

Genesis of the South Pit Deposit in Jiama District, Tibet: Constraints from Geology, Geochronology and Amphibole Geochemistry

Pan Tang^{1,2,3}, Juxing Tang⁴, Bin Lin⁵, Aorigele Zhou^{*4}, Faqiao Li⁵, Xiang Fang⁴, Jing Qi⁶, Mengdie Wang⁵, Yan Xiong⁵, Yuke Xie^{1,2}, Zhengkun Yang³, Xiaofeng Yao⁷

1. Key Laboratory of the Ministry of Education on Solid Waste Treatment and Recycling, School of Environment and Resource, Southwest University of Science and Technology, Mianyang 644000, China

2. SinoProbe Laboratory, Beijing 100037, China

3. Tibet Huatailong Mining Co., Ltd., Lhasa 850212, China

4. Chinese Academy of Geological Sciences, Beijing 100037, China

5. MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China

6. School of Earth Science and Resources, China University of Geosciences, Beijing 100083, China

7. Development and Research Centre, China Geological Survey, Beijing 100037, China

ABSTRACT: The giant Jiama deposit is a post-collisional porphyry Cu-polymetallic system located in the Gangdese metallogenic belt of Tibet. It consists of three deposits: The Main deposit, the Zegulangbei deposit, and the South Pit deposit according to exploration and research. The South Pit deposit is a high-grade Cu-Pb-Zn deposit, but its genesis is unclear. To investigate its genesis, a detailed study was conducted on the deposit geology, geochronology and amphibole geochemistry. The results indicate that the weighted average ²⁰⁶Pb/²³⁸U age of the zircons from the granite porphyry in the South Pit is 15.38 ± 0.45 Ma, and the molybdenite from the mineralized skarn yield a Re-Os isochron age of 15.23 ± 0.22 Ma, in line with the age of the Main deposit (15.7–14.3 Ma). The amphiboles in the granite porphyry of the South Pit, magnesiohornblende and actinolite, are high in Mg and Ca and low in K. They crystallized at temperatures of 705–749 °C, pressures of 0.44–0.67 kbar, oxygen fugacity of -14.31– -13.69 (NNO), and depths of 1.7–2.5 km. Mapping of structure and alteration indicates that the South Pit skarn developed due to the metasomatism of marble of hornfels or carbonate in fold hinge dilation and an interlayer detachment zone by magmatic hydrothermal fluids. According to the age of magmatism and geological features, the South Pit deposit and the Main deposit have originated from the same Miocene magmatism, but the South Pit deposit was affected by the gliding nappe tectonic system. The amphibole geochemistry indicates that the ore-related magma of the South Pit has a high oxygen fugacity and is rich in water.

KEY WORDS: geochronology, amphibole geochemistry, porphyry Cu-polymetallic system, Gangdese metallogenic belt, Tibet.

0 INTRODUCTION

Porphyry deposits, which are a major source of copper and molybdenum and significant contributors of gold to the global market, are typically associated with dioritic to monzonitic intrusive rocks both spatially and temporally (Richards, 2015, 2003; Sillitoe, 2010). Most porphyry deposits form in subduction-related calc-alkaline felsic arc

magmas found worldwide (Sillitoe, 2010, 1972; Richards, 2003). However, recent research has revealed that porphyry deposits in continental collision zones are also linked to collision-related high-K felsic magmas (Hou et al., 2009, 2003; Richards, 2009). For example, numerous Miocene large collision-related porphyry-skarn deposits, such as Qulong, Jiama, and Bangpu, are found in the Gangdese porphyry Cu belt in Tibet (Tang P et al., 2021, 2019; Yang and Cooke, 2019; Tang J X et al., 2012). Skarn deposits, a key component of the porphyry metallogenic system, often surround porphyry deposits and are high-grade with great economic value, providing valuable information on the magmatic hydrothermal fluids of the porphyry metallogenic system.

*Corresponding author: zhouaorigele@163.com

© China University of Geosciences (Wuhan) and Springer-Verlag GmbH Germany, Part of Springer Nature 2025

Manuscript received June 20, 2022.

Manuscript accepted May 16, 2023.

The Jiama deposit, located in the eastern part of the Gangdese porphyry Cu belt in Tibet, is the largest porphyry Cu-polymetallic system in the region. It consists of Cu-polymetallic skarn, Cu-Mo hornfels, and Mo $\pm$ Cu porphyry mineralization and has estimated reserves of 11.08 Mt Cu, 1.07 Mt Mo, 1.75 Mt Pb + Zn, 305 t Au, and 15 840 t Ag. The deposit comprises three ore sectors: the Main deposit, the Zegulangbei deposit, and the recently found South Pit deposit (Lin et al., 2024; Tang et al., 2023). The South Pit deposit has estimated reserves of 0.7 Mt Cu with an average grade of 0.99%, 1.20 Mt Pb + Zn with an average grade of 2.88%, 0.02 Mt Mo with an average grade of 0.038%, 20 t Au with an average grade of 0.33 g/t, and approximately 2 000 t Ag with an average grade of 28.18 g/t. However, the mineralization and alteration of the South Pit deposit differ from the Main deposit, and its chronology of petrogenesis and metallogeny, as well as the relationship between structure and mineralization are unclear, making the genesis of the deposit is controversial. In this study, we present a comprehensive geologic investigation of the South Pit deposit, including structure and alteration, U-Pb dating of LA-ICP-MS zircon, Re-Os dating of molybdenite, and amphibole geochemistry, to clarify the genesis of the deposit.

1 REGIONAL GEOLOGICAL SETTING

The Gangdese metallogenic belt, a world-class porphyry-skarn-epithermal copper polymetallic belt in China,

is nearly E-W trending and situated at the southwest margin of the Lhasa Terrane, southern Tibet (Figure 1) (Zheng et al., 2021; Gao et al., 2019; Lin et al., 2017a, b; Tang et al., 2017; Hou et al., 2009). The Lhasa Terrane, bounded by the Yarlung-Zangbo suture zone (YZSZ) and the Bangong-Nujiang suture zone (BNSZ), is composed mainly of Mid-Proterozoic and Early Cambrian orthogneiss basement and Paleozoic–Mesozoic cover strata consisting of a sequence of Ordovician–Triassic shallow marine clastic sedimentary rocks (Zhang et al. 2014). The Late Triassic separation of the Lhasa Terrane from Gondwanaland (Yin and Harrison, 2000) was followed by Jurassic island-arc orogeny, Cretaceous continental margin arc superposition, Paleogene collisional orogeny and Miocene crustal deformation, all of which led to the formation of the 1 500 km E-W-oriented Gangdese tectono-magmatic belt (Zhao et al., 2015).

The Gangdese tectonic-magmatic belt formed because of the northward subduction of the Neo-Tethyan oceanic lithosphere below Asia, followed by the Indo-Asian collision (Yin and Harrison, 2000). This belt primarily comprises Late Paleocene to Early Eocene (60–40 Ma) Linzizong Formation volcanic rocks (Mo et al., 2008) and Cretaceous to Tertiary (120–24 Ma) granite batholiths (Allégre et al., 1984). The Indo-Asian collision can be divided into three stages: the main collisional convergent stage (65–41 Ma), the late collisional transform stage (40–26 Ma), and the post-collisional crustal exten-

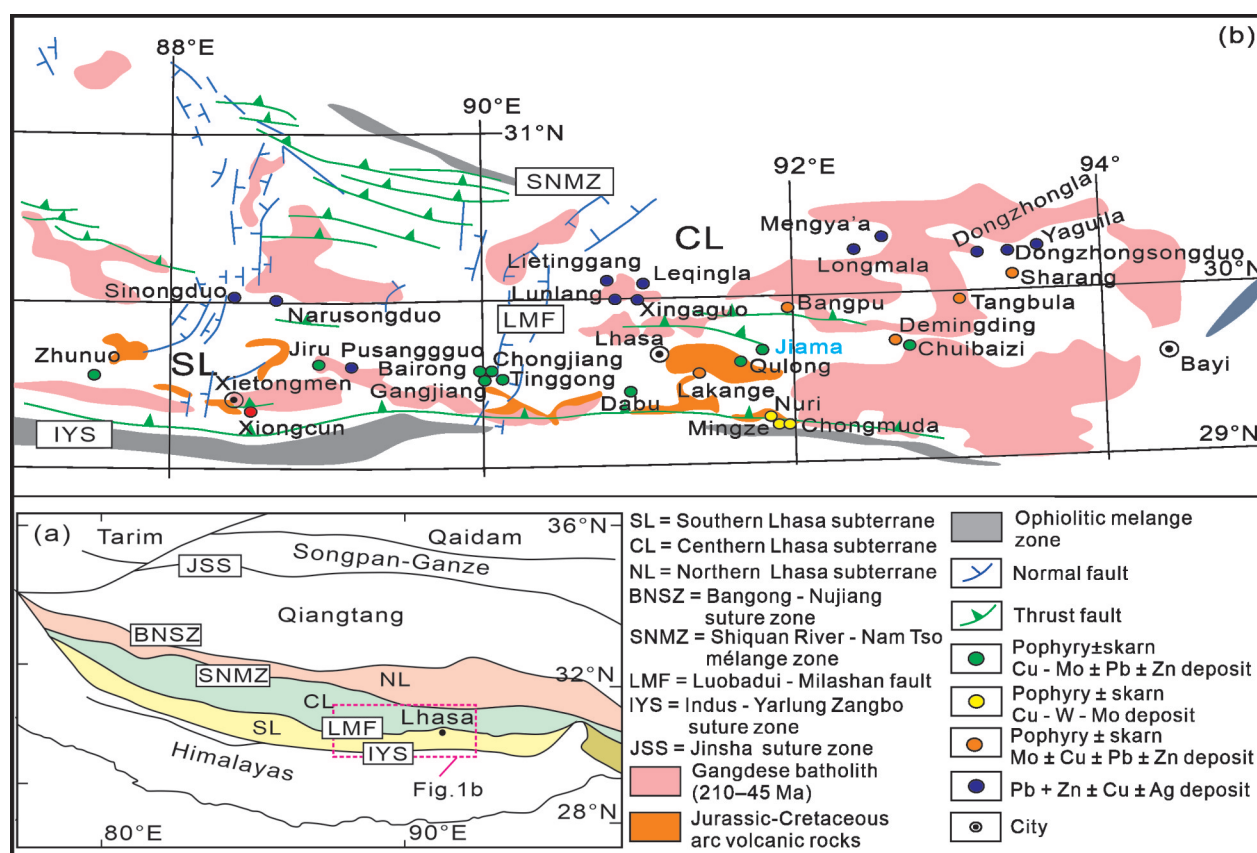


Figure 1. (a) Tectonic framework of the Tibetan Plateau showing its structures and tectonic belts (after Zhu et al., 2011 and Yin and Harrison, 2000); (b) geological sketch of the Gangdese Porphyry copper belt (modified from Tang et al., 2017 and Yang et al., 2009).

sion stage (25–0 Ma). During these stages, multiple metallogenic events occurred (Hou et al., 2006; Chung et al., 2005), increasing mineral deposits related to the northward subduction of the Neo-Tethyan slab. These deposits are classified into three types: (1) porphyry Cu-Au deposits formed during subduction (180–160 Ma), such as the Xiongcu Cu-Au deposit (Lang et al., 2020, 2019, 2014; Xie et al., 2018); (2) porphyry Mo $\pm$ W and associated skarn Pb-Zn deposits formed during syn-collision (70–50 Ma), such as the Sharang Mo deposit, Xin'aguo Pb-Zn deposit, and Yaguila Pb-Zn deposit (Huang et al., 2025; Tang et al., 2020; Wang et al., 2018); (3) porphyry Cu-Mo and associated skarn Cu-polymetallic deposits formed during post-collisional stage (20–12 Ma), such as the Bangpu Mo-Cu deposit, Qulong Cu-Mo deposit, Lakang'e Mo(Cu) deposit and Jiama Cu-polymetallic deposit (Tang et al., 2021, 2019; Leng et al., 2016; Zheng et al., 2016; Yang et al., 2009).

