Geological Characteristics and Ore-controlling Factors of the Beiya Gold–Polymetallic Ore Deposit, Northwestern Yunnan Province

ZHOU Yunman¹, ZHANG Changqing², *, HE Zhonghua¹, LIU Huan², ZHOU Guiwu¹, SUN Jia² and LIU Bo³

¹ Yunnan Gold & Mining Group Co. Ltd., Kunming 650224, China
² MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China
³ Beijing Research Institute of Uranium Geology, Beijing 100029, China

Abstract: Based on comprehensive petrological, geochronological, and geochemical studies, this study analyzed the relationships between the Beiya gold-polymetallic skarn deposit and quartz syenite porphyries, and discussed the source(s) and evolution of magmas. Our results suggest that syenite porphyries (i.e. the Wandongshan, the Dashadi, and the Hongnitang porphyries), which formed between the Eocene and the early Oligocene epochs, are the sources for the gold-polymetallic ores at the Beiya deposit. Carbonate rocks (T₂b) of the Triassic Beiya Formation in the ore district provide favorable host space for deposit formation. Fold and fault structures collectively play an important role in ore formation. The contact zone between the porphyries and carbonates, the structurally fractured zone of carbonate and clastic rocks, and the zone with well-developed fractures are the ideal locations for ore bodies. Four types of mineralization have been recognized: 1) porphyry-style stockwork gold–iron (copper) ore, 2) skarn-style gold-iron (copper and lead) ore in the near contact zone, 3) strata-bound, lense-type lead–silver–gold ore in the outer contact zone, and 4) distal vein-type gold–lead–silver ore. Supergene processes led to the formation of oxide ore, such as the weathered and accumulated gold–iron ore, the strata-bound fracture oxide ore, and the structure-controlled vein-type ore. Most of these ore deposits are distributed along the axis of the depressed basin, with the hypogene ore controlling the shape and characteristics of the oxide ore. This study provides critical geology understanding for mineral prospecting scenarios.

Key words: porphyry-skarn type, quartz syenite porphyries, ore-controlling factors, Beiya gold–polymetallic deposit, northwestern Yunnan province

1 Introduction

The Beiya ore deposit is a super large porphyry-skarn gold polymetallic deposit discovered by Yunnan Gold & Mining Group Co., Ltd., and has been explored continuously throughout the past 10 years. Several previous studies have been conducted in the Beiya deposit, which provide important data about geological characteristics, rock types and distribution, rock-forming and ore-forming ages of porphyries and ores, and deposit genesis in the Beiya gold field, as well as ore deposit and prospecting models, prospecting methods and predictions (Cai Xiping et al., 1991; Cai Xiping, 1993; Chen Aibin et al., 2011; Cui Yinliang et al., 2001, 2003; Deng Jun et al., 2010, 2012; Ge Liangsheng et al., 2002; Li Jinghong et al., 1991; Ma Deyun and Han Runsheng, 2001; Fu Weimin and Hu Chaoping, 1994; Ren Zhiji et al., 2001; Song Huanbin and He Mingqin, 1994; Wu Kaixing et al., 2005; Xiao Qibin et al., 2003; Xiao Xiaoniu et al., 2009a, 2009b, 2011; Xu Shouming et al., 2006; Xu Xingwang et al., 2006, 2007; Yan Jianguo et al., 2002, 2003; Xue Chuandong et al., 2008; Yang Shiyu and Wang Rixue, 2002; Ying Hanlong and Cai Xiping, 2004; Zhong Kunming and Yang Shiyu, 2000; Zou Guangfu et al., 2013). In recent years, a scientific research team, organized by Yunnan Gold & Mining Group, has carried out “Three-in-One” prospecting prediction research in the Beiya gold-polymetallic ore exploration area (He Wenyan et al., 2018).
et al., 2012, 2013; He Wenyan, 2014; He et al., 2014; 2015; He Zhonghua et al., 2013, 2014, 2016; Jia Ruya et al., 2016; Jiang Wentao et al., 2015; Deng et al., 2015a; ; 2015b; Fu et al., 2015; 2016; Zhou et al., 2016; Li et al., 2016; Liu Fei et al., 2016; Mao et al, 2017; Niu Haobin et al., 2015; Wang Jianhua et al., 2015, 2016; Wang Mingzhi et al., 2016; Li and Wang, 2014; Li et al., 2016; Yang Jian et al., 2014, 2015; Zhou Yunman et al., 2013, 2014, 2015, 2016, 2017). Based on previous study results and intensive geological investigation in this study, this paper analyzed key metallogenic geological processes and ore-controlling factors and clarified prospecting directions and target orebodies in the ore district and its peripheries, by carrying out geochemical analysis of alkali-rich porphyry intrusive bodies and zircon dating for quartz syenite and quartz monzonite porphyry samples from several ore sections. Therefore, this study is of some significance for better understanding the ore-controlling factors and ore-forming mechanism of this deposit.

2 Geological Backgrounds

2.1 Regional geology

Located on the northeastern side of Jinsha River–Ailaoshan–Red River strike slip fault, the Beiya superlarge gold ore deposit is an archetype deposit within the large Tethys porphyry-skarn-type copper polymetallic metallogenic belt (Hou et al., 2007; Mao et al., 2014), and formed by the decomposition of an oblique collision between the southeastern Indian continental margin and the Asian continent (Xu Zhiqin, 2011). The deposit geotectonically belongs to the Heqing terrace (T2-3)–Songgui faulted basin (T3) in the central region of the Yanyuan-Lijiang passive continental margin rift basin (Pz2) along the western margin of the Yangtze block. Structurally controlled by the NNW faults are mainly F21 and F28; and NE faults are SN are F1–F6; EW faults mainly have F22, F25, and F26; northwest (NW), and northeast (NE). Faults oriented in the orientation of southnorth (SN), eastwest (EW), geomorphological characteristics. Four sets of faults exist in the orientation of southnorthly (i.e. a wide-flat short axis syncline) where strata from the T2b1-5 are exposed in the west limb, and strata from the T2b1-5, T2q, and Pβ are exposed in the east limb. The strata at the core are gentle and give the northsouth-trending intermountain basin its geomorphological characteristics. Four sets of faults exist in the orientation of southnorth (SN), southeast (SE), southwest (SW), and northeast (NE). Faults oriented in SN are F1–F6; EW faults mainly have F22, F25, and F26; NW faults are mainly F21 and F28; and NE faults are mainly F23 and F27 (Fig. 1). Magmatic rocks are dominantly Himalayan alkali-rich porphyries. The rock body is dominated by quartz syenite porphyry, followed by syenite porphyry, with biotite quartz syenite porphyry and lamprophyre veins throughout the region.

The ore district contains both hypogene and supergene mineralization types, with the former being important in reserves. Hypogene mineralization mainly occurs in the alkali-rich porphyry and T2b carbonate rocks. The porphyry-skarn-type ore bodies, in the exocontact zone, are distributed in a ring pattern around the rock body, and their occurrences synchronously change with the contact zone of the rock body. The supergene mineralization occurs in N2s and weathering-accumulation type ore bodies along the unconformity above the T2b and the porphyry body. According to shape and spatial position, the porphyry-skarn-type ore bodies can be divided into four sub-types: 1) an Fe–Au (Cu/Mo) ore body hosted in steep fissures occurring as lenticulars and veins in the alkali-rich porphyry; 2) an Fe–Au–Cu–Pb or Fe–Cu (Mo) ore body hosted in skarns occurring as block shape and
stratiform in the contact zone; 3) an Fe–Au–Pb–Ag or Fe–Cu ore body occurring as stratoid and large lenticular shapes, hosted in the interlayer fracture zone of the T2b carbonate rocks near the contact zone; and 4) a Pb–Zn–Ag ore body occurring as small lenticulars and veins, in the fracture and fissure zone of the T2b carbonate rocks apart from the contact zone. More than 1,800 polymetallic ore bodies exist in the ore district, composed of Au, Fe, Cu, Ag, Pb, and Zn, which includes more than 50 relatively large ore bodies. The main ore bodies are KT4, KT10, KT11, KT52, KT54, as well as KT63, and the amount of gold within a single ore body classifies each as greater than a medium-sized deposit (YGMGC, 2014). The main ore body is 400–1,680 m long and 570–1,420 m wide, with an average thickness of 4.27–13.27 m and an average grade of 1.65–2.83 ppm Au, 25.06–37.55% TFe, 18.47–28.11% mFe, 0.63–0.65% Cu, 0.91–4.04% Pb, 0.28–1% Zn, as well as 24.52–67.29 ppm Ag. The main characteristics of a typical ore body are illustrated in Table 1 and Figure 2. The weathering-accumulation type ore bodies are hosted in N2s, with a length of 1,840 m along the strike, a width of 0.90–35.32 m and a grade of 0.90–20.24 ppm Au, 25.06–63.63% TFe, 0.10–1.29% Cu, 1.21–2.04% Pb, 0.23–0.70% Zn, as well as 15.36–23.33 ppm Ag.

