China Geology 1 (2021) 1−16

China Geology

Journal homepage: http://chinageology.cgs.cn
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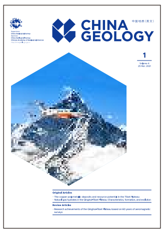

The copper polymetallic deposits and resource potential in the Tibet Plateau

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ARTICLE INFO

Article history:
Received 24 February 2021
Received in revised form 2 March 2021
Accepted 16 March 2021
Available online 25 March 2021

Keywords:
Porphyry-epithermal-skarn Cu deposit
Gangdese metallogenic belt
Bangong Co-Nujiang metallogenic belt
Resource potential
Tethys Ocean
Mineral exploration engineering
Tibet Plateau

ABSTRACT

Many large and super-large copper deposits have been discovered and explored in the Tibet Plateau, which makes it the most important copper resource reserve and development base in China. Based on the work of the research team, the paper summarizes the geological characteristics of the main copper deposits in Tibet and puts forward a further prospecting direction. A series of large accumulated metal deposits or ore districts from subduction of Tethys oceanic crust to India-Asia collisionhave been discovered, such as Duolong Cu (Au) ore district and Jiama copper polymetallic deposit. The ore deposits in the Duolong ore district are located in the lowstand domain, the top of lowstand domain, and the highstand domain of the same magmatic-hydrothermal metallogenic system, and their relative positions are the indicators for related deposits in the Bangong Co-Nujiang metallogenic belt. The polycentric metallogenic model of the Jiama copper polymetallic deposit is an important inspiration for the exploration of the porphyry mineralization related to collision orogeny. Further mineral exploration in the Tibet Plateau should be focused on the continental volcanic rocks related to porphyry-epithermal deposits, orogenic gold deposits, hydrothermal Pb-Zn deposits related to nappe structures, skarn Cu (Au) and polymetallic deposits, and the Miocene W-Sn polymetallic deposits.

1. Introduction

The Tibet Plateau, known as the “roof of the world”, has become the most important resource reserve and development base in China. A series of super large metal deposits including porphyry-skarn-epithermal copper polymetallic and magmatic-hydrothermal vein deposits in the Tibet Plateau have been discovered and evaluated. These deposits formed from the subduction of Tethys oceanic crust to India-Asia continental collision mainly between 170 Ma and 12 Ma and are characterized by complicated ore controlling factors, big metallogenic epoch, complex ore-forming elements, and high-quality ores (Tang JX et al., 2019).

Different from the typical porphyry copper deposits related to island arc and continental margin arc of oceanic subduction (for example, porphyry copper deposits in the Andean metallogenic belt), a large number of porphyry copper deposits in the Tibet Plateau and its adjacent areas were related to continental collision. The geological characteristics, metallogenic mechanism, and model are significantly different between oceanic subduction-related porphyry copper deposits and continental collision-related ones. Where to find the porphyry-skarn-epithermal Cu (Au) deposits formed in island arc and the continental arc of oceanic subduction is a major scientific problem faced by global mineralogists. Besides, the subduction-collision

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doi:10.31035/cg2021016

accretion in the Tibet Plateau leads to large-scale uplift and the formation, preservation, and exhumation of the porphyry metallogenic system. The shallow epithermal deposits on the upper part of the porphyry metallogenic system might be completely eroded or partially preserved. Moreover, the development of permafrost, strong terrain cutting, and large elevation difference in the alpine area of the Tibet Plateau make it very difficult to integrate and develop the exploration and evaluation methods of the continental collision-related porphyry metallogenic system.

Based on the first-hand geological phenomena and the first-hand data obtained by experiments, a series of important achievements have been made in porphyry deposit exploration in the Tibet Plateau through 1∶50000 regional geological survey project and comprehensive research aimed at solving the key scientific problems restricting the breakthrough of prospecting in recent years. The controlled copper of the Duolong ore district in the Bangong Co-Nujiang metallogenic belt is more than 20×10^6 t, controlled associated gold and silver are more than 400 t and 5000 t, and the prospective copper, gold, and silver could be 30×10^6 t, 1000 t and 5000 t, respectively (Tang JX et al., 2016b). The copper in the Qulong-Jiama-Bangpu-Lakange ore district exceeds 25×10^6 t, and the copper in the Zhunuo-Xiongcun ore district will potentially exceed 15×10^6 t. This paper mainly introduces the geological characteristics of several important copper deposits in Tibet and puts forward the areas with copper metallogenic potential based on existing work and research.

2. Copper metallogenic belts in the Tibet

The Tibet Plateau is mainly located in the Tethys Himalayan metallogenic domain, one of the three major porphyry copper metallogenic domains in the world. Four metallogenic belts including the Sanjiang metallogenic belt (Hou ZQ et al., 2004a, 2007, 2009, 2011) in eastern Tibet, the Gangdese metallogenic belt (Hou ZQ et al, 2004b) in central Tibet, the Bangong Co-Nujiang metallogenic belt (Qu XM et al., 2006) in northwestern Tibet, and the North Himalayan metallogenic belt (Li GM et al., 2017) in southern Tibet developed in the Tibet Plateau (Lin B et al., 2017a; Fig.1). The total copper resources of the first three copper metallogenic belts have already exceeded 55×10^6 t (Table 1).

2.1. Bangong Co-Nujiang metallogenic belt

The Bangong Co-Nujiang suture zone is a large and complex tectonic belt, which starts from the Bangong Lake in the west, passes through the Gaize and Dongqiao in the east, turns southeast through the Luolong and Basu, and then extends along the bottom of Nujiang valley in western Yunnan to foreign countries. It is composed of the ophiolite, melange, deep-sea flysch, and Paleozoic metamorphic rock (Geng QR et al., 2011; Qu XM et al., 2006). The copper deposits are distributed in the east-west direction along the Gaer-Gaize County-Bange in the Ali area, with a length of 800 km from east to west and a width of 50 km from south to north. The discovered and explored deposits include the Tiegelongnan deposit super-large porphyry-epithermal Cu