2 DEPOSIT GEOLOGY

2.1 Stratigraphy

Outcrops in the Jiama District mainly consist of epicontinental passive clastic-carbonate rocks, including the Upper Jurassic Duodigou Formation (J_3d) made up of limestone, the Lower Cretaceous Linbuzong Formation (K_1l) composed of sandstone, siltstone, slate and hornfels, and, in some areas, Quaternary colluvium and alluvi-

um (Figure 2). The South Pit deposit is located at the southwest region of the Jiama mining district, where the Duodigou and Linbuzong formations outcropped (Figure 2).

2.2 Structural Geology

The ore-controlling structures play a crucial role in the formation of the Jiama porphyry Cu-polymetallic system and consist of a thrust nappe structure and a gliding nappe structure. The thrust nappe structure at Jiama exhibits progressive southward facing deformation, characterized by overturned strata composed of Upper Jurassic and Lower Cretaceous clastic-carbonate rocks, and dates back to ~50 Ma (Zhong et al., 2012), close to the time of the India-Asia continental collision (Mo et al., 2007; Yin and Harrison, 2000). The Niumatang overturned anticline in the nappe structure was the primary factor in porphyry intrusion, hornfels, and porphyry orebody formation (Zheng et al., 2016). The interlayer detachment in the nappe structure also controlled the formation of the 1[#] skarn orebody in the Main deposit. The gliding nappe structure is only present in the South Pit of the ore district, covering an area of 4 km² (Figure 2), and resulted from the northward slippage of the unstable high anticline block formed by thrust deformation. The secondary folds and cracks developed in the gliding nappe structure (Zhong et al., 2012) provide ample space for the

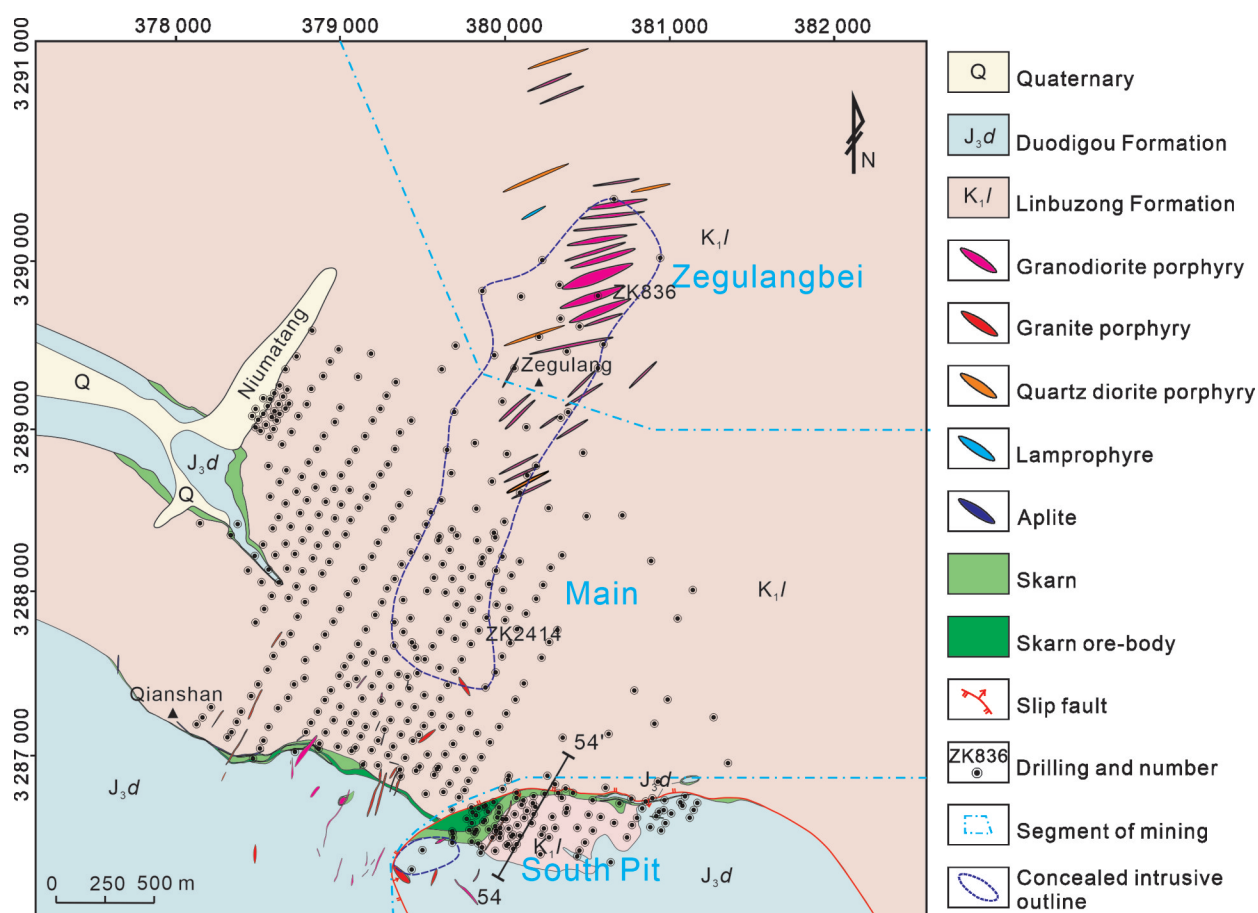


Figure 2. Geological map of the Jiama District (modified after Zheng et al., 2016).

transport and deposition of ore-forming fluids and control the formation of the 2[#] skarn orebody in the South Pit deposit.

2.3 Igneous Rocks

Few intrusions in the Jiama District are outcrops. They primarily consist of granodiorite porphyry, monzogranite porphyry, quartz diorite porphyry, granite porphyry, and minor diorite, lamprophyre and aplite. Most of the intermediate-acidic igneous rocks are closely related to hornfels in the Copper Mountain-Zegulang area.

In South Pit, the intrusions are primarily granite porphyry, with minor granodiorite porphyry and quartz diorite porphyry (Figure 3a–3c). The granite porphyry is large-scale and outcrops at the southwest with a thickness of over 1 000 m. It has undergone moderate silicification and weak chlorite alteration, with locally unidirectional solidification textures. The post-mineralization granodiorite porphyry and quartz diorite porphyrite occur as dikes or stocks with thicknesses of 2 to 50 m and have experienced moderate to strong chlorite, epidote, and phyllic alteration, with no veins present.

2.4 Mineralization and Alteration

The main alteration types in the Main deposit are potassic, phyllic, argillic, propylitic, and skarn alterations. Potassic alteration, characterized by biotite, quartz, and anhydrite, is mainly biotite alteration. Phyllic alteration, which occurs mainly above the potassic alteration zone and results from feldspar or hornblende replacement, is represented by fine-grained sericite and pyrite. Argillic alteration, represented by kaolin and sericite, occurs in the upper part of the hornfels and in some fractures. Propylitic alteration is characterized by abundant chlorite, epidote, and calcite and occurs on the periphery. Skarn has a distinct zonation pattern from proximal to distal. The Main deposit mainly consists of the 1[#] skarn Cu-polymetallic orebody, the 3[#] hornfels Cu-Mo orebody, and the 4[#] porphyry Mo ± Cu orebody. The South Pit deposit mainly consists of the 2[#] skarn Cu-polymetallic orebody and manto-type orebodies.

The prograde skarn of the South Pit is primarily composed of garnet, diopside, and wollastonite, with minor vesuvianite and anhydrite (Figures 3d–3i). The retrograde skarn of the South Pit is characterized by chlorite, epidote, calcite, and quartz, with minor tremolite (Figures 3d–3i). In the South Pit, hornfels, skarn, and marble interbedding occurs due to the refolded folds and five-fold interbedding can be seen in some drillholes. However, the zonation of skarn in both vertical and plane is unclear. Locally, the zonation of skarn can be recognized from the hornfels contact zone outwards to the marble. The skarn ranges from garnet skarn to garnet pyroxene skarn to wollastonite skarn, the garnet color changes from red-brown to brown-yellow to green, and the ore minerals range from molybdenite ± chalcopyrite to chalcopyrite ± molybdenite to bornite ± galena ± sphalerite ± chalcopyrite (Figures 3j–3o). The South Pit deposit mainly com-

prises Cu-Pb-Zn skarn mineralization with minor Cu-Mo hornfels mineralization. The 2[#] skarn orebody is thick and lens-shaped, with a maximum thickness of 381.2 m in a single drillhole and elevations of 4 600–5 100 m. The orebody strikes east-west, dips south at 50°–80° and is generally over 100 m thick.

The hornfels alteration in the South Pit is mainly chlorite and epidote alteration, and the hornfels mineralization is weak, consisting of molybdenite and chalcopyrite. Locally, vein gold orebodies can be found in the hornfels, and high-grade manto-type orebodies, often occurring in marble and consisting of over 85% sulfides (mainly galena, sphalerite, chalcopyrite, tetrahedrite, pyrrhotite), can have thicknesses of 0.01 to 2 m (Figure 3o). In addition, a large amount of pyrrhotite can be found in the hornfels, skarn, or manto-type orebody in the east of South Pit (far from the intrusions in the southwest) and is closely related to gold mineralization (Yang et al., 2020).