Primary ores are composed of a number of metallic minerals, such as magnetite, pyrite, chalcopyrite, siderite, hematite, galena, pyrrhotite, and sphalerite. Oxidized ores contain mainly limonite, malachite, galena, cerussite, smithsonite, and cerargyrite. Gangue minerals include
Table I Geological features of main ore bodies within the Beiya gold–polymetallic deposit

<table>
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<th>Deposit type</th>
<th>Skarn type in the contact zone of the Wangdangshan porphyry body</th>
<th>Hydrothermal vein type in the interlayer or fault fracture zone (including interior of rock body)</th>
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<tr>
<td>Main mineralized elements</td>
<td>Au-Fe-Cu (Mo)</td>
<td>Au-Fe-Cu, Cu-Fe, Pb-Ag</td>
<td>Au-Fe, Pb-Ag</td>
<td>Cu-Fe</td>
<td>Au-Fe</td>
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<td>Typical ore body</td>
<td>KT52 ore body</td>
<td>KT63 ore body</td>
<td>KT10 ore body</td>
<td>KT18 ore body</td>
<td>KT4B ore body</td>
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<td>Characteristics of ore body</td>
<td>The ore body in the Wangdangshan ore section occurs in the exocontact zone between alcali-rich porphyry and Tj3 carbonate rocks as stratiform, showing ring distribution around rock body, and its occurrence varies synchronously with the contact zone of the rock body, with a length of 1,600 m in SN (strike) direction, a width of 113–1,420 m in the EW direction and a thickness of 0.8–115.26 m. Au: 0.86–2.39 ppm; TFe: 22.37–66.94%; mFe: 16.04–52.46%; Cu: 0.20–25.72%; Pb: 0.40–1.12%; Zn: 0.13–0.45%; Ag: 29.75–44.60 ppm. Identified resource reserves: Au&gt;200t, Cu&gt;3×10^4 t, total iron ore &gt;1×10^4 t, Ag&gt;4000 t</td>
<td>The ore body occurs in the interlayer fracture zone of Tj3 carbonate rocks as lenticular -stratiform and vein, with a length of 174–540 m along the strike, a width of 100–810 m and a thickness of 1.0–36.88 m. Au: 1.67–3.12 ppm; TFe: 31.44–38.63%; mFe: 18.15–52.19%; Cu: 0.34–7.72%; Pb: 0.40–1.12%; Zn: 0.13–0.45%; Ag: 29.75–44.60 ppm. Identified resource reserves: Au&gt;10 t, Cu&gt;2×10^4 t, total iron ore &gt;6×10^4 t, Ag&gt;360 t</td>
<td>The ore body in the Hongnitang ore section occurs in skarn of the contact zone between the Hongnitang porphyry and Tj3 carbonate rocks as lenticular -stratiform. The length is 1,600 m along the strike, the width is 74–813 m, and thickness is 0.81–24.9 m with an average value of 5.51 m of the ore body. Au: 0.81–19.30 ppm, ave. of 2.48 ppm; TFe: 25.03–49.36%, ave. of 32.73%; Cu: 1.02–16.42%, ave. of 2.71%; Zn: 1.31–4.51%, ave. of 1.86%; Ag: 1.90–84.27 ppm, ave. of 86.76 ppm. Identified resource reserves: Au&gt;10 t, Cu&gt;2×10^4 t, Zn&gt;5×10^4 t, total iron ore &gt;3.76×10^4 t, Ag&gt;225 t</td>
<td>The ore body in the Hongnitang ore section occurs in skarn of the contact zone between the Dashadi porphyry and Tj3 carbonate rocks as lenticular -stratiform, dips to W direction steeply. The length is 660 m along the strike, the extension depth is from 115 m to 385 m, and the thickness is between 1.12 m and 32.5 m, with an average value of 7.48 m of the orebody. TFe: 21.04–45.52%, ave. of 30.55%; Cu: 0.24–0.98%, ave. of 0.54%. Identified resource reserves: Cu&gt;4×10^4 t, total iron ore &gt;700 t</td>
<td>The ore body in the Wangdangshan-Hongnitang ore section occurs in unconformable contact surface between Tj6 and Nj2 as stratiform. The length is 1,840 m along the strike, the width is from 420 m to 500 m, and the thickness is between 0.90 m and 35.32 m. Au: 0.90–20.24 ppm; TFe: 50.66–63.63%; Cu: 0.10–1.29%; Pb: 1.21–2.04%; Zn: 0.23–0.70%; Ag: 15.36–23.33 ppm. Identified resource reserves: Au &gt; 8 ×10^4 t, Cu &gt; 7×10^4 t, iron(TFe) &gt; 4 ×10^5 t, Ag = 80 t.</td>
</tr>
</tbody>
</table>

| Metas: minerals | Magnetite, pyrohite, pyrite, chalcopyrite, siderite, hematite, galena, sphalerite, limonite, and cerussite | Magnetite, pyrohite, pyrite, siderite, hematite, galena, chalcopyrite, malachite, galena, sphalerite, limonite, and cerussite | Magnetite, hematite, pyrite, chalcopyrite, malachite, galena | Limonite, cerussite, and magnetite | Magnetite, pyrohite, pyrite, chalcopyrite, malachite, galena, sphalerite, limonite, and cerussite |

| Gangue minerals | Garnet, diopside, chlorite, epidote, calcite, dolomite and quartz | Calcite, dolomite, quartz and kaolin | Quartz, feldspar, diopside, chloride, epidote and kaolin | Clay and gravel |

| Ore texture and structure | Poikilitic, xenomorphic granular, euhedral, metamorphic relict, massive and star point structures, etc.; the oxide ores occur as pseudomorphic, colloform, euhedral, massive and star point structures, etc. | Xenomorphic granular, metasomatic relict, honeycomb, euhedral, and powder structures | Granular, poikilitic, euhedral, metamorphic relict, massive, star point structures, etc. | Granular, poikilitic, metasomatic relict, massive, star point structures, etc. | Colloform, pseudomorphic, honeycomb, euhedral, massive and star point structures |

| Alteration type | Skarnification, silicification, marlization, carbonatization, magnetitization, pyrritization, chalcopyritization, and molybdenitization | Silicification, carbonatization, magnetitization, pyrritization, chalcopyritization, galenitization, and molybdenitization | Silication, carbonatization, horfelsitization, pyrritization, chalcopyritization, galenitization, and molybdenitization | Silication, carbonatization, magnetitization, pyrritization, chalcopyritization, and molybdenitization | Limonitization and galenitization |

| Ore-controlling factors | Ore controlled by the contact alteration zone of the Wangdangshan rock body in branches and bifurcate of the rock body, protruding and turning parts | Ore controlled by the contact alteration zone of the Hongnitag pore body with a steep, gentle occurrence change of the rock body and the transition position | Ore controlled by contact alteration zone of the Hongnitang ore section occurs in skarn of the contact zone between the Dashadi porphyry and Tj3 carbonate rocks as lenticular -stratiform, dips to W direction steeply. The length is 660 m along the strike, the extension depth is from 115 m to 385 m, and the thickness is between 1.12 m and 32.5 m, with an average value of 7.48 m of the orebody. TFe: 21.04–45.52%, ave. of 30.55%; Cu: 0.24–0.98%, ave. of 0.54%. Identified resource reserves: Cu>4×10^4 t, total iron ore >700 t | Ore controlled by contact alteration zone of the Dashadi rock body with a steep-gentle occurrence change of the rock body and the transition position | Unconformable contact surface |

| Scale of ore body | All Cu deposits in superlarge scale, and co-associated deposits of Pb, Zn, Ag, Cu and Fe in medium to large scale. | Au deposits in medium-large scale, and the co-associated deposits of Fe, Pb-Zn and Ag in small to medium scale. | Fe and Cu deposits in medium scale, and the co-associated deposits of Pb-Zn and Ag in small to medium scale. | Fe deposits in small-to-medium scale, and the co-associated deposits of Fe and Ag in small-to-medium scale. |

| Ore bodies of the same type | Branch ore bodies of KT52, etc. | KT43, KT46, KT49 (interior of rock body), KT6, KT13, KT15, KT22, KT20, KT31–32, KT34–57, etc. | KT17, KT19, etc. | KT1, KT3, KT4A-KT4E, KT5, etc. |

quartz, calcite, garnet, diopside, wollastonite, scapolite, chlorite, epidote, dolomite, and kaolinite. The primary ores have poikilitic, xenomorphic granular, euhedral, as well as metasomatic relict textures, with massive and disseminated structures. Oxidized ores have pseudomorphic, colloform, honeycomb, earthy, and powder structures.