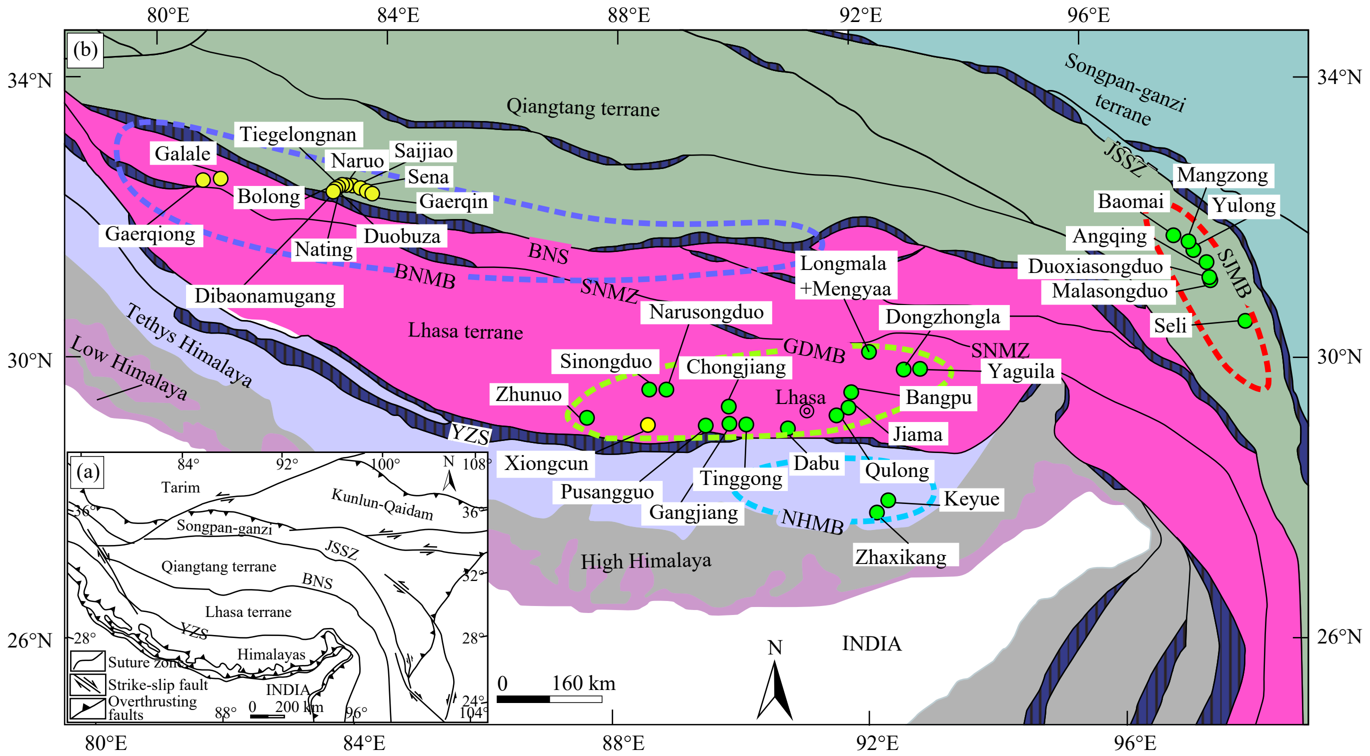

Fig. 1. Geological map of the Qinghai-Tibetan Plateau, showing the locations of the major metallogenic belts and the main ore deposits (modified from Tang JX et al., 2017). JSSZ–Jinshajiang suture zone; BNS–Bangong Co-Nujiang suture zone; SNMZ–Shiquan River-Nam Tso melange zone; YZS–Yarlung Zangbo suture zone; SJMB–Jinshajiang metallogenic belt; BNMB–Bangong Co-Nujiang metallogenic belt; GDMB–Gangdese metallogenic belt; NHMB–North Himalayan metallogenic belt; yellow dot– Mesozoic ore deposits; green dot–Cenozoic ore deposit.

(Au) deposit, Duobuza and Bolong large porphyry Cu deposits, the Naruo and Duobuzaxi large porphyry copper deposits, as well as the Qingcaoshan, Dibaonamugang, Sina, Gaerqin, Gaerqiong-Galale, Shesuo, and Xiongmei copper deposits (Wang Q et al., 2017).

2.2. Gangdese metallogenic belt

The Gangdese metallogenic belt begins from the Sharang Mo deposit in the Gongbujiangda County in the east and ends at the Zhunuo Cu deposit in the Angren County in the west,

Table 1. Statistics of typical deposits in the Tibet Plateau.

Metallogenic belt	Deposit	Location	Metal production	Deposit size	Reference
Sanjiang metallogenic belt	Yulong	Jiangda County	Cu>6.5×10^{6} t @ 0.59%; Mo @ 0.028%	Super-large	Wang Q et al., 2017; Tang JX et al., 2017
	Malasongduo	Chaya County	Cu>1.5×10^{6} t @ 0.44%; Mo @ 0.014%	Large	Wang Q et al., 2017; Liang HY et al., 2009
	Mangzong	Changdu County	Cu<0.4%	Medium	Tang R et al., 1995; Liang HY et al., 2006
	Duoxiasongduo	Gongjue County	Cu>0.85×10^{6} t @ 0.38%; Mo @ 0.04%; Au @ 0.05×10^{-6}	Large	Wang Q et al., 2017; Liang HY et al., 2006; Wu WZ et al., 2013
	Baomai	Changdu County	Cu=0.21×10^{6} t @ 0.22%; Mo=0.06×10^{6} t @ 0.06%	Medium	Lin B et al., 2017b
	Angqing	Changdu County	Ag=806 t @ 160.7×10^{-6}; Pb=0.12×10^{6} t @ 2.34%; Zn=0.14×10^{6} t @ 2.81%; Cu=0.018×10^{6} t @ 0.36%; Au=0.85 t @ 0.17×10^{-6}	Large	Tang JX et al., 2017
	Seli	Mangkang County		Mineralization occurrence	Chen XL et al., 2016
Gangdise metallogenic belt	Qulong (including Zhibula)	Mozhugongka County	Cu>10×10^{6} t @ 0.4%; Mo=0.47×10^{6} t @ 0.03%; Cu=0.47×10^{6} t @ 1.5% (Zhibula)	Large	Wang LL et al., 2006; Yang ZM et al., 2008; Yao XF et al., 2015; Li Y et al., 2017
	Jiama	Mozhugongka County	Cu>11×10^{6} t @ 0.46%; Mo=0.7×10^{6} t @ 0.045%; Pb+Zn>1.7×10^{6} t @ 2.68%; Au=170 t @ 0.3×10^{-6}; Ag=0.01×10^{6} t @ 19×10^{-6}	Large	Tang JX et al., 2010, 2011; Ying LJ et al., 2014; Zheng WB et al., 2016
	Bangpu	Mozhugongka County	Mo=0.6×10^{6} t @ 0.08%; Cu=1.2×10^{6} t @ 0.28%	Large	Wang LQ et al., 2011, 2012, 2015a; Zhao XY et al., 2015
	Dongzhongla	Mozhugongka County	Pb+Zn =3.5×10^{6} t @ 12%	Medium	Fei GC et al., 2010
	Yaguila	Gongbujiangda County	Pb+Zn >5.2×10^{6} t @ 5.51% (Pb), 3.44% (Zn); Ag=1965 t @ 93×10^{-6}	Large	Gao YM et al., 2010a, 2010b; Du X et al., 2010; Zheng YC et al., 2015
	Longmala+ Mengyaa	Jiali County	Pb+Zn > 2×10^{6} t @ 7%	Large	Wang LQ et al., 2015b, 2017
	Pusangguo	Nanmulin County	Cu=0.12×10^{6} t @ 0.85%; Pb=0.16×10^{6} t @ 4.05%; Zn=0.41×10^{6} t @ 3.47%	Large	Cui XL et al., 2012
	Gangjiang	Nimu County	Cu>1.4×10^{6} t @ 0.281%; Mo>0.16×10^{6} t @ 0.035%	Large	Tang JX et al., 2017
	Tinggong	Nimu County	Cu>1.3×10^{6} t; Mo>0.03×10^{6} t; Au=23 t; Ag=1249 t	Large	Tang JX et al., 2017
	Chongjiang	Nimu County	Cu>0.5×10^{6} t	Large	Tang JX et al., 2017
	Dabu	Qushui County	Cu>0.3×10^{6} t @ 0.26%; Mo>0.03×10^{6} t @ 0.029%	Medium	Zhang QL et al., 2003; Gao YM et al., 2012; Ouyang Y et al., 2016
	Xiongcun	Xietongmen County	Cu>2.3×10^{6} t @ 0.4%; Au>200 t @ 0.4×10^{-6}; Ag>1000 t @ 3×10^{-6}	Large	Tang JX et al., 2010a, 2012, 2015; Lang XH et al., 2014, 2017
	Narusongduo	Xietongmen County	Pb+Zn>2×10^{6} t	Large	Ji XH et al., 2013
	Sinongduo	Xietongmen County	Pb+Zn =0.3×10^{6} t @ 5%; Au=470 t @ 50×10^{-6}	Medium-Large	Tang JX et al., 2016a
	Zhunuo	Angren County	Cu>2.7×10^{6} t	Large	Ci Q et al., 2016

Table 1. (*Continued*)