3 SAMPLES AND ANALYTICAL METHODS

The samples for U-Pb dating of LA-ICP-MS zircon, Re-Os dating of molybdenite, and amphibole geochemistry analyses were collected from different depths of drillhole. The samples of zircon U-Pb dating were collected from granite porphyry in ZK4280 (Figure 2). The samples of molybdenite Re-Os dating were collected from skarn Mo orebody. The samples of amphibole geochemistry were collected from granite porphyry and monzonite granite porphyry with weak alteration. Granite porphyry are mainly composed of quartz, K-feldspar, plagioclase, and minor biotite and amphibole with weak silicification and chloritization (Figure 4).

The U-Pb dating of zircon were performed by LA-ICP-MS at Xi'an Center, China Geological Survey. Zircon standard 91500 was used as external standard during U-Pb dating analytical runs, and was analyzed after every 5 unknown analyses. Time-dependent drifts of U-Th-Pb isotopic ratios were corrected using a linear interpolation (with time) for every five analyses according to the variations of 91500 following the methodology of Liu et al. (2010). *In-situ* zircon trace element analyses were performed on the same zircon grains that had been analysed for U-Pb isotopes, and the analysis procedures and conditions are the same as those for the U-Pb isotopic analysis. The time-resolved spectra were processed offline using ICP-MS DataCal software (Liu et al., 2010).

Re-Os isotope analysis of molybdenite grains was completed at the Re-Os isotope laboratory at the National Research Center for Geoanalysis, Chinese Academy of Geological Sciences using a TJA Xseries ICP-MS. The standard used for Re-Os analysis was GBW04435 (HLP; 221.4 ± 5.6 Ma). Data acquisition and processing followed the methodology described by Du et al. (2004, 2001).

Major elements of amphibole were determined using a JCSA8230 electron microprobe at the MNR Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological

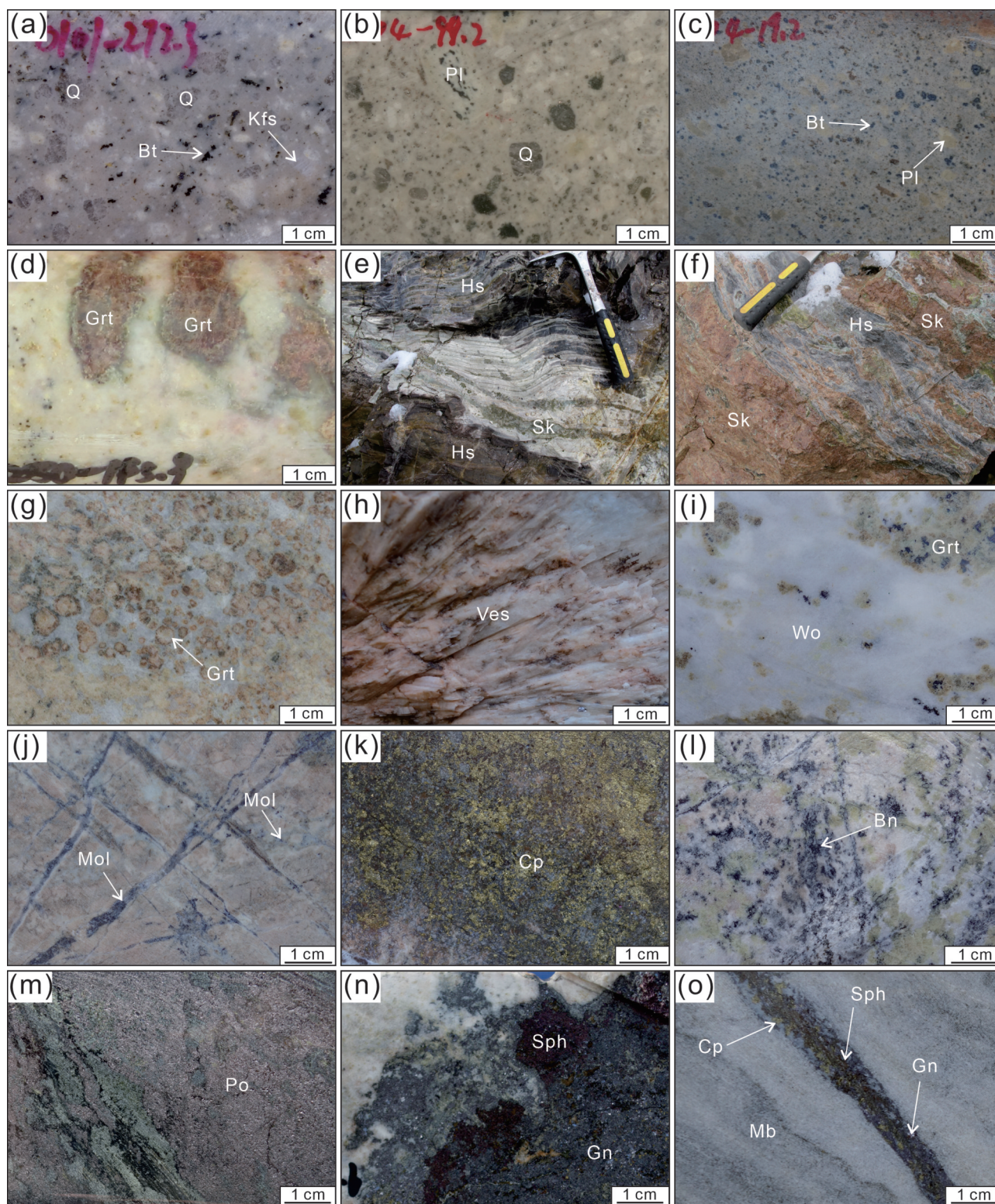


Figure 3. Magmatic rock, mineralization and alteration in South Pit. (a) Hand specimen of granite porphyry; (b) hand specimen of granodiorite porphyry; (c) hand specimen of quartz diorite porphyry; (d) skarn altered granite porphyry; (e) skarn altered hornfels; (f) skarn formed by hornfels, comprising red-brown garnet, minor diopside and hornfels patches; (g) brown garnet skarn; (h) vesuvianite skarn; (i) pale green garnet wollastonite skarn; (j) vein and disseminated molybdenite in brown garnet skarn; (k) massive chalcopyrite in garnet skarn; (l) disseminated bornite in garnet wollastonite skarn; (m) massive pyrrhotite in skarn; (n) massive galena and sphalerite in wollastonite skarn; (o) manto chalcopyrite, galena and sphalerite in marble. Q. Quartz; Bt. biotite; Kfs. K-feldspar; Pl. plagioclase; Gp. granite porphyry; Mb. Marble; Hs. Hornfels; Sk. Skarn; Grt. Garnet; Ves. Vesuvianite; Wo. Wollastonite; Mol. Molybdenite; Cp. Chalcopyrite; Bn. Bornite; Po. Pyrrhotite; Sph. Sphalerite; Gn. galena.

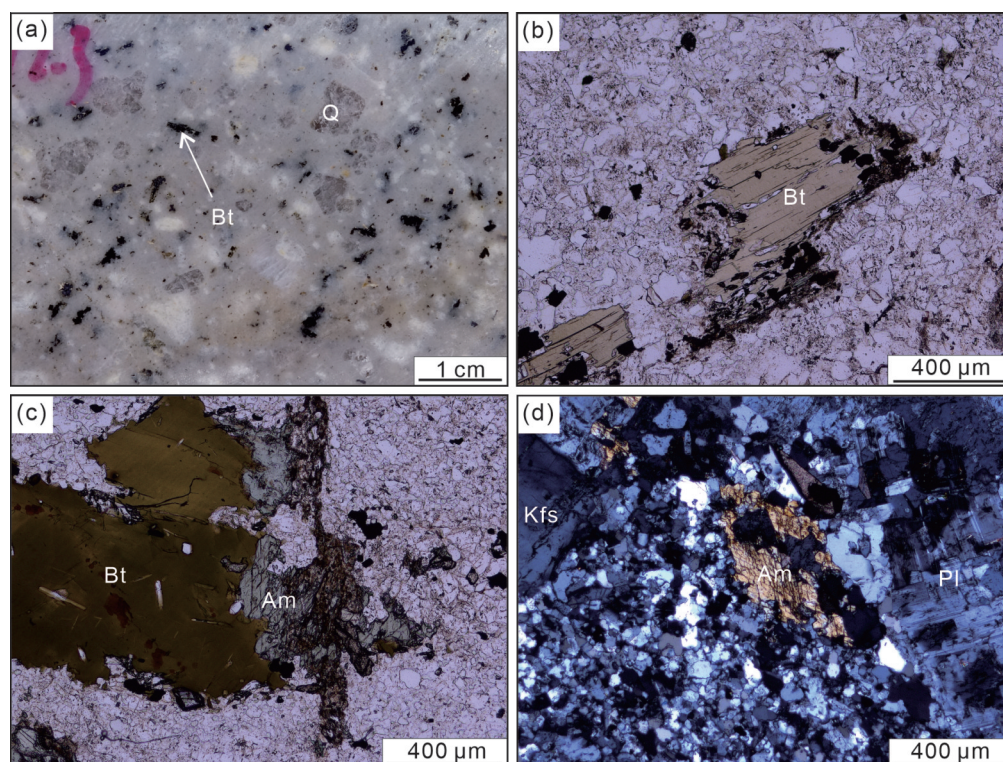


Figure 4. The hand specimen photo (a) and micrograph (b)–(d) of the granite porphyry in the South Pit. Q. Quartz; Bt. biotite; Am. Amphibole; Pl. plagioclase; Kfs. K-feldspar.

Sciences. Standard operating conditions include an accelerating potential of 15 kV, a beam current of 20 nA, a beam diameter of 3 μm , and counting times between 10 and 30 s. The analytical reproducibility was within 2%.

4 RESULTS

4.1 Zircon U-Pb Ages

The results of the LA-ICP-MS zircon U-Pb analysis for samples from the granite porphyry are listed in Table S1. Representative CL images of the zircon and their corresponding U-Pb concordia plots can be seen in Figures 5a–5b. The zircons from the granite porphyry sample are colorless and have euhedral shapes, with lengths ranging from 80 to 250 μm and aspect ratios of 1 : 1 to 3 : 1 (Figure 5a). The zircons display clear oscillatory and sector zoning in the CL images (Figure 5a), and have Th/U ratios of 0.38 to 1.71, indicating a magmatic origin (Belousova et al., 2002). The zircons have variable amounts of U (346 ppm–1 407 ppm, with a mean of 754 ppm) and high Th/U ratios (0.38–1.71). A total of 24 zircon grains analyses resulted in a weighted mean age of 15.38 ± 0.45 Ma, with a $^{206}\text{Pb}/^{238}\text{U}$ age range of 13.9–16.96 Ma (1σ , MSWD = 6.1; Figure 5b, Table S1).