2.3 Metallogenic geological characteristics of the deposit
2.3.1 Distribution characteristics of alkali-rich porphyry intrusions

There are eight Himalayan alkali-rich porphyries exposed throughout the ore district (Fig. 1), located near the core of the Beiya syncline, where the distribution is mainly controlled by the four sets of faults. In addition to the buried Dashadi rock body, there are seven other rock bodies exposed at the surface, with a total area of 0.34 km². The semi-buried Wangdongshan rock body, the buried Dashadi rock body, and the semi-buried Hongnitang rock body are the main metallogenic rock bodies, of a relatively large scale, and occur as a stock, whereas the remaining ones occur as veins, dikes, and sills.

The semi-buried Wangdongshan stock is distributed throughout the Wandongshan ore section in the northern part of the ore district, with a nearly SN strike, generally dipping to the west, decreasing in elevation from north to south, and pitching to the southwestern side. The length in the SN direction is 1,300 m, the width in the EW direction is between 100 and 500 m, and the extended depth...
between exploration lines 60 and 80 is between 500 and 600 m (not a closed boundary). The rock body is exposed intermittently on the surface, between exploration lines 68 and 96, has a length of 470 m in the SN direction, and a width between 30 and 65 m in the EW direction. Between exploration lines 48 and 100, the rock body extends in depth below 1,700 m in elevation, with a length of 1,100 m in the SN direction and a width of 600 m in the EW direction. Between exploration lines 56 and 72, the maximum width of the rock body is approximately 600 m, and the lowest controlled elevation is 1,352 m. The hanging wall contains more regular occurrences of the contact zone, whereas the presence of the contact zone is more complex in the footwall, with a general dip angle of 43–85° (Fig. 2a). Well-developed rock body structures at the contact zone contain the majority of the skarn zone and the main ore body deposits. Steep, hydrothermal, vein-shaped ore bodies occur along well-developed fissures in the rock body interior.

The semi-buried Hongnitang rock body appears in regions with steep slopes in the western margin of the basin, in the west side of the Hongnitang ore section and the southern part of the ore district. It is exposed between exploration lines 43 and 71, with a length of 480 m in the SN direction and a width of approximately 160–190 m in the EW direction. Shattered and crypto-explosive breccia exists on the eastern surface. The exposed surface elevation is between 2,100 and 1,950 m, and the depth is controlled by drill holes along exploration line 55, with a minimum controlled elevation of 1,378 m. The rock body (stock) strikes toward the SN and dips westward with a gentle dip angle of less than 10° above 1,900 m and a relatively steep dip angle of 20–30° below 1,900 m. The hanging wall has a contact with the fourth section of the Beiya formation, and there is a constant contact zone occurrence, with a dip angle between 10° and 20°. The

Fig. 2. Geological section along No. 56 and No. 63 exploration lines in the Beiya gold–polymetallic deposit.
(1), Quaternary elurium; (2), Pliocene Sanying Formation, sandy conglomerate and sand-gravel-bearing claystone; (3), Middle Triassic Beiya Formation, carbonate rock; (4), Lower Triassic Qingianbao Formation, sandstone; (5), quartz syenite porphyry; (6), lamprophyre vein; (7), ore-bodies and their serial numbers; (8), geological boundary; (9), unconformable boundary; (10), measured and inferred faults as well as their serial numbers; (11), drill hole.
occurrence of the contact zone in the footwall is more complex, with an overall dip angle of 35–40°. Well-developed rock body structures at the contact zone contain the majority of the skarn zone and the main ore body deposits (Fig. 2b).

The buried Dashadi rock body is located in the central zone of the Beiya basin, between exploration lines 47 and 71 in the middle of the Hongnitang ore section, in the southern part of the ore district. It is to the east side of the Hongnitang rock body, where the horizontal distance between the two is generally 400–700 m, with a slightly lower elevation than that of the Hongnitang rock body (42–300 m lower). The rock body occurs in the form of a stock (spindle), with a southward pitch, dipping to the west at an angle of 40–88°, and has an extended depth from 240–320 m along its dip. The length along the SN strike is 720 m; the width along the EW dip is 100–750 m; and the distribution height is between 1,818 and 1,220 m (Fig. 2b). The contact interface between the Dashadi rock body and the Beiya wall rock is irregularly concave and convex. There are well-developed skarn zones in both the east and west contact zones of the rock body, mainly Fe and Cu (Mo) deposits (mineralization). At the edge of the rock body, there are areas of chloritization and partial silicification, accompanied by limonitization, pyritization, chalcopyritization, molybdenitization, lead and zinc mineralization, as well as magnetitization. The interior of the rock body is strongly altered by pyritization, chalcopyritization, and molybdenitization.

In the eastern part of the ore district, the Bijiashan and Weiganpo dyke occur intermittently along the F1, F2, and F3 faults, with lengths of 460, 400, and 1,700 m as well as widths of 5–11, 3–13, and 50–120 m, respectively. They strike in the SN direction and dip westward at a dip angle of 20–40°, 60–78°, and 30–40°, respectively. Vein-shaped as well as lenticular Fe–Au and Pb–Ag mineralization is present in veins in the contact zone near the F2 and F3 faults and at the interlaminar fracture zone.

In the ore district, the lamprophyre and late biotite syenite porphyry veins are common along secondary faults and cut the quartz syenite porphyry and ore bodies. They formed later, with little to no association with mineralization.

2.3.2 Petrological characteristics of the alkali-rich porphyry intrusive body

The lithologies of the Wandongshan and Hongnitang rock bodies are quartz syenite porphyry, with a gray–white color, whose surface has been altered by limonitization, with some instances of chloritization. These rocks have a porphyritic texture and contain phenocrysts of orthoclase and quartz (50–60%). The orthoclase phenocrysts have euhedral–subhedral tabular textures (35–45%). Carlsbad twinning is visible with a hexagonal shape, and granularity of 0.5–4.0 mm. Occasionally, crystals exhibit alteration patterns that formed metasomatic relic textures (Fig. 3a and b). The surface of the quartz is clean, and the grain size is between 0.1 and 3.0 mm (5–10%). The crystals are irregular, mostly with a round and embayed shape, because of corrosion. Plagioclase phenocrysts occasionally occur as short column subhedral, with obvious polysynthetic twinning, which is often replaced and intercalated with late-stage potassium feldspar. The matrix is cryptocrystalline and composed of feldspar as well as quartz. Accessory minerals include apatite, zircon, and titanite. Mineralization of magnetite, pyrite, galena, sphalerite, and chalcopyrite has been identified locally. The quartz syenite porphyry is strongly altered by potassium. Plagioclase crystals, in which sericitization is common, have potassium feldspar free rims. Quartz phenocrysts have dissolved into an embayed shape, and the matrix has also been altered. Additionally, fresh potassium feldspar phenocrysts are visible.

The Dashadi rock body contains quartz monzonite porphyry, with a gray-off–white color, a porphyritic texture, and a massive structure. Phenocrysts are mainly potash feldspar (40%), with a subhedral shape, and particle sizes ranging from 2 to 6 mm. Carlsbad twinning, as well as potash feldspar sericitization, is visible under cross-polarized light (Fig. 3c). Plagioclase (25%) is hypautomorphic, with a particle size of 2–4 mm. Polysynthetic twinning and plagioclase sericitization are both visible under microscope. Quartz (25%) occurs as xenomorphic grains, with a grain diameter of approximately 3 mm. Matrix components are predominantly quartz and feldspar, as well as accessory minerals, such as zircon and sphene, with minor amounts of pyrite.

Lithologies in the Bijiashan and Weiganpo bodies, in the eastern region, are all quartz monzonite porphyry, with a grayish brown color, a porphyritic texture, and a massive structure. The phenocrysts are orthoclase and plagioclase (Fig. 3d–f), with contents between 50% and 65%. Orthoclase (30–40%) has a euhedral–subhedral texture, mostly altered to relic textures, and the crystal grain size is between 2 and 5 mm. Plagioclase (15–20%) is transparent, white, and subhedral. Quartz (<5%) contains minor amounts of biotite, plagioclase, and hornblende. The matrix (30–40%) is mainly composed of plagioclase and potash feldspar, with signs of weak sericitization.

3 Method and Results

3.1 Geochemical analysis of alkali-rich porphyry
Fresh samples were collected from the semi-buried Wandongshan, the buried Dashadi, and the semi-buried Hongnitang rock bodies from drill cores and open mining pits. The major, trace, and rare earth elements were analyzed at the Key Laboratory of Orogenic Belts and Crustal Evolution, Peking University. Geochemical results are presented in Table 2.

