A Downgoing Indian Lithosphere Control on Along-Strike Variability of Porphyry Mineralization in the Gangdese Belt of Southern Tibet

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Abstract

The E-trending Gangdese porphyry copper belt in southern Tibet is a classic example of porphyry mineralization in a continental collision zone. New zircon U-Pb geochronological, zircon Hf-O, and bulk-rock Sr-Nd isotope data for the Miocene mineralizing intrusions from the Qulong, Zhumuo, Jiiru, Chongjiang, and Lakange porphyry copper deposits and Eocene igneous rocks from the western Gangdese belt, together with literature data, show that both Paleocene-Eocene igneous rocks and Miocene granitoids exhibit coupled along-arc isotopic variations, characterized by bulk-rock εNd(t) and zircon εHf(t) values increasing from ~84° to ~92°E and then decreasing toward ~95°E. These are interpreted to reflect increasing contributions of subducted Indian continental materials from ~92° to ~84°E and from ~92° to ~95°E, respectively. The Miocene mineralizing intrusions were derived from subduction-modified Tibetan lower crust represented isotopically by the Paleocene-Eocene intrusions, with contributions from Indian plate-released fluids and mafic melts derived from mantle metasomatized by subducted Indian continental materials. Involvement of isotopically ancient Indian continental materials increased from east (Qulong) to west (Zhunuo), which is interpreted to reflect an increasingly shallower angle of the downgoing Indian slab from east to west, consistent with geophysical imaging. Exploration of Gangdese Miocene porphyry copper deposits should focus on the Paleocene-Eocene arc where the subarc mantle was mainly enriched by fluids from the subducted Neo-Tethyan oceanic slab. Neodymium-Hf isotope data for mineralizing igneous rocks from porphyry copper deposits globally show no obvious correlations with Cu endowment. Although Nd-Hf isotopes are useful for imaging lithospheric architecture through time, caution must be taken when using Nd-Hf isotopes to evaluate the potential endowment of porphyry copper deposits, because other factors such as tectonic setting, crustal thickening, magma differentiation, fluid exsolution, and ore-forming processes all play roles in determining Cu endowments and grades.

Introduction

Porphyry-type mineralization above subduction zones generally shows some variability of mineralization styles and ages and geochemistry of mineralizing intrusions along and across strike of magmatic arcs (Kay et al., 1999; Hollings et al., 2005; Sillitoe and Perelló, 2005; Jones et al., 2015; Angerer et al., 2018). However, it is not clear whether such variability occurs in continental collision zones. Many porphyry copper deposits have been recognized in the continental collision zones of the Tethys orogen, including the Gangdese belt in southern Tibet, the Chagai belt in Pakistan, and the Arasbaran-Kerman belt in Iran (Hou and Zhang, 2015). Variability of collision-related porphyry copper deposits along or across these orogens has been poorly understood. In this study, we focus on porphyry mineralization in the Gangdese belt. It was recently noted that the Gangdese porphyries exhibit distinct across-strike metatetic variability characterized by porphyry Cu mineralization in the southern Lhasa subterrane and porphyry Mo mineralization in the central Lhasa subterrane (Fig. 1B; Sun et al., 2017b). However, it is unclear whether there is along-strike variability of porphyry copper mineralization in the Gangdese belt, despite many studies providing geochronological and geochemical data for ore-related intrusions and associated mineralization (Hou et al., 2004, 2015a; Li et al., 2011; Leng et al., 2013; Lu et al., 2015; Wang et al., 2015; Yang et al., 2015, 2016a; Sun et al., 2017a, 2018).

Here, we present new zircon U-Pb and Hf-O and bulk-rock Sr-Nd isotope data for the Miocene ore-related intrusions from five Gangdese porphyry copper deposits (Qulong, Lakange, Chongjiang, Jiiru, Zhunuo) and Eocene felsic and gabbroic rocks from the western Gangdese belt. Combined with literature data, our new results enable recognition of the contrasting isotopic characteristics of porphyry copper mineralization along the strike of the Gangdese belt, which has important implications for exploration of collision-related porphyry copper deposits.