4.2 Molybdenite Re-Os Ages

Five molybdenite samples analyzed in this study contained Re in the range of 382 508 ppb to 1 800 563 ppb, common Os in the range of 0.338 4 ppb to 3.053 ppb, and ^{187}Os in the range of 61.59 ppb to 288.0 ppb (Table S2). The Re-Os molybdenite model ages, determined through analysis, range from 15.26 ± 0.23 to $15.38 \pm$

0.22 Ma and exhibit excellent reproducibility. The results yield a ^{187}Re – ^{187}Os isochron age of 15.23 ± 0.22 Ma (MSWD = 0.27; Figure 5c) and a weighted mean Re-Os age of 15.30 ± 0.1 Ma (MSWD = 0.17; Figure 5d, Table S2). This isochron age of 15.23 ± 0.22 Ma is considered as the mineralization age of the molybdenite.

4.3 Amphibole Geochemistry

The results of the electron microprobe analysis of amphiboles from the granite porphyry and monzogranite porphyry are presented in Table S3. The amphiboles in the granite porphyry are magnesiohornblende and actinolite (Figure 6a) and have similar contents of MgO, CaO, K_2O , Na_2O , TiO_2 , and Al_2O_3 , which range from 12.80 wt.% to 14.64 wt.%, 11.29 wt.% to 11.77 wt.%, 0.53 wt.% to 0.63 wt.%, 1.19 wt.% to 1.81 wt.%, 0.29 wt.% to 0.47 wt.%, and 3.33 wt.% to 4.83 wt.%, respectively. The amphiboles in the monzogranite porphyry are magnesiohornblende (Figure 6a) and have similar contents of MgO, CaO, K_2O , Na_2O , TiO_2 , and Al_2O_3 , which range from 13.22 wt.% to 14.82 wt.%, 11.04 wt.% to 11.31 wt.%, 0.5 wt.% to 0.87 wt.%, 1.32 wt.% to 1.63 wt.%, 0.79 wt.% to 1.65 wt.%, and 5.22 wt.% to 7.23 wt.%, respectively.

The amphiboles from these two rock types have high $\text{Mg}^\#$ (> 0.65) and Ca contents but low K contents. Compared to the amphiboles in the monzogranite porphyry, the amphiboles in the granite porphyry have lower contents of MgO, TiO_2 , and Al_2O_3 . The plot of TiO_2 and Al_2O_3 in the amphiboles suggests that the granite porphyry and monzogranite porphyry are from a mixed crust-mantle source (Figure 6b). Here, pressure, temperature,

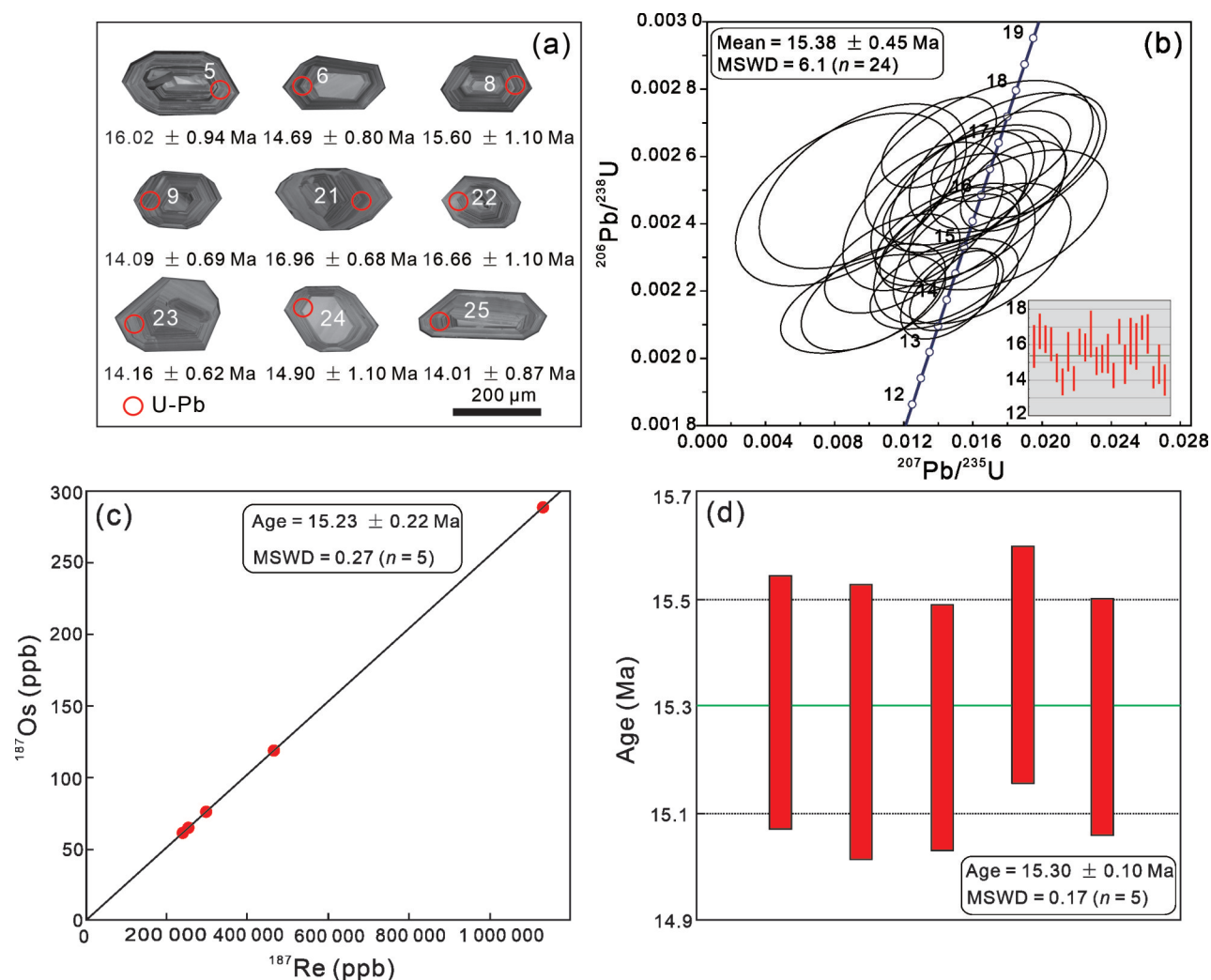


Figure 5. Part of CL images and testing points of zircons from the granite porphyry (a), zircon U-Pb age of the granite porphyry (b), and Re-Os isochron (c) and weighted average (d) ages of molybdenite from the South Pit.

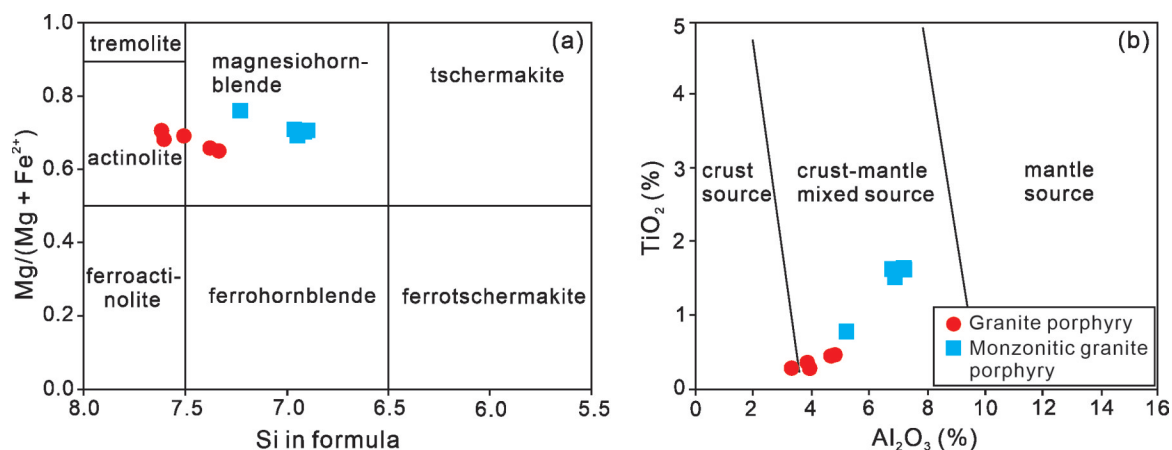


Figure 6. Classification of amphiboles (a) (after Leake, 1978) and TiO_2 - Al_2O_3 for amphiboles (b) (after Jiang and An, 1984).

melt H_2O concentration, and oxygen fugacity of the magmas are determined using the empirical amphibole formulation (Ridolfi et al., 2010). The amphiboles in the granite porphyry and monzogranite porphyry crystallized at temperatures of 705 to 749 °C and 745 to 801 °C, pressures of 0.44 to 0.67 kbar and 0.68 to 1.14 kbar, oxygen fugaci-

ty of -14.31 to -13.69 and -13.36 to -12.78, and depths of 1.7 to 2.5 km and 2.58 to 4.30 km, respectively.

5 RESULTS

5.1 Timing of Magmatism and Mineralization

The South Pit large Pb-Zn-Cu deposit, an important

part of the Jiama porphyry metallogenic system, is located southeast of the Jiama District and 1 km from the Main deposit. The key to understanding the genesis of the South Pit deposit is the age of its magmatism and mineralization. The granite porphyry of the South Pit was emplaced at 15.38 ± 0.45 Ma, which along with the age (14.8 Ma) of granodiorite porphyry of South Pit (Zou et al., 2019) and the calculated molybdenite Re-Os age of 15.23 ± 0.22 Ma from skarn orebody samples, indicate mineralization at the South Pit deposit occurred approximately 15.3 Ma and is linked to magmatism. Furthermore, the timing of the South Pit deposit's magmatism and mineralization aligns with that of the Main deposit and Zegulangbei deposit (Figure 7), indicating they both resulted from the same Miocene magmatism.