(1) Major elemental characteristics

The quartz syenite and quartz monzonite porphyries, in the ore district, were classified as acidic rocks (the content of SiO$_2$ is between 65.31% and 72.82%) with a relatively high total alkali content (the content of K$_2$O + Na$_2$O is between 9.30% and 12.53%). On a TAS diagram, most samples were plotted in the quartz monzonite and alkaline series field (Fig. 4a). On a SiO$_2$-K$_2$O diagram, samples were plotted in the shoshonite series field (Fig. 4b). The A/CNK values (Al$_2$O$_3$/(CaO+K$_2$O+Na$_2$O) mole ratio) are between 0.91 and 1.65, which belong to the metaluminous –peraluminous series (Fig. 4c). The Al$_2$O$_3$ and Na$_2$O contents of most samples decrease with increasing SiO$_2$ content. Compared with the quartz monzonite porphyry, the quartz syenite porphyry is more acidic (SiO$_2$ content of 67.79–72.82%), with a higher K$_2$O content (6.16–12.15%) and K$_2$O/Na$_2$O ratio (1.51–31.97) as well as decreased Nb (7.01–24 ppm), La (5.81–28.4 ppm), Ce (14.8–54.8 ppm), and Y (2.7–12.25 ppm) contents. The TiO$_2$ varies between the different quartz monzonite porphyries (0.15–0.87%). Due to strong potassic alteration, the quartz syenite porphyry, at Hongnitang, has a higher K$_2$O content (8.50–12.15%) and K$_2$O/Na$_2$O ratio (3.48–31.97) as well as decreased CaO (0.02–0.34%) and Na$_2$O (0.38–2.66%) contents compared with the quartz syenite porphyry at Wandongshan.

(2) Trace elemental characteristics

The primitive mantle-normalized diagram (Fig. 5a) indicates that the trace element distribution curve is inclined to the right. The quartz syenite and quartz monzonite porphyry have similar trace elemental compositions, i.e. they are rich in the large ion lithophile element (LILE; e.g., Rb, K, Sr, and Pb) and are depleted in the high field strength elements (HFSE; e.g., Ta, Nb, P, Ti, and HREE); this is evidence of comagmatic evolution. Compared with the quartz monzonite porphyry, the quartz syenite porphyry has increased Rb (168–538 ppm), Ba (1,160–5,547 ppm), and Pb (15.60–756.13 ppm) contents as well as decreased Nb (7.01–24 ppm), La (5.81–28.4 ppm), Ce (14.8–54.8 ppm), and Y (2.7–12.25 ppm) contents. The quartz syenite porphyry, at Hongnitang, relative to other rock bodies, has the highest Rb, Ce, La, and Pb contents.

(3) Rare earth element characteristics

The chondrite-normalized spidergram (Fig. 5b) indicates that the rare earth element (REE) distribution...
The quartz syenite and quartz monzonite porphyry have similar REE distribution patterns, which display relatively low total REE contents (SREE=36.3–503.6 ppm, with an average value of 138.53 ppm), light rare earth element enrichments (LREE), and a depletion of the heavy rare earth elements (HREE; LREE/HREE=7.06–14.26). The (La/Yb)_N ratio varies between 5.15 and 39.43. The REE compositions of most samples have weak to moderate negative Eu anomalies (Eu=0.42–0.99), but the quartz monzonite porphyry, at Dashadi, does not display any obvious negative Eu anomaly. The quartz syenite porphyry has a higher total REE content and (La/Yb)_N ratio as well as a weaker negative Eu anomaly compared with the quartz monzonite porphyry. Additionally, the total REE content in the Wandongshan quartz syenite porphyry is relatively low.

### Intrusion ages of the alkali-rich porphyries

Three quartz syenite and quartz monzonite porphyry samples from the Wandongshan, Hongnitang, and Dashadi rock bodies related to the Beiya deposit were analyzed by LA-MC-ICP-MS zircon U–Pb geochronology at the Institute of Mineral Resources, Chinese Academy of Geological Sciences. The analytical results indicate that the rock-forming ages of the semi-buried Wandongshan, the buried Dashadi, and the semi-buried Hongnitang rock bodies are 35.00±0.17 Ma, 35.06±0.16 Ma, and...
4 Discussion

4.1 Alkali-rich porphyry

4.1.1 Source and genesis of the alkali-rich porphyries

In the ore district, the quartz syenite porphyry, compared with the quartz monzonite porphyry, has higher contents of SiO$_2$, K$_2$O, Rb, Ba, and Pb, larger K$_2$O/Na$_2$O ratios, as well as lower contents of Al$_2$O$_3$, CaO, Na$_2$O, Nb, La, and Ce, which are possible due to the insignificant amount of plagioclase and the presence of strong, potassic alteration in the quartz syenite porphyry. The high Fe$_2$O$_3$ content, in the quartz syenite, is possibly a result of limonitization, and the high MgO content may derive from the large amount of hornblende. Although there are some differences between the quartz syenite and quartz monzonite porphyry, they have similar textures, SiO$_2$ content, trace element compositions and REE distribution patterns, indicating that they have similar sources.

The porphyries in the ore district have a relatively elevated Sr content and Sr/Y ratio, a decreased amount of Y and Yb, enrichment in the LILEs, and depletions in the HFSEs, which are similar to the characteristics of the adakitic rocks formed by the partial melting of a subducting slab (Richards and Kerrich, 2007; Jia Tuya et al., 2016). However, the porphyries differ from the adakitic rocks because they have a higher K$_2$O content and lower MgO, Cr, and Ni contents, indicating that the alkaline rock bodies of the Beiya ore district and adakitic rocks both formed by partial melting of a subducting slab but from different source areas in different geodynamic settings.

The rock bodies have a high K$_2$O content, which may be caused by a potassium-enriched source and/or the upper crust. Electron probe results indicate that potash feldspars have high K$_2$O/Na$_2$O ratios and that the potash feldspar formed by potassic alteration has a higher K$_2$O content and K$_2$O/Na$_2$O ratios than those formed by fractional crystallization. The developed melts and fluids are both rich in K, suggesting that the magma source is also rich in K. Additionally, zircons have high δD$_{18}$O values (Lu et al., 2013), and the rock body contains dark microgranular enclaves. The higher K$_2$O content may be related to an upper crustal mixture. However, Hf isotopic results for zircon (εHf(t)= −6.82−4.9) indicate that mixing of the upper crust is limited. Only crustal contamination can cause such a high K$_2$O content (higher than the upper crustal average). Therefore, this suggests that the high K$_2$O content of the rock body originates from a combination of a high K source area and a certain degree of upper crustal material mixture.

The rock bodies have a higher SiO$_2$ content and (La/Yb)$_N$ ratios as well as lower MgO, Cr, Ni, Co, and V contents, indicating that they formed by partial melting of the crust rather than that of the mantle (Wyllie, 1977). Weak–very weak negative Eu anomalies imply that the rock bodies formed in the thickened lower crust (Deng Wanning et al., 1998). Hf isotopic zircon values vary widely, thus indicating the diversity of zircon sources. Positive εHf(t) values reflect zircons that formed in the juvenile lower crust, whereas negative εHf(t) values indicate that zircons formed in the ancient metamorphic basement (Lai et al., 2013).
The two-stage Hf zircon model age is approximately 1.0 Ga (He, 2014), which is consistent with the age of the new crust of the Neo-proterozoic Yangtze craton (Wang et al., 2012), indicating that the new component is probably the basic component of Neo-proterozoic.

Lead isotope variations in the porphyry are relatively small. Values of 206/238Pb, 207/235Pb, and 208/232Pb are 18.691–18.931, 15.664–15.703, and 38.898–39.124, respectively. The εNd(t) composition is from 0.70753–0.70862, and the εNd(t) composition varies from −6.87 to −8.60. The two-stage depleted-mantle Nd model age (tDM2) is from 1.4 to 1.5 Ga, indicating that diagenetic materials were derived from the lower crust (Wang et al., 2016).

The rock body has low (Dd/Lu)y ratios as well as high Sr/Y, (La/Yb)y, and (Dy/Yb)y ratios, indicating that the rock body originated from the partial melting of a hornblende–garnet source region. The quartz syenite and quartz monzonite porphyry also have similar Sr, Nd, and Pb isotopic compositions with amphibolite xenoliths in Eocene acidic rocks from the western Yunnan province. Sulfur isotopic compositions of the alkali-rich porphyry bodies (1.0–2.5‰) are similar to deep mantle sulfur compositions (0±3‰; Hoefs, 1997), indicating that the rock body is partially derived from a deep mantle magma. Therefore, the rock bodies likely originated from the thickening of the lower crust with a hornblende-garnet facies and may have been affected by the upwelling of the lithospheric mantle.

Rock bodies were emplaced between 34.62±0.25 and 36.72±0.25 Ma, a period of dynamic tectonic transition after the collision of the India and Eurasian blocks (Zhang et al., 2015). The ore district is part of the Jinsha River–Aila mountain alkali-rich porphyry belt (40–35 Ma) that formed via strong crust-mantle interaction. The alkali-rich porphyry metallogenic belt is located in the back arc extension zone of the Myitkyina collision zone (the southern extension of the Gangdese collision zone). During the collision process, alkali-rich porphyry magma, formed by the partial melting of metasomatized mantle along the Jinsha River–Red River strike slip fault zone, locally intruded upward and differentiated to form the Beiya-bearing Cu–Au–Mo porphyry-type metallogenic belt (Mao et al., 2017).

