Chronology and Crust-Mantle Mixing of Ore-forming Porphyry of the Bangongco: Evidence from Zircon U-Pb Age and Hf Isotopes of the Naruo Porphyry Copper-Gold Deposit

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Abstract: The Naruo porphyry copper-gold deposit (hereinafter referred to as the Naruo deposit) in Tibet is a potentially ultra-large, typical gold-rich porphyry copper deposit, which was recently discovered in the Bangongco-Nujiang metallogenic belt. This study analyzed U-Pb chronology and Hf isotopes of the ore-bearing granodiorite porphyry in the Naruo deposit using the LA-ICPMS dating technique. The results show that the weighted average age is 124.03±0.94 Ma (MSWD=1.7, n=20), and 206Pb/238U isochron age is 126.2±2.7 Ma (MSWD=1.02, n=20), both of which are within the error. The weighted average age represents the crystallization age of the granodiorite porphyry, which indicates that the ore-bearing porphyry in the Naruo deposit area was formed in the Early Cretaceous and further implies that the Neo-tethys Ocean had not been closed before 124 Ma under a typical island-arc subduction environment. The εHf(t) of zircons from the granodiorite porphyry varies from 2.14 to 9.07, with an average of 5.18, and all zircons have εHf(t) values greater than 0; 176Hf/177Hf ratio is relatively high (0.282725–0.282986). Combined with the zircon age—Hf isotope correlation diagram, the aforementioned data indicate that the source reservoir might be a region that is mixed with depleted mantle and ancient crust, which possibly contains more materials sourced from depleted mantle. Rock-forming ages and ore-forming ages of the Duolong ore concentrate area are 120–124 Ma and 118–119 Ma, respectively, which indicate 124–118 Ma represents the main rock-forming and ore-forming stage within the area. The Naruo deposit is located in the north of the Bangongco-Nujiang suture, and it yielded a zircon LA-ICPMS age of 124.03 Ma. This indicates the Bangongco-Nujiang oceanic basin subducted towards the north at about 124 Ma, and the Neo-tethys Ocean had not been closed before the middle Early Cretaceous. It is possible that the crust-mantle mixing formed the series of large and giant porphyry copper-gold deposits in the Bangongco.

Key words: gold-rich porphyry copper deposit, ore-bearing porphyry, zircon, LA-ICPMS dating, Hf isotope, Bangongco-Nujiang suture, Naruo, Tibet

1 Introduction

The Bangongco-Nujiang suture is a significant plate boundary in the northern Tibet Plateau (Chang et al., 1973; Pan et al., 2004; Ren and Xiao, 2004), and is also the third largest porphyry copper metallogenic belt following the Yulong porphyry copper metallogenic belt and Gangdise porphyry copper metallogenic belt in Tibet. The Longduo ore cluster, taken as an example, is approximately 60km long from east to west and approximately 150 km wide from south to north, with an area of approximately 900 km². The cluster contains 9 deposits (occurrences), like the Duobuza porphyry copper-gold deposit, Bolong and Naruo porphyry copper-gold deposits, Nadun gold deposit, Tiegelong porphyry copper deposit, Gai'erqin porphyry copper-gold deposit, Dibaonanugang porphyry copper-gold deposit, and Saijiqiao occurrence. Geological surveys suggest that, the Duobuza,
Bolong and Duolong deposits are large-scale, the Naruo porphyry copper-gold deposit and Gaiqin copper deposit are middle-scale and the other deposits (occurrences) are encouraging prospects. Ore-hosted rocks, chalcopyrite distribution and grade variation in the Naruo deposit are extremely similar to those in the Bolong and Duobuza porphyry copper deposits. Thus, the Naruo deposit is interpreted to be prospective and have a great potential for being upgraded into an ultra-large scale.

Tectonic setting is an important factor controlling the formation of porphyry copper deposits (Solomon, 1990; Sillitoe, 1997; Kerrich et al., 2000). There are mainly three interpretations about the geodynamic setting of the Bangonuco-Nujiang metallogenic belt: northward subduction of the Neo-tethys Oceanic crust(Pearce and Deng, 1988; Shi et al., 2004; Shi, 2007; Shi et al., 2008; Murphy et al., 1997; Ding et al., 2003), southward subduction of the Bangonuco-Nujiang Tethys oceanic crust (Guo et al., 1991; Hsu et al., 1995; Qiu et al., 2006; Zhu et al., 2006, 2008, 2009; Kang et al., 2010; Wang et al., 2010; Gao et al., 2011), and bidirectional subduction (Xu et al., 2007; Du et al., 2011). Based on detailed field work of the Naruo porphyry copper-gold deposit, we conducted systematic sampling from the ore-bearing porphyry in the deposit area, and constrained the age of the ore-bearing porphyry by precise U-Pb zircon LA-ICPMS chronology, to discuss the formation age of the Naruo porphyry copper-gold deposit and the properties of its magmatic source reservoir, as well as to provide a certain basis for the study of plate subduction.

