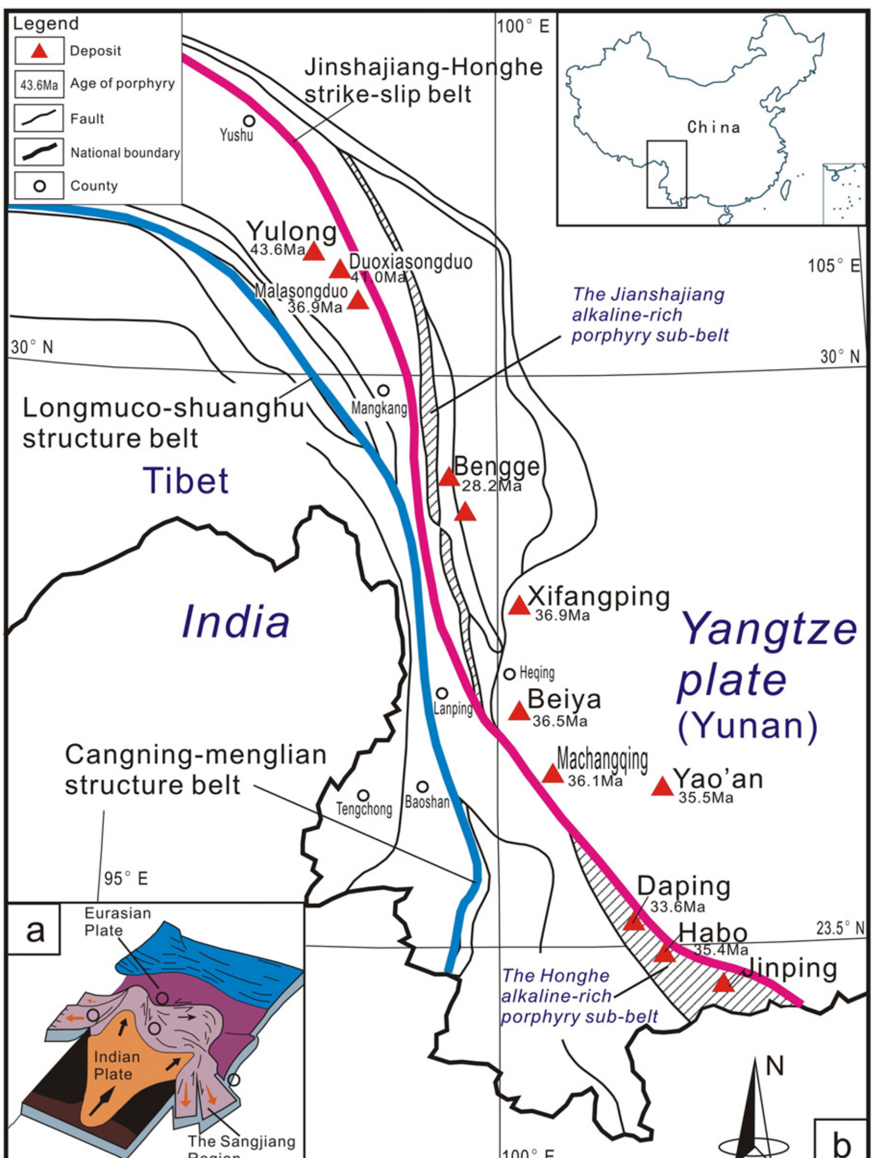

Fig. 1. (a). Strike–slip faults formed after strike–slip collision; the escape of crustal blocks as a result of wedge-shaped collision; (b). Map showing the tectonic location and characteristics of the Jinshajiang–Honghe alkaline-rich porphyry belt in west Yunnan, SW China.

with carbonate wall rocks, and the Au (Cu) and Pb–Zn–Ag style of mineralization in the outer region.

2. Geological setting

2.1. Regional geology

The Beiya gold deposit is located in Heqing County in Yunnan Province, SW China, between the Qinghai–Tibet plateau and the Yangtze plate (Fig. 1). The deposit and associated alkaline porphyries are hosted in stratigraphy belonging to the upper Permian Emeishan Formation, the lower Triassic Qingtianbao Formation, the middle Triassic Beiya Formation, the upper Triassic Zhongwo Formation, and the upper Triassic Songgui Formation (Fig. 2). The Emeishan Formation, mainly developed in the southeastern portion of the area, is dominantly amygdaloidal basalt, plagioclase porphyritic basalt (tholeiite), with volcanic breccia and tuff. The Qingtianbao Formation comprises arkose and hornstone greywacke with thin layers of argillaceous and fine-grained limestone at the top and basaltic breccia at the base. The rocks of the Beiya Formation are dominantly fine-grained limestone with layers of

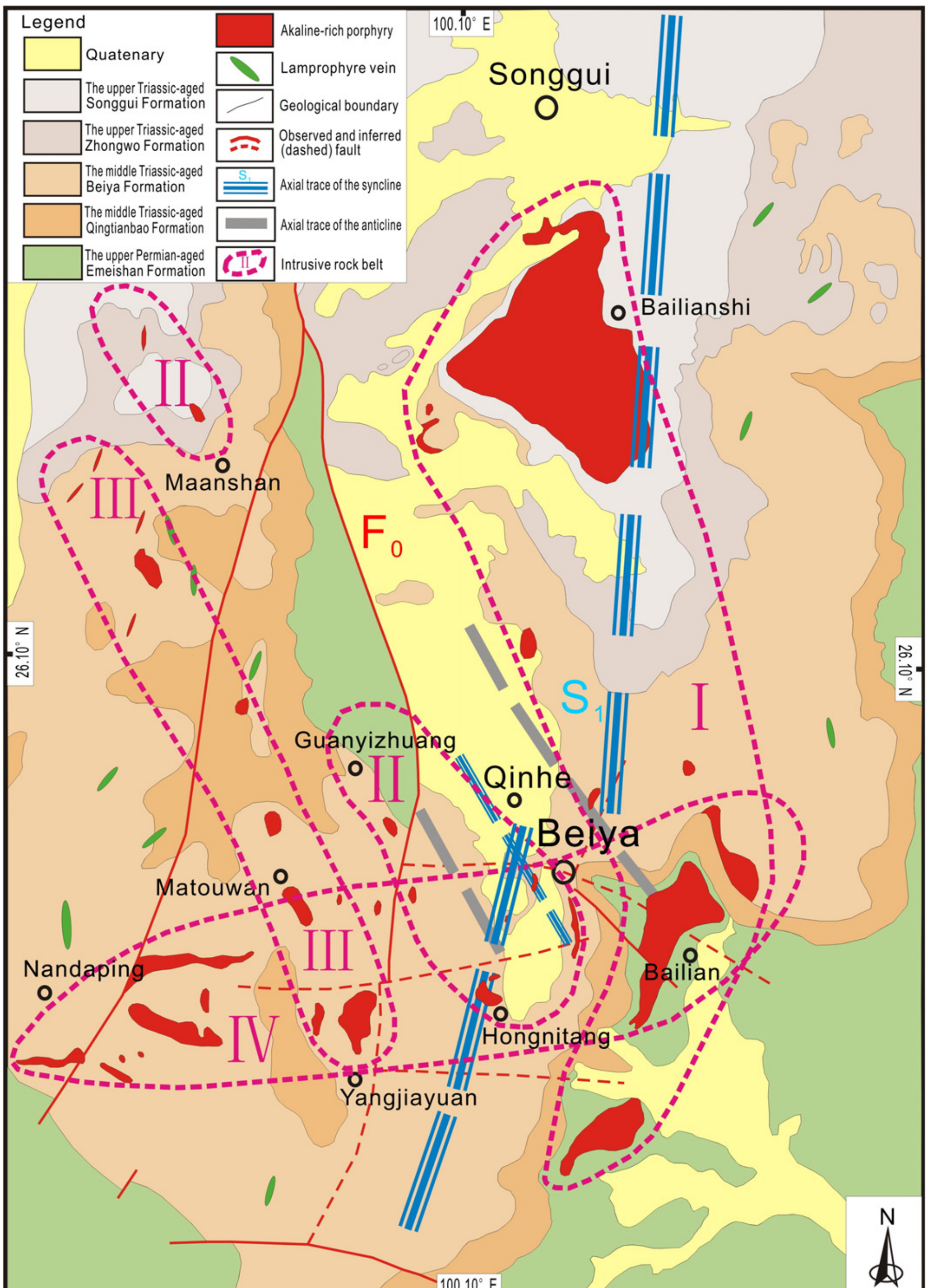

Fig. 2. Geological map showing the distributions of magmatic rocks and structures in Beiya. I. The Songgui–Bailian intrusive rock belt; II. The Guanyizhuang–Hongnitang intrusive rock belt; III. The Yangjiayuan–Matouwan intrusive rock belt; IV. The Nandaping–Bailian intrusive rock belt.

siltstone and bioclastic limestone. The Beiya Formation is divided into five members that are generally cut by faults and fracture zones (Yang et al., 2014).