4.1.2 Relationship between alkali-rich porphyry and mineralization

There is a close spatial relationship between the Au–polymetallic deposits and the rock bodies, in which the ore bodies, with different types of mineralization, occur as rings around the rock bodies. The contents of Au, Fe, Ag, Cu, Pb, Zn, and other elements in the rock body are generally several times higher than the average values of syenite and granite in China (Tables 4-5). Compared with the Wangdongshan and Hongnitang rock bodies, the Dashadi rock body, a major source of ore-forming elements, is characterized by relatively well-developed Cu (Mo) mineralization, a lack of Au mineralization and enrichments in Cu (3.6–2254 ppm), Mo (2.91–24 ppm), and other trace elements related to metallogeny. The rock-forming age of the porphyries is between 34.62 and 36.72 Ma, which agrees with the ore-forming age ranging from 36.46 to 39.44 Ma.

The genesis of the deposit is closely related to the alkaline intrusive rocks, because the alkali-rich porphyry is the source of ore-forming materials and fluids, which is supported by the following evidence:

(1) REE distribution patterns for many types of gold ore samples, from the deposits, are consistent with the quartz monzonite and quartz syenite porphyries. On REE pattern diagrams, the REE distribution curves for all samples are

Table 4 Trace elemental results related to mineralization in the main ore-forming rocks in the Beiya Au–polymetallic deposit

<table>
<thead>
<tr>
<th>Ore-forming element</th>
<th>Wangdongshan rock body</th>
<th>Hongnitang rock body</th>
<th>Dashadi rock body</th>
<th>Syenite in China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Quartz syenite porphyry)</td>
<td>(Quartz syenite porphyry)</td>
<td>(Quartz monzonite porphyry)</td>
<td>(Quartz monzonite porphyry)</td>
</tr>
<tr>
<td>Au (ppb)</td>
<td>0.80</td>
<td>1070</td>
<td>167.20(20)</td>
<td>0.25</td>
</tr>
<tr>
<td>Ag (ppb)</td>
<td>236</td>
<td>8830</td>
<td>1844(20)</td>
<td>1420</td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>44.1</td>
<td>390</td>
<td>147.91(13)</td>
<td>5.26</td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>15.60</td>
<td>650</td>
<td>116.65(18)</td>
<td>43.44</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>30.8</td>
<td>143</td>
<td>59.26(13)</td>
<td>11.36</td>
</tr>
<tr>
<td>Mo (ppm)</td>
<td>0.832</td>
<td>154</td>
<td>14.30(13)</td>
<td>0.05</td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>0.278</td>
<td>1.38</td>
<td>1.06(13)</td>
<td>0.05</td>
</tr>
<tr>
<td>As (ppm)</td>
<td>2.31</td>
<td>269</td>
<td>37.98(20)</td>
<td>32</td>
</tr>
<tr>
<td>Cd (ppm)</td>
<td>0.08</td>
<td>1.38</td>
<td>0.42(20)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Data source: Data of Au, Ag, As and Cd from Yang et al., 2015; data of Cu, Zn, Mo, Sb and Bi from Deng et al., 2015a and Liu et al., 2015; data of Pb from this paper and Deng et al., 2015a; data of Pb from this paper and Yan et al., 1996; data of Cu, Zn and Mo from Wang et al., 2016; data of Au, Ag from Wang et al., 2016; data of Pb from this paper and Deng et al., 2015a.
consistent, with LREE-enriched and HREE-depleted right-inclined smooth curves indicating that the genesis of the Au–polymetallic deposit is closely related to the two types of intrusive bodies. The PGE characteristics of the samples from the skarn-type Au and hydrothermal Au deposit, in the outer zone, indicate that the alkali-rich porphyry supplies the Au (Jiang et al., 2015).

(2) The δ34S sulfide values for ore deposits range from −3 to +1% and are mostly between −1 and 0‰, with tower distribution characteristics, indicating that the sulfur source is highly homogeneous (Zhou et al., 2016). Sulfur isotopic data for hydrothermal Pb–Zn–Ag and Au deposits in stratoid and vein form, from the Qin River ore section in the remote zone, vary from −2.4 to +2.8‰, indicating that the source is uniform and that its range is narrow. The sulfur isotopic composition of the alkali-rich porphyry body (1.0–2.5‰) is basically the same. The sulfur isotopic composition of sulfide in this deposit is similar to that of the deep source sulfur (0±3‰; Hoefs, 1997), indicating that the deposit has the same sulfur source (magmatic sulfur) as the alkali-rich porphyry and that mineralization is closely associated with magmatic hydrothermal fluids.

(3) The 206Pb/204Pb ore values are 18.626–18.699, with an average of 18.653207; the 207Pb/204Pb values are between 15.642 and 15.725, with an average of 15.682 (Wu Song and Li Wenchang, 2015). Porphyry Pb isotopes in the ore district are nearly identical. On the Pb isotopic composition diagram, both Pb from ores throughout the different deposits and Pb from the alkali-rich porphyry are very similar indicating that their initial source is similar and that the formation of ore-forming fluids may be related to fractional crystallization in the alkali-rich porphyry.

The above results indicate that the S and Pb isotopic compositions of the ores are in good agreement with the alkali-rich porphyry in the ore district. This reveals that the source of ore-forming materials is related to deep magma. Previous studies using Pb isotopes found that almost all ore-forming materials are associated with fluids separated by alkali-rich magma, and most of them are directly derived from the source area of the alkali-rich magma.

4.1.3 Comparison of various rock bodies

Results on the Himalayan alkali-rich porphyry bodies or lamprophyry in the ore district and the surrounding area indicate that the petrological characteristics of the mineralized and non-mineralized rock bodies are basically the same, especially for the quartz syenite and quartz monzonite porphyry (monzogranite porphyry), and their constituent minerals, texture, structure, as well as major, trace, and rare earth element contents exhibit obvious consistency (Zhou et al., 2016).

Compared with the other five small rock bodies without mineralization in the ore district, potassium silicate alteration is strong with certain instances of pyritization in the interior of the Wangdongshan, Hongnitang and Dashadi rock bodies. The contents of Au, Fe, Cu, Pb, Zn, and Ag are higher in the mineralized intrusions, which also display lower Al, Fe and Mg contents. This is a possible cause for insignificant strong mineralization in the five small rock bodies.

4.2 Ore-forming wall rocks (Middle Triassic Beiya Fm. (T2b) carbonate rocks)

Impure carbonate rocks (T2b) from the Middle Triassic Beiya Formation provide favorable surrounding conditions and hosting space for the formation of deposits, i.e. the strata necessary for skarn formation.

According to lithological associations, the Middle Triassic Beiya Formation (T2b) can be divided into five lithologic members from the bottom to up: 1) T2b1 is a light gray, middle-layered reticulate, banded argillaceous fine-grained limestone and brecciod-like limestone, occasionally intercalating thin middle-layered arkosic sandstone, with a thickness of 33–112 m; 2) T2b2 is a gray–dark gray, middle thick-bedded brecciod-like argillaceous fine-grained limestone, with a thickness of 30–156 m; 3) T2b3 is a light gray, middle thick-bedded argillaceous limestone, locally intercalating banded limestone, with a thickness of 25–165 m; 4) T2b4 is a middle thick-layered, rhythmic interlayer of gray brecciod dolomite and banded dolomite, locally intercalating gray iron calcarenite, containing dolomitic calcarenite and lump limonite (an important ore-bearing horizon), with a thickness of 30–156 m, and 5) T2b5 is a gray-off–white, middle thick-bedded dolomitic calcarenite and dolomite, with strong, broken alteration and weathering, typically occurring as brown sucrosic, with a thickness of 45–107 m.

The Beiya formation is a suite of impure carbonate rocks, especially vermicular argillaceous limestone and bioclastic limestone (T2b3), irony limestone (T2b5), and dolomitic calcarenite (T2b6), with active chemical properties, developed karst structures, as well as rigid mechanical properties and performance. Under stress, it is not easily deformed and forms, instead, structural fissures and interlayer fracture zones that are favorable for mineralization, acting as channels for an ore-forming fluid or space for mineral precipitation. In the porphyry contact zone, ore-bearing hydrothermal fluids replaced carbonate rocks to form skarn type Au–Fe ore bodies. Away from the porphyry, the ore-bearing hydrothermal fluid
4.3 Metallogenic structures

The SN Beiya syncline, fracture, and interlayer fracture formed during the early Yanshan–Himalayan period as well as the contact zone formed by the emplacement of alkali-rich porphyries in the middle Himalayan period comprise the important metallogenic structures. The Beiya syncline, the secondary structure of the west limb of the SN Heqing–Songgui wide and gentle compound syncline, SN faults (F1, F2, F3, F4, F5, and F6), EW faults (F22, F25, and F26), NE fault (F27), and NW faults (F21 and F28) (Fig. 1) belong to the pre-metallogenic and metallogenic structures. The NNW shear fault and the SN low-angle overthrust fault, developed in N$_2$SN strata since the Quaternary period, are the post-metallogenic structures.