Metallogenic belt	Deposit	Location	Metal production	Deposit size	Reference
Bangong Co-Nujiang metallogenic belt	Tiegelongnan	Gaize County	Cu>10×10^{6} t @ 0.53%; Au=100 t @ 0.08×10^{-6}; Ag=2609 t @ 1.83×10^{-6}	Super-large	Tang JX et al., 2014, 2016b; Lin B et al., 2017a, 2017b
	Duobuza	Gaize County	Cu>2.7×10^{6} t @ 0.46%; Au=93 t @ 0.14×10^{-6}	Large	She HQ et al., 2009; Li YB et al., 2012a; Zhang Z et al., 2014
	Bolong	Gaize County	Cu>2.5×10^{6} t @ 0.33%; Au=126 t @ 0.196×10^{-6}	Large	Li YB et al., 2012b; Chen HA et al., 2013; Yang Y et al., 2015
	Naruo	Gaize County	Cu>2.5×10^{6} t @ 0.38%; Au=82 t @ 0.19×10^{-6}; Ag=873 t @ 2.21×10^{-6}	Large	Ding S et al., 2014; Gao K et al., 2016a; Ding S et al., 2017
	Nating	Gaize County	Cu>1.5×10^{6} t @ 0.32%; Au>110 t @ 0.24×10^{-6}	Large	Tang JX et al., 2017
	Dibaonamugang	Gaize County		Mineralization occurrence	Lin B et al., 2016b; Zhang WL et al., 2016
	Gaerqin	Gaize County	Cu>0.06×10^{6} t @ 0.27%	Small	Zhang Z et al., 2017
	Sena	Gaize County		Mineralization occurrence	Gao K et al., 2016b; Wei SG et al., 2016
	Saijiao	Gaize County		Mineralization occurrence	Li XK et al., 2015
	Gaerqiong	Geji County	Au>20 t @ 2.61×10^{-6}; Cu>0.08×10^{6} t @ 0.94%	Large	Yao XF et al., 2013
	Galale	Geji County	Au=40 t @ 2.8×10^{-6}	Large	Zhang GZ et al., 2017b
North Himalayan metallogenic belt	Zhaxikang	Longzi County	Pb=0.7×10^{6} t @ 1.74%; Zn=1.3×10^{6} t @ 3.31%; Sb=0.35×10^{6} t	Large	Liang W et al., 2015
	Keyue	Longzi County	Pb=0.17×10^{6} t @ 2%; Zn=0.18×10^{6} t @ 2.11%	Medium	Lin B et al., 2016a

with an east-west span of more than 550 km (Qu XM et al., 2017; Wang R et al., 2015, 2016; Liu H et al., 2018). The copper deposits such as the Qulong, Jiama, Xiongcun, and Zhunuo within the metallogenic belt are characterized by multi-stage mineralization (Huang HX et al., 2019; Hou ZQ et al., 2015a; Zheng YC et al., 2015). The mineralization is mainly concentrated in three stages: Middle Jurassic (174–160 Ma), the mineralization was related to the northward subduction of the Neo-Tethyan oceanic crust of the Yarlung Zangbo (Huang Y et al., 2017; Tafti R et al., 2009; Lang XH et al., 2017, 2019), and the representative deposit is the Xiongcun; Eocene (49–51 Ma), the mineralization was related to the India-Eurasia collision (Yang ZM et al., 2016; Zhao JX et al., 2014), and the representative deposits are the Jiru and Sharang (Tang JX et al., 2009); Late Oligocene to Miocene (25 –12 Ma), the mineralization was related to the post-collision extension of the India-Eurasia continent (Huang Y et al., 2017, 2020; Zheng YY et al., 2007; Hu YB et al., 2015; Lin B et al., 2019b; Tang JX et al., 2010b), and the representative deposits are the Qulong, Jiama, Zhunuo, Chongjiang, Bairong, Gangjiang, Tinggong, Nanmu and Qiangdui.

2.3. Sanjiang metallogenic belt

The Sanjiang area is located in the southeast of Tibet Plateau. It is divided into east and west parts along the Jinshajiang-Ailaoshan-Honghe fault zone. The eastern part is dominated by the western margin of the Yangtze Plate, which is mainly composed of Archean metamorphic basement, Paleo-Mesoproterozoic sedimentary rocks, and Phanerozoic clastic and carbonate rocks. The western part is considered to be the eastern extension of the Tibet Plateau, which is mainly composed of Precambrian metamorphic basement, Late Paleozoic clastic and carbonate rocks, Mesozoic-Cenozoic granites, intrusive rocks, and volcanic rocks (Tapponnier P et al., 2001; Ji JQ et al., 2000). The Yulong copper metallogenic belt is an important metallogenic belt in the northern Sanjiang metallogenic belt, and the representative deposit is Yulong super-large porphyry Cu (Mo) deposit. Others include the Malasongduo, Duoxiasongduo, Zhanaga, Mangzong, Angqing large-medium porphyry-skarn Cu (Mo) deposits, and the Seli, Secuo, Jicuo, Riqu, Zunxi, Mayoumu, Cuozhala, Longmu, Mangzha, Hengxingcuo, Baomai mineralization occurrences (Tang R et al., 1995).

3. Geological characteristics of copper deposits

At least thirty important copper deposits including porphyry deposits and skarn deposits have been discovered in the Tibet Plateau. Porphyry deposit accounts for about 84% of the total discovered deposits, porphyry-skarn deposit accounts for about 7%, skarn deposit accounts for about 5%, and others account for 4%, respectively (Wang Q et al., 2017).