The tectonic framework of the terrain containing the Beiya deposit trends broadly in a NW–SE direction. The Maanshan fault (F_0) trends in an approximately N–S direction, and controls the regional Songgui compound syncline (S_1) as well as secondary fractures (Fig. 2). The N–S oriented faults, such as the Maanshan fault, belong to the secondary fault system of the Jinshajiang–Honghe strike–slip fault, which not only controls the emplacement of the main porphyry intrusions in the mineral belt but it also controls the emplacement of numerous porphyry polymetallic deposits located in the Jinshajiang–Honghe belt (Yang et al., 2014).

Intrusions in the Beiya mining area are mainly composed of alkaline Himalayan porphyries with an outcrop area of $<0.096\ km^2$. Three porphyry intrusive events in the area are recognized; the first produced a quartz-albite porphyry at ~65 Ma (Xu et al., 2006a); the second a quartz orthoclase porphyry at ~37 Ma to 26 Ma (Ying and Cai, 2004; Xu et al., 2006a; Xiao et al., 2009a; He et al., 2013; Liu et al., 2015); the third intrusion to be emplaced was a biotite orthoclase porphyry at ~3.78 ± 0.08 Ma (Xu et al., 2006a). The first two stages of porphyry rocks are generally accompanied by lamprophyre dykes (31.6 Ma to 35.5 Ma) (Xu et al., 2006a; Mo and Zeng, 2008). The porphyry intrusions in the Beiya region have SiO_2 content from 67.6 to 72.8 wt.%, total alkali contents ($K_2O + Na_2O$) ranging from 9.93 to 11.88 wt.% and K_2O/Na_2O ratios of >1. They have low total REE concentrations (36–503 ppm, with an average of 134 ppm) and are enriched in light REE with LREE/HREE ratios ranging from 6.09 to 18.21, $(La/Yb)_N$ ratios 4.9 to 28.9. The intrusions are enriched in large-ion lithophile elements (e.g., Rb and Ba) and are depleted in high-field-strength elements (e.g., Ta and Hf); there are slight positive Eu-anomalies ($\delta Eu = 0.42$ to 0.99) (Xu et al., 2006a,b; Mo and Zeng, 2008; Deng et al., in press; Liu et al., 2015).

The porphyry intrusions have a faulted or irregularly intrusive contact with the country rocks, and most of these porphyries trend ~N–S and dip towards the west (dip angles range from 21° to 85°). The porphyries are distributed as long narrow intrusions in surface outcrop, and they have a bell-like to lenticular cross-section shape. The main porphyries such as the Wandongshan and Hongnitang porphyries are partially covered in overburden. The lamprophyre dykes are widely distributed in the Beiya mining area (Fig. 2) and spatially associated with quartz orthoclase porphyry. The largest lamprophyre oriented west-east and has a lenticular cross section (Liu, 2004). The age of formation of the lamprophyres (31.6 Ma to 35.5 Ma) is concurrent with the crystallization age of the quartz orthoclase porphyry intrusion which is the dominant (90% in volume) type of magmatism at Beiya (Mo and Zeng, 2008).

2.2. Characteristics of the Beiya Au-polymetallic metallogenic system

Cu (Mo)–Au anomalous mineralization occurs in the Wandongshan and Hongnitang ore-bearing porphyries. Some of the porphyry intrusions contain Cu–Au (Fe) ore bodies, and others contain Mo mineralization. In the contact zone between the porphyries and the middle Triassic Beiya Formation carbonate rocks, skarn type gold-bearing ore bodies account for 70% of the total Au endowment of the region. In the outer portion of the ore-bearing porphyries, Au bearing ore bodies occur in the strata of the lower Triassic Qingtianbao Formation and the middle Triassic Beiya Formation. Pb–Zn–Ag sulfide mineralization occurs as veins which are distributed between the fracture zones in the middle Triassic Beiya Formation and in the contact zone of the Beiya Formation with the lower Triassic Qingtianbao Formation. The distribution of mineralization and ore bodies in strata indicate that the formation of the mineralization was largely associated with fault/fracture rather than the specific host stratigraphy (Fig. 3). Fig. 3 also illustrates outcrops of the Wandongshan and Hongnitang porphyries (in red) and their buried portions (dashed line); based on the distribution of the outcrops and drilled sub-surface extent, it appears likely that the Wandongshan and Hongnitang porphyries (and perhaps also the Dashadi porphyry) are connected at depth.

To date, over 400 Au–Fe–Cu–Pb–Zn–Ag mineral zones have been discovered in the Beiya mine area. The proven reserves are 125.6 million tons (Mt) of gold ore with a mean grade of 2.42 g/t, along with 138 Mt of iron ore with an average grade of 33.34% Fe, 122.9 Mt of copper ore with an average grade of 0.48% Cu, 131.5 Mt of lead ore with an average grade of 1.84% Pb, 145.7 Mt of zinc ore with an average grade of 0.35% Zn, and 169.6 Mt of silver ore with an average grade of 42.56 g/t Ag (Yang et al., 2014). As the exploration in the Beiya mine area is still proceeding, an increase in the total amount of mineralization remains possible.

Based on field studies and mine-scale data, we established that mineralization at Beiya is characterized by a zoned distribution pattern (Fig. 3). From the center to the outer zones of the porphyries, there is a transition from Cu–(Mo)–Au-porphyry mineralization through skarn Au–Cu–Fe mineralization to epithermal Au–(Cu) and Pb–Zn–Ag mineralization.

2.2.1. Porphyry Cu (Mo)–Au mineralization

Porphyry-hosted Cu–(Mo)–Au mineralization occurs in the Wandongshan and Hongnitang porphyries and brecciated rocks of the upper part of the Hongnitang porphyry. The mineralization consists of a peripheral zone of sparsely disseminated Cu (Mo)–Au minerals and densely disseminated veinlets of Cu–Au minerals in the phreatomagmatic breccia. The mineral assemblage is composed of pyrite, chalcopyrite, molybdenite, and some pyrrhotite. Alterations include silicification, potassic, K-feldspathization, biotitization, sericitization, and chloritization. Some of these porphyries are mineralized with anomalous Cu–(Mo)–Au, such as the No. 72 prospecting line section at the Wandongshan (Fig. 4). The 17th bore hole in this section (72ZK17) crosses the mineralization between 455.98 and 519.18 m, with a thickness of 63.2 m. Sampling at 1 m intervals and systematic analyze yielded average grades of 0.16% Cu and 0.44 g/t Au. Molybdenite mineralization is also observed in this drill core interval.