5.2 Relationship between Structure, Alteration and Mineralization

Its skarn and hornfels mineralization of the South Pit is spatially associated with the granite porphyry (Figure 8), suggesting a connection to magmatism. The structures in the South Pit deposit broadly consist of a thrust nappe structure and a gliding nappe structure. Drillhole logging reveals that hornfels, skarn, and marble are interbedded in South Pit (Figure 8). Mapping of the structure and alteration reveals that refolded folds and at least two deformations occur in the South Pit (Figures 9a–9d). The skarn in South Pit can be divided into two types (Figures 8, 9b). One type is formed by the contact metamorphism of the hornfels and consists of garnet and pyroxene. These skarns are chalcopyrite and molybdenite mineral-

ization and occur some distance from the marble/hornfels contact at South Pit (Figures 8, 9b). These skarns develop within the fold hinge dilation and secondary fractures formed by folds. The other type is formed by the contact metamorphism of marble and consists of wollastonite and garnet. These skarns, which contain chalcopyrite, bornite, galena, and sphalerite mineralization, develop in the marble at or near the hornfels/marble contact (Figures 8, 9b).

The genesis of the refolded folds in the South Pit is controversial. The gliding nappe structure developed due to the northward slippage of the unstable high anticline block formed by thrust deformation (Zhong et al., 2012). This gliding nappe is only discernible at the peak of the South Pit (Copper Mountain), where there are many Z-folds and cleavage structures, which provide sufficient space for the transport and deposition of ore-forming fluids and control the formation of the South Pit deposit (Zheng et al., 2016; Zhong et al., 2012). According to drill-hole logging, continuous fractures or fracture zones can be seen in multiple drillholes, which may be the trace of the gliding nappe structure. The Qianshan and South Pit, which have similar elevation and are 900 m apart (Figure 2), have a surface contact zone of the Linbuzong Formation and the Duodigou Formation. Although there is no refolded fold in Qianshan, numerous refolded folds occur in the South Pit. Therefore, the South Pit may have had a gliding nappe structure that was later than the thrust nappe structure. Furthermore, the thick skarn orebody develops within the hanging wall of the gliding nappe structure, but no skarn develops in the footwall (Figure

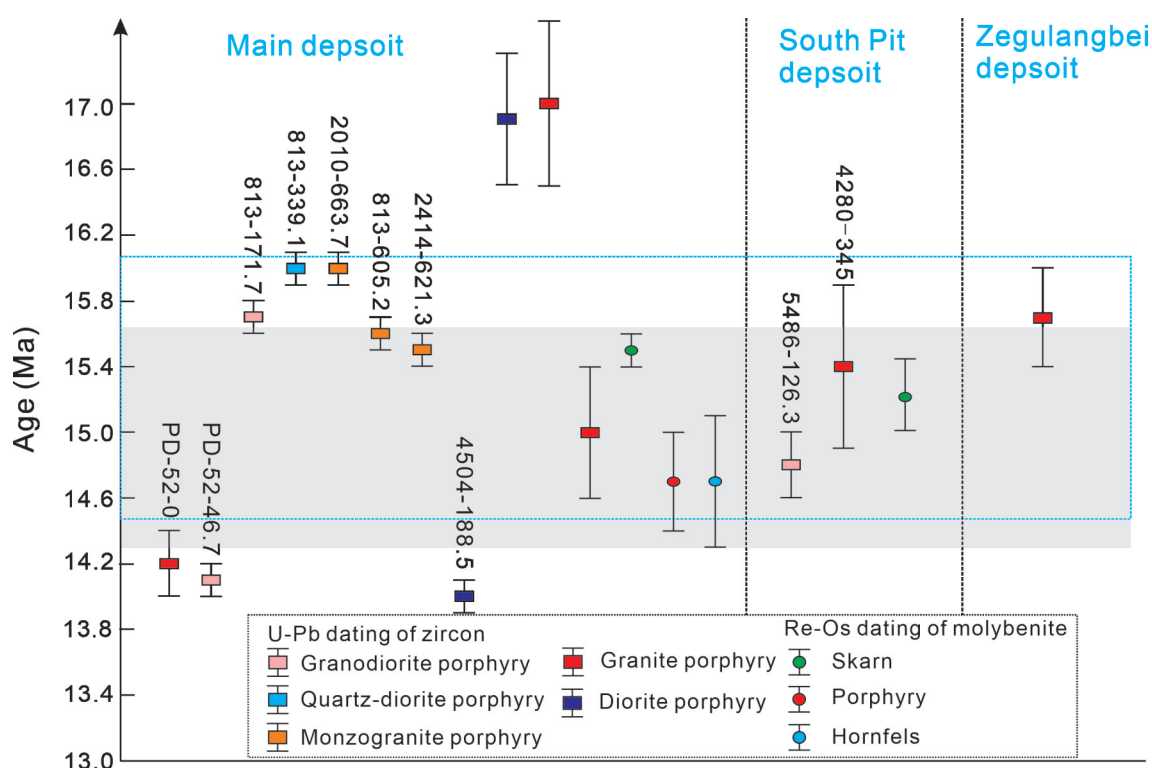


Figure 7. Geochronology of magmatism and mineralization in the Jiama District (other data after Qi et al., 2021; Zou et al., 2019; Zheng et al., 2016; Qin et al., 2011; Ying et al., 2011, 2010, 2009; Chung et al., 2003).

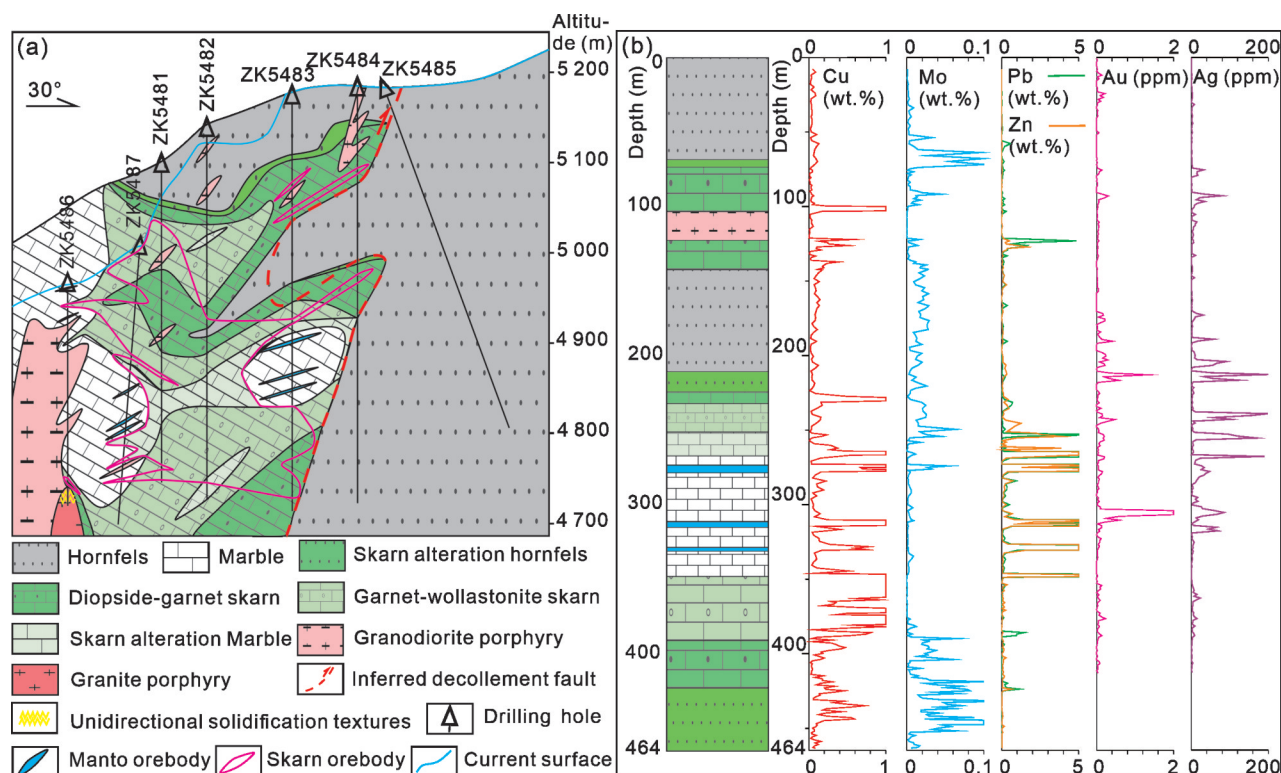


Figure 8. (a) No. 54 cross-section through the center of South Pit and (b) geological information of drilling ZK5483.

8a). This evidence indicates that the South Pit deposit was clearly controlled by a gliding nappe structure system. The gliding nappe structure, interlayer structure, and secondary faults are ore-guiding structures, and the fold hinge dilation provides space for ore precipitation.

5.3 Formation Mechanism of the South Pit Deposit

The skarn orebody, the main mineralization in the South Pit, mainly consists of chalcopyrite, molybdenite, bornite, sphalerite, galena, and tetrahedrite, and can be either disseminated or massive structure. Cu-Mo mineralization mainly develops in skarn altered hornfels and garnet skarn near hornfels, while Pb-Zn-Cu mineralization mainly occurs in the wollastonite skarn and skarn altered marble near the marble. The metallogenic elements ranges from Cu-Mo to Pb-Zn-Cu from the intermediate fluid channel to the distal fluid channel. Additionally, there are locally occurring high-grade Pb-Zn (Cu) orebodies (manto orebodies) in marble (Meinert et al., 2005). This makes the South Pit deposit an example of a porphyry-skarn style mineralization.

The $\delta^{34}\text{S}$ value of sphalerite (-2.9‰ – 0.31‰ , unpublished data) and pyrrhotite (-1.3‰ – -0.5‰ , Yang et al., 2020) from the South Pit is similar to that of magmatic-hydrothermal deposits (Ohmoto, 1986; Rye and Ohmoto, 1974), indicating that the ore-forming fluid is from magmatic source. The weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of the zircons from the granite porphyry in the South Pit is 15.38 ± 0.45 Ma, and the molybdenite from the mineralized skarn yield a Re-Os isochron age of 15.23 ± 0.22 Ma, in line with the age of the Main deposit (15.7 – 14.3

Ma, Zheng et al., 2016). The granodiorite porphyry belongs to the calc-alkaline series, with adakitic affinities and weak negative Eu anomalies, and are enriched in LREEs and LILEs (Rb, U, and K), depleted in HFSEs (Ta, Nb, P, and Ti) (Chen G L et al., 2021), which are similar to those found in the Main deposit (Zheng et al., 2016). Zircon grains from the granodiorite porphyry in the South Pit have a positive $\varepsilon_{\text{Hf}}(t)$ value (1.4 – 4.9), consistent with $\varepsilon_{\text{Hf}}(t)$ value (1.8 – 9.4 , Sun et al., 2022) of intrusions in the Main deposit, indicating that they formed through partial melting of the juvenile mafic lower crust. The geochemistry, Hf isotopic composition and the timing of magmatism and mineralization of the South Pit deposit and Main deposit are consistent. These findings suggest that the South Pit deposit and Main deposit have originated from the same magma source and belong to the same mineralizing event in the Jiama District.