3.1. Duolong porphyry-epithermal Cu (Au) ore district

The Duolong ore district is located in the middle of Tibet

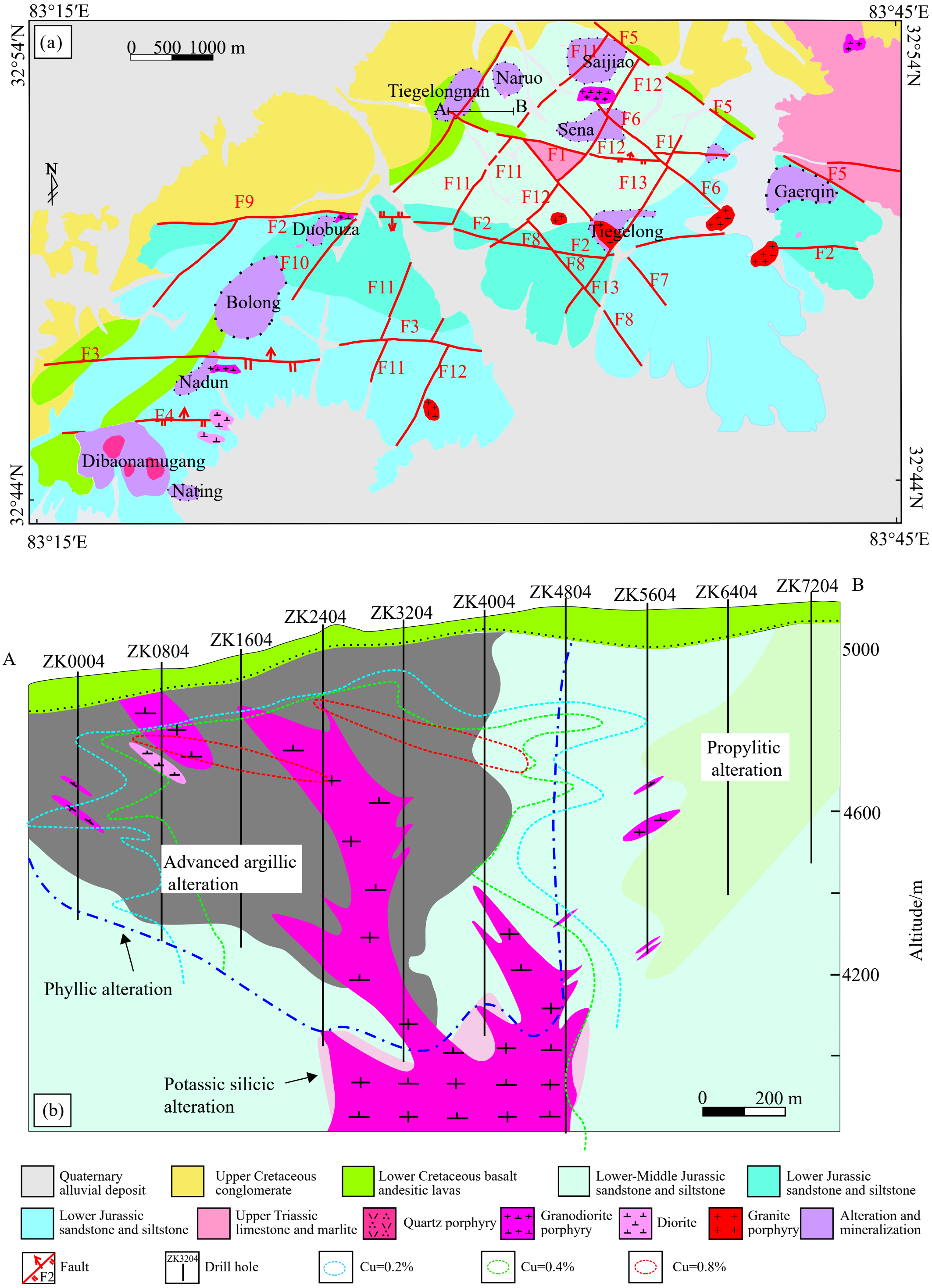

Fig. 2. Geological map of the Duolong mining district (a) and the profile of drill holes in the Tiegelongnan deposits (b) (modified from Wang Q et al., 2015; Lin B et al., 2018b).

Plateau, the western part of Bangong Co-Nujiang metallogenic belt, the southern edge of the Qiangtang terrane (Fig. 2a). Several porphyry-epithermal deposits developed in the area, including the Tiegelongnan with the copper resource of more than 10×10^6 t and gold resource of 100 t, Duobuza with the copper resource of more than 2.76×10^6 t and associated gold of 70 t, Bolong with the copper resource of more than 2.5×10^6 t and associated gold of more than 120 t, Naruo with the copper resource of more than 2.5×10^6 t and associated gold of more than 70 t, Nating with the copper resource of more than 1.1×10^6 t and associated gold of more than 90 t. The discovered porphyry-epithermal Cu (Au) deposits are related to the granodiorite porphyry developed on the edge of the shallow magma chamber (mainly diorite), and the diagenetic and metallogenic ages range from 122 Ma to 116 Ma (Tang JX et al., 2014, 2016a, 2016b; Lin B et al., 2016b, 2016c, 2017a; Fang X et al., 2015; Wei SG et al., 2018). The dynamic mechanism of major Cretaceous mineralization (130–110 Ma) in Duolong ore district is related to the roll-back of the northward subduction plate from Bangong Co-Nujiang Ocean (Li JX et al., 2008; Lin B et al., 2019a).

3.1.1. Tiegelongnan porphyry-epithermal Cu (Au) deposit

The Tiegelongnan located in the northwest of Duolong ore district is the first discovered porphyry-epithermal Cu (Au) deposit in Tibet (Tang JX et al., 2014). The Tiegelongnan deposit is characterized by deep porphyry orebodies and shallow superimposed high sulfide epithermal orebodies (Fig. 2b). Metallic minerals are mainly composed of pyrite, chalcopyrite, bornite, tetrahedrite group minerals, enargite, digenite, covellite, chalcocite, and a small amount of molybdenite, sphalerite, galena, chalcopyrite, hematite. Non-metallic minerals mainly include quartz, biotite, sericite, k-feldspar, hornblende, chlorite, calcite, kaolinite, dickite, alunite, pyrophyllite, boehmite, APS (aluminophosphate-sulfate) mineral, barite (Wang YY, 2018). A series of Early Cretaceous diorite porphyry, quartz monzonite, granodiorite porphyry, quartz diorite porphyry, and andesitic volcanic rocks developed in the area. The ore-related granodiorite, diorite, and granite porphyries are enriched in LREE and large ion lithophile elements (Rb, Ba, U), and depleted in HREE and high field strength elements (Lin B et al., 2018b, 2019a). The Tiegelongnan deposit has experienced multi-stage of uplift and erosion attributed to the subduction of Bangong Co-Nujiang ocean, the Lhasa-Qiangtang collision, and the India-Eurasia collision. The preservation of the deposit benefits from the covering of Early Cretaceous Meiriqiecuo Formation volcanic rocks and the thickening of strata caused by the Lhasa-Qiangtang collision (Yang HH et al., 2019, 2020).

3.1.2. Naruo porphyry-breccia Cu (Au) deposit

The Naruo porphyry-breccia Cu (Au) deposit is located about 0.5 km northeast of the Tiegelongnan deposit. Porphyry copper orebody mainly developed in the sandstone near the granodiorite porphyry and its contact zone, and the breccia orebody covered by Quaternary eluvial and slope sediments is located in the southwest of the mining area (Fig. 3). The breccia can be divided into sandstone breccia, diorite breccia and granodiorite breccia according to the breccia lithology. The high-grade ore is mainly developed in the granodiorite breccia. Metallic minerals mainly include chalcopyrite, pyrite, molybdenite, bornite, magnetite, hematite, chalcocite, and digenite. Field geological and geochemical evidence show that the magmas related to porphyry and breccia mineralization are different dikes from the same magma chamber and are spatially independent (Lin B et al., 2018a).

3.2. Jiama copper polymetallic deposit

The Jiama deposit with a total of over 21×10^6 t of copper is one of the most important copper deposits in the Gangdese metallogenic belt. As a typical porphyry-skarn deposit in Gangdese metallogenic belt, it is an ideal object to study the genesis of continental collision porphyry-skarn copper deposit. The intrusive rocks including quartz diorite porphyry, granite porphyry, monzonite granite porphyry, granodiorite porphyry, and dark diorite porphyry intruded into the Duodigou Formation and Linbuzong Formation. The monzonite granite porphyry and granite porphyry are related to mineralization, quartz diorite porphyry intruded before the mineralization, and granodiorite porphyry and dark diorite porphyry intruded post the mineralization at about 15 Ma (Tang JX et al., 2010b; Fig. 4). These Miocene porphyries formed postdate continent collision in chronological order from early to late are quartz diorite porphyry, granite porphyry, monzonitic granite porphyry, granodiorite porphyry, dark diorite porphyry (Qin ZP et al., 2012, 2013; Zhang ZB et al., 2019).

The orebody is mainly composed of skarn copper polymetallic orebody, hornfels copper-molybdenum orebody,

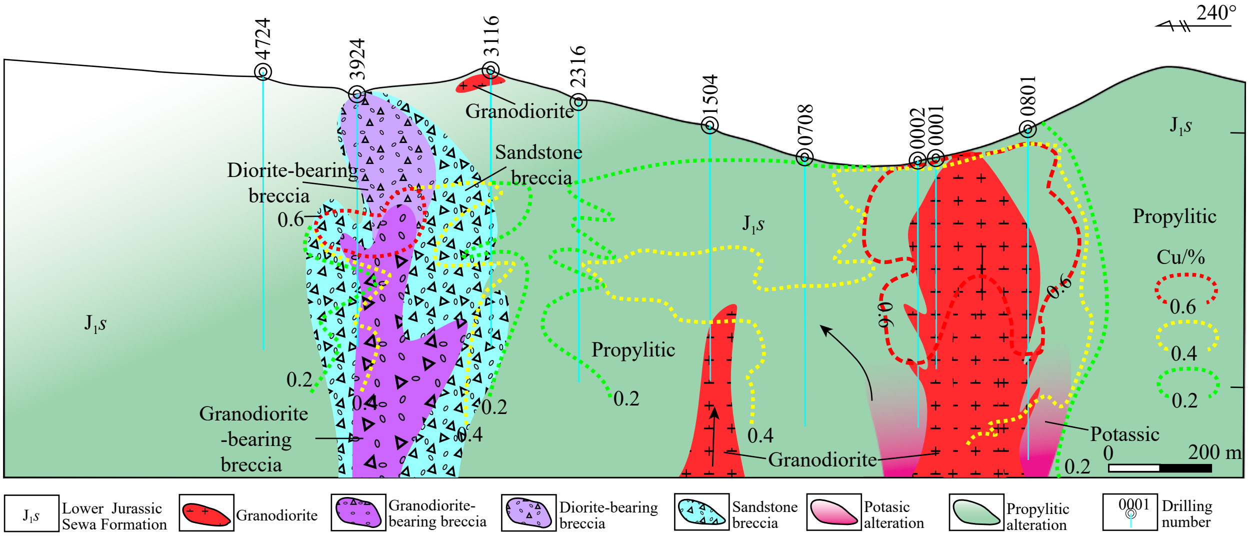

Fig. 3. Simplified cross-section through the Naruo porphyry-breccia Cu deposit (after Lin B et al., 2018a).