2.2.2. Skarn Au–Cu–Fe mineralization

Skarn type Au–Cu–Fe mineralization represents the most important style of mineralization developed at Beiya. These ore bodies mainly formed within the contact zone between the porphyry and the wall rocks (carbonate) of the middle Triassic Beiya Formation, and extend into the carbonate in some locations. The Wandongshan Ore body KT52 (Fig. 4) is a typical example of the skarn style of mineralization. It has an extent of 1700 m (N–S) by 607 m (E–W), and is composed of veins which branch and vary in thickness from 0.37 to 115.26 m. The deposit contains massive magnetite and disseminated pyrite-(chalcopyrite) skarns that are composed of magnetite, pyrite, chalcopyrite, pyrrhotite, and skarn minerals, with minor contributions of hematite (2%) and native copper (1%). The proven reserves of the ore body KT52 are 87.2 Mt of gold ore with a mean grade of 2.35 g/t, along with 90.27 Mt of iron ore with an average grade of 34% Fe, 111.8 Mt of copper ore with an average grade of 0.34% Cu (Yang et al., 2014).

Based on data from the No. 72 prospecting line at Wandongshan (Fig. 4), the KT52 ore body was primarily found at depths of 286.32–517.80 m in borehole 72ZK17. The body contains mineral zones with an apparent total thickness of 123.49 m (depth intervals of 286.32–334.49 m; 346.47–380.78 m; 398.52–439.53 m) averaging 0.59% Cu in zones with an apparent total thickness of 6.55 m (353.86–356.75 m; 412.69–416.35 m) averaging 1.89 g/t Au. The KT52 ore body was encountered between 243.53 and 453.07 m depth in borehole 72ZK14; this ore body contains mineral zones with an apparent total thickness of 49.77 m (243.53–274.35 m; 372.74–376.26 m; 397.51–401.98 m; 411.19–430.94 m) averaging 0.48% Cu. Over an apparent total thickness of 26.19 m (253.68–265.07 m; 438.21–453.07 m) gold grades 2.21 g/t Au. In borehole 72ZK15, the KT52 ore body was encountered between 421.18 and 505.81 m depth; drilling encountered 38.51 m (424.36–

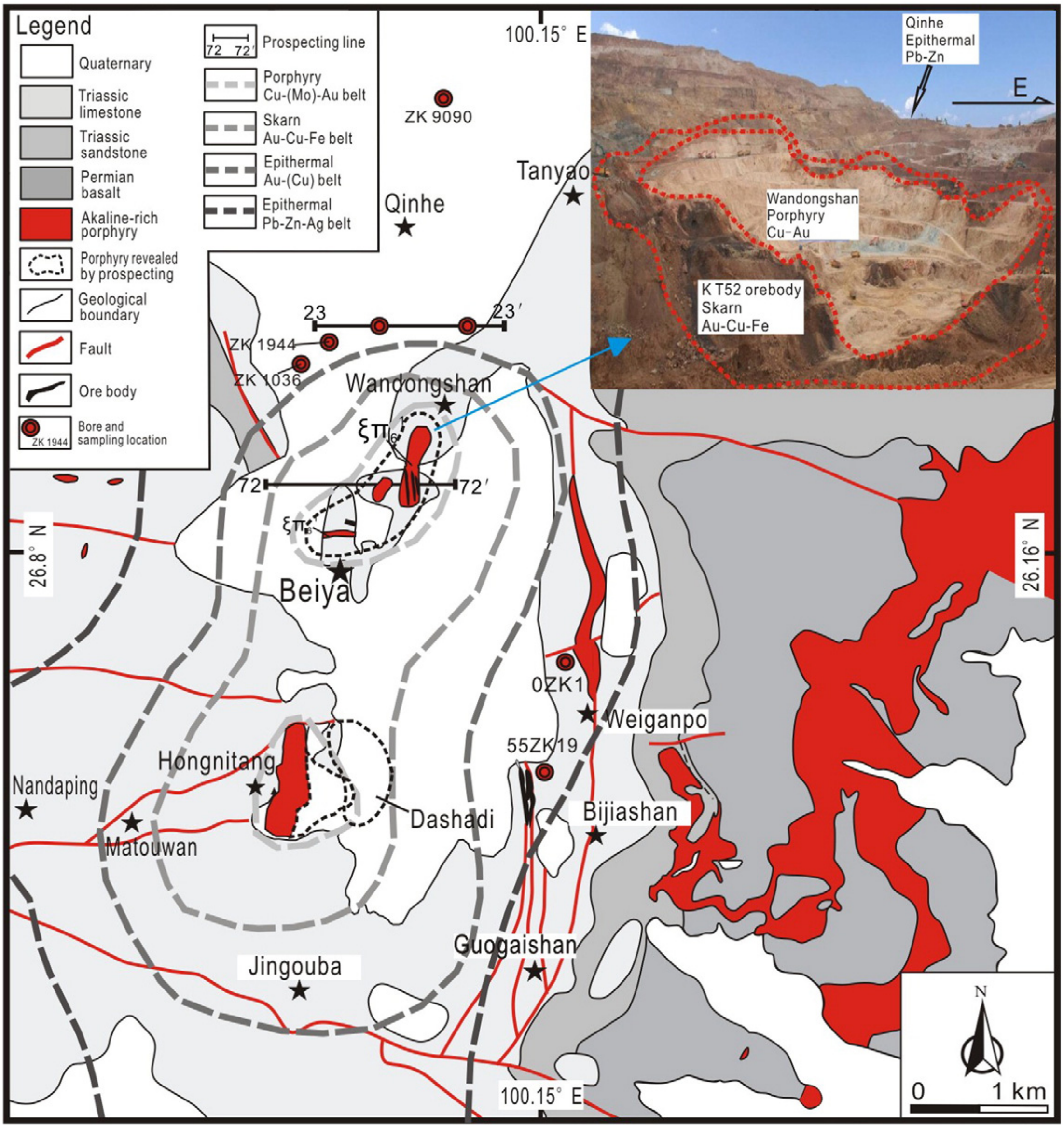

Fig. 3. Geological map of the ore body zones in the Beiya region.

450.81 m; 465.14–484.89 m) containing 0.44% Cu, 38.82 m (421.18–454.50 m; 472.63–478.13 m) containing 4.56 g/t Au.

2.2.3. Epithermal Au (Cu) mineralization

Epithermal Au (Cu) mineralization is present in ore bodies as veinlets, layers, and lenticular bodies; the disseminated mineralization primarily developed in the fracture zones of the five members of the middle Triassic Beiya Formation. The mineral assemblages are primarily pyrite, chalcopyrite, limonite, siderite, hematite, calcite, and dolomite. Newly discovered veinlet Au ore bodies to the east of the Hongnitang porphyry and in the southern part of the Jingouba deposit are 15.4 m thick with an average grade of 11.5 g/t Au (Yang et al., 2014).

2.2.4. Epithermal Pb–Zn–Ag mineralization

Epithermal Pb–Zn–Ag mineralization primarily occurs in the outer portion of the mineralized part of the porphyry intrusions. Around the Wandongshan–Hongnitang porphyries, 98 mineral zones had been discovered in the Qinhe and the eastern Bijiashan area. Among them, four Pb–Zn–Ag-dominated ore bodies have large-scale ore reserves. The proven reserves are 46.65 Mt of lead ore with an average grade of 1.52% Pb, 11.55 Mt of zinc ore with an average grade of 0.93% Zn, and 27.6 Mt of silver ore with a mean grade of 40.61 g/t Ag (Yang et al., 2014). The veinlet and layer-like ore bodies have often been discovered within the transition between the middle Triassic Beiya Formation and the lower Triassic Qingtianbao Formation and in the fault/fracture zones in the middle Triassic Beiya Formation (Fig. 5). These ore bodies are generally disseminated and densely disseminated vein styles. The mineral assemblages comprise galena, sphalerite, pyrite, chalcopyrite, and limonite, minor siderite, calcite and dolomite. Associated mineral alteration includes silicification, carbonatization, sericitization, and chloritization. In a review of the No. 23 prospecting line section (Fig. 5) from the Qinhe deposit, the ore bodies are mainly preserved in layer-parallel fracture zones at the contact of the carbonate (the middle Triassic Beiya Formation) and the arkose (the lower Triassic Qingtianbao Formation). Au–Ag–Pb and Pb–Zn–Ag mineralization coexist together. The Pb and Ag concentrations increase with depth from 1.20% to 3.68% and 6.30 g/t to 43.0 g/t respectively, but Zn does not change with depth (Fig. 5). Above the carbonate-arkose contact in the eastern portion of the Wandongshan and the Hongnitang porphyry intrusions (the Bijiashan deposit), two Pb–Zn–Ag ore bodies were encountered in boreholes 0ZK1 and 55ZK19 (Fig. 3). One such body was encountered in borehole 0ZK1 at depths of 231.2 to 242.1 m, this body contained ore