Geologic Setting

The Tibetan Plateau consists primarily of four terranes; from north to south, they are the Songpan-Ganzi, Qiangtang, Lhasa, and Himalaya terranes (Fig. 1A). The Lhasa terrane is bounded by the Bangong-Nujiang suture zone to the north and by the Indus-Yarlung Zangbo suture zone to the south. The Lhasa terrane is composed of northern, central, and southern subterranes, separated by the Shiquanhe-Nam
Fig. 1. (A) Tectonic framework of the Tibetan Plateau (after Zhu et al., 2011). Abbreviations: BNSZ = Bangong-Nujiang suture zone, IYZSZ = Indus-Yarlung Zangbo suture zone, JSSZ = Jinsha suture zone. (B) Simplified geologic map of the Lhasa terrane showing porphyry copper deposits and Cenozoic porphyry-skarn Mo ± Cu ± W deposits (modified after Blisniuk et al., 2001; Wang et al., 2015; Sun et al., 2017a; Li and Song, 2018). Samples for zircon U-Pb dating and isotopic analyses are also shown in Figure 1B and documented in Table 2. Abbreviations: CL = central Lhasa subterrane, CR = Comei rift, LGR = Lunggar rift, NL = northern Lhasa subterrane, PXR = Pumqu-Xianza rift, SL = southern Lhasa subterrane, TYR = Tangra Yum Co rift, YGR = Yadong-Gulu rift, YRR = Yari rift.
Tectonics of porphyry mineralization, Gangdese Belt, Tibet

Tso mélange zone and Luobadi-Milashan fault, respectively (Yin and Harrison, 2000; Zhu et al., 2011; Deng et al., 2014). The Gangdese belt in the southern Lhasa subterrane experienced northward-directed subduction of the Neo-Tethyan oceanic plate from the Middle Triassic to Paleocene, after which the Indo-Asian continental collision occurred at ~65 to 50 Ma (Ding et al., 2005; Leech et al., 2007; Replumaz et al., 2010; Wu, F.Y., et al., 2014; Hu, X.M., et al., 2015, 2016; Zhu et al., 2015). The Middle Triassic to Eocene Gangdese batholiths, Jurassic-Cretaceous volcanic rocks, and ~60 to 52 Ma Lintzing volcanic rocks were emplaced over a large area in the southern and central Lhasa subterranes (Fig. 1B; Mo et al., 2008; Lee et al., 2009; Zhu et al., 2015). Adakite-like Oligocene to Miocene (33–13 Ma) intrusions mainly occur in the southern Lhasa subterrane (e.g., Hou et al., 2004, 2015b; Yang et al., 2016a). Miocene (~27–10 Ma) ultrapotassic volcanic rocks were emplaced in the central Lhasa subterrane and to a lesser extent in the southern Lhasa subterrane (Miller et al., 1999; Zhao et al., 2009; Liu et al., 2014; Sun et al., 2018). These Oligocene to Miocene igneous rocks formed in response to slab breakoff of the Indian continent or convective removal of lithospheric mantle (Chung et al., 1998; Miller et al., 1999; Williams et al., 2004; Hou et al., 2015a).

Many Miocene adakite-like intrusions are spatially and temporally associated with porphyry copper deposits in the 50- to 100-km-wide, 700-km-long E-trending Gangdese porphyry Cu belt (Fig. 1B). This belt, which is located in the south of the Lhasa subterrane, includes the giant Qulong deposit and many smaller deposits such as Zhunuo, Da’bu, Chongjiang, Lakange, and Jiru (Fig. 1B). The hydrology, geothermal alteration, and mineralization features of these six deposits are summarized below (Table 1).