2 Geology of Ore Deposits

The Naruo porphyry copper deposit lies at the southern margin of the Qiangtang-Sanjian composite slice (Fig. 1a), and is situated within the Duolong ore cluster in the western section of the Bangonuco-Nujiang metallogenic belt. Its geographic coordinates are E 83°32′30″–83°35′30″ and N 32°52′30″–32°53′45″, covering an area of 10.41 km² (Fig. 1b).

Stratigraphic outcrops in the deposit area are simple, mainly Middle Jurassic Sewa Formation (J1,s), with a small amount of Quaternary sediments (Q4). The Middle Jurassic Sewa Formation (J1,s) is a succession of epimetamorphic littoral facies clastic rock formation, whose lithological outcrops are mainly grayish black argillaceous slate, grayish green metamorphic feldspar-quartz sandstone, grayish white feldspar-quartz sandstone and grayish white quartz sandstone, with a dip angle of 35°–65°; the formations are in conformable contact and they are in discordant occurrence at the mouth of Naruo Valley. The Quaternary (Q) sediments are widely distributed along low-lying and gentle slope areas, like rivers, swamps and lakes, which are mainly residual and slope materials, and loose sands and gravels accumulation formations. These accumulative sediments are mainly composed of sands, gravels/pebbles, boulders, clay, sandy oil, sand loam and humus (Fig. 1c).

Magmatic activities are relatively intense in the deposit area. The exposed granodiorites mainly occur as stocks with strong alteration, and they are the main ore-bearing porphyry in the area. The granodiorites mostly have porphyritic and porphyry-like texture, and massive structure; phenocrysts account for approximately 45%, with size between 2–5 mm, mainly plagioclase (60%), potash feldspar (10%), quartz (10%), biotite (5%); the matrix are mainly felsic minerals, followed by altered and secondary minerals which are mainly epidote, chloride and quartz, with minor sericite and metal sulfides; the grain size of the matrix is less than 0.1 mm; the matrix mostly displays granitic and granulocrystalline texture, with partial micro-poecilitic texture, micro-insert texture and local aphanitic texture.

The phenocryst is dominated by plagioclase, with secondary potash feldspar, quartz and dark minerals. Plagioclase: the phenocrysts are mostly corroded into perfectly rounded shape with grain sizes of 2–5 mm; they were extremely unstable during alteration and mineralization, and commonly replaced by potash feldspar, quartz, clay minerals, chloride and epidote, even by metal sulfides. Potash feldspar: there are primary and secondary phenocrysts, with euhedral and subhedral crystals, and carlsbad twins can be observed; the potash feldspar phenocrysts are small among all the phenocrysts, with grain sizes of 2–5 mm; potash feldspar shows unobvious growth zoning due to replacement by plagioclase or self-growing; the zoning is colored off grayish white under naked eyes, lighter than flesh red of potash feldspar. Quartz: the quartz phenocrysts are milk white and perfectly rounded under naked observation; they are transparent and commonly have wave extinction under microscopy; quartz occurs as equidimensional, anhedral grains, with erosion configuration; grain size is 0.2–5 mm. Biotite: brown pleochroism, euhedral–subhedral, grain size is approximately 0.3 mm, commonly replaced by chloride. Hornblende: all are primary, euhedral and subhedral, with grain size of 1–3 mm.

Main metallic minerals are chalcopyrite, pyrite and magnetite; metallic minerals in the hypergenesis-oxidation orebodies are mainly malachite, azurite, limonite and native copper. Gangue minerals are mostly quartz, feldspar, sericite and anhydrite, followed by chloride, calcite and epidote.