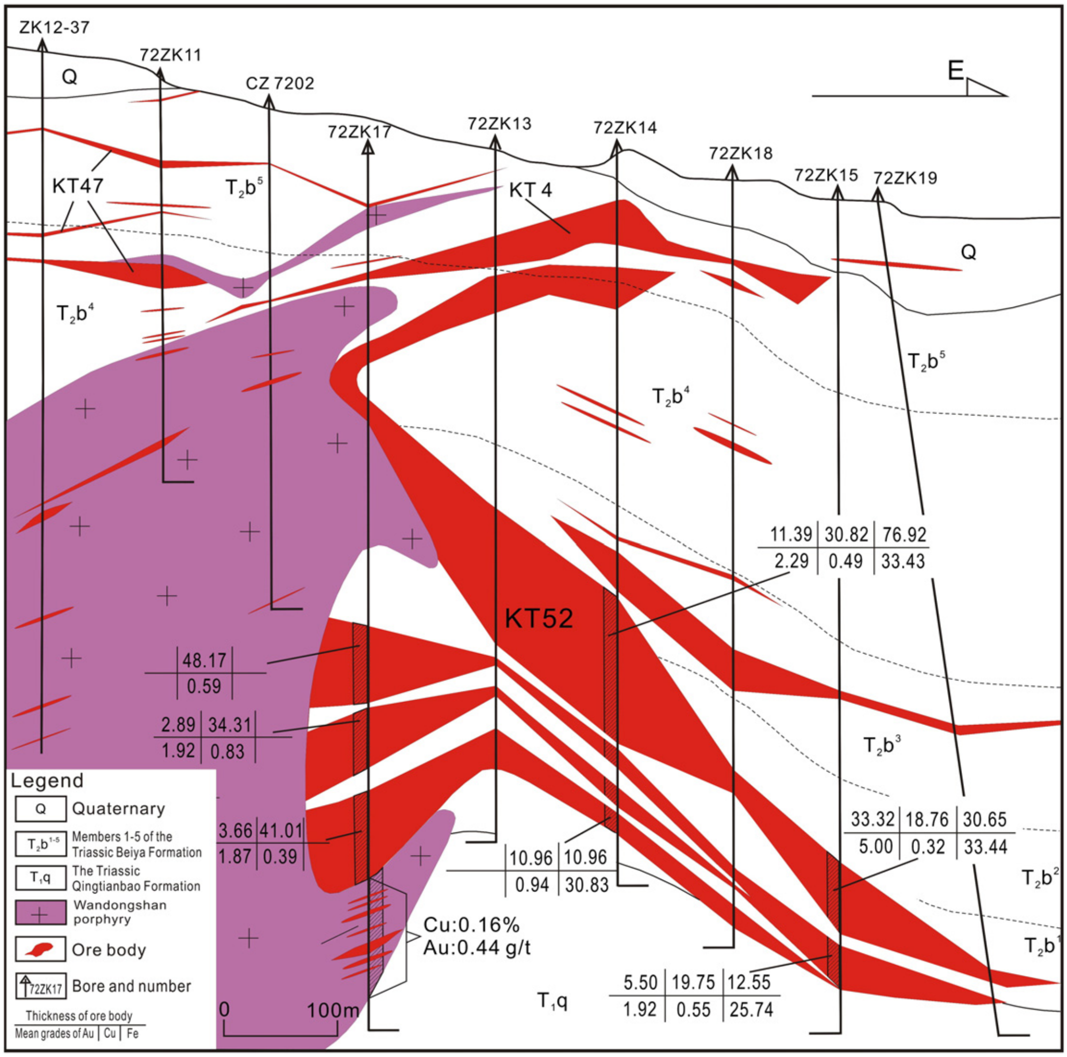

Fig. 4. Cross-section of the No. 72 prospecting line of Wandongshan.

with an average grade of 1.53% Pb, 1.55% Zn, and 29 g/t Ag. The second body in borehole 0ZK1 was encountered at depths of 351.4 to 363.1 m and contained ore with an average grade of 1.54% Pb, 1.27% Zn, and 34 g/t Ag. In borehole 55ZK19, the two ore bodies were encountered at depths of 167.3 to 197.7 m and 212.2 to 242.7 m and they host ore with an average grade of 1.30% Pb, 2.86% Zn, 63 g/t Ag and 1.16% Pb, 1.74% Zn, and 48 g/t Ag.

3. Analytical methods and results

3.1. Sr–Nd isotope data

The Sr–Nd isotope ratio method provides important information about the source of the magmas from which the host rocks at Beiya were generated. In Table 1, the Sr and Nd isotope ratios of samples LPD-13, LPD-14, LPD-15, LPD6 from the Qinhe intrusion were determined by the National Key Lab of Metallogeny in the School of Earth Sciences of Nanjing University of China, using inductively coupled plasma mass spectrometry (ICP-MS) and thermal ionization mass spectrometry (TIMS) respectively.

The initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the Qinhe porphyries are ranged from 0.707710 to 0.708496 and 0.512364 to 0.512391, respectively (Table 1), which are, in general, lower than the ratios of the other porphyries (B46-1, B24 and B50-1) listed in Table 1. The initial $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios shown in Fig. 6 can be used to establish the relative contributions of magma from different mantle reservoirs. Enriched mantle II (EMII) is thought to reflect a mantle member that has been mixed with upper crustal materials including continental sediment, continental crust, metamorphic oceanic crust, or oceanic island basalt in the process of plate subduction, and Enriched mantle I (EMI) is a mantle that contains lower crustal contributions (Zhang and Xie, 1995; Liu et al., 2000; Zhong et al., 2000). The compositions of EMI or EMII are shown, and their position on a plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ (Fig. 7) is indicative of an EMII source.

3.2. Sulfur isotope data

Isotopes of S provide a useful tool in the determination of the source of the sulfur. Table 2 partly reports data collected for samples from the Qinhe deposit to the north of the Wandongshan porphyry. These samples were analyzed by the National Key Lab of Metallogeny, School of Earth Sciences of Nanjing University of China, using a MAT251 element analyzer-isotope ration mass spectrometer (EA-IRMS).

The $\delta^{34}S$ values of pyrite, galena and sphalerite collected from the Qinhe deposit are ranged from 1.25‰ to 2.75‰ (Table 2), approximately 0‰, which are very close to the $\delta^{34}S$ values of sulfides from other areas (e.g. the Wandongshan, Hongnitang, Chenjiapo) in the Beiya deposit listed in Table 2.