Drillhole logging of ZK4280 in the southwest of the South Pit shows that there is an inner skarn, and molybdenite mineralization in the contact between the granite porphyry and the skarn. From the granite porphyry upward, the skarn ranges from Mo mineralization to Cu-Mo mineralization to Pb-Zn-Cu mineralization, indicating that the granite porphyry was formed slightly earlier or at the same time as the skarn. The granite porphyry in the South Pit could be formed by the high silica residual melt evolved from the magma of adakitic monzonitic granite porphyry due to the mineral crystallization differentiation of magma in the chamber (Chen S R et al., 2021). Amphibole geochemistry indicates that the granite porphyry has a lower temperature, pressure, and crystallization depth

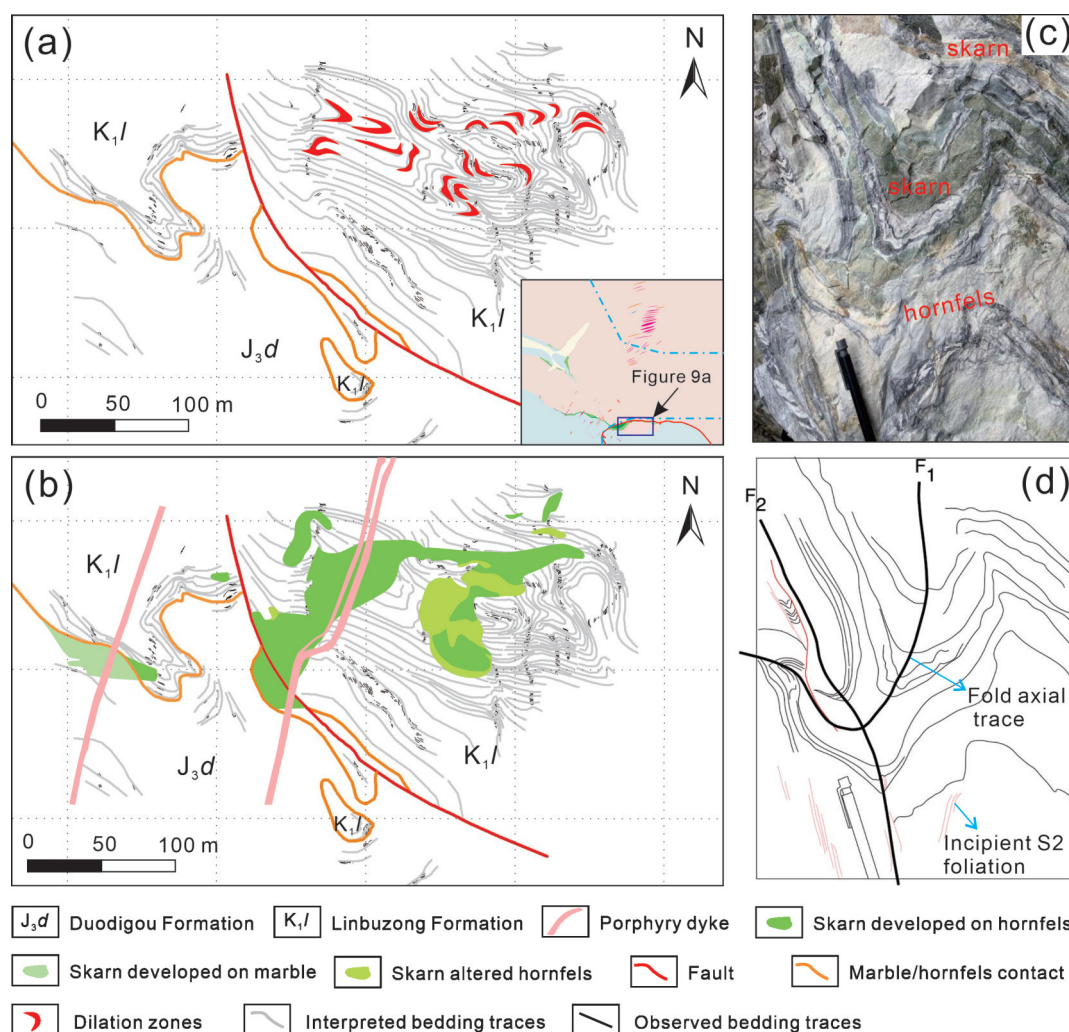


Figure 9. Interpretation of structure and alteration in the South Pit of Jiama (modified after Mason, 2016). (a) Interpretation of possible dilation zones developed during D₂ deformation (fold hinge dilation); (b) lithology map of South Pit with interpretation of porphyry dykes; (c) refolded fold, early fold F₁ is refolded by second contractional deformation fold F₂; (d) line drawing and depiction of fold axial traces. Incipient S₂ foliation marked in red.

than the monzogranite granite porphyry (Figures 10a–10b), and is from a saturated melt (Figure 10c). Although the highly-fractionated I-type granite cannot form porphyry Cu deposits, it can indicate the information of a deep magmatic chamber. Additionally, the amphibole of the granite porphyry in the South Pit shows that the melt was saturated, had a high oxygen fugacity, and was rich in water (3.23 wt.%–4.67 wt.%), which favors the migration and enrichment of ore-forming elements.

The element zoning and porphyry fracture system reveals that the magmatic-hydrothermal center of the Main deposit in the Jiama District is mainly concentrated between ZK1616 and ZK3216 (Lin et al., 2012; Zheng et al., 2010). From the concealed porphyry of ZK4280 to the east northeast, the thickness of the skarn orebody gradually decreases, and the mineralization elements range from Cu–Mo to Pb–Zn–Cu. This indicates that the hydrothermal center of the South Pit is mainly concentrated in the concealed porphyry between ZK4280 and ZK5486, and the fluid migration direction is from south-

west to east northeast, which is distinct from the Main deposit. Hence, the ore-forming fluid in the South Pit may have come from deep magma and precipitated in the South Pit gliding nappe along the emplacement channel of the concealed granite porphyry.

6 CONCLUSIONS

(1) The granite porphyry at the South Pit was emplaced at 15.38 ± 0.45 Ma. A Re–Os isochron age of 15.23 ± 0.22 Ma, obtained from molybdenite, is consistent with the emplacement of the granite porphyry. The timing of magmatism and mineralization of the South Pit deposit aligns with that of the Main deposit, suggesting that they occurred at separate spatially but were sourced from the same Miocene magmatism.

(2) The amphibole found in the granite porphyry at the South Pit, consisting of magnesiohornblende and actinolite, has high levels of Mg and Ca and low levels of K. The amphibole crystallized at temperatures of 705–749 °C, pressures of 0.44–0.67 kbar, oxygen fugacities of

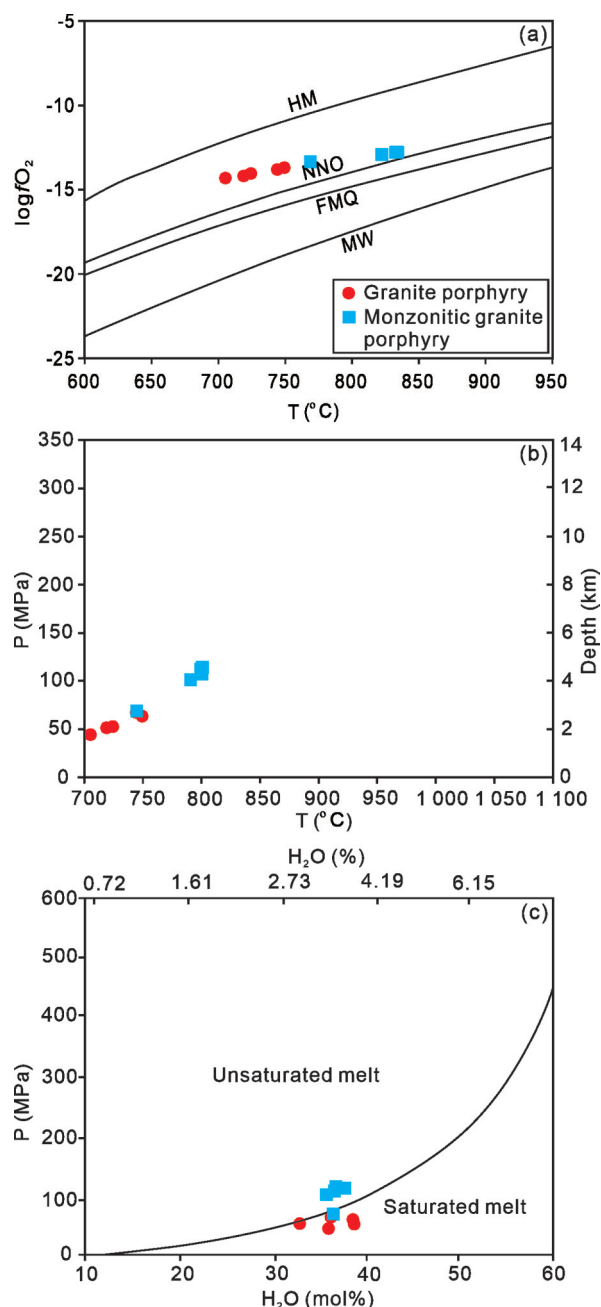


Figure 10. The diagram of oxygen fugacity diagram (a) (after Eugster and Wones, 1962), temperature versus pressure and depth (b), and water content versus pressure calculated from amphiboles (c) (after Cline, 1995).

-14.31– -13.69 (NNO), and depths of 1.7–2.5 km.

(3) The skarn orebody in the South Pit, which was formed through the metasomatism of hornfels or marble, was influenced by a gliding nappe structure system and developed at fold hinge dilation and the interlayer detachment zone between the hornfels and marbles. The ore-related magma in the South Pit had a high oxygen fugacity and was rich in water.

ACKNOWLEDGMENTS

This work was supported by the National Key Research and Development Program of China (No.