porphyry copper (molybdenum) orebody, and independent gold orebodies in diorite porphyry and structural fracture zone, which constitute a "four-in-one" orebody structure model (Tang JX et al., 2010b). In recent years, a major breakthrough in prospecting has been made in the Nankeng area. The amount of copper (average grade of 0.99%), lead+zinc (average grade of 2.88%), molybdenum (average grade of 0.038%), associated gold (average grade of 0.33×10^{-6}), and silver (average grade of 28.18×10^{-6}) is more than 0.79×10^{6} t, 1.2×10^{6} t, 0.02×10^{6} t, 20 t and 2000 t, respectively (Tang P et al., 2017).

According to the characteristics of petrography, petrochemistry, geochronology, isotope geochemistry, and mineral chemistry, it is considered that the granite porphyry, monzonitic granite porphyry, granodiorite porphyry, and quartz diorite porphyry are the products of partial melting of the thickened juvenile lower crust. While the dark diorite enclave and dark diorite porphyry are the product of mixing between ultrapotassic mafic magma from the metasomatic enriched lithospheric mantle and medium acid adakite magma from the thickened juvenile lower crust. During Miocene, the lithospheric extension and convective thinning have different effects on the whole Gangdese belt. The injection of mafic magma provides water, Cu, Au, and other minerals for the medium acid magma system of the Jiama, and activates the Jiama intermediate acid magma system, which has made important contributions to the mineralization of the Jiama porphyry metallogenic system (Zhang ZB et al., 2019).

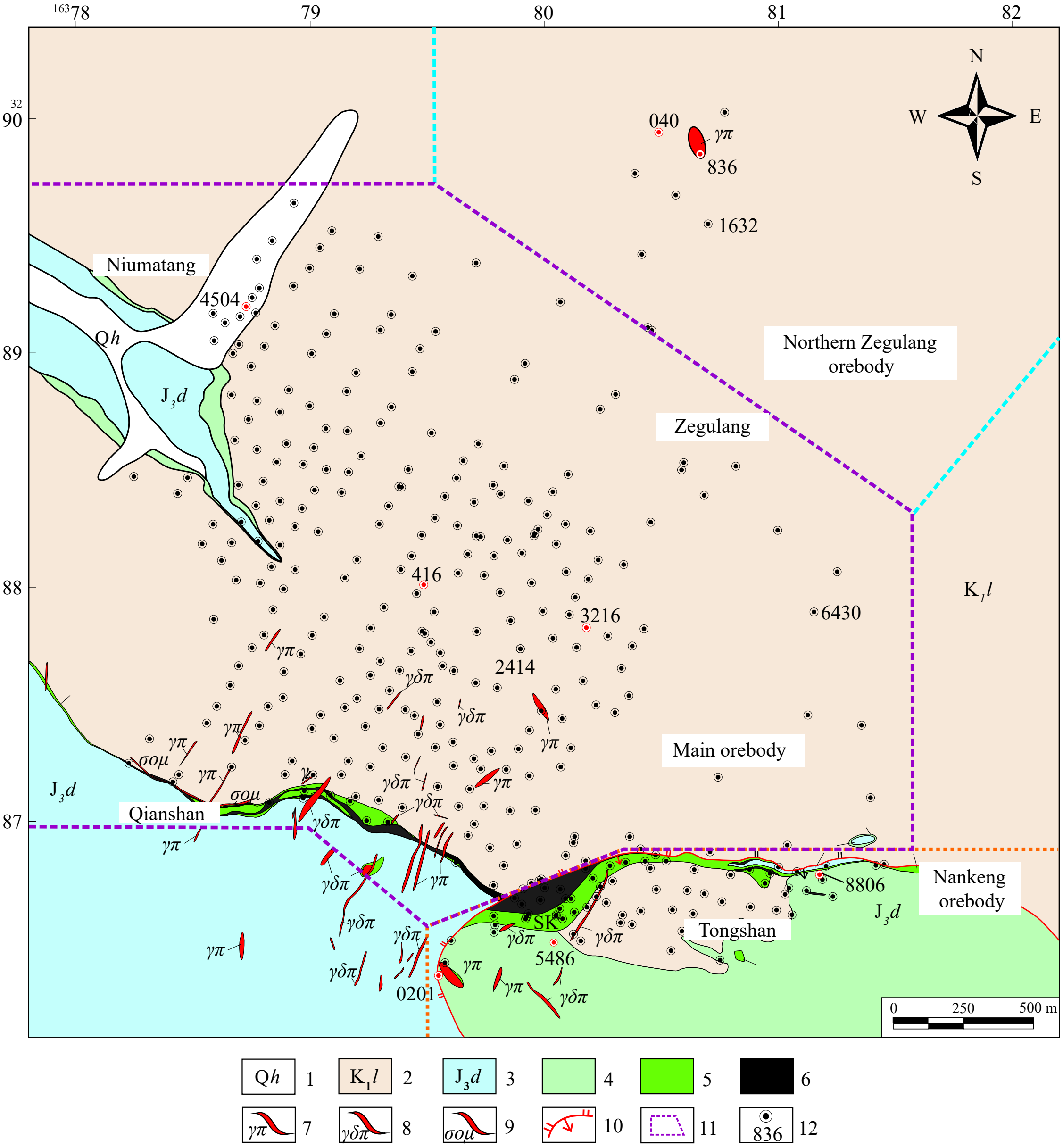

Fig. 4. Geological map of the Jiama mining area (modified from Lin B et al., 2019b). 1–Quaternary sedimentary rocks; 2–sandstone, slate, and hornfels of Linbuzong Formation in lower Cretaceous; 3–limestone and marble of Duodigou Formation in upper Jurassic; 4–skarn marble; 5–skarn; 6–skarn ore-body; 7–granite porphyry veins; 8–granodiorite porphyry veins; 9–quartz-diorite porphyry veins; 10–slip fault; 11–the segment of mining; 12–drilling and number.

3.3. Xiongcun copper-gold ore district

The Xiongcun ore district located in the south margin of the Gangdese copper belt is the only porphyry copper (gold) ore district related to the early subduction of the Neo-Tethys ocean in this belt (Fig. 5). The No.1, No.2 and No.3 orebodies have been found successively in the ore district in recent years (Tafti R et al., 2009; Lang XH et al., 2014). The amount of Cu, Au, and Ag in No.1 orebody is 1.04×10^{6} t with a grade of 0.48%, 143.31 t with a grade of $0.66\times10^{-6,}$ and 900.43 t with a grade of 4.19×10^{-6}, respectively. The alteration includes potassic-silicification, sericitization, and propylitization, and the ore mineral occurs in disseminated or veined form. The main metal mineral including chalcopyrite, pyrite, pyrrhotite, and a small amount of arsenopyrite, galena, molybdenite, and sphalerite. No minerals indicating high oxygen fugacities such as magnetite, hematite, and anhydrite were revealed in No.1 orebody (Lang XH et al., 2019). The amount of Cu, Au, and Ag in No.2 orebody is 1.34×10^{6} t with a grade of 0.35%, 76.34 t with a grade of 0.22×10^{-6}, and 193.78 t with a grade of 1.3×10^{-6}, respectively. The alteration includes potassic-silicification, sodification-calcification, sericitization, and propylitization. The main metal mineral is composed of chalcopyrite, pyrite, magnetite, and a small amount of molybdenite, galena, and sphalerite. A large amount of anhydrite is developed in No.2 orebody. The alteration and main minerals in No.3 orebody are similar to No.2 orebody, the grade of Cu, associated Au, and Ag in No.3 orebody is 0.26%, 0.11×10^{-6}, and 1.2×10^{-6}, respectively (Lang XH et al., 2019).