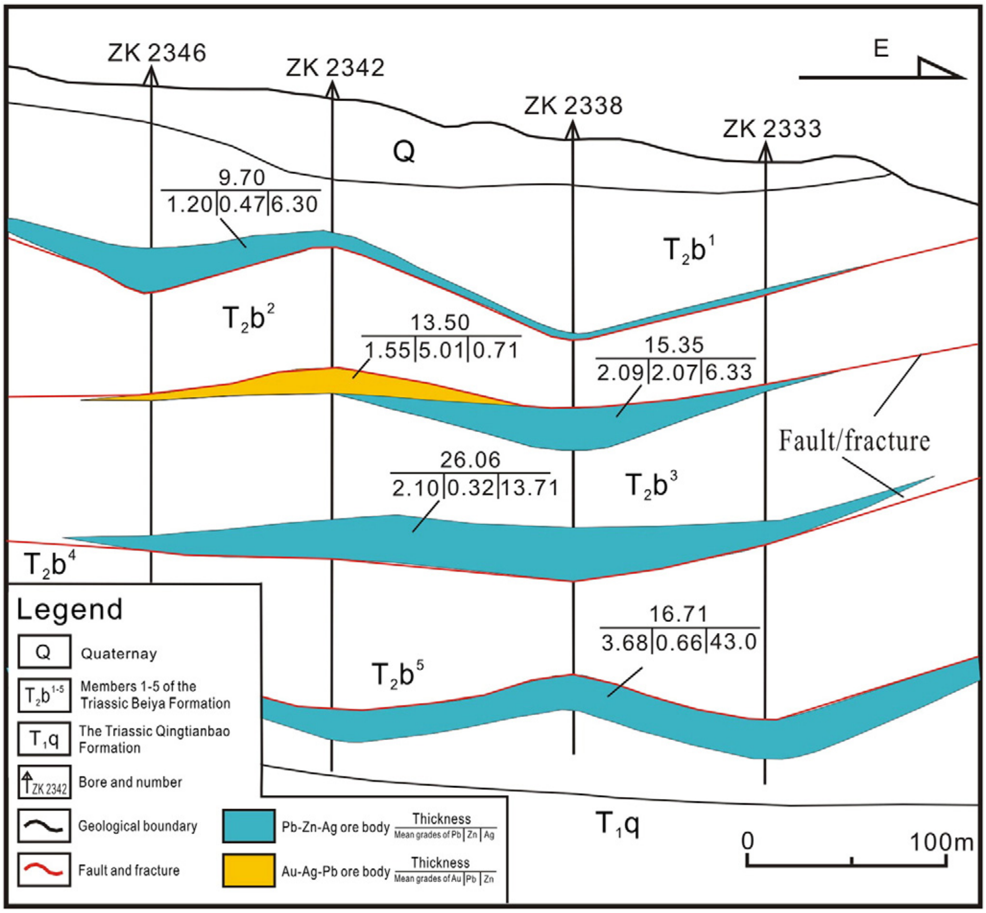

Fig. 5. Cross-section of the No. 23 prospecting line of Qinhe.

3.3. Oxygen isotope data

O isotopes can be used to determine the properties and evolution of metallogenic fluids. In Table 3. Samples LPD-6, LPD-7, LPD-8, LPD-9, and LPD-10 in this study were collected from the Qinhe deposit, and analyzed by the National Key Lab of Metallogeny, School of Earth Sciences of Nanjing University of China, using a MAT251 element analyzer-isotope ration mass spectrometer (EA-IRMS).

The $\delta^{18}O_{SMOW}$ values of samples from the Qinhe deposit ranged from 13.28‰ to 14.68‰ (Table 3), which are generally similar to those of the calcites of stage III in Wu et al. (2010) listed in Table 3. To investigate the ore-forming fluids of mineralization in the Qinhe deposit (outer portion of the Beiya mining area) in this study, the calcite-water isotope fractionation algorithm of O'Neil et al. (1969) (i.e., $1000\ln\alpha_{calcite\text{-}water} = 2.78 \times 10^6 / T^2 - 3.39$) was used. In this calculation, the $\delta^{18}O$ data for calcite in the Qinhe deposit are from Table 3 and the homogenization

Table 1
Sr–Nd–Pb isotope compositions of porphyries and lamprophyres from the Beiya region.

Sample	Rock type	Location	$(^{87}Sr/^{86}Sr)_i$		$(^{143}Nd/^{144}Nd)_i$		$^{206}Pb/^{204}Pb$		$^{207}Pb/^{204}Pb$		$^{208}Pb/^{204}Pb$		Reference
			Ratio	2σ	Ratio	2σ	Ratio	2σ	Ratio	2σ	Ratio	2σ	
LPD-13	QOP	Qinhe 108 m in Bore ZK9090	0.707710	0.000009	0.512379	0.000006	–		–		–		This study
LPD-14	QOP	Qinhe 121 m in Bore ZK9090	0.708496	0.000012	0.512364	0.000008	–		–		–		
LPD-15	QOP	Qinhe 133 m in Bore ZK9090	0.707930	0.000008	0.51239	0.000006	–		–		–		
LPD-16	QOP	Qinhe 146 m in Bore ZK9090	0.708016	0.000009	0.512391	0.000010	–		–		–		
B46-1	QOP	Hongnitang	0.708170	0.000018	0.512372	0.000020	18.5691	0.027	15.6149	0.031	38.8119	0.030	Xu et al. (2006a)
B24	QAP	Wandongshan	0.709010	0.000018	0.512404	0.000011	18.6536	0.036	15.6964	0.050	39.0955	0.055	
B50-1	BOP	Weiganpo	0.711051	0.000019	0.512425	0.000020	18.5574	0.026	15.6169	0.032	38.8574	0.033	
WD40CD-2	LAM	Hongnitang	0.707322	0.000018	0.512536	0.000010	18.4949	0.056	15.6426	0.057	38.8396	0.056	Mo and Zeng, 2008
HN392	LAM	Wandongshan	0.707380	0.000018	0.512445	0.000007	18.5694	0.058	15.5991	0.061	38.7484	0.068	

Notes: QAP: quartz albite porphyry; QOP: quartz orthoclase porphyry; BOP: biotite orthoclase porphyry; LAM: lamprophyre. Initial ratios were calculated at 35 Ma.

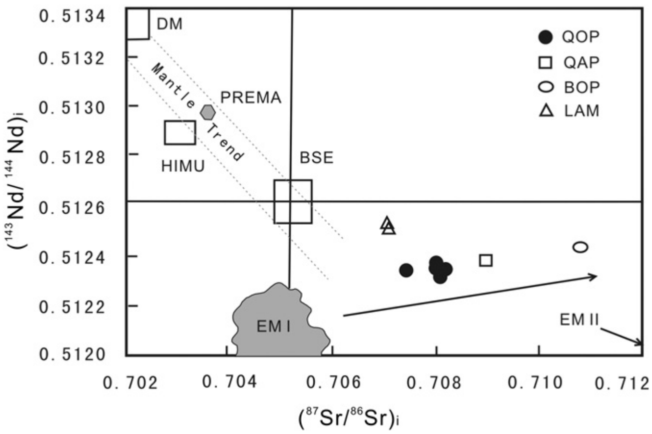

Fig. 6. Initial $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram for alkaline-rich porphyries and lamprophyres in Beiya (Zindler and Hart, 1986). Initial ratios were calculated at 35 Ma.

temperatures of the fluid inclusions from the Qinhe deposit is taken to be 300 °C (Xiao et al., 2009b). The resulting $\delta^{18}O$ values were 8.10–9.61‰.

4. Discussion

4.1. Formation of the Beiya alkaline-rich porphyries

The fact that the intrusions in Beiya originated mainly from an EMII type mantle (Figs. 6 and 7) demonstrates that crust–mantle interaction played a significant role in the formation of the Beiya alkaline-rich porphyries in the Jinshajiang–Honghe belt.

Sun et al. (2009) analyzed the noble gas composition of the sulfide quartz veins in the Daping gold deposit (located at the southern part of the Jinshajiang–Honghe alkaline-rich porphyry belt), and the results demonstrate that the ore-forming fluids of the Daping deposit were derived from the transition zone between the lower crust and the upper mantle. Based on their results, Sun et al. (2009) proposed that crust–mantle interaction have played an important role in the development of the mineralization found in the Daping deposit.