According to the relationship of altered mineral
Fig. 1. Sketch tectonic and location map (a) (after Hou et al., 2004), regional geological map (b) and the generalized geologic map of the Naroq porphyry copper-gold deposit (c).

composition, three alteration zones can be divided from porphyry to wall rocks, i.e., potassic alteration zone (potash feldspar, biotite, chlorite, and silification)–quartz sericitization zone (sercite, quartz)–propylitization zone (banded chloritization, epidotization and carbonatization), which are similar to the typical zonation of porphyry copper deposits (Lowell et al., 1970; Sillitoe, 2010).

3 Sampling and Analytical Methods

In this study, one ore-bearing granodiorite porphyry sample was selected for LA-ICP-MS zircon U-Pb dating and Hf isotope analysis. The sample of DL023 was taken from Naruo mining area with geographic coordinates of X=3641916, Y=734141, Z=4976 m. The sample crushing and zircon selection were carried out by the Geological Laboratory of Regional Geological Survey, Hebei Province. The analysis of zircon cathode luminescence (CL), U-Pb and Hf isotope test were carried out in the State Key Laboratory of Continental Dynamics of Northwestern University. The cathode luminescence analysis was conducted by the subsidiary Mono CL3+ system of field emission scanning electron microscope produced by FEI. The zircon U-Pb dating was done by Varian 820-MS quadrupole plasma mass spectrometry of Varian. The laser ablation system is GeoLas2005 produced by MicroLAS of Germany, which is composed of ComPex102 Excimer laser (operation material: ArF, wave length: 193nm) and MicroLAS’s optical system. The zircon Hf isotope test was carried out by multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) of Nu Plasma.

Zircon cathode luminescence (CL) analyzing was performed by affiliated MonoCL3+ system of the field emission scanning electron microscope produced by FEI Company. The system is composed of ComPex102 Excimer laser (operation material: ArF, wave length: 193nm) by German’s Lambda Physik Company and MicroLAS’s optical system. U-Pb dating was performed with Agilent 7500 a ICP-MS. The laser spot size was 30μm in diameter and 8 Hz in frequency. ICP-MS laser ablation sampling was constructed with single-point ablation. He was taken as a carrier of ablation materials. Equipment was optimized with NIST610 analysis developed by National Institute of Standards and Technology (NIST) before data analysis. Data was collected by means of peak jumping, i.e., one point is collected at one mass peak; Zircon 91500 was used as a standard to calibrate after each five samples analyzed. Common Pb corrections were made by the method of Andersen (2002); please refer to Yuan et al. (2003) for detailed analyzing process. All dates were calculated using the program ICPMSDataCal (V7.0) (Liu et al., 2009). Zircon 91500 was used as an external standard to calibrate isotope fractionation when calculating dates; NIST610 was used as an external standard, and Si was used as an internal standard. Concordia diagrams and average diagrams of zircons were all gained through the ISOPLOT program (V3.0) (Ludwig, 2003). During sample analysis, tandard 91500 yielded an age of 1064.1±3.2 Ma and Standard GI-1 yielded an age of 603.1±3.0 Ma, which are fully consistent with corresponding ages recommended (Wiedenbeck et al., 1995; Simon et al., 2004) within the error.

Zircon in-situ Hf isotopic analyses were performed by Nu Plasma HR (Wrexham, UK) multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) coupled with Geolas-195 laser ablation. The laser spot size was 32 μm in diameter, its pulsing frequency is 10 Hz and its energy density is 10 J/cm². Due to the disturbance of $^{176}$Hf, $^{152}$Lu/$^{176}$Lu=0.02655 and $^{176}$Yb/$^{172}$Yb=0.5886 (Chu et al., 2002) were used to calibrate by monitoring the signal strength of $^{78}$Lu and $^{176}$Yb. Cross analyzing between Standard Zircon 91500 and zircon samples was conducted for external monitor. During analysis process in this study, the concentrations of $^{176}$Hf/$^{177}$Hf of Standards Zircon 91500 and GI-1 are 0.282295±0.000027 (n=14, 2σ) and 0.282734±0.000015 (n=16, 2σ), respectively, which are consistent with the results by Wu et al.(2007) and Elhlou (2006) within error.

4 Test Results

4.1 Cathodoluminescence (CL) images

Twenty zircons from the ore-bearing porphyry in the Naruo copper deposit area have similar shapes, mostly long columnar or short columnar, light yellow. They are 280–100 μm long, and 50–150 μm wide, with length/width ratio varying between 2 and 3. The analyzed zircons display densely distributed vibration zoning (Fig. 2), and are featured by magmatic-origin zircons in CL images (Möller et al., 2003).