The Qulong porphyry Cu-Mo deposit is situated ~50 km east of Lhasa (Fig. 1) and has a resource of 2,200 million tonnes (Mt) ore at average grades of 0.5% Cu and 0.04% Mo (Qin et al., 2014). It is associated with the Miocene Rongmuqula pluton, which varies from granodiorite to monzogranite in composition and has zircon U-Pb ages of 19.5 ± 0.4 to 16.4 ± 0.4 Ma (Wang et al., 2006; Yang, 2008). The pluton intruded the Early Jurassic Yeba Formation volcanic-sedimentary rocks and Jurassic granite porphyry (zircon U-Pb age of 182.3 ± 1.5 Ma; Yang et al., 2009). An intermineralization monzonite porphyry with zircon U-Pb ages of 17.6 ± 0.7 to 16.2 ± 0.3 Ma intruded the Rongmuqula pluton (Hou et al., 2004; Zhao et al., 2016), and a postmineralization high-Mg diorite porphyry with zircon U-Pb ages of 15.7 ± 0.2 to 15.3 ± 0.3 Ma crosscut the Rongmuqula pluton and monzogranite porphyry (Yang et al., 2015; Zhao et al., 2016). Paleocene monzogranite (64.6 ± 2.5 Ma), quartz gabbro (64.0 ± 1.4 Ma), and Late Cretaceous mafic rocks (~92–85 Ma) crop out near Qulong (Wen, 2007; Ma et al., 2015). Porphyry-type Cu and minor skarn-type Cu-Pb-Zn mineralization occurred at Qulong. Porphyry-related hydrothermal alteration produced an inner potassic zone centered on the Miocene monzogranite porphyry and the adjacent Rongmuqula pluton and an outer propylitic zone in the Yeba Formation (Yang et al., 2009). Potassic alteration includes early-stage K-feldspar alteration (quartz + K-feldspar + local anhydrite) and late-stage biotite alteration. Veins associated with potassic alteration include K-feldspar ± quartz, quartz ± K-feldspar ± anhydrite ± chalcopyrite ± pyrite ± bornite, quartz-K-feldspar-molybdenite ± anhydrite ± chalcopyrite ± pyrite, and biotite ± chalcopyrite veins. Propylitic alteration affected the Yeba Formation rocks and is characterized by replacement of plagioclase by epidote. The associated veins are composed of epidote and quartz. Late phyllic alteration (quartz + muscovite + illite + chlorite + pyrite) was generally superimposed on potassic-altered rocks and occurred as pervasive alteration and vein halos. Veins associated with phyllic alteration include chalcopyrite(pyrite ± anhydrite, pyrite-quartz ± anhydrite veins. The main Cu-bearing mineral at Qulong is chalcopyrite with lesser bornite, which mainly occurs as disseminations within phyllic-altered rocks, or as chalcopyrite ± biotite and chalcopyrite-pyrite ± anhydrite veins/veinlets (Yang and Cooke, 2019). Skarn mineralization formed within interbeds between tuff and marble of the Yeba Formation. Re-Os model ages of molybdenite from the Qulong porphyry and skarn mineralization occurred at 16.4 ± 0.5 and 16.9 ± 0.6 Ma, respectively (Meng et al., 2003; Li et al., 2005; Wang et al., 2006).

The Lakange porphyry Cu deposit is located ~20 km east of Lhasa (Fig. 1). Its Cu tonnage and grade are unknown at this preliminary stage of exploration. Early Jurassic Yeba Formation andesite, tuff, volcaniclastic rocks, and interbedded sandstones and slates crop out in the center and north of the district. Limestones and sandstones of the Late Jurassic Dvodgou Formation crop out in the south of the district and are in fault contact with the Yeba Formation. Miocene granodiorite porphyry (zircon U-Pb age = 13.6 ± 0.4 Ma) was emplaced into the Yeba Formation (Leng et al., 2016). An Re-Os molybdenite model age constrains copper mineralization to 13.4 ± 0.2 Ma (Leng et al., 2015). Potassic alteration of the granodiorite porphyry produced secondary K-feldspar, biotite, and quartz. Phyllic alteration (muscovite + illite + quartz + pyrite) typically occurred along the contact zones between granodiorite porphyry and wall rocks of the Yeba Formation. Chalcopyrite is the dominant hypogene copper sulfide, occurring as disseminations within potassic- and phyllic-altered rocks, and in quartz-chalcopyrite ± pyrite ± molybdenite and chalcopyrite ± pyrite veins.