Two stages of mineralization developed in the Xiongcun ore district. The early mineralization event was related to the Early Jurassic quartz diorite porphyry (181–175 Ma) and No.1 and No.2 orebodies were formed in about 172 Ma. The late mineralization occurred at 161.5 Ma and was related to the Middle Jurassic quartz diorite (167–161 Ma). The ore-related magma was formed in the oceanic island arc environment related to the northward subduction of the Neo-Tethys ocean rather than the continental margin arc environment (Lang XH et al., 2019).

3.4. Qulong porphyry copper deposit

The Qulong porphyry copper deposit containing Cu of more than 10×10^{6} t is located in the Gangdese metallogenic belt of the Tethys Himalayan metallogenic domain, and the eastern part of the volcanic-magmatic arc belt in the Gangdese continental margin (Qin KZ et al., 2014). Porphyry copper mineralization related to granodiorite, biotite monzogranite, biotite granite porphyry is the main orebody and located in the porphyry rocks and its contact zone (Rui ZY et al., 2003; Li GM et al., 2003, 2004; Meng XJ et al., 2004; Zheng YY et al., 2004; Wang LL et al., 2006). Ore minerals mainly include chalcopyrite, molybdenite, tetrahedrite, and natural copper. The early potassium silicate alteration (k-feldspar biotitization), propylitization alteration (epidote-chloritization), and feldspar decomposition alteration (quartz-sericite-chlorite-clayization) developed in the deposit and late feldspar decomposition alteration are strongly superimposed on the early potassium silicate alteration (Yang ZM et al., 2008; Fig. 6). The sulfur isotopic compositions of metal sulfides and gypsum are uniform indicating they have the characteristics of deep magma sulfur in the lower crust or upper mantle (Meng XJ et al., 2006). The diagenesis and ore-forming materials of the deposit come from the juvenile lower crust formed by the partial melting of wedge-shaped mantle intruded into the lower part of the crust during the subduction of the Yarlung Zangbo Tethys oceanic crust (Hou ZQ et al., 2004b; Yang ZM and Hou ZQ, 2009).

4. Metallogenic model of copper deposits in Tibet

4.1. Metallogenic mode of the Duolong in the Bangong Co-Nujiang metallogenic belt

The Duolong district is a typical representative of porphyry-epithermal copper (gold) deposits in the Bangong Co-Nujiang metallogenic belt. Its metallogenic model is an important guiding for mineral exploration in the Bangong Co-Nujiang metallogenic belt. According to the geophysical data and high-precision remote sensing image interpretation results, Wang Q et al. (2019) identified the concealed plutonic intrusion and reconstructed the structural framework and metallogenic model of the Duolong ore district (Fig.7).

The Ocean Island Basalt (OIB) formed in the Duolong district in the Late Jurassic (Li JX et al., 2014; Li SM et al., 2015). The Tiegeshan and Jiushan areas were lifted, accompanied by the formation of magma dome and strong hornfelization alteration due to the upwelling of magma. A series of ring structures and radial structures around the intrusion center formed with the continuous magma rising. The intersections of the fractures are weak stress zone, which provides space and initial elements for the later porphyry magma emplacement and mineralization.

The deposit experienced different processes of change and preservation after its formation. Part of the orebody might be eroded by the post mineralization structure, such as the nappe structure in the Duobuza mining area (Geng QR et al., 2016; Tang JX et al., 2016b). The rapid uplift of the southern margin of Qiangtang terrane resulted in the exhumation of ore bodies in the Duolong area. The orebodies in the shallow region of Duobuza and Bolong might be eroded and deposited in the drainage of the mining area forming placer gold orebodies. The reason why the Tiegelongnan deposit is well preserved is due to the good coverage of volcanic rocks that erupted after mineralization (about 110 Ma; Wang Q et al., 2015; Song Y et al., 2017).

The porphyry, breccia, and epithermal deposits in the Duolong area are the products of the same magmatic-hydrothermal metallogenic system. They are located in the low-level domain, the top of the low-level domain, and the high-level domain of the metallogenic system, respectively. Their spatial location can be used as prospecting indicators for related deposits in the metallogenic system.

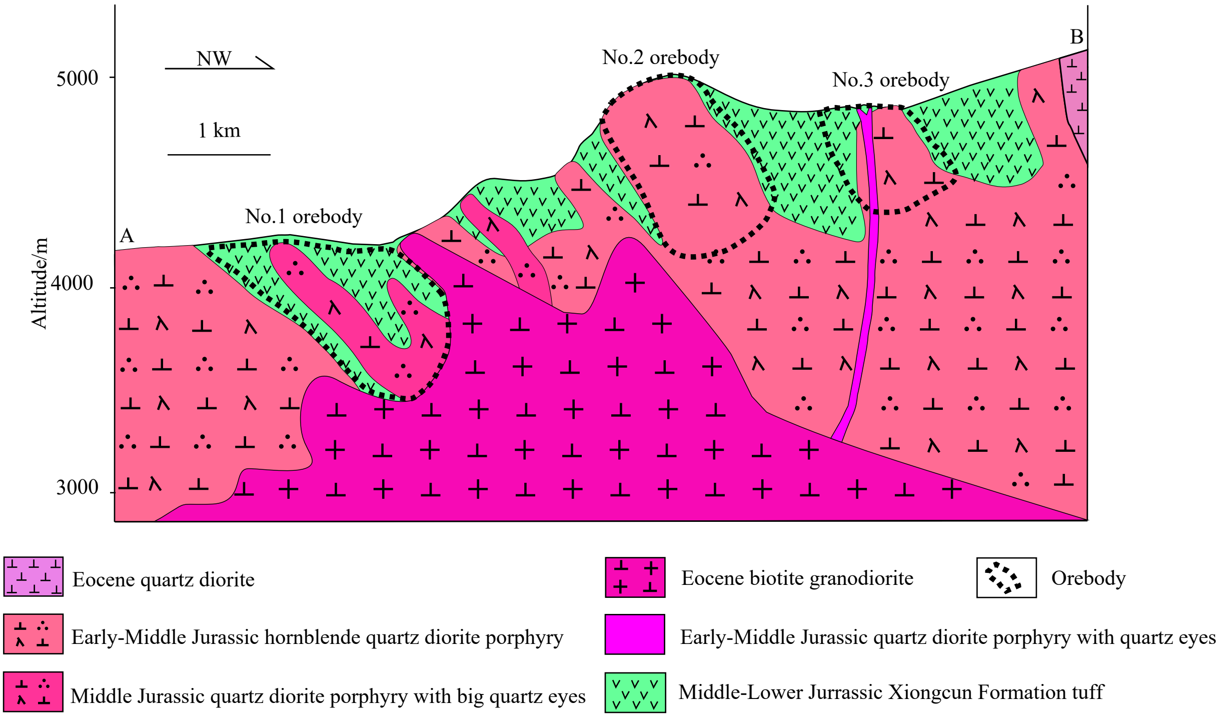

Fig. 5. Schematic diagram of comprehensive exploration model in the Xiongcun mining area (after Lang XH et al., 2017).