4.2 LA-ICPMS zircon U-Pb dating

Due to different half-life periods, the abundance of radiogenic $^{207}$Pb from the zircons is lower an order of magnitude than the abundance of radiogenic $^{206}$Pb. Thus, for young zircons, $^{206}$Pb/$^{238}$U age has higher precision (Sui, 2007). The rocks analyzed in this paper were all formed in the Phanerozoic eon, and the results were calculated in the form of $^{206}$Pb/$^{238}$U age, with error of 1σ. Twenty zircons from Sample DL023 were analyzed
using U-Pb isotopic dating. Detailed analytical results are listed in Tab.1. Th/U ratios of the zircons are between 0.17–0.74, which are lower than typical magmatic zircons but markedly higher than metamorphic zircons (Wu and Zheng, 2004). Combined with the characteristics of CL images (Fig. 2), the zircons analyzed are inferred to be magmatic. Thus, the U-Pb dating results can represent the crystallization age of magma (Zhang et al., 2008).

DL023 yielded surface ages varying from 115.6Ma to 134.7Ma (Tab. 2). According to the 17 testing points in Table 1, $^{206}$Pb/$^{238}$U weighted average age is 124.03±0.94 Ma (MSWD=1.7, n=20) (Fig. 3), and $^{206}$Pb/$^{238}$U isochron age is 126.2±2.7 Ma (MSWD=1.02, n=20) (Fig. 4), which are very similar, indicating the analytical results are reliable. Therefore, the weighted average age (124 Ma) can represent the crystallization age of the granodiorite porphyry, indicating the ore-bearing porphyry in the Naruo deposit area was formed prior to the middle Early Cretaceous.

4.3 LA-ICPMS zircon Hf isotopic
Eighteen zircon grains were selected from the 21 zircon grains from DL023 which have been analyzed by zircon U-Pb dating. Their testing points are located in the same magmatic oscillatory zoning with U-Pb dating.
Table 1  Zircon LA-ICPMS data of or-occurring porphyry intrusives from Namra porphyry copper-gold deposit in Tibet from DL023

<table>
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<tr>
<th>Sample number</th>
<th>Pb/ U</th>
<th>Th/ U</th>
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<th>Arens porphyry granite from DL023</th>
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<td>44.5</td>
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<td>DL023-3</td>
<td>7.9</td>
<td>16.5</td>
<td>32.9</td>
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<td>44.9</td>
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<td>26.6</td>
<td>47.5</td>
<td>0.0182</td>
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<tr>
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<td>12.7</td>
<td>82.7</td>
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<td>29.5</td>
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<td>55.1</td>
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Fig. 3. Weighted average age.

Fig. 4. 206Pb/235U, 206Pb/238U Concordia plot of zircon LA-ICPMS Dating.

Calculation of Hf isotope composition and related parameters are listed in Table 2. It is shown that the zircons analyzed from the ore-bearing granodiorite porphyry in the Namra deposit area have low 176Lu/177Hf ratios varying within a minor range of 0.008183–0.027283, indicating the zircons have low Hf accumulation after formation. Thus, the 176Hf/177Hf ratios can represent the composition of Hf isotopes in a magmatic system when zircons are in crystallization.

Hf isotope composition in the zircons analyzed from DL023 is relatively homogenous; 176Hf/177Hf varies from 0.282725 to 0.282986, with a weighted average of 0.282875±0.000010; εHf(t) is in the range of 2.14–9.03, averaging 5.18; single-stage model age (t0M) is in the range of 601.0–1499.2 Ma and two-stage model age is 604.3–1039.7 Ma. The two-stage model age can better reflect the average residence time/age of source-reservoir materials in the crust (Wu et al., 2007). Therefore, the results of Hf isotope analysis indicate that the granodiorite porphyry in the Namra deposit area was mainly sourced from the partial melting of the Neoproterozoic and early
Table 2 Zircon Hf isotopic compositions of zircon LA-ICPMS Dating of ore-forming porphyry granodiorite from Naluoo porphyry copper-gold deposit in Tibet

<table>
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<tr>
<th>Plot</th>
<th>Age (Ma)</th>
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<th>2σ</th>
<th>$^{176}$Lu/$^{177}$Hf</th>
<th>2σ</th>
<th>$^{178}$Hf/$^{177}$Hf</th>
<th>2σ</th>
<th>εHf(0)</th>
<th>εHf(1)</th>
<th>TDM/Ma</th>
<th>TDM/Ma</th>
<th>TDM/Ma</th>
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Mesoproterozoic ancient crustal materials. Besides, the two-stage model age ($t_{DM2}$) is markedly larger than the formation age of the zircons, indicating the source-reservoir materials were reserved for a relatively long time.