The Dabu (also known as Namnu) porphyry Cu-Mo deposit is located ~40 km west of Lhasa (Fig. 1) and has a resource of 250 Mt at average grades of 0.2% Cu and 0.02% Mo. It has an Eocene monzonite (zircon U-Pb age = 46 ± 1 Ma), Miocene intermineralization monzonite porphyry (zircon U-Pb age = 15 ± 1 Ma), and Miocene postmineralization lamprophyre dike (Wu, S., et al., 2014, 2016). An Eocene quartz gabbro and granodiorite (zircon U-Pb age = 46.4 ± 1.0 Ma) has also been reported to the north of the district (Wen, 2007). Re-Os molybdenite ages indicate that Dabu mineralization occurred at 14.7 ± 0.2 Ma (Hou et al., 2003). Hydrothermal alteration produced early potassic alteration within the monzonite porphyry and late phyllic alteration within monzonite porphyry and the adjacent granodiorite. Potassic alteration caused pervasive alteration of plagioclase to K-feldspar and hornblende and magmatic biotite to hydrothermal biotite. Veins associated with potassic alteration include quartz-biotite ± K-feldspar ± chalcopyrite ± pyrite and quartz-K-feldspar ± chalcopyrite veins. Phyllic alteration caused replacement of silicate minerals by muscovite, illite, quartz, and pyrite and was associated with chalcopyrite-pyrite ±...
| Deposit | Longitude (°E) | Latitude (°N) | Tonnage/grade | Igneous rocks within and near ore districts and zircon U-Pb ages | Hydrothermal alteration and mineralization | Molybdenite Re-Os age (Ma) | References |
|---------|---------------|---------------|---------------|---------------------------------------------------------------|------------------------------------------|--------------------------|-------------|
| Qulong  | 91.60         | 29.63         | 2,200 Mt @ 0.5% Cu, 0.04% Mo | Early Jurassic Yeba Formation volcanic-sedimentary rocks (182.3 ± 1.5 Ma) | Porphyry Cu-Mo: hydrothermal alteration centered on the monzogranite porphyry and adjacent Rongmuqula pluton and characterized by inner potassic zone, an outer propylitic zone, and late phyllic alteration superimposed on the potassic and propylitic zones; copper mineralization associated with potassic and phyllic alteration | 16.4 ± 0.5 | Meng et al. (2003) |
| Lakange | 91.34         | 29.59         | No data       | Early Jurassic Yeba Formation volcanic-sedimentary rocks | Porphyry Cu-Mo: potassic alteration centered on the granodiorite porphyry surrounded by phyllic alteration, both of which were overprinted by argillic alteration; copper mineralization associated with potassic and phyllic alteration | 13.4 ± 0.2 | Leng et al. (2015, 2016) |
| Dabu    | 90.87         | 29.48         | 250 Mt @ 0.2% Cu, 0.02% Mo | Premineralization monzogranite (46. ± 1 Ma) quartz gabbro to granodiorite (46.4 ± 1.0 Ma) | Porphyry Cu-Mo: potassic alteration affected monzogranite porphyry, overprinted by phyllic alteration | 14.7 ± 0.2 | Hou et al. (2003) |
| Zhunuo  | 87.47         | 29.65         | 403 Mt @ 0.57% Cu, 0.02% Mo | Eocene rhyolite (51.6 ± 1.0 Ma) and quartz porphyry (49.1 ± 0.6 Ma) | Porphyry Cu-Mo: inner potassic alteration centered on porphyry and adjacent monzogranite, outer propylitic alteration in the Shexing Formation; phyllic alteration overprinted potassic alteration; copper mineralization associated with potassic and phyllic alteration | 13.9 ± 0.2 | Zheng et al. (2007) |