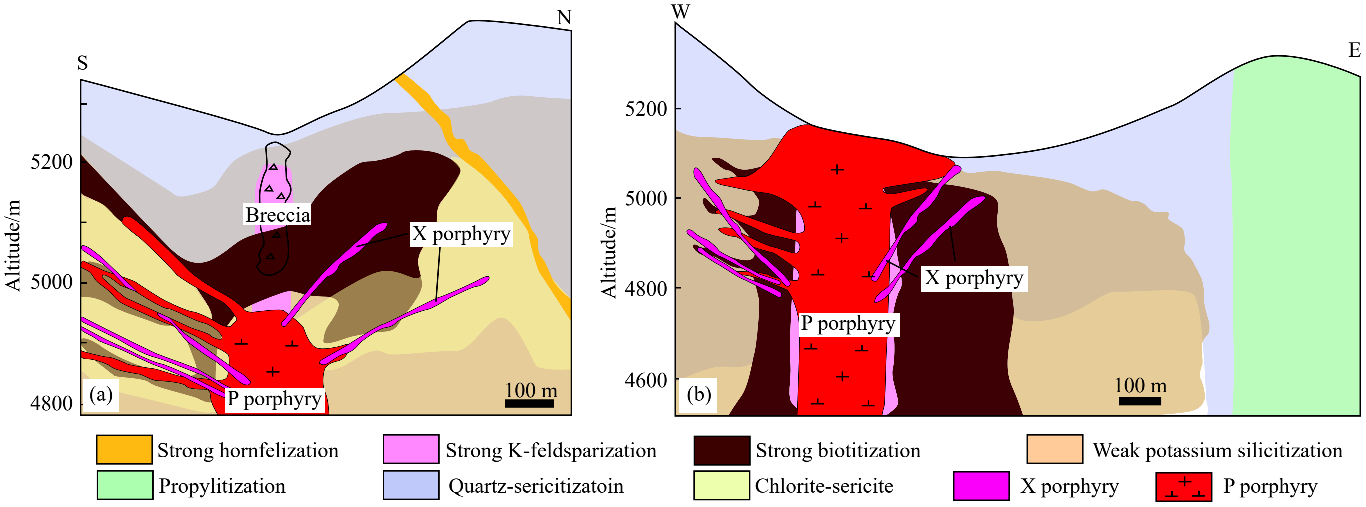

Fig. 6. Alteration distribution along representative section of the Qulong deposit (modified from Yang ZM et al., 2008).

4.2. Polycentric metallogenic model of the Jiama in the Gandese metallogenic belt

The Jiama super-large deposit, as a typical post-collisional porphyry deposit in the Gangdese metallogenic belt, has a metallogenic model of "polycentric metallogenic mineralization" (Lin B et al., 2019b; Fig. 8).

Different from the traditional model, the Jiama deposit in the Gangdese metallogenic belt formed in the post-collisional extensional environment, that is, the Indian Plate subducted and collided with the Eurasian Plate, and then extended in the east-west direction, with the development of North-South faults (Hou ZQ et al., 2015a). The Andes metallogenic belt and the southwest Pacific metallogenic belt belong to the products of oceanic subduction, and the collisional orogenic environment of the Gangdese metallogenic belt is the product of late orogeny after oceanic subduction from the perspective of tectonic evolution (Lin B et al., 2019b).

In the Gangdese metallogenic belt, the host rocks of Jiama, Bangpu, Qulong, and some other mining areas are mainly Mesozoic marine sedimentary strata or pyroclastic rocks, with most of them developing obvious hornfelization. Cenozoic continental volcanic rocks developed in some areas (Wang DH et al., 2011). The Jiama developed well-preserved porphyry and skarn orebodies in the orogenic environment. The epithermal mineralization formed by leaching and filling of acidic low-temperature fluid with andesitic and dacitic volcanic rocks may be eroded and destroyed. The strong silicified alteration on the surface of the main ore block in the Jiama may be the residual product of high sulfide mineralization. The Nankeng ore block and the independent gold ore body in the fracture zone of Niumatang might be epithermal orebodies. Besides, a large hornfels orebody with a good economic value has been formed in the Jiama mining area.

The existing geological facts reveal that multiple heat source centers developed in and around the Jiama mining area, and different hydrothermal centers can form multiple

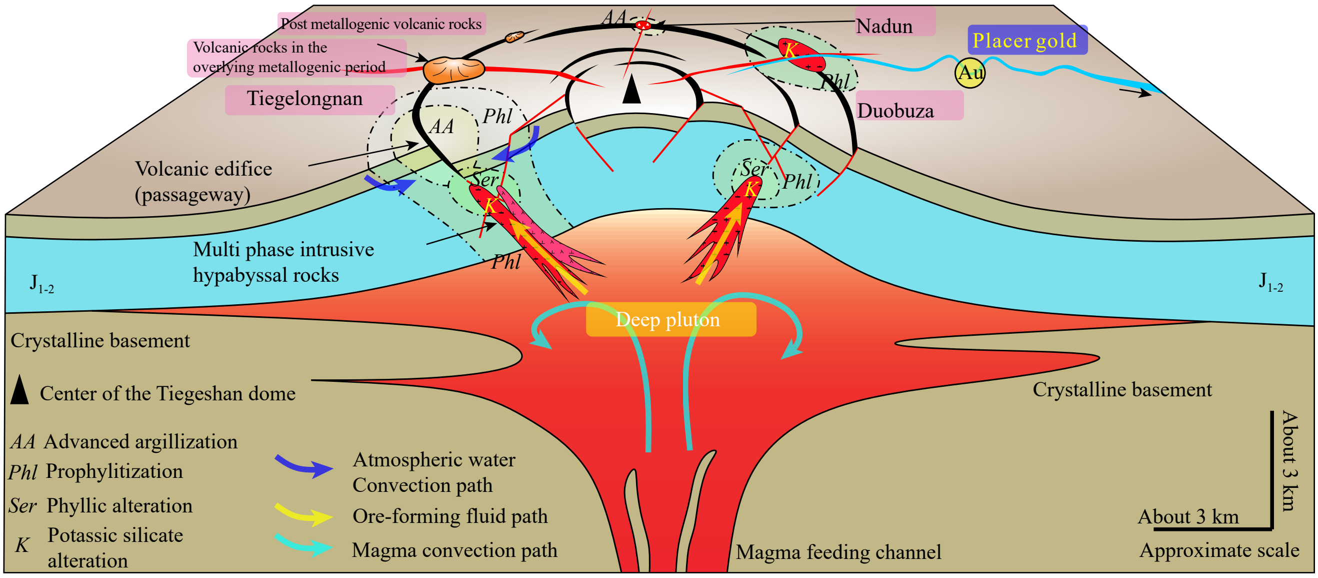

Fig. 7. Regional metallogenic model in Duolong district and inheritance of deposits (modified from Wang Q et al., 2019).