5 Discussions

5.1 Rock-forming age of the ore-bearing porphyry of the Naluoo porphyry copper deposit

Zircons selected from the ore-bearing monzonitic granite-porphyry samples of the Naluoo deposit are all magnetic. Thus, their zircon U-Pb ages represent the rock-forming age of the porphyry. According to the latest results obtained in this paper, the ore-bearing porphyry yielded a zircon U-Pb weighted average age of 124.03 ± 0.94 Ma (SWD = 1.7, n = 20) (Fig. 3), indicating the ore-bearing porphyry was formed in the Early Cretaceous. This age is consistent with the rock-forming and ore-forming ages of other giant porphyry copper-gold deposits in the Duolong ore cluster (Table 3).

Rock-forming ages within the Duolong concentrate in the range of 120–124 Ma, and ore-forming ages in the range of 118–119 Ma (Table 3), showing 124–18 Ma is the important rock-forming and ore-forming stage in the ore district. Based on the distribution map of deposits in the Duolong ore district as well as the distribution of rock-forming and ore-forming ages (Fig. 1a), deposit distribution and rock-forming ages show concentration, rock-forming and ore-forming ages show consistency, and deposits were all formed in the Early Cretaceous. The abovementioned analysis indicates that the entire Duolong ore Bangongco-Nuijiang belongs to the same ore-forming system under the same metamorphic setting, and its rock-forming and ore-forming processes are controlled by the same deep metamorphic dynamic process.

5.2 Magma source and crust-mantle mixing process

Gold-rich porphyry copper deposits are most possibly sourced from metasomatic mantle wedges, and the fluids or melts (containing water and Fe$^{3+}$) sourced from subducted slabs provide high oxygen fugacity condition (Brandon and
Draper, 1999; Ulmer, 2001; Mungall, 2002); the process of fluids or melts replacing mantle wedges make sulfides from mantle entering the melts more effectively (Mungall, 2002). The Duobuza, Bolong and Naruo deposit in the ore clusters are in a typical island-arc subduction tectonic setting, the Duobuza ore-bearing granodiorite–porphyry was directly derived from partial melting of subduction oceanic crust, and normal island-arc volcanic rocks were sourced from mantle wedges replaced by subducted fluids (Li et al., 2008). Terrigenous sediments contributed to the formation of island-arc magmatic rocks (Ben et al., 1989; McCulloch and Gamble, 1991; Hawkesworth, et al., 1993). Lithochemical analysis shows that the Bolong deposit has the signatures of island-arc magmatic rocks; Sr-Nd-Hf isotopic data indicates that magma formed the granodiorite-porphyry in the deposit was derived from lower crust, possibly mixed with mantle-sourced materials; there seemed to be much more mantle-sourced materials mixing in the late stage of magmatic evolution (Chen et al., 2013). The study of Re-Os isotope implies that the ore-forming materials were mainly sourced from mantle (Zhu et al., 2011). Qu et al., (2012) believed that A-type granites in the Bangongo-Nuijiang suture was formed by the partial melting of mantle-sourced mafic crustal materials or the mantle-sourced, mafic magma differentiation.

Wu et al. (2007) considered that composition of Hf isotopes is different in variable geochemical storge, like chondrite, depleted mantle and crust, and can be thus used for discriminating source area. The zircons from DL023 have $\varepsilon_{Hf}(t)$ values vary from 2.14 to 9.03, averaging 5.18, and $\varepsilon_{Hf}(t)$ values in the zircons are all more than 0, indicating the granodiorite porphyry is mantle-derived. As is shown from the zircon age—Hf isotope correlation diagram (Fig. 5), the points fall in the field between depleted mantle and lower crust limit, suggesting the source reservoir of the granodiorite porphyry was a region mixed with depleted mantle and ancient crust. The $^{176}Hf/^{177}Hf$ ratios are relatively high for the 20 zircon grains (0.282725–0.282986), and $\varepsilon_{Hf}(t)$ values are all more than 0, which may imply there are more contributions of materials sourced from depleted mantle in the source reservoir.