**Table 1. Summary of the Geology, Hydrothermal Alteration, and Mineralization of Porphyry Copper Deposits in the Gangdese Belt**
The Zhunuo porphyry Cu deposit is located at Angren (Fig. 1). It has a resource of 403 Mt at average grades of 0.57% Cu and 0.02% Mo. The Miocene intrusive complex was emplaced into Eocene quartz porphyry and rhyolite, which have zircon U-Pb ages of 51.6 ± 1.0 and 49.1 ± 0.6 Ma, respectively (Sun et al., 2020). The Miocene intrusive complex is composed of premineralization monzogranite (zircon U-Pb age = 14.7 ± 0.3 Ma), intermineralization monzogranite porphyry (zircon U-Pb age = 14.5 ± 0.2 Ma), late-mineralization diorite porphyry (zircon U-Pb age = 14.2 ± 0.2 Ma), and postmineralization lamprophyre and granite porphyry (zircon U-Pb ages of 12.2 ± 0.1 and 12.0 ± 0.2 Ma, respectively; Sun et al., 2018, 2020). The Re-Os ages of molybdenite from Zhunuo ores range from 14.78 ± 0.11 to 13.51 ± 0.07 Ma (Zheng et al., 2007; Sun et al., 2020). Early potassic alteration affected the monzogranite porphyry and adjacent monzogranite, producing hydrothermal K-feldspar, biotite, and quartz and local anhydrite and magnetite. Veins related to potassic alteration include biotite ± quartz ± K-feldspar ± pyrite ± chalcopyrite ± bornite, quartz-K-feldspar ± pyrite, quartz-K-feldspar ± chalcopyrite ± pyrite, quartz-K-feldspar ± anhydrite-molybdenite-chalcopyrite veins. Distal propylitic alteration formed in the rhyolite and is characterized by replacement of plagioclase by epidote. Late phyllic alteration produced pyrite, muscovite, illite, chlorite, quartz, and tourmaline in the monzogranite porphyry and adjacent monzogranite and quartz porphyry and generally overprinted potassic alteration. Veins associated with phyllic alteration include tourmaline ± quartz ± chalcopyrite ± pyrite, quartz-molybdenite ± chalcopyrite ± pyrite, pyrite ± quartz ± chalcopyrite, and quartz-muscovite-illite-pyrite ± chalcopyrite veins (Sun et al., 2020). The main Cu-bearing mineral is chalcopyrite with lesser bornite, which occurs as disseminations within potassic- and phyllic-altered rocks and associated quartz veins.

**Analytical Methods**

Samples of Miocene intrusions, including the Chongjiang premineralization monzogranite, Jiru intermineralization monzogranite porphyry, and Zhunuo intermineralization monzogranite porphyry, were collected for zircon U-Pb dating and Hf-O isotope analyses. Additional samples of Miocene intrusions from Qulong (premineralization monzogranite and intermineralization monzogranite porphyry), Lakange (intermineralization granodiorite porphyry), and Chongjiang (premineralization monzogranite and intermineralization monzogranite porphyry) were collected for bulk-rock Sr-Nd isotope analyses. Eocene igneous rocks from Zhunuo and Jiru were collected for zircon Hf isotope analyses. Eocene igneous rocks from the western Gangdese belt (Dejilin dacite, Xiani granite and gabbro, Zhongba monzogranite) were collected for zircon U-Pb dating, zircon Hf isotope, and bulk-rock Sr-Nd isotope analyses. The locations and characteristics of the newly studied samples are listed in Table 2, which includes 35 Sr-Nd samples, 10 zircon Hf samples, five zircon U-Pb geochronology, and three zircon O samples.