The main fold structure in the ore district is the SN Beiya syncline, located on the southern tilting end of the Songgui compound syncline, which belongs to a secondary structure of the Heqing–Songgui compound syncline. The Beiya syncline is closed north of the Shuijing and south of the Jimingsi–Guanyining areas, with an axial length of nearly 12 km and a width between two limbs of 1.2–1.8 km. The Beiya syncline is a wide and slow brachy syncline with an axial direction of NNE. The outcropped stratum in the west limb is T$_2$b$^{1,5}$, inclined to the east at a dip angle of 30–60°. The east limb contains T$_2$b$^{1,5}$, T$_g$q, and P$_2$b$^{1,5}$, inclined to the west at a dip angle of 10–40°. Local sections in the two limbs were influenced by faults and a magmatic intrusion, developing secondary folds, faults, joints, and fissures. The occurrence of the stratified portion of T$_2$b$^{1,5}$ in the west limb has a nearly EW orientation and the Sn-Ni and Cu-Pb deposits are well developed in the lower Miocene Sanying formation (N$_2$s$_b$), formed during the Middle Triassic period, whereas the alkali-rich porphyry and skarn groups, located in the core and both limbs of the Beiya syncline, mainly including the F1, F2, F3, F4, and F5 of the east limb as well as F6 and F5 of the west limb. The F6 and F5 are thrust faults occurring in the shallow, flat, and deep steep. F2, F3 and F4 are the steep compressive faults on the hanging side of the F1 fault, and rocks from the hanging wall and footwall have different degrees of breakage and alteration. The stratified, lentoid, and vein ore bodies occur in parallel along the fissure fracture zone, indicating that the faults are the main ore-control and ore-host structures in the ore district, with characteristics of multi-period activities. Near EW faults are transtension transverse faults such as F22, F25, and F26, whereas NE and NW faults are transpressional shear lateral faults such as F21, F27 and F28. Multi-period activities displaced and destroyed the strata, rock, ore body as well as early faults and later lamprophyre dikes that were intruded along the faults.

4.4 Weathering-accumulation-type (paleo-weathering crust-type) Fe–Au deposit

The weathering-accumulation-type (paleo-weathering crust-type) Fe–Au deposit occurs in predominantly polymeric Au–limonite-bearing sand gravel and claystone from alluvial and lacustrine deposition in the bottom of the lower Miocene Sanying formation (N$_2$s$_b$), where the upper part is gray limy breccia bodies formed by a gliding nappe. This suite of strata forms an angular unconformable contact with the overlying carbonate rocks of the Beiya formation (T$_2$h), formed during the Middle Triassic period, whereas the alkali-rich porphyry and skarn-type Au–Fe ore body formed during the Himalayan period penetrated along the structural fissures and interlayer fracture zones to form stratoid and vein Au–Fe ore bodies.

Table 5 Trace element results of other ore-forming rock bodies in the Beiya Au–polymetallic deposit

<table>
<thead>
<tr>
<th>Ore-forming element</th>
<th>Matouwan rock body</th>
<th>Bailiuchuan rock body</th>
<th>Weiganpo rock body</th>
<th>Bijia Shan rock body</th>
<th>Yanshuiling rock body</th>
<th>Putaishan rock body</th>
<th>Unknown rock body</th>
<th>Syenite in China</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (ppb)</td>
<td>0.025</td>
<td>2.92</td>
<td>0.71(17)</td>
<td>1.56(20)</td>
<td>0.62(7)</td>
<td>0.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ag (ppb)</td>
<td>30.0</td>
<td>2460</td>
<td>399.6(17)</td>
<td>107.6(20)</td>
<td>28.10(7)</td>
<td>0.037</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu (ppm)</td>
<td>5.10</td>
<td>652</td>
<td>176.34(18)</td>
<td>4.12(2)</td>
<td>7.28(8)</td>
<td>7.99(1)</td>
<td>27.95(20)</td>
<td>15</td>
</tr>
<tr>
<td>Pb (ppm)</td>
<td>25.40</td>
<td>143</td>
<td>56.89(18)</td>
<td>233.51(2)</td>
<td>37.16(8)</td>
<td>47.93(1)</td>
<td>33.80(20)</td>
<td>31</td>
</tr>
<tr>
<td>Zn (ppm)</td>
<td>17.1</td>
<td>84.5</td>
<td>45.24(18)</td>
<td>64.67(2)</td>
<td>265.0(8)</td>
<td>44.70(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo (ppm)</td>
<td>0.26</td>
<td>4.35</td>
<td>1.71(17)</td>
<td>2.04(20)</td>
<td>0.35(7)</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sb (ppm)</td>
<td>0.26</td>
<td>9.12</td>
<td>1.38(17)</td>
<td>5.36(20)</td>
<td>0.23(7)</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi (ppm)</td>
<td>0.03</td>
<td>2.23</td>
<td>0.29(17)</td>
<td>3.10(20)</td>
<td>0.12(7)</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As (ppm)</td>
<td>0.40</td>
<td>29.1</td>
<td>5.65(17)</td>
<td>5.62(20)</td>
<td>5.10(7)</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cd (ppm)</td>
<td>0.03</td>
<td>0.80</td>
<td>0.26(17)</td>
<td>0.14(20)</td>
<td>0.04(7)</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data source: Yang et al., 2015; added data of Cu, Zn and Pb analyzed in this paper

This paper: Xu et al., 2007, Wu et al., 2005, Yang et al., 2015, Yan et al., 1996
The ore bodies are distributed in a relatively low-lying depression near the axis of the Beiya basin, with a large extension along the SN axis, up to 1,840 m; a maximum thickness, near the axis, of 10–35.32 m; and a higher grade (2.00-20.24ppm Au). On both sides of the EW direction basin, the extension is relatively narrow with a width of 420–500 m, a small thickness, a reduced grade, and a rapidly changing local section. The geological characteristics of the ore bodies are listed in detail in Tables 1 and 6 as well as Figure 2a. Since the Beiya is cut by biotite syenite porphyry veins, with an isotopic age of 3.8–3.6 Ma (Xu et al., 2006), the depressionsedimentation of the Cenozoic Beiya intermontane basin occurred during the period from (35–36.72) to 3.8 Ma.

The geological characteristics of the ore bodies indicate that primary Au ore bodies and Au-bearing altered rocks experienced hypergenesis and transformation, and then migrated to the Beiya mountain basin to accumulate and form the weathering-accumulation-type Au deposit. The deposits formed over long periods and with diversity, mostly occurring in the negative terrain near the primary ore body.

4.5 Ore-controlling factors

4.5.1 Alkali-rich porphyry and wall rock

(1) The alkali-rich porphyry and the wall rock controlled the spatial distribution of polymetallic deposits.

In the Wandongshan ore section, the mineralized zoning of the rock body interior, the skarn zone, and the distal contact zone formed around the Wandongshan rock body. The small and enriched ore bodies occurred as lenticulars and veins in the steep fissures in the rock body. Near the contact zone of the rock body, the contact-zone-type ore bodies such as KT52 formed along the contact skarn zone between the rock body and the Middle Triassic Beiya formation (T2β) carbonate rocks and were then distributed intermittently around the rock body on the horizontal section. In the EW exploration line section, the ore body is tilted to the west with an irregular inverted "U" shape, whose top part has been eroded. Only the ore body on the upper and lower contact zones has been preserved. In the southern turning point for the emplacement of the rock body (exploration lines 50 and 80. The ore body in the contact zone is located in the 0–500 m area around the rock body, and that in the outer belt-distal zone is 1–5 km from the rock body (Table 6).

The KT10, KT11, and KT12 ore bodies are controlled by the Hongnitang rock body that occurred in the contact skarn zone in the upper and lower plates of the rock body, distributed between exploration lines 31 and 111, whose controlled length is 1,600 m, width is from 74 to 813 m, and extension depth is between 80 and 824 m, with a distributive elevation of 1,781.80–2,116.46 m and a buried depth of 0–429 m. Between exploration lines 31 and 79 in the north, the ore body moves towards the SN direction and generally tilts to the west. Between exploration lines 79 and 111 in the south (Jingouba ore section), the ore body occurs along the interlayer fracture zone of T2β and dips to the east.

The KT17 and KT18 ore bodies are controlled by the Dashadi rock body that occurs along the east contact zone of the rock body with the presence of steep slopes, distributed between exploration lines 35 and 69, with a controlled length of 600 m, a controlled depth from 80 to 824 m, and a distributive elevation between 1,781 and 2,116 m. In the Middle Triassic Beiya formation (T2β) carbonate rocks between Hongnitang and Dashadi rock bodies, KT13 and KT15, are ore bodies that occurred along the interlayer fracture zone.