The Duobuza deposit and Bolong deposit in the cluster have $\varepsilon_{Hf}(t)$ ranges of 3.7–8.4 (averaging 5.7) and −7.8–12.2 (averaging 6.0), respectively, which correspond to that of the Naruo ore-bearing porphyry. According to the zircon age-Hf isotope correlation diagram (Fig. 5), the points are projected in the field between depleted mantle and lower crust limit, indicating the ore-bearing porphyry of porphyry copper-gold deposits in the duolong district is characteristic of crust-mantle mixing. The Duolong ore district contains Naruo, Duobuza and Bolong deposits etc., which were all formed in the Early Cretaceous; the ore-bearing porphyry had underwent a mixing of mantle-sourced basic magma and crust-sourced granitic magma; the crust-mantle mixing process played a key role in the formation of the ore-bearing porphyry in the Naruo, Duobuza and Bolong deposits.

5.3 Tectonic setting analysis

The geodynamic setting of the Bangongo-Nuijiang metallogenic belt is mainly composed of three models: northward subduction, southward subduction and bidirectional subduction. We support the first model much more, and our evidence is as follows: 1) magmas of the Duoma pillow basalts and Tarenben basalts in the Bangongo-Nuijiang suture activated at approximately middle-upper Early Cretaceous (~110 Ma); the Tarenben and Duoma OIB basalts were formed under oceanic island environment with oceanic crust as the basement, which implies the Bangongo-Nuijiang oceanic basin had not been completely consumed at about 110Ma (Zhu et al., 2006), which possibly implies the Bangongo-Nuijiang oceanic basin was not closed in the late stage of Early Jurassic (Wang, 2000), but markedly later than Late Jurassic-early stage of Early Cretaceous which was an early understanding (Xiao and Li, 2000; Yin and Harrison, 2000), implying the Tethys Ocean should be closed in the late stage of Early Cretaceous (Qiu et al., 2004). Boninite formed under intraoceanic forearc environment was discovered in the Bangongo ophiolitic mélangé, Tibet. Thus, the Bangongo-Nuijiang metallogenic belt is referred to have undergone intraoceanic subduction (Shi et al., 2004). Accordingly, the tectonic setting of the Bangongo-Nuijiang metallogenic belt should be a subduction environment; 2)
Wang et al. (1987) believed that this oceanic basin was formed under back-arc basin environment; Kapp et al. (2003) proposed that the Tethys oceanic basin in Bangongco is a single oceanic basin which subducted towards north; 3) according to the distribution of island-arc magmas (Fig.1a, b), in the Ritu subduction zone to the north and the Shiquanhe subduction zone to the south, island-arc type granites are all developed to the north of ophiolite, which implies that in the late Middle Jurassic (165.5 Ma), the two subduction zones almost subducted toward the north at the same time (Qu et al., 2009); 4) “the low resistance layer in the lower crust in the Bangongco-Nujiang suture dips to the north compared with the high-conductivity layer”, “the reflection event in deep seismic reflection sections dip to the north” to the south of the Bangongco-Nujiang suture, which supports the Bangongco-Nujiang suture subducted towards the north (Shi et al., 2004) from the perspective of deep geophysics; 5) the Laguocuo ductile shear zone possibly represents a part of the major fault zone during closure of the Bangongco-Nujiang oceanic basin, while the Chaerkangcuo nappe zone is merely a secondary reverse fault formed during the fast/strong collision of Qiangan terrane with Lasa terrane, which indirectly proves that the Bangongco-Nujiang oceanic basin subducted and consumed toward north (Zhang, 2007).