**Zircon U-Pb dating**

U-Pb dating of zircons from the Jiru monzogranite porphyry (JR11-1) was performed using a sensitive high-resolution ion
| Sample     | Location      | Longitude (°E) | Latitude (°N) | Elevation (m) | Lithology          | Mineral assemblage | Alteration              | Mineralization | Age (Ma) | Applied analytical analyses          |
|------------|---------------|----------------|----------------|---------------|--------------------|--------------------|----------------------|----------------|----------|--------------------------------------|
| ZBL207-330-3 | Qulong        | 91.6058        | 29.5983        | 4,870         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor potassic alteration | Interminalization | 16.4     | Bulk-rock Sr-Nd isotopes             |
| ZBL207-330-5 | Qulong        | 91.6058        | 29.5983        | 4,871         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor potassic alteration | Interminalization | 16.4     | Bulk-rock Sr-Nd isotopes             |
| ZBL2014-427  | Qulong        | 91.6044        | 29.5981        | 4,813         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 17.0     | Bulk-rock Sr-Nd isotopes             |
| ZBL2014-417  | Qulong        | 91.6044        | 29.5981        | 4,823         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 17.0     | Bulk-rock Sr-Nd isotopes             |
| L4705-189    | Qulong        | 91.6028        | 29.6022        | 4,877         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor potassic alteration | Interminalization | 13.6     | Bulk-rock Sr-Nd isotopes             |
| ZBL2014-427  | Qulong        | 91.6044        | 29.5981        | 4,871         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor potassic alteration | Interminalization | 13.6     | Bulk-rock Sr-Nd isotopes             |
| ZBL2014-417  | Qulong        | 91.6044        | 29.5981        | 4,823         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 13.6     | Bulk-rock Sr-Nd isotopes             |
| LK201-35     | Lakange       | 91.3436        | 29.5983        | 4,813         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Premineralization | 14.9     | Bulk-rock Sr-Nd isotopes             |
| LK201-86     | Lakange       | 91.3436        | 29.5983        | 4,823         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Premineralization | 14.9     | Bulk-rock Sr-Nd isotopes             |
| LK201-505    | Lakange       | 91.3436        | 29.5983        | 4,851         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 14.9     | Bulk-rock Sr-Nd isotopes             |
| CJ1501-147   | Chongjiang    | 89.9688        | 29.6156        | 4,330         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor phyllic alteration | Interminalization | 14.9     | Bulk-rock Sr-Nd isotopes             |
| CJ1501-138   | Chongjiang    | 89.9688        | 29.6156        | 4,330         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Minor phyllic alteration | Interminalization | 14.9     | Bulk-rock Sr-Nd isotopes             |
| CJ001        | Chongjiang    | 89.9688        | 29.6156        | 4,310         | Monzogranite        | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 14.9     | Zircon U-Pb dating and HI-O isotopes |
| ZN-2015-165-1 | Zhunuo       | 87.4703        | 29.6506        | 5,029         | Quartz porphyry     | Kfs + Pl + Qz          | Minor phyllic alteration | Barren          | 50.6     | Bulk-rock Sr-Nd isotopes             |
| ZN-2015-161  | Zhunuo        | 87.4703        | 29.6506        | 5,033         | Quartz porphyry     | Kfs + Pl + Qz          | Minor phyllic alteration | Barren          | 50.6     | Bulk-rock Sr-Nd isotopes             |
| ZN1511-15    | Zhunuo        | 87.4719        | 29.6544        | 5,033         | Quartz porphyry     | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Preminalization   | 50.6     | Zircon U-Pb dating and HI-O isotopes |
| DJ15-7       | Dejilin       | 87.2719        | 29.5392        | 5,029         | Dacite              | Kfs + Pl + Qz + Hb + Bt | Minor phyllic alteration | Barren          | 50.6     | Bulk-rock Sr-Nd isotopes             |
| DJ15-4       | Dejilin       | 87.2722        | 29.5391        | 5,033         | Dacite              | Kfs + Pl + Qz + Hb + Bt | Minor phyllic alteration | Barren          | 50.6     | Bulk-rock Sr-Nd isotopes             |
| DJ15-7       | Dejilin       | 87.2726        | 29.5395        | 5,036         | Dacite              | Kfs + Pl + Qz + Hb + Bt | Minor phyllic alteration | Barren          | 50.6     | Bulk-rock Sr-Nd isotopes             |
| ZB-28        | Zhongba       | 84.4314        | 29.9071        | 5,237         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Interminalization | 47.2     | Zircon U-Pb dating and HI-O isotopes |
| ZB-34        | Zhongba       | 84.4316        | 29.9073        | 5,237         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Interminalization | 47.2     | Zircon U-Pb dating and HI-O isotopes |
| ZB-33        | Zhongba       | 84.4315        | 29.9072        | 5,237         | Monzogranite porphyry | Kfs + Pl + Qz + Hb + Bt | Unaltered            | Interminalization | 47.2     | Zircon U-Pb dating and HI-O isotopes |

Abbreviations: Bt = biotite, Cpx = clinopyroxene, Hb = hornblende, Kfs = K-feldspar, Pl = plagioclase, Qz = quartz
Zircon Hf isotopic analyses

In situ zircon Hf isotope compositions of the studied Miocene and Eocene igneous rocks were determined using a Neptune multicollector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) instrument equipped with a Geolas-193 laser ablation system at the National Research Center of Geoanalysis and the State Key Laboratory of Geological Process and Mineral Resources. Details about the analytical procedures and data acquisition are provided in Hu et al. (2012), Zhou et al. (2018), and Sun et al. (2018). Model ages and εHf values of the samples were calculated with an assumption that the 176Lu/177Hf ratio of average crust is 0.015, and the 176Hf/177Hf and 176Lu/177Hf ratios of present chondrite and depleted mantle are 0.282772 and 0.0332, 0.28325 and 0.0384, respectively (Vervoort et al., 1996; Blichert-Toft et al., 1997; Griffin et al., 2002). The decay constant of 176Lu used for this study is 1.865 × 10^{-11} (Scherer et al., 2001).