Currently, the ore bodies discovered in reconnaissance are distributed mainly in the Middle Triassic Beiya formation (T2β) carbonate rocks. There are no industrial ore bodies in the underlying upper Permian basalt formation (P2β) basalt intercalating tuff, the contact zone between the rock body and lower Triassic Qingtianbao formation (T1q) sandy conglomerate and sandstone or strata. The alkali-rich porphyry intrusive bodies and Middle Triassic Beiya formation (T2β) carbonate rocks control the range of distribution of the polymetallic deposits spatially.

(2) The alkali-rich porphyry bodies control the spatial zonation of the mineralization type of the porphyry hydrothermal metallogenic system.

The ore-controlling regularity of the Wandongshan rock body is represented by ore zonation from the hydrothermal Cu–Au ore body to the skarn-type Au–Cu–Fe ore body to the skarn-type Au–Fe ore body to the hydrothermal Au–Fe–Pb ore body to the hydrothermal Pb–Ag ore body with the location from the rock body to the contact zone to carbonate formation (outer zone to distal). The ore-controlling regularity of the Hongnitang rock body is represented by ore zonation from the skarn-type Au–Fe–Cu ore body to the skarn-type Au–Fe–Pb ore body to the hydrothermal Au–Pb–Ag ore body with the location from
Table 6 Metallogenic geological characteristics of each ore section in the Beiya gold–polymetallic deposit

<table>
<thead>
<tr>
<th>Ore section</th>
<th>Wandongshan ore section</th>
<th>Qinhe ore section</th>
<th>Hongniang ore section (west)</th>
<th>Hongniang ore section (east)</th>
<th>Jingouba ore section</th>
<th>Weigangpo–Bijiashan ore section</th>
<th>Yangjiayuan ore section</th>
<th>Bailiancun ore section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td></td>
<td></td>
<td>It is located at the northernmost end of the ore district and outcropped strata are Tª 3 dolomite, dolomitic limestone, Neogene Sanying Fm. X 5 sand-mudstone. Structures are NWNW-Beiya-Qinhe syncline, well-developed interlayer fracture zone and NWNW-trending F2 fault in the northern part. Small veins of quartz syenite porphyry occur sporadically.</td>
<td>It is located in the west limb of the Beiya syncline in the central part of the ore district, with outcropped strata of Tª 3 dolomite and dolomitic limestone. SNNW-trending F5 and EW-trending F25, F22 and F23. Hongniang quartz syenite porphyry body occurs along the junction among F5, F22 and F23.</td>
<td>It is located in the core and west limb of the Beiya syncline in the south part of the ore district, with outcropped strata of Tª 3 dolomite and dolomitic limestone. SNNW-trending F5 and F6 and EW-trending F25, F22 and F23. Dashadi butes quartz monzonite porphyry body occurs along F6 fault.</td>
<td>It is located in the east limb of the Beiya syncline in the central part of the ore district, with outcropped strata of Tª 3 dolomite and dolomitic limestone. SNNW-trending F1, F2, F3 and F4 and EW-trending F21. Small veins of quartz syenite porphyry occur sporadically, and lamprophyre veins occur along F21 fault.</td>
<td>It is located in the east limb of the Beiya syncline in the northeastern part of the ore district, with outcropped strata of Pybasalt intercalating tuff. NW-trending F28. Bailiancun quartz monzonite porphyry body exposed here.</td>
<td></td>
</tr>
<tr>
<td>ORE-bearing rocks</td>
<td>Wandongshan quartz syenite porphyry</td>
<td>Wandongshan quartz syenite porphyry</td>
<td>Hydrothermal vein-type Au-Fe-(Pb-Zn) mineralization in fractured and brecciated rocks; skarn-type Au-Fe-Cu mineralization in contact zone of porphyry body, hydrothermal vein type and paleo weathering crust type Au-Fe mineralization in interlayer or faulted fracture zone</td>
<td>Hydrothermal type layered Skarn-type Fe-Cu mineralization in the contact zone of the Wandongshan quartz syenite porphyry</td>
<td>Hydrothermal vein-type Au-Cu mineralization in interlayer or faulted fracture zone</td>
<td>Hydrothermal vein-type Au and Pb-Zn mineralization in interlayers or faulted fracture zone</td>
<td>Hydrothermal vein-type Au and Pb-Zn mineralization in interlayers or faulted fracture zone</td>
<td>Skarn-type thien-vein Au (Py-Ag) mineralization in the interlayer of steep shear fracture zone</td>
</tr>
<tr>
<td>Alteration type</td>
<td></td>
<td></td>
<td>Silicification, skarnification, decalcification of carbonate rocks, pyritization, magnetization, chloritization, hornfelsification, sideritization and carbonatization</td>
<td>Silicification, carbonization and hornfelsification</td>
<td>Silicification, skarnification, pyritization, carbonization, sideritization and carbonatization</td>
<td>Silicification, hornfelsification and carbonatization</td>
<td>Silicification, skarnification and carbonatization</td>
<td>Silicification, hornfelsification and carbonatization</td>
</tr>
<tr>
<td>Occurrence position of ore body</td>
<td></td>
<td></td>
<td>Ore bodies in the contact zone of the rock body, with relative large thickness of X 5.</td>
<td>Ore body in Tª 3 interlayer fracture zone in the interior of the rock body, Tª 3 interlayer or faulted fracture zone are about 400–700 m away from the rock body. Eluvial ore body on the paleo weathering crust distributes in the periphery of the axis of the Beiya basin with relative large thickness of X 5.</td>
<td>Ore body in Tª 3 interlayer fracture zone in the outer zone is about 500–1000 m away from Dashiadi buried rock body.</td>
<td>Ore body in Tª 3 interlayer fracture zone in the outer zone is about 500–1000 m away from Dashiadi buried rock body.</td>
<td>Ore body in steep shear fracture zone in distal zone is about 4000–5000 m away from Weigangpo and Hongniang quartz monzonite porphyry rock bodies.</td>
<td></td>
</tr>
</tbody>
</table>
### Continued Table 6

<table>
<thead>
<tr>
<th>Ore section</th>
<th>Wandiogg ore section</th>
<th>Qinhe ore section</th>
<th>Hongnitang ore section (west)</th>
<th>Hongnitang ore section (east)</th>
<th>Jingouba ore section</th>
<th>Weigang–Bijiaoshan ore section</th>
<th>Yangjiavun ore section</th>
<th>Bailiancun ore section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main ore bodies</td>
<td>The ore bodies in the contact zone are mainly KT52 and its branch ore bodies. The ore bodies in interlayers or fractured fracture zone include KT63, KT43, KT46, KT49 (in the interior of the rock body), KT54–57, etc. Eluvial type ore bodies are KT48, KT1, KT3 and KT5 and so on. The characteristics of the representative ore bodies are shown in Table 1.</td>
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</tr>
<tr>
<td>Ore minerals</td>
<td>Magnetite, pyrrhotite, pyrite, chalcopyrite, siderite, hematite, galena, sphalerite, limonite and cerussite.</td>
<td>Metallic minerals: galena, siderite, limonite, cerussite, sphalerite, pyrrhotite, natural gold, etc.</td>
<td>Magnetite, pyrrhotite, siderite, hematite, pyrite, chalcopyrite and galena.</td>
<td>Magnetite, pyrrhotite, siderite, hematite and galena.</td>
<td>Galena, siderite, limonite and cerussite etc.</td>
<td>Galena, siderite, natural gold, limonite, etc.</td>
<td>Pyrite, natural gold, and limonite etc.</td>
<td></td>
</tr>
<tr>
<td>Gangue minerals</td>
<td>Garnet, diopside, chlorite, epidote, calcite, dolomite and quartz.</td>
<td>Calcite, quartz, and dolomite and so on.</td>
<td>Quartz, feldspar, diopside, chlorite, epidote, and kaolin.</td>
<td>Calcite, dolomite, quartz, feldspar, and epidote.</td>
<td>Calcite, quartz and dolomite etc.</td>
<td>Granular, metasomatic reticulate and poikilitic textures, and disseminated, porphyritic, colloidal structures.</td>
<td>Granular, metasomatic reticulate and poikilitic textures, and disseminated, veinlet, porphyritic and colloidal structures.</td>
<td>Granular, metasomatic reticulate and poikilitic textures, and veinlet and porphyritic structures.</td>
</tr>
<tr>
<td>Texture and structure</td>
<td>Granular, metasomatic reticulate and poikilitic textures, and disseminated, porphyritic, colloidal structures:</td>
<td></td>
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<tr>
<td>Resources/reserves</td>
<td>Au 254.574 t with a grade of 2.73ppm; Pb+Zn 189.67×10^4 t with a grade of 1.56%; Ag 579.217t with a grade of 35.01ppm; Cu 47.51×10^4 t with grade of 0.57%; Fe ores 4748.15×10^4 t with a grade of 32.17%</td>
<td>Pb 64.1257×10^4 t; Au 174.545 kg; Ag 107.5 t; TFe ores 557.98×10^4 t; Associated Pb 1.1948×10^4 t; Au 1330.3 kg; Ag 916.0 t; Zn 9.891×10^4 t; Cu 1.5434×10^4 t; TFe ores 604.43×10^4 t</td>
<td>Au 38.167t with a grade of 2.27ppm; Pb+Zn 57.57×10^4 t with a grade of 3.79%; Cu 5.15×10^4 t with a grade of 0.49%; Fe ores 2483.6×10^4 t with grade of 33.21%; Mo 3782 t with a grade of 0.047%</td>
<td>Au 384.9 kg; Ag 480 t; Fe ores 43.46×10^4 t; Au 16.46 t; Pb-Zn 16.14×10^4 t</td>
<td>Au 34.17×10^4 t; Fe ores 43.46×10^4 t; Ag 480 t; Pb-Zn 16.14×10^4 t</td>
<td>Pb 5.64×10^4 t; Au 2744 kg; Ag 122.6 t; TFe ores 46.46×10^4 t</td>
<td>Au 0.62 t</td>
<td></td>
</tr>
</tbody>
</table>
the contact zone of the rock body to carbonate formation (outer zone to distal). That of the Dashadi rock body is represented by ore zonation from the porphyry-type Cu–Au to skarn-type Cu (Mo)–Fe to hydrothermal Au and Pb–Ag in turn with the location from the rock body to peripheral strata. The skarn Fe–Cu ore bodies formed in the interlayer fracture zone of carbonate rocks (T2 b) between Dashadi and Hongnitang rock bodies.