Yuan et al. (2010) pointed out that abundant crustal material was recycled into the mantle by plate subduction in the Late Paleozoic in the Jinshajiang–Honghe alkaline-rich porphyry belt, and the magmas derived from the melting of these mixed crust–mantle materials subsequently ascended and were emplaced in the Himalayan tectonic extension environment (Yuan et al., 2010). Other studies

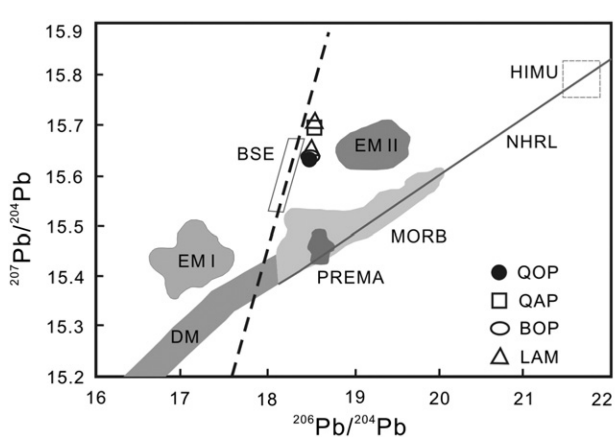

Fig. 7. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram for alkaline-rich porphyries and lamprophyres in Beiya (Zindler and Hart, 1986).

Table 2
S isotope compositions of ores from the Beiya region.

Sample	Location	Mineral	$\delta^{34}S_{V\text{-}CDT}$/‰	2σ	Reference
LPD-1	Qinhe 441 m in Bore ZK1944	Pyrite	2.26	0.12	This study
LPD-2	Qinhe 420 m in Bore ZK1944	Pyrite	2.75	0.03	
LPD-3	Qinhe 325 m in Bore ZK1944	Galena	1.83	0.01	
LPD-4	Qinhe 192 m in Bore ZK1036	Galena	1.25	0.01	
LPD-10	Qinhe 320 m in Bore ZK1036	Sphalerite	2.73	0.01	
WDS-1	Wandongshan	Pyrite	2.70	–	Xiao et al. (2011)
WDS-5	Wandongshan	Pyrite	2.20		
WDS-5	Wandongshan	Galena	1.40		
WDS-10	Wandongshan	Pyrite	3.60		
ZK3-1	Chenjiapo	Pyrite	2.50		
ZK3-2	Chenjiapo	Galena	1.00		
ZK3-3	Chenjiapo	Galena	1.20		
MTW-2	Matouwan	Pyrite	0.00		
WS1	Wandongshan	Pyrite	0.49	–	Liu et al. (1999)
WS2	Wandongshan	Pyrite	4.50		
WS3	Wandongshan	Pyrite	1.20		
WS4	Wandongshan	Pyrite	−1.58		
hs1	Hongnitang	Galena	0.56		
hs2	Hongnitang	Galena	0.60		
bs2	Bijiashan	Galena	−1.40		
gc1	Guochanghe	Galena	−2.40		

Note: CDT = Canyon Diablo Troilite.

(Zhang and Xie, 1995; Liu et al., 2000; Zhong et al., 2000; Hou et al., 2004; Bi et al., 2004; Bi, 2005; Li et al., 2010) indicate that the Jinshajiang–Honghe belt recorded subduction of the Paleo-Tethys oceanic crust and that the lithospheric mantle beneath the Beiya mine area was metasomatized by fluids derived from this subducted plate. These studies strongly confirm the crust–mantle interaction history in the Jinshajiang–Honghe alkaline-rich porphyry belt as well as the Beiya area.

The Indian and Eurasian plates collided after 65 Ma, resulting in the formation of the Qinghai–Tibet plateau (Hou et al., 2004; Xu et al., 2006c; Li et al., 2010). Due to the accelerating rate of collision (over the short interval between 42 and 25 Ma), large-scale rotation, strike-slip faulting, thrusting, and fluid migration occurred in the mid-south part of the Sanjiang Region at the southeast margin of the Qinghai–Tibet Plateau (Li et al., 2010). During the convergence of the Indian and Eurasian plates, the north margin of the Indian plate collided with the Eurasian continent, and in the Sanjiang Region, the blocks on the Eurasian continent were displaced to the south relative to the Indian plate; strike–slip faults were formed along the block boundaries (Fig. 1a; Xu et al., 2006c). Transpressional strain produces vertical, extensional volumes (pull-aparts) at localized discontinuities along strike–slip fault systems, which channeled the ascent and pooling of magma in the upper crust (Richards, 2003; Fig. 8). The expansion centers (e.g., the Heqing and Lanping basins) that formed after the large-scale strike–slip and pull-apart process became the pathways for subsequent transportation of magma. Alkaline porphyries in the Jinshajiang–Honghe belt were emplaced into the secondary fault system of the Jinshajiang–Honghe strike–slip belt as the result of the upwelling of magma associated with the strike–slip fault movements; hydrothermal fluid systems were driven by the porphyry magmas. For these reasons, the alkaline-rich porphyries emplacement and the large-scale tectonic–magmatic–hydrothermal metallogenic events were spatially restricted to the Jinshajiang–Honghe strike–slip fault zone (Fig. 8; Li et al., 2010).

Table 3
C–O isotope compositions of calcites from the Beiya region.

Sample	Location	Mineral (stage)	$\delta^{13}C_{PDB}$/‰	2σ	$\delta^{18}O_{SMOW}$/‰	2σ	Reference
Wd1	Wandongshan	Calcite(I)	−5.050	0.001	11.57	0.001	Liu et al. (1999)
HN-29	Hongnitang	Calcite(II)	0.051	0.007	18.464	0.002	Wu et al. (2010)
BJ-2-4	Bijiashan	Calcite(II)	−1.020	0.008	14.712	0.012	
HN-19	Hongnitang	Calcite(III)	−4.146	0.006	15.858	0.008	
WD-20	Wandongshan	Calcite(III)	−4.809	0.007	14.637	0.011	
WD-19	Wandongshan	Calcite(III)	−3.180	0.005	14.400	0.003	
WD-13	Wandongshan	Calcite(III)	−5.837	0.004	13.946	0.022	
WD-2	Wandongshan	Calcite(III)	−5.704	0.009	14.370	0.012	
BJ-2-2	Bijiashan	Calcite(III)	−1.060	0.004	18.706	0.012	
BJ-2-5	Bijiashan	Calcite(III)	−5.494	0.014	14.218	0.027	
BJ-2-7	Bijiashan	Calcite(III)	−3.777	0.005	13.325	0.012	
BJ-2-1	Bijiashan	Calcite(III)	−3.766	0.007	13.011	0.014	
BJ-13	Bijiashan	Calcite(III)	–5.268	0.005	14.160	0.017	
BJ-3	Bijiashan	Calcite(III)	–2.872	0.012	13.590	0.008	
LPD-6	Qinhe 433 m in Bore ZK1944	Calcite	–		13.83	0.002	This study
LPD-7	Qinhe 319 m in Bore ZK1944	Calcite	–		14.68	0.016	
LPD-8	Qinhe 187 m in Bore ZK1944	Calcite	–		13.47	0.011	
LPD-9	Qinhe 209 m in Bore ZK1036	Calcite	–		13.28	0.011	
LPD-10	Qinhe 294 m in Bore ZK1036	Calcite	–		13.41	0.002	

Notes: PDB = Pee Dee Belemnite; SMOW = Standard Mean Ocean Water.

The spatially-related porphyries and the lamprophyres in Beiya have similar REE and multi-element normalized patterns, indicating a co-magmatic (Xu et al., 2006a,b; Mo and Zeng, 2008). Both rock series have similar Sr–Nd–Pb isotopic compositions (Figs. 6–7), which is also indicative of a common magma source.