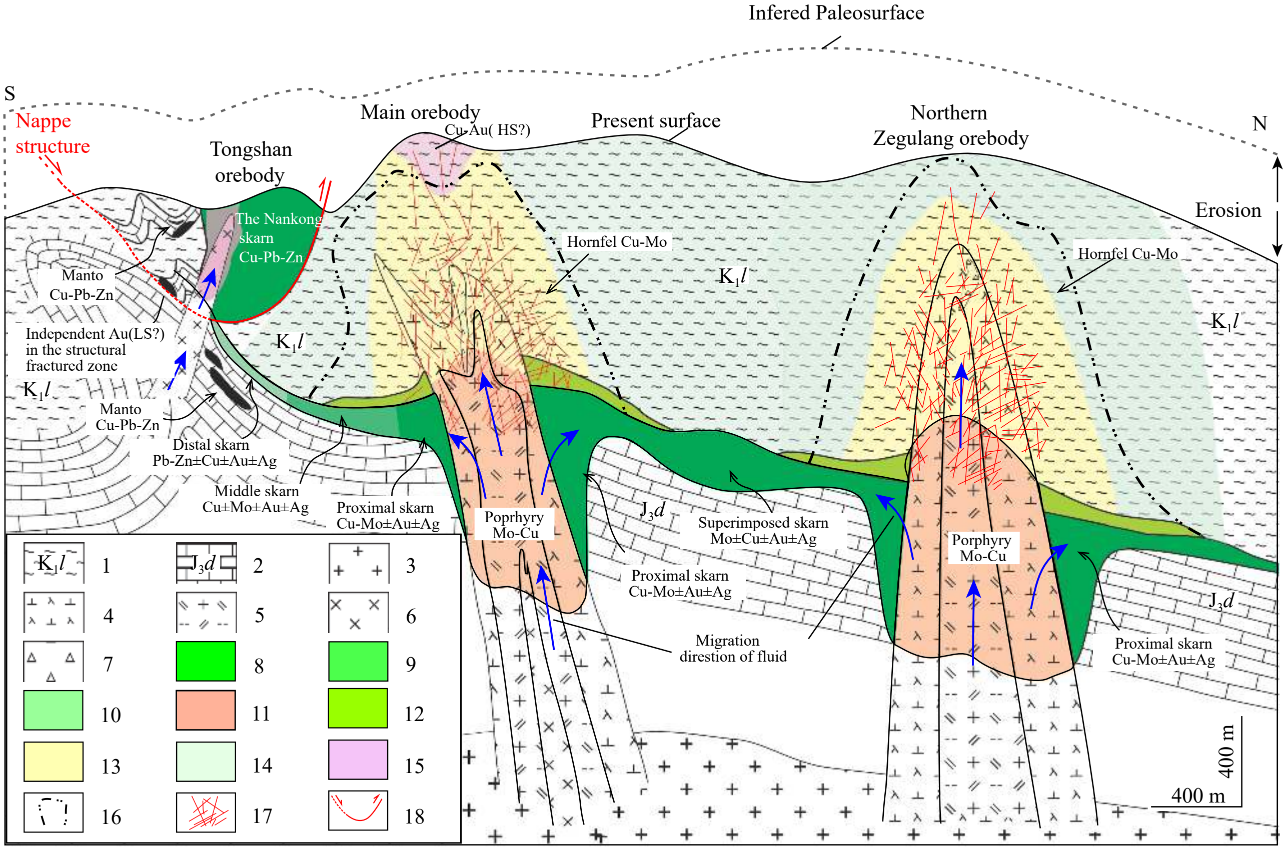

Fig. 8. Polycentric mineralization model of Jiama deposit (modified from Lin B et al., 2019b).1–sandstone and slate in Linbuzong Formation; 2–limestone and marble in Duodigou Formation; 3–upper magma chamber; 4–granodiorite porphyry; 5–monzonitic granite porphyry; 6–granite porphyry; 7–breccias; 8–proximal sharn; 9–intermediate skarn; 10–distal skarn; 11–potassic-silicate alteration; 12–chlorite-epidote alteration; 13–phyllic and argillic alteration; 14–hornfel alteration; 15–strong silicic alteration; 16–boundary of ore-body; 17–fissure system; 18–thrust and slip faults; HS–High sulphidation epithermal deposit; LH–Low sulphidation epithermal deposit.

orebodies. The hydrothermal center of the main ore block is near drill cores from ZK1616 to ZK3216 (Lin B et al., 2012), the hydrothermal center of north Zegulang ore block is near drill core 836, and the mineralization and alteration zoning model of the Nankeng ore block indicates that the hydrothermal center may be near the granite porphyry in the southwest margin (Lin B et al., 2019b). Besides, it is speculated that there is an independent magmatic-hydrothermal center in the deep part of the mining area according to mineralization anomalies of Xiangbeishan and Mogulang in the periphery of the mining area. The existing sections clearly show that the ore-forming fluid of different ore sections can be combined and formed large-scale and high-grade superimposed orebodies in the main ore block and Zegulangbei ore block.

5. Prospecting potential of metal deposits in Tibet

The volcanic activities in the Gangdese and Bangong Co-Nujiang metallogenic belts are well developed from 180 Ma to 40 Ma. More than half areas of these two metallogenic belts develop continental volcanic rocks, so the metallogenic potential is beyond doubt. The low sulfide epithermal-breccia silver polymetallic deposit related to the Linzizong Group volcanic rocks is the target deposit of the Gangdese belt. The low sulfide epithermal-breccia-skarn silver polymetallic deposit will be formed if the skarn deposit developed in the contact area between intermediate-acid intrusive and carbonate rocks (Tang JX et al., 2016b, 2017).

Volcanic edifice and cryptoexplosive breccia tube are widely developed in 145–110 Ma continental volcanic rocks of the Bangong Co-Nujiang suture zone, and the Cu, Au, Pb, Zn, and Ag anomalies are well combined. Therefore, except for the Duolong area, other areas still have great metallogenic potential (Tang JX et al., 2017). Most porphyry-skarn deposits in the Xietongmen-Gongbujiangda County were discovered and evaluated because of the exposure of Xietongmen and Nimu batholith and uplift of the deposits due to the huge exhumation of continental volcanic rocks. The porphyry-skarn-epithermal deposits will be most likely discovered in the west of Xietongmen-Angren, especially in the outcropping area of the Dianzhong Formation continental volcanic rocks (69–52 Ma) considering the weak exhumation of the Linzizong Group volcanic rocks (Tang JX et al., 2017).

Other areas with metallogenic potential in the Tibet Plateau include orogenic gold deposits in the Bangong Co-Nujiang suture zone, Yarlung Zangbo suture zone, and southern Tibet; porphyry-epithermal deposits and nappe related hydrothermal Pb-Zn deposits in the North Qiangtang terrane of the Longmucuo-Shuanghu suture zone; skarn Cu-Ag and polymetallic deposits in the northern margin of Gangdese metallogenic belt; and the Miocene W-Sn polymetallic deposits related to the acidic magmatism formed by crustal thickening or mantle-derived material injection and anataxis.

6. Conclusions

(i) A series of metal deposits or ore districts (such as Duolong, Jiama, Qulong, Xiongcun copper polymetallic deposit) formed in the background from subduction of Tethys oceanic crust to India-Asia collision have been discovered and evaluated in the Tibet Plateau.

(ii) The spatial distribution of deposits in the Duolong district can be used as a prospecting indicator for related deposits in Bangong Co-Nujiang metallogenic belt. The polycentric metallogenic model of the Jiama deposit provides important enlightenment for the exploration and evaluation of the porphyry metallogenic system under the background of collisional orogeny in the Tibet Plateau.

(iii) The porphyry-epithermal deposits related to Linzizong Formation continental volcanic rocks, orogenic Au deposits in Bangong Co-Nujiang suture zone, Yarlung Zangbo suture zone and southern Tibet, hydrothermal Pb-Zn deposits related to nappe structures, skarn Cu (Au) polymetallic deposits in the northern margin of Gangdese, and the Miocene W-Sn polymetallic deposits related to the acidic magmatism formed by crustal thickening or mantle source material injection and anataxis are the key points of future exploration work.

CRediT authorship contribution statement

Ju-xing Tang conceived of the original idea. Huan-huan Yang, Yang Song, Li-qiang Wang, Zhi-bo Liu, and Bao-long Li developed the theory. Bin Lin, Bo Peng, Gen-hou Wang, Qing-gao Zeng, Qin Wang, Wei Chen, Nan Wang provided figures and tables in the manuscript. Zhi-jun Li, Yu-bin Li, Yan-bo Li, Hai-feng Li, and Chuan-yang Lei improved the manuscript. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

Acknowledgment

In the short four years since 2015, more than 700 geologists and technicians have been working hard in the hinterland of the Tibetan Plateau. 1∶50000 geological surveys of 32900 km^2 and more than 34000 km of field mapping were completed. Outstanding contributions and a series of achievements have been made to complete the national public geological survey task and ensure national resources and energy security. The authors would like to express their heartfelt thanks and best wishes to all the geologists who worked hardly in the Tibet Plateau. The discoveries, new understandings, and new developments will be published one after another for readers. This study was financially supported by the project of the China Geological Survey (DD20190167), the National Key Research and Development Program of China (2018YFC0604101, 2018YFC0604106), the Special Funds for Basic Scientific Research of the Institute of mineral resources, Chinese Academy of Geological Sciences (kk2017), and the National Natural Science Foundation of China (42002103, 41902097).

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