Bulk-rock Sr-Nd isotopic analyses

The Sr and Nd isotope compositions of the Miocene and Eocene igneous rocks were determined by thermal ionization mass spectrometry (TIMS) in the State Key Laboratory Geological Process and Mineral Resources. The detailed analytical procedures are provided in Liu et al. (2004) and Sun et al. (2018). The measured Sr and Nd isotope ratios were normalized against 86Sr/88Sr = 0.1194 and 146Nd/144Nd = 0.7219.

Results

Zircon U-Pb geochronology

Zircon U-Pb geochronological data for five intrusions are listed in Appendix Table A1 and shown in Figure 2. All the zircon samples have numerous narrow oscillatory zones and Th/U ratios of 0.4 to 2.0, indicating their magmatic origin (Hoskin and Schaltegger, 2004). The Chongjiang monzogranite sample (CJ001) and Jiru monzogranite porphyry sample (JR11) yielded the weighted mean 207Pb-corrected 206Pb/238U ages of 1064 ± 10 Ma, which is similar to the recommended age of 1065 Ma (Wiedenbeck et al., 1995). Isotopic ratios and element concentrations of zircons were calculated using ICPMSDataCal (Liu et al., 2008). Common Pb correction and ages of the samples were calculated using LA-ICP-MS common lead correction, according to the method of Andersen (2002). Details of the analytical procedures are provided in Liu et al. (2010).

Zircon O isotope analyses

In situ zircon oxygen isotopes of mineralizing intrusions from Chongjiang (CJ001), Jiru (JR11-1), and Zhunuo (ZN005-189) were analyzed using the SHRIMP-IIe/CMC at the Beijing SHRIMP Center. The analytical spot size is approximately 23 μm in diameter. Values of oxygen isotope ratios were standardized to Vienna-standard mean ocean water (V-SMOW, δ18O/δ16O = 0.0020052) and reported in standard per mil notation. The instrumental mass fractionation factor was corrected using the Penglai and Qingshu zircon standards with δ18O values of 5.31 ± 0.10‰ (2SD) and 5.4 ± 0.20‰ (2SD), respectively (Li et al., 2010, 2013). Detailed instrument conditions, analytical procedures and data reduction procedures are described in Ickert et al. (2008).
Fig. 2. Tera-Wasserburg diagrams for zircons from monzogranite (CJ001) from Chongjiang (A), monzogranite porphyry (JR11) from Jiru (B), granite (XL-21) from Xiani (C), gabbro (XL-07/14) from Xiani (D), monzogranite (ZB-28) from Zhongba (E), and dacite (DJL17-2) from Dejilin (F). Error crosses are 1σ. Note that Dejilin data are from Sun et al. (2017a).
granite porphyry (ZN005-189) has zircon $\varepsilon_{\text{Hf}}(t)$ values of $-2.8$ to $0$ and $\delta^{18}O$ values of $5.5$ to $8.4\%e$.