(3) The alkali-rich porphyry bodies control the spatial zonation of the alteration type of the deposit. Alteration occurs in the contact zone between the rock body and the surrounding rock, the interlayer fracture zone of carbonate formation (T2 b), or the faulted fracture zone in the strata, including two alteration-mineralized zones that are the inner and outer contact zones. From the rock body to the contact zone to the carbonate formation (the outer zone to the distal), alteration types include self-metamorphic potassic alteration of the rock body, silicification to epidotization and diopsidization in the internal contact zone, then garnetization and diopsidization of the surrounding rock occurs in the outer contact zone, and later chloritization and carbonatization.

(4) The contact modes and forms of the alkali-rich rock bodies and the surrounding rock control the occurrence, form and scale of the main ore bodies. For the intrusion contact mode of the rock body gently inclined to the strata, the heat and ore fluid are not easily lost; this is beneficial to contact metasomatism. The mineralization scale of the contact zone of the Wandongshan rock body is larger than that of other skarn-type ore zones near the contact zone, which may be related to the contact mode. The position where contact relationship between intrusions and strata becomes gentle and the depressions formed by contact of the rock body are the most favorable parts for forming thick and large ore bodies. For example, KT52 Au–Fe polymetallic ore bodies discovered in exploration lines 50, 54, and 56, in the Wandongshan ore section, have a relatively large thickness, and between exploration lines 69 and 70, of the Hongnitang rock body, KT10 and KT11 ore bodies have the maximum thickness in the position where the contact zone changes from sharp to gentle. This is mainly due to contact mode increases in the contact area and the fact that the stress in the depression is small and the ore fluid is easily gatherable. The ore body becomes thinner in areas where the contact zone is sharp (Fig. 2).

The above-mentioned results indicate that the alkali-rich porphyries control the internal and external zoning structure of four mineralization styles, i.e. from vein Au–Fe (Cu) ore bodies in the interior of the rock body to the skarn-type Au–Fe (Pb–Cu) massive ore body in the contact zone to the stratoid and lenticular Pb–Ag–Au ore body in interlayer fracture zone of the outer zone to vein Au–Pb–Ag ore body in the distal zone. The deposit belongs to the porphyry–skarn-type Au–Fe–Cu–Pb–Zn (Ag) polymetallic metallogenic system formed by the gradual evolution of magmatic differentiated hydrothermal solutions.

4.5.2 Structures on mineralization

The structures in the ore district and geological characteristics of the deposit indicate that Au–polymetallic ore bodies in the ore district occur in both limbs of the Beiya syncline, the contact fracture zone between the rock body and the wall rock, the axial part of the syncline where joints and fissures are well developed or interlayer fracture zone in the limb. This indicates that folds control the distribution of the rock (ore) bodies. The near SN faults in both limbs of the syncline control the distribution of porphyry (veins) bodies, and related Au–polymetallic ore bodies are the main rock-control and ore-control structures, the channels for magma intrusion and migration of the ore-forming fluid, as well as the main metallogenic structures and ore-hosted structures. The faults also control the scale, mineralization direction, and spatial distribution of the ore bodies. The matched secondary fractures and fissures directly control the form, occurrence, scale, and enrichment of the gold-bearing ore bodies. In the ore district, the contact fracture zone between the rock body and carbonate rocks, the tectonic fracture zone in the interlayer of carbonate layers as well as between carbonate and clastic rocks, and the section where fissures are well developed are the main hosts for ore bodies. The form and occurrence of the ore bodies agree with the contact of the rock body, the structural belt, the interlayer structural fracture zone, and the fissure zone.

4.5.3 Weathering-accumulation-type Fe–Au deposit formed by supergenesis

The porphyry–skarn-type ore bodies in the contact zone, interlayer fracture-zone-type ore bodies, vein-shaped ore bodies in secondary fracture fissures related to the alkali-rich porphyries formed in the Himalayan period, and the form of the basement depression of the basin are the main ore-controlling factors for the weathering-accumulation-type (paleo weathering crust type) Fe–Au deposit formed by supergenesis. After the formation of porphyry–skarn-type deposits, the Beiya area subsided and eroded throughout the Neogene to form the SN, narrow, small intermontane eroded depression basins at the center of Beiya, with a length, in SN direction, of 4–5 km and a width, in the EW direction, of 1–2 km. The wall rocks on the surface, in the shallow part of the basement of the basin, and the ore bodies experienced long-term weathering and denudation
to form uneven paleo-geomorphological features and
developed Pliocene lacustrine deposition (N2y). In the
depressed section above the unconformity, Fe–Au deposits
accumulated and were preserved by the cover of lacustrine
sediments.

5 Conclusions

1) The emplacement of three alkali-rich intrusive
bodies (the semi-buried Wangdongshan rock body, the
buried Dashadi rock body, and the semi-buried
Hongnitang rock body) formed between the late Eocene
and the early Oligocene, resulting in the formation of the
Beiya porphyry–skarn-type Au–polymetallic deposit.

2) Alkali-rich porphyries consisting of quartz syenite
and quartz monzonite porphyry belong to the alkaline
metaluminous–peraluminous series (shoshonitic Series)
formed during the Himalayan period. The porphyries have
high SiO2 content, high (La/Yb)N and (Dy/Yb)N ratios,
relatively low contents of MgO, Cr, Ni, Co, and V,
relatively high Sr content and Sr/Y ratios, as well as a low
(Dd/Lu)N ratio and contents of Y and Yb, enriched in the
LILEs and depleted in the HFSEs.

3) The rock-forming ages of the main ore-forming
porphyries are 34.62–36.72 Ma and are nearly identical to
the ore-forming ages 36.46–39.44 Ma. The metallogenic
rock body may originate from partial melting of the lower
crustal material. The ascent and emplacement of magmas
along the Jinsha River–Red River large strike-slip deep
fracture zone and the secondary Ma’anshan fracture zone,
formed by the oblique collision along Indian plate to
Eurasian plate, led to the formation of the alkali-rich
porphyries.

4) Vein-shaped Au–Fe (Cu) ore body in the core of
alkali-rich porphyry, skarn type Au–Fe (Cu–Pb) massive
ore body in the contact zone, stratoid and lenticular Pb–Ag
–Au ore body in interlayer fracture zone of the outer zone,
and vein-shaped Au–Pb–Ag ore body in distal zone
constitute the porphyry-skarn type Au–Fe–Cu–Pb–Zn
(Ag)–polymetallic metallogenic system.

5) Impure carbonate rocks from the Middle Triassic
Beiya Fm. (T2b) provide favorable surrounding conditions
and hosting space for the formation of deposits. The
contact fracture zone between the rock body and carbonate
rocks, tectonic fracture zone in the interlayer of carbonate
layers and between carbonate and clastic rocks and the
section where fissures are well developed are the main
hosting positions for ore bodies.

6) The metallogenic parent ores of weathering-
accumulation-type (paleo weathering crust-type) Fe–Au
deposits formed by supergene processes are the porphyry–
skarn-type ore body and the interlayer fracture-zone-type
ore body, which is the vein-shaped ore body in secondary
fracture and fissures formed early. The small intermontane
eroded basin in the core of the Beiya syncline controlled
the spatial distribution of ore bodies.

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About the first author

ZHOU Yunman, male, born in 1965, PhD from China University of Geosciences (Beijing) in 2008, professorate senior engineer, interested in the study of geological mineral resources exploration, mineral deposits and ore prospecting prediction for a long time.