2022YFC2905004), Open Fund from SinoProbe Laboratory (No. SL202405), the Basic Research Fund of Institute of mineral Resource, Chinese Academy of Geological Sciences (No. JKYZD202316), the National Natural Science Foundation of China (Nos. 42272093, 42230813), China Scholarship Council Project, and the Geological Survey Project (No. DD20230054), Science and Technology Support Project in a new round of prospecting breakthrough strategic action (No. ZKKJ202429) and the Central Government Guided Local Scientific and Technological Development Funding Project (No. XZ202401YD0006). The authors would like to thank two anonymous reviewers and editors for their constructive comments and input. The final publication is available at Springer via <https://doi.org/10.1007/s12583-023-1855-x>.

Electronic Supplementary Materials: Supplementary materials (Tables S1–S3) are available in the online version of this article at <https://doi.org/10.1007/s12583-023-1855-x>.

Conflict of Interest

The authors declare that they have no conflict of interest.

REFERENCES CITED

- Allégre, C. J., Courtillot, V., Tapponnier, P., et al., 1984. Structure and Evolution of the Himalaya-Tibet Orogenic Belt. *Nature*, 307 (5946): 17–22. <https://doi.org/10.1038/307017a0>
- Belousova, E. A., Griffin, W. L., O'Reilly, S. Y., et al., 2002. Apatite as an Indicator Mineral for Mineral Exploration: Trace-Element Compositions and Their Relationship to Host Rock Type. *Journal of Geochemical Exploration*, 76(1): 45–69. [https://doi.org/10.1016/S0375-6742\(02\)00204-2](https://doi.org/10.1016/S0375-6742(02)00204-2)
- Chen, G. L., Zhang, Z. K., Sun, M., et al., 2021. High Fractionated I-Type Granite Porphyry and Mineralogical Characteristics of Its Biotite in the Nankeng Oreblock of Jiama Deposit, Tibet, China. *Bulletin of Mineralogy*, 40(2): 411–424. <https://doi.org/10.19658/j.issn.1007-2802.2021.40.001> (in Chinese with English Abstract)
- Chen, S. R., Wang, Q., Zhu, D. C., et al., 2021. Reheating and Magma Mixing Recorded by Zircon and Quartz from High-Silica Rhyolite in the Coqen Region, Southern Tibet. *American Mineralogist*, 106(1): 112–122. <https://doi.org/10.2138/am-2020-7426>
- Chung, S. L., Liu, D. Y., Ji, J. Q., et al., 2003. Adakites from Continental Collision Zones: Melting of Thickened Lower Crust beneath Southern Tibet. *Geology*, 31(11): 1021–1024. <https://doi.org/10.1130/g19796.1>
- Chung, S. L., Chu, M. F., Zhang, Y. Q., et al., 2005. Tibetan Tectonic Evolution Inferred from Spatial and Temporal Variations in Post-Collisional Magmatism. *Earth-Science Reviews*, 68(3/4): 173–196. <https://doi.org/10.1016/j.earscirev.2004.05.001>
- Cline, J. S., 1995. Genesis of Porphyry Copper Deposits: The Behavior of Water, Chloride, and Copper in Crystallizing Melts. *Arizona Geological Society Digest*, 20: 69–82
- Du, A. D., Zhao, D. M., Wang, S. X., et al., 2001. Precise Re-Os Dating for Molybdenite by ID-NTIMS with Carius Tube Sample Preparation. *Rock and Mineral Analysis*, 20(4): 247–252 (in

- Chinese with English Abstract)
- Du, A. D., Wu, S. Q., Sun, D. Z., et al., 2004. Preparation and Certification of re-Os Dating Reference Materials: Molybdenites HLP and JDC. *Geostandards and Geoanalytical Research*, 28 (1): 41–52. <https://doi.org/10.1111/j.1751-908X.2004.tb01042.x>
- Eugster, H. P., Wones, D. R., 1962. Stability Relations of the Ferruginous Biotite, Annite. *Journal of Petrology*, 3(1): 82–125. <https://doi.org/10.1093/petrology/3.1.82>
- Gao, S. B., Zheng, Y. Y., Jiang, J. S., et al., 2019. Geochemistry and Geochronology of the Gebunongba Iron Polymetallic Deposit in the Gangdese Belt, Tibet. *Journal of Earth Science*, 30(2): 296–308. <https://doi.org/10.1007/s12583-018-0984-0>
- Huang, Q., Wu, S., Liu, X. F., et al., 2025. The Metallogenic Age of Tangge Skarn-Type Copper-Lead-Zinc Deposit in Xizang: Constraints from Garnet U-Pb Geochronology. *Earth Science*, 50 (2): 621–638. <https://doi.org/10.3799/dqkx.2024.017> (in Chinese with English Abstract)
- Hou, Z. Q., Ma, H. W., Zaw, K., et al., 2003. The Himalayan Yulong Porphyry Copper Belt: Product of Large-Scale Strike-Slip Faulting in Eastern Tibet. *Economic Geology*, 98(1): 125–145. <https://doi.org/10.2113/gsecongeo.98.1.125>
- Hou, Z. Q., Cook, N. J., Zaw, K., 2009. Metallogenesis of the Tibetan Collisional Orogen. *Ore Geology Reviews*, 36(1/2/3): 1. <https://doi.org/10.1016/j.oregeorev.2009.07.002>
- Hou, Z. Q., Yang, Z. S., Xu, W. Y., et al., 2006. Metallogenesis in Tibetan Collisional Orogenic Belt: I. Mineralization in Main-Collisional Transformation Setting. *Mineral Deposits*, 25: 337–358 (in Chinese with English Abstract)
- Jiang, C. Y., An, S. Y., 1984. On Chemical Characteristics of Calcic Amphiboles from Igneous Rocks and Their Petrogenesis Significance. *Journal of Mineralogy and Petrology*, 4(3): 1–9. <https://doi.org/10.19719/j.cnki.1001-6872.1984.03.001> (in Chinese)
- Lang, X. H., Tang, J. X., Li, Z. J., et al., 2014. U-Pb and Re-Os Geochronological Evidence for the Jurassic Porphyry Metallogenic Event of the Xiongcu District in the Gangdese Porphyry Copper Belt, Southern Tibet, PRC. *Journal of Asian Earth Sciences*, 79: 608–622. <https://doi.org/10.1016/j.jseaes.2013.08.009>
- Lang, X. H., Deng, Y. L., Wang, X. H., et al., 2020. Reduced Fluids in Porphyry Copper-Gold Systems Reflect the Occurrence of the Wall-Rock Thermogenic Process: An Example from the No. 1 Deposit in the Xiongcu District, Tibet, China. *Ore Geology Reviews*, 118: 103212. <https://doi.org/10.1016/j.oregeorev.2019.103212>
- Lang, X. H., Wang, X. H., Deng, Y. L., et al., 2019. Hydrothermal Evolution and Ore Precipitation of the No. 2 Porphyry Cu-Au Deposit in the Xiongcu District, Tibet: Evidence from Cathodoluminescence, Fluid Inclusions, and Isotopes. *Ore Geology Reviews*, 114: 103141. <https://doi.org/10.1016/j.oregeorev.2019.103141>
- Leng, Q. F., Tang, J. X., Zheng, W. B., et al., 2016. Geochronology, Geochemistry and Zircon Hf Isotopic Compositions of the Ore-Bearing Porphyry in the Lakang'e Porphyry Cu-Mo Deposit, Tibet. *Earth Science*, 41(6): 999–1015. (in Chinese with English Abstract)
- Leake, B. E., 1978. Nomenclature of Amphiboles. *Mineralogical Magazine*, 42(324): 533–563. <https://doi.org/10.1180/minmag.1978.042.324.21>
- Lin, B., Tang, J. X., Chen, Y. C., et al., 2017a. Geochronology and Genesis of the Tiegelongnan Porphyry Cu(Au) Deposit in Tibet: Evidence from U-Pb, Re-Os Dating and Hf, S, and H-O Isotopes. *Resource Geology*, 67(1): 1–21. <https://doi.org/10.1111/rge.12113>
- Lin, B., Chen, Y. C., Tang, J. X., et al., 2017b. $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb-Sr Ages of the Tiegelongnan Porphyry Cu- (Au) Deposit in the Bangong Co-Nujiang Metallogenic Belt of Tibet, China: Implication for Generation of Super-Large Deposit. *Acta Geologica Sinica: English Edition*, 91(2): 602–616. <https://doi.org/10.1111/1755-6724.13120>
- Lin, B., Tang, J. X., Zhang, Z., et al., 2012. Preliminary Study of Fissure System in Jiama Porphyry Deposit of Tibet and Its Significance. *Mineral Deposits*, 31(3): 579–589. <https://doi.org/10.13722/j.cnki.jrme.2020.0446> (in Chinese with English Abstract)
- Lin, B., Tang, J. X., Tang, P., et al., 2024. Multipulsed Magmatism and Duration of the Hydrothermal System of the Giant Jiama Porphyry Cu System, Tibet, China. *Economic Geology*, 119(1): 201–217. <https://doi.org/10.5382/econgeo.5054>
- Liu, Y. S., Hu, Z. C., Zong, K. Q., et al., 2010. Reappraisal and Refinement of Zircon U-Pb Isotope and Trace Element Analyses by LA-ICP-MS. *Chinese Science Bulletin*, 55(15): 1535–1546. <https://doi.org/10.1007/s11434-010-3052-4>
- Mason, R., 2016. South Pit, Structure and Skarn Development Jiama Copper-Polymetallic Deposit, Metrorongka County, Tibet Autonomous Region the People's Republic of China: [Research Report]. Tibet Huatailong Ming Co., Ltd., Lhasa
- Meinert, L. D., Dipple, G. M., Nicolescu, S., 2005. World Skarn Deposits. In: Hedenquist, J. W., Thompson, J. F. H., Goldfarb R. J., et al., eds., *Society of Economic Geologists*, 100th Anniversary Volume: 299–336. <https://doi.org/10.5382/AV100.11>
- Mo, X. X., Hou, Z. Q., Niu, Y. L., et al., 2007. Mantle Contributions to Crustal Thickening during Continental Collision: Evidence from Cenozoic Igneous Rocks in Southern Tibet. *Lithos*, 96(1/2): 225–242. <https://doi.org/10.1016/j.lithos.2006.10.005>
- Mo, X. X., Niu, Y. L., Dong, G. C., et al., 2008. Contribution of Syncollisional Felsic Magmatism to Continental Crust Growth: A Case Study of the Paleogene Linzizong Volcanic Succession in Southern Tibet. *Chemical Geology*, 250(1/2/3/4): 49–67. <https://doi.org/10.1016/j.chemgeo.2008.02.003>
- Ohmoto, H., 1986. Stable Isotope Geochemistry of Ore Deposits. *Reviews in Mineralogy and Geochemistry*, 16(1): 491–559. <https://doi.org/10.1515/9781501508936-019>
- Qi, J., Tang J. X., Lin, B., et al., 2021. Zircon U-Pb Age and Geochemistry of the Granite Porphyry in Northern Zegulang of Jiama Deposit, Tibet. *Acta Geologica Sinica*, 95(3): 822–836 (in Chinese with English Abstract)
- Qin, Z. P., Wang, X. W., Duo, J., et al., 2011. LA-ICP-MS U-Pb Zircon Age of Intermediate-Acidic Intrusive Rocks in Jiama of Tibet and Its Metallogenic Significance. *Mineral Deposits*, 30(2): 339–348. <https://doi.org/10.16111/j.0258-7106.2011.02.017> (in Chinese with English Abstract)
- Richards, J. P., 2003. Tectono-Magmatic Precursors for Porphyry Cu- (Mo-Au) Deposit Formation. *Economic Geology*, 98(8): 1515–1533. <https://doi.org/10.2113/gsecongeo.98.8.1515>
- Richards, J. P., 2009. Postsubduction Porphyry Cu-Au and