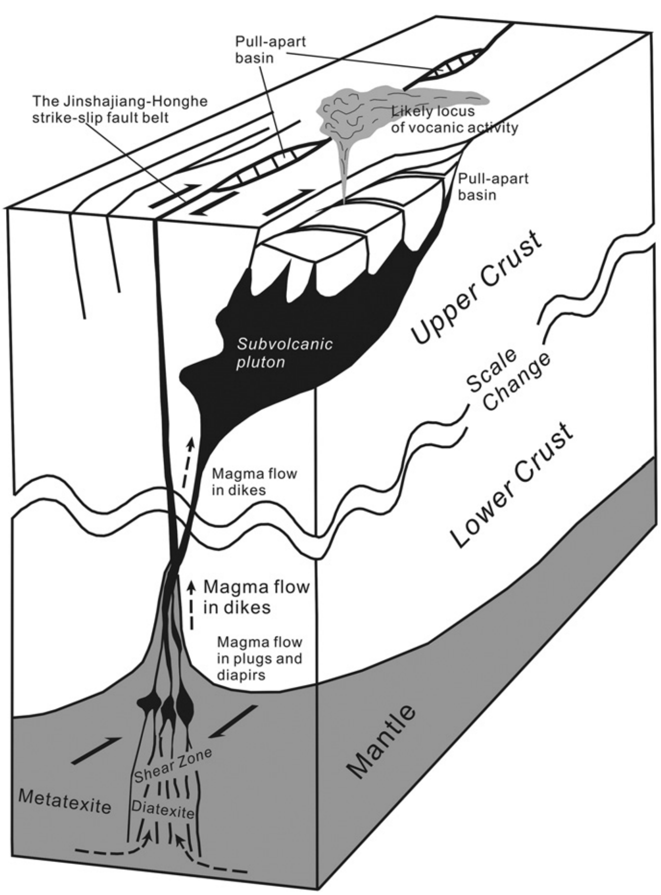

Fig. 8. Formation model of the Jinshajiang–Honghe alkaline-rich porphyry belt (modified from Richards, 2003). (The emplacement of alkaline-rich porphyries in the secondary fault system of the lithosphere-penetrating Jinshajiang–Honghe strike–slip belt).

The Beiya alkaline-rich porphyries are located in the central part of the Jinshajiang–Honghe strike–slip fault zone, and the ages of the porphyries (dominated by quartz orthoclase porphyries) associated to the main mineralization stage in Beiya range from 37 Ma to 26 Ma, approximately the same as the ages of the other structurally-controlled alkaline-rich porphyries in the Jinshajiang–Honghe alkaline porphyry belt (Fig. 1b; Bi et al., 2006; Chen et al., 2009; Ge et al., 2010; Shu et al., 2012; Wang et al., 2012; Wu et al., 2013; Huang et al., 2013).

A model for the emplacement of magma in Beiya can be summarized as follows: During the late stage of the India–Eurasian plate collision (45–25 Ma), the south-side-forward displacement of blocks caused the Jinshajiang–Honghe strike–slip faulting activities which further triggered intensive alkaline-rich magma emplacement. As a result of this, the Beiya alkaline-rich porphyries were produced in the secondary fault system of the mantle-penetrating Jinshajiang–Honghe strike–slip belt, around which the porphyry Au-polymetallic mineralization developed.

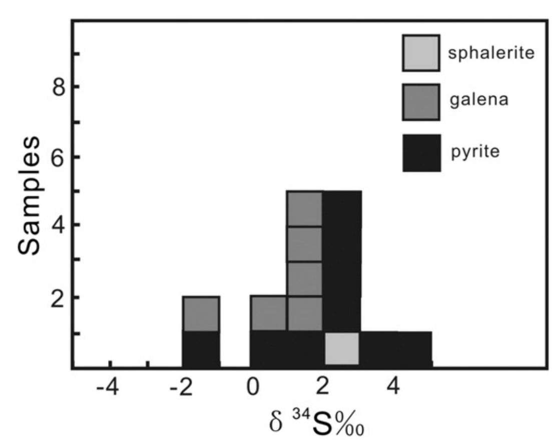

Fig. 9. Histogram showing S isotope ratio data for samples from various parts of the Beiya region.

4.2. Metallogenic model of the Beiya Au-polymetallic deposit

4.2.1. Source of metals and fluids

The $\delta^{34}S$ values of pyrite, galena and sphalerite collected from the Wandongshan, Hongnitang, Bijiashan and Qinhe (Table 2) are approximately 0‰. There is a narrow range in composition (Fig. 9). The limited variation in the $\delta^{34}S$ values ($\delta^{34}S = 0‰$) of the ore samples among these areas of Beiya indicates that the S may be derived from the mantle.

Comparison of the Pb isotope ratio signatures of the ores from different deposits and the altered porphyry, unaltered porphyry, altered limestone, and unaltered country rocks (e.g., limestone, sandstone, basalt) in the Beiya region provides information about the source of the metals. The Pb isotope ratio characteristics of the ores are similar to those of the altered porphyry, unaltered porphyry, and alteration limestone, but different to the unaltered country rocks. These observations indicate that the ore-forming materials are related to the alkaline-rich porphyries rather than to the wall rocks (Wu et al., 2005).

Calcites of different attitudes throughout various ore forming stages are widely developed at Beiya mining area. So studies on these calcites are informative to understand the evolutionary history of ore forming fluids in Beiya. Generally, there are three stages of calcite formation at Beiya (Table 3). In stage I, calcite veins are contained in the porphyry rocks that pre-date ore-formation; in stage II, massive and vein calcite linked to the main stage of ore formation in the limestone of the wall rocks; in stage III, the stockwork calcite veins cut the ore bodies and the wall rocks. Based on C and O isotopic studies of carbonates by Wu et al. (2010), it was shown that the $\delta^{13}C$ and $\delta^{18}O$ values of the stage I calcites are −5.05‰ and 11.57‰, respectively, which are similar to those of magmatic fluids ($\delta^{13}C = -9‰$ to $-4‰$, $\delta^{18}O = 6‰$ to 15‰; Zheng and Chen, 2001). The C and O isotopic compositions (Table 3) and the homogenization temperatures of the fluid inclusions in Beiya (300 °C, Xiao et al., 2009b) show that the $\delta^{13}C$ and $\delta^{18}O$ values of the ore-forming fluids associated with the formation of calcites during stage II are −5.5‰ and 10.5‰, respectively, and −12‰ and 7‰ for stage III. Based on these relationships, the C–O isotopic compositions of the ore-forming fluids associated with the calcites formed during stage II (the main ore-forming stage) are similar to those of the calcites formed during stage I. The ore-forming fluids present during stage II are therefore probably magmatic fluids derived from alkaline porphyries. The decrease in the $\delta^{13}C$ and $\delta^{18}O$ values of the ore-forming fluids associated with the formation of calcites during stage III ($\delta^{13}C$: −5.5‰ → −12‰; $\delta^{18}O$: 10.5‰ → 7‰) are inferred to be the product of the mixing of meteoric water with the magmatic fluids after ore formation.

In comparison with the above discussed $\delta^{18}O$ value (10.5‰) of the stage II calcites (Wu et al., 2010; magmatic fluids derived from alkaline porphyries), the resulting lower $\delta^{18}O$ values of the ore-forming fluids associated with the formation of calcites in the Qinhe deposit probably indicate a late-stage ore-forming fluids which are products of magmatic fluids mixed with meteoric water during the late stage of metallogeny in Beiya.

Xiao et al. (2011) compared the trace element concentrations in both the fluid inclusions and porphyries in Beiya, and suggested that they are similar to each other. This provides more support for our proposal that the ore-forming fluids were derived from the alkaline porphyries.

He et al. (2013) reported an age date for the quartz orthoclase porphyry in the Hongnitang intrusion by LA–ICP-MS U–Pb zircon geochronology at 36.48 ± 0.26 Ma, which is coincident with an age of a skarn ore body of the Hongnitang porphyry which was dated by Re–Os dating on molybdenite at 36.87 ± 0.76 Ma in their study. The similar ages of the main ore-forming process (the skarn mineralization) and the alkaline porphyries (quartz orthoclase porphyry) indicate that they were formed in close association.