Cooke et al. (2005) held the view that the favorable locations for the formation of porphyry copper deposits are seafloor highland and island-arc orogenic belt resulted from ocean-ridge subduction. Granites in the Bangongco-Nujiang metallogenic belt are classified as island-arc type granites (Du et al., 2011; Qu et al., 2009), indicating a typical island-arc subduction setting (Li et al., 2008). All island-arc type granites were formed by partial melting of wedged mantle, and the magmatic source reservoir underwent replacement of sedimentary melt from subducted slices. The Duobuzha, Bolong and Naruo porphyry copper-gold deposits in the Duolong ore cluster all spread linearly along NE-trending strike-slip faults (Fig.1b). Rock-forming ages within the Duolong cluster are in the range of 120–124 Ma, and ore-forming ages in the range of 118–119 Ma (Table 3), showing 124–118 Ma is the important rock-forming and ore-forming stage in the cluster. The distribution of deposits in the Duolong ore cluster and their rock-forming and ore-forming ages display a cluster distribution. Kapp et al. (2007) suggested that in the Nima area, east of the Naruo deposit, the sedimentary environment transformed into continental facies from marine facies at 125–118 Ma, which means that the Lasa-Qiangtang collision seems to be formed under a subduction tectonic environment. This conclusion is different from Qu and Xin (2006), i.e., “under crust uplifting stage after collision”. Zircon $^{206}$Pb/$^{238}$U weighted average age of the Naruo porphyry copper-gold deposit is 124.03±0.94 Ma, and the Neo-tethys Ocean had not been closed before 124 Ma. The Naruo deposit lies to the north of the Bangongco-Nujiang suture, which implies that the Neo-tethys Ocean subducted toward the north in the Early Cretaceous at least.

As suggested previously, the Bangongco-Nujiang oceanic basin subducted toward the north in the Early Cretaceous, resulting in the change of tectonic stress mechanism within the area and forming a series of strike-slip faults; fluids formed by the dehydration of subducted oceanic crust replaced wedged mantle, resulting in partial melting and forming basic magma; the basic magma underwent MASH process during upward invading and formed large-scale primary island-arc magma in the Mash belt, e.g., primary magma of the porphyry copper deposits (Peacock, 1993; Arculus, 1994; Richards, 2005); at the same time, as magma invaded upward driven by pressure difference, lower crustal rocks were partially melted and assimilated, finally forming a stable magma chamber in the shallow crust. The melt mass of subducted slices/fluids carried volumes of ore-forming materials, which resulted in the wedge mantle featuring high oxidability and enriched mineralized elements, providing a great amount of mantle-derived materials which were mixed with crust-derived materials, and making $e_{Hf}(t)$ values more than 0. Magma in the chamber emplaced by means of pulse along strike-slip faults, associated with ore-forming fluids which carried ore-forming elements, finally forming the Naruo porphyry copper-gold deposit at favorable structures. The two-stage model age ($t_{PM2}$) (604.3–1039.7 Ma) is far larger than zircon U–Pb age (124.03±0.94 Ma), which further reveals the granites possibly sourced from mantle-derived basic magma which was mixed with materials sourced from ancient crust but dominated by the former. Besides, large-scale primary island-arc magma was formed in the Mash belt, i.e., primary magma of the porphyry copper deposits (Peacock, 1993; Arculus, 1994; Richards, 2005). It is possible that the crust-mantle mixing formed the series of large and giant porphyry copper-gold deposits in the Bangongco.

6 Conclusions

1) Zircon $^{206}$Pb/$^{238}$U weighted average age is 124.03±0.94 Ma (MSWD=1.7, n=20), and $^{206}$Pb/$^{238}$U isochron age is 126.2±2.7 Ma (MSWD=1.02, n=20), both of which are extremely similar. Thus, the analyzed results are reliable. The weighted average age (124 Ma) can represent the crystallization age of the granodiorite, indicating the ore-bearing porphyry in the Naruo
porphyry copper deposit area was formed in the middle of the Early Cretaceous.

(2) The Hf isotopic composition of zircons is relatively homogeneous. $\varepsilon_{Hf}(t)$ and $\theta_{DM2}$ reveal source-reservoir materials were reserved for a relatively long time in the crust, and the source reservoir of the granodiorite porphyry should be a region mixed with depleted mantle and ancient crust, which possibly contains more materials derived from depleted mantle.

(3) The Duobuzha, Bolong and Naruo porphyry copper deposits in the Duolong ore cluster all spread linearly along NE-trending strike-slip faults. Rock-forming ages within the cluster concentrate in the range of 120–124 Ma, and ore-forming ages in 118–119 Ma; the concentration of deposit distribution and rock-forming age shows 124–118 Ma is the important rock-forming and ore-forming stage in the cluster. Zircon $^{206}\text{Pb}/^{238}\text{U}$ weighted average age of the Naruo porphyry copper-gold deposit is 124.03±0.94 Ma, and the deposit lies to the north of the Bangongco-Nujiang suture, which indicates the Neo-Tethys Ocean underwent northward subduction in the Early Cretaceous at least, and the ocean had not been closed before 124 Ma. It is possible that the crust-mantle mixing formed the series of large and giant porphyry copper-gold deposits in the Bangongco.

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References


Note


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