- Epithermal Au Deposits: Products of Remelting of Subduction-Modified Lithosphere. *Geology*, 37(3): 247–250. <https://doi.org/10.1130/G25451A.1>
- Richards, J. P., 2015. The Oxidation State, and Sulfur and Cu Contents of Arc Magmas: Implications for Metallogeny. *Lithos*, 233: 27–45. <https://doi.org/10.1016/j.lithos.2014.12.011>
- Ridolfi, F., Renzulli, A., Puerini, M., 2010. Stability and Chemical Equilibrium of Amphibole in Calc-Alkaline Magmas: An Overview, New Thermobarometric Formulations and Application to Subduction-Related Volcanoes. *Contributions to Mineralogy and Petrology*, 160(1): 45–66. <https://doi.org/10.1007/s00410-009-0465-7>
- Rye, R. O., Ohmoto, H., 1974. Sulfur and Carbon Isotopes and Ore Genesis: A Review. *Economic Geology*, 69(6): 826–842. <https://doi.org/10.2113/gsecongeo.69.6.826>
- Sillitoe, R. H., 2010. Porphyry Copper Systems. *Economic Geology*, 105(1): 3–41. <https://doi.org/10.2113/gsecongeo.105.1.3>
- Sillitoe, R. H., 1972. A Plate Tectonic Model for the Origin of Porphyry Copper Deposits. *Economic Geology*, 67(2): 184–197. <https://doi.org/10.2113/gsecongeo.67.2.184>
- Sun, F., Zhang, J. B., Wang, R., et al., 2022. Magmatic Evolution and Formation of the Giant Jiama Porphyry-Skarn Deposit in Southern Tibet. *Ore Geology Reviews*, 145: 104889. <https://doi.org/10.1016/j.oregeorev.2022.104889>
- Tang, J. X., Dorji, Liu, H. F., et al., 2012. Minerogenetic Series of Ore Deposits in the East Part of the Gangdise Metallogenic Belt. *Acta Geoscientica Sinica*, 33(4): 393–410. <https://doi.org/10.3975/cagsb.2012.04.02> (in Chinese with English Abstract)
- Tang, J. X., Wang, Q., Yang, H. H., et al., 2017. Mineralization, Exploration and Resource Potential of Porphyry-Skarn-Epithermal Copper Polymetallic Deposits in Tibet. *Acta Geoscientica Sinica*, 38(5): 571–613 (in Chinese with English Abstract)
- Tang, P., Tang, J. X., Lin, B., et al., 2019. Mineral Chemistry of Magmatic and Hydrothermal Biotites from the Bangpu Porphyry Mo(Cu) Deposit, Tibet. *Ore Geology Reviews*, 115: 103122. <https://doi.org/10.1016/j.oregeorev.2019.103122>
- Tang, P., Tang, J. X., Wang, Y., et al., 2020. Zircon U-Pb Geochronology, Geochemistry, S-Pb-Hf Isotopic Compositions, and Mineral Chemistry of the Xin'gaguo Skarn Pb-Zn Deposit, Tibet, China. *Geological Journal*, 55(6): 4790–4809. <https://doi.org/10.1002/gj.3713>
- Tang, P., Tang, J. X., Wang, Y., et al., 2021. Genesis of the Lakang'e Porphyry Mo(Cu) Deposit, Tibet: Constraints from Geochemistry, Geochronology, Sr-Nd-Pb-Hf Isotopes, Zircon and Apatite. *Lithos*, 380/381: 105834. <https://doi.org/10.1016/j.lithos.2020.105834>
- Tang, P., Tang, J. X., Lin, B., et al., 2023. Geology, Geochemistry, and Geochronology of the Zegulangbei Deposit in the Jiama Ore District: Implications for a Polycentric, Complex Porphyry Mineralization System Model. *Ore Geology Reviews*, 159: 105558. <https://doi.org/10.1016/j.oregeorev.2023.105558>
- Wang, L. Q., Tang, J. X., Yang, Y., et al., 2018. Zircon U-Pb Geochronology, Geochemistry, and S-Pb Isotopic Compositions of the Lietinggang Iron Polymetallic Deposit, Tibet, China. *Ore Geology Reviews*, 98: 62–79. <https://doi.org/10.1016/j.oregeorev.2018.05.017>
- Xie, F. W., Tang, J. X., Chen, Y. C., et al., 2018. Apatite and Zircon Geochemistry of Jurassic Porphyries in the Xiongcu District, Southern Gangdese Porphyry Copper Belt: Implications for Petrogenesis and Mineralization. *Ore Geology Reviews*, 96: 98–114. <https://doi.org/10.1016/j.oregeorev.2018.04.013>
- Yang, Z. M., Hou, Z. Q., White, N. C., et al., 2009. Geology of the Post-Collisional Porphyry Copper-Molybdenum Deposit at Qulong, Tibet. *Ore Geology Reviews*, 36(1/2/3): 133–159. <https://doi.org/10.1016/j.oregeorev.2009.03.003>
- Yang, Z. M., Cooke, D. R., 2019. Chapter 5 Porphyry Copper Deposits in China. In: Chang, Z. S., Goldfarb, R. J., eds., Special Publications of the Society of Economic Geologists: Mineral Deposits of China. 133–187. <https://doi.org/10.5382/sp.22.05>
- Yang, Y., Tang, J. X., Wu, C. N., et al., 2020. Typomorphic Mineralogical Characteristics of Pyrrhotite in Jiama Cu Polymetallic Deposit, Tibet, and Its Geological Significance. *Mineral Deposits*, 39(2): 337–350. <https://doi.org/10.1611/j.0258-7106.2020.02.008> (in Chinese with English Abstract)
- Yin, A., Harrison, T. M., 2000. Geologic Evolution of the Himalayan-Tibetan Orogen. *Annual Review of Earth and Planetary Sciences*, 28: 211–280. <https://doi.org/10.1146/annurev.earth.28.1.211>
- Ying, L. J., Tang, J. X., Wang, D. H., et al., 2009. Re-Os Isotopic Dating of Molybdenite in Skarn from the Jiama Copper Polymetallic Deposit of Tibet and Its Metallogenic Significance. *Rock and Mineral Analysis*, 28(3): 265–268. <https://doi.org/10.3969/j.issn.0254-5357.2009.03.014> (in Chinese with English Abstract)
- Ying, L. J., Wang, D. H., Tang, J. X., et al., 2010. Re-Os Dating of Molybdenite from the Jiama Copper Polymetallic Deposit in Tibet and Its Metallogenic Significance. *Acta Geologica Sinica*, 84(8): 1165–1174. <https://doi.org/10.19762/j.cnki.dizhixuebao.2010.08.009> (in Chinese with English Abstract)
- Ying, L. J., Tang, J. X., Wang, D. H., et al., 2011. Zircon SHRIMP U-Pb Dating of Porphyry Vein from the Jiama Copper Polymetallic Deposit in Tibet and Its Significance. *Acta Petrologica Sinica*, 27(7): 2095–2102 (in Chinese with English Abstract)
- Zhang, Z. M., Dong, X., Santosh, M., et al., 2014. Metamorphism and Tectonic Evolution of the Lhasa Terrane, Central Tibet. *Gondwana Research*, 25(1): 170–189. <https://doi.org/10.1016/j.gr.2012.08.024>
- Zhao, X. Y., Yang, Z. S., Zheng, Y. C., et al., 2015. Geology and Genesis of the Post-Collisional Porphyry-Skarn Deposit at Bangpu, Tibet. *Ore Geology Reviews*, 70: 486–509. <https://doi.org/10.1016/j.oregeorev.2014.09.014>
- Zheng, W. B., Tang, J. X., Zhong, K. H., et al., 2016. Geology of the Jiama Porphyry Copper-Polymetallic System, Lhasa Region, China. *Ore Geology Reviews*, 74: 151–169. <https://doi.org/10.1016/j.oregeorev.2015.11.024>
- Zheng, W. B., Chen, Y. C., Song, X., et al., 2010. Element Distribution of Jiama Copper-Polymetallic Deposit in Tibet and Its Geological Significance. *Mineral Deposits*, 29(5): 775–784. <https://doi.org/10.1611/j.0258-7106.2010.05.005> (in Chinese with English Abstract)
- Zheng, Y. Y., Wu, S., Ci, Q., et al., 2021. Cu-Mo-Au Metallogenesis and Minerogenetic Series during Superimposed Orogenesis Process in Gangdese. *Earth Science*, 46(6): 1909–1940 (in Chinese with English Abstract)

- Zhong, K. H., Li, L., Zhou, H. W., et al., 2012. Features of Jiama-Kajunguo Thrust-Gliding Nappe Tectonic System in Tibet. *Acta Geoscientica Sinica*, 33: 411 – 423. <https://doi.org/10.3975/cagsb.2012.04.03> (in Chinese with English Abstract)
- Zhu, D. C., Zhao, Z. D., Niu, Y. L., et al., 2011. The Lhasa Terrane: Record of a Microcontinent and Its Histories of Drift and Growth. *Earth and Planetary Science Letters*, 301(1/2): 241–255. <https://doi.org/10.1016/j.epsl.2010.11.005>
- Zou, B., Lin, B., Zheng, W. B., et al., 2019. The Characteristics of Alteration and Mineralization and Geochronology of Ore-Bearing Porphyry in South Pit of Jiama Copper-Polymetallic Deposit, Tibet. *Acta Petrologica Sinica*, 35(3): 953–967. <https://doi.org/10.18654/1000-0569/2019.03.20> (in Chinese with English Abstract)