4.2.2. Genetic model for the Beiya Au-polymetallic deposit

The results discussed above demonstrate that the ore-forming materials in Beiya are primarily related to the alkaline porphyry magmas; the ore-forming fluids originated from alkaline porphyries and the epithermal ore bodies in the outer region are the products of interaction of magmatic fluids with meteoric waters.

Based on the isotope ratio and fluid inclusion evidences, the ore-forming fluids of the Beiya region contained abundant volatiles. Metals were concentrated from their magma during the late-stage of the evolution of the alkaline porphyry magma. Accompanying the upwelling of magma, the ore-forming elements (e.g., Cu and Au) were extracted by fluids. When the fluids migrated to the top of the porphyries, continuous accumulation of fluids caused brecciation of the wall rocks, which led to a decrease in the system pressure. The fluids boiled as a consequence, which produced phreatomagmatic breccias (e.g., the phreatomagmatic breccias at the top of the Hongnitang porphyry). Simultaneously, at shallower depths, due to the decrease in the temperature and pressure of the volatile ore-bearing hydrothermal fluids, ore-materials precipitated in fractures within the alkaline-rich porphyries and wall-rocks, and in voids of the phreatomagmatic breccias. The sparsely disseminated, densely concentrated, veinlet-style and vein-style of Cu (Mo), and Cu–Au ore bodies were developed in this way (Fig. 10).

Forced by heat and upwelling of magma, a portion of the ore-bearing fluids migrated to the contacts between the alkaline-rich porphyries and the carbonate wall-rocks. During the formation of the skarns, due to the high permeability of the Beiya Formation carbonate rocks, the ore-bearing fluids were able to mix with meteoric waters (inferred by formerly discussed C–O isotope studies) and produced metasomatism (Luo et al., 2007). In the fracture voids of the wall-rocks, with the decrease in pressures and temperature, the solubility of the ore-bearing fluids decreased which led to the precipitation of Fe, Cu, and Au and formation of layered, layer-like, veinlet, and lenticular skarn ore bodies in the fractures and empty spaces of the contact zones between the alkaline porphyries and the wall rocks (Fig. 10).

In the intensely faulted/fractured zones in the wall rocks (e.g., wall rocks of the outer portions of the Beiya mine area), the ore-forming fluids were able to continue to move and further mix with meteoric waters. Where the physical and chemical conditions (e.g., T, P, pH, and Eh) became favorable, Au, Pb, Zn, and Ag precipitated within the distal zones of the wall rocks and formed epithermal, veinlet Au-ore bodies and layer-like, lenticular, and veinlet Pb–Zn–Ag-ore bodies (Fig. 10).

In summary, mineralization in the Beiya area is typical of porphyry Au-polymetallic metallogenic systems. The deposit is centered by the alkaline-rich porphyries, the formation of which was driven by magmatism, hydrothermalism, and metasomatism. In addition, the high-grade ores tend to concentrated in certain favorable structural zones.

5. Conclusions

1. The Beiya alkaline-rich porphyries and the Au-polymetallic ores formed by emplacement of magma into a secondary fault system of the mantle-penetrating Jinshajiang–Honghe strike–slip belt during the late stage of the India–Eurasian plate collision (45–25 Ma).
2. The Beiya ore district is characterized as a “porphyry → contact zone → wall rock” metallogenic system, with the centers of alkaline-rich porphyries providing the ore-forming materials, ore-forming fluids, and heat. From the center of the system (i.e., the alkaline-rich porphyries), Cu–Au ore bodies are disseminated in the porphyry; layer-controlled lenticular skarn Au–Cu–Fe ore bodies formed within the contract zones; and lenticular, veinlet Au (Cu), Pb–Zn–Ag ore bodies formed at the outer parts of the system. All of these patterns constitute a large, integrated porphyry Au-polymetallic metallogeny system.

The latest exploration data reveal that the buried southern portion of the Wangdongshan porphyry, the contact zones and deep zones

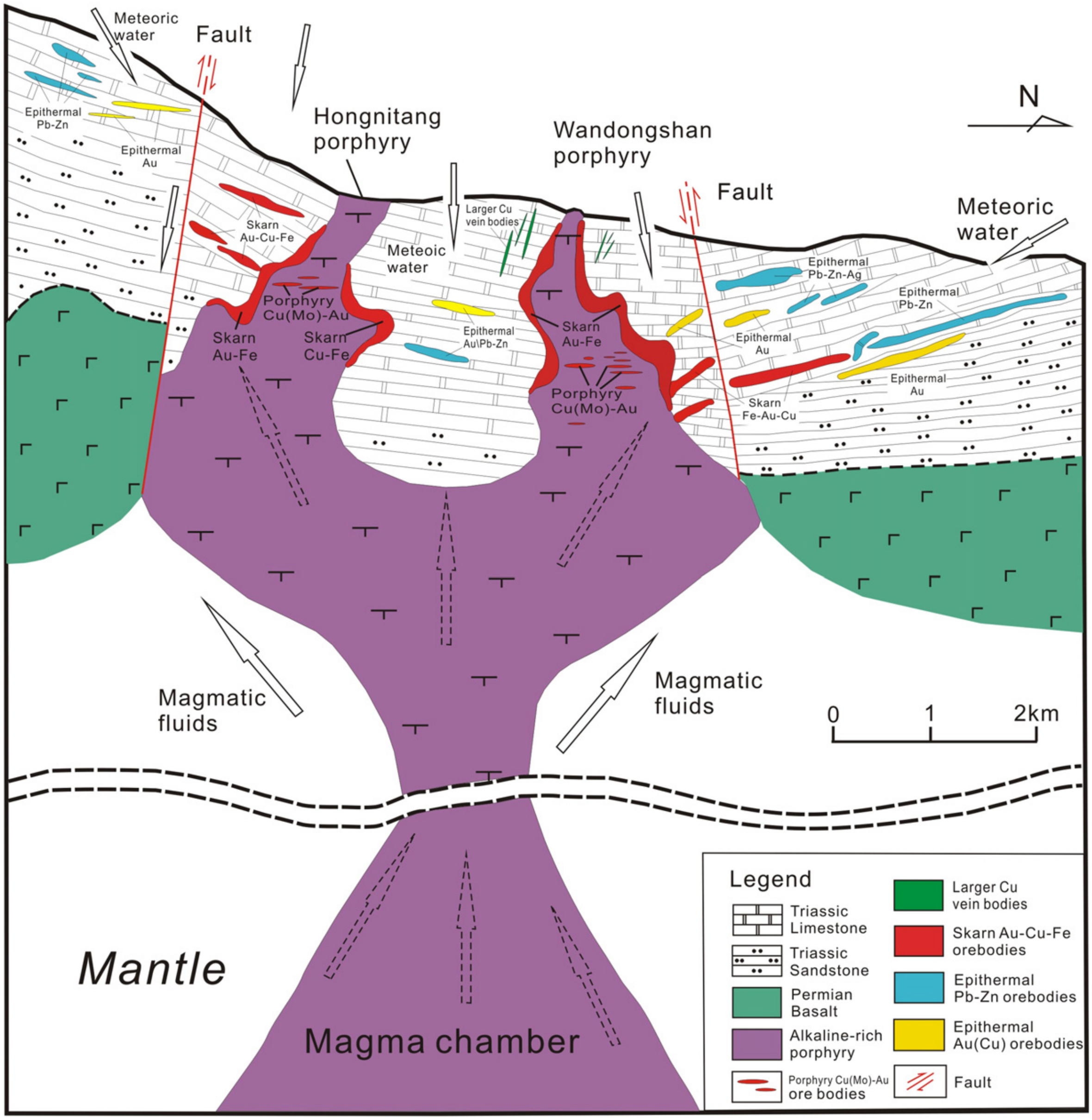

Fig. 10. A proposed model for the porphyry Au-polymetallic metallogenic system in Beiya.

surrounding the Hongnitang porphyry exhibit high potential for future mineral discoveries.

Acknowledgments

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