**Zircon Hf isotopes**

Results for in situ zircon Hf isotope analyses for the Eocene igneous rocks are listed in Appendix Table A3. The Zhunnuo rhyolite (ZN11-7) and quartz porphyry (ZN1511-15) have $\varepsilon_{\text{Hf}}(t)$ values of $-0.2$ to $3.2$ and $-0.2$ to $4.1$, and second-stage Hf depleted mantle models ($T_{2DM}$) of 1140 to 923 and 1142 to 866 Ma, respectively. The Jiru monzogranite (JR11-8) has $\varepsilon_{\text{Hf}}(t)$ values of $2.6$ to $7.1$ and $T_{2DM}$ of 958 to 669 Ma. The Dejilin dacite (DJL17-2) has $\varepsilon_{\text{Hf}}(t)$ values of $1.0$ to $4.4$ and $T_{2DM}$ of 1060 to 846 Ma. The Xiani granite (XL-21) and gabbro (XL-07/14) have $\varepsilon_{\text{Hf}}(t)$ values of $-0.7$ to $3.9$ and $-1.2$ to $1.5$, and $T_{2DM}$ of 1171 to 575 and 1202 to 1030 Ma, respectively. The Zhongba granite (ZB-2S) has $\varepsilon_{\text{Hf}}(t)$ values of $1.2$ to $3.8$ and $T_{2DM}$ of 1045 to 854 Ma.

**Bulk-rock Sr-Nd isotopes**

Results for 35 bulk-rock Sr-Nd isotope analyses for the Eocene and Miocene igneous rocks are listed in Appendix Table A4. All the Miocene samples have evolved Sr-Nd isotope compositions, with initial $87^{\text{Sr}}/86^{\text{Sr}}$ and $\varepsilon_{\text{Nd}}(t)$ values ranging from 0.70459 to 0.70565 and $-4.2$ to $-0.0$ for the Qulong monzogranite and granodiorite, 0.70517 to 0.70532 and $-0.2$ to $0.2$ for the Lakange granodiorite, and 0.70459 to 0.70565 and $-4.2$ to $-2.5$ for the Zhongjiang monzogranite.

The Eocene samples have evolved isotopic compositions. The initial $87^{\text{Sr}}/86^{\text{Sr}}$ ratios and $\varepsilon_{\text{Nd}}(t)$ values are 0.70326 to 0.70675 and $-3.8$ to $-1.7$ for the 10 rhyolite and quartz porphyry samples from Zhunnuo, 0.70558 to 0.70562 and $-2.7$ to $-2.2$ for the three dacite samples at Dejilin, and 0.71121 to 0.71146 and $-8.4$ to $-8.2$ for the two monzogranite samples at Zhongba. At Xiani, the three granite samples (initial $87^{\text{Sr}}/86^{\text{Sr}} = 0.70584-0.70614$; $\varepsilon_{\text{Nd}}(t) = -3.9$ to $-3.6$) yielded more evolved isotopic compositions than the four gabbro samples (initial $87^{\text{Sr}}/86^{\text{Sr}} = 0.70558-0.70562$; $\varepsilon_{\text{Nd}}(t) = -2.7$ to $-2.2$).

**Discussion**

**Isotopic variations along strike of the Gangdese belt**

The Gangdese batholiths in the southern Lhasa subterrane were emplaced from the Middle Triassic to the Miocene (Ji et al., 2009; Zhu et al., 2011, 2015; Hou et al., 2015b, and references therein). Our syntheses of all published and new Nd-Hf isotopes indicate that there are distinct spatial isotopic variations along the Gangdese belt from precollisional to collisional magmatism (Fig. 3).

Both the Middle Triassic-Jurassic (~237–152 Ma) and the Cretaceous (~137–65 Ma) are magmatic rocks with depleted Nd-Hf isotopic compositions, consistent with their derivation mainly from the juvenile Neo-Tethyan mantle wedge (Fig. 3A-D). Exceptions are at Daggyai Co and from Lhasa to Gongbogynada (~91°–93°E; Fig. 1B), where there are large variations of $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$, suggesting probable crustal contamination by local Archean-Paleoproterozoic Lhasa basement (Fig. 3A-D; Hou et al., 2015b).

The Paleocene-Eocene (~65–40 Ma) and Miocene (~21–13 Ma) intrusions were emplaced during the India-Asia continental collision over a large area from Gaer to Nyingdegi (Fig. 1B). It was previously shown that the Paleocene-Eocene rocks in the western Gangdese belt (west of ~89°E) generally have higher initial $87^{\text{Sr}}/86^{\text{Sr}}$ ratios and lower $\varepsilon_{\text{Nd}}(t)$ values than those in the eastern Gangdese belt (east of ~89°E; Wang et al., 2015). Our new isotopic data such as the ca. 50 Ma Xiani gabbror and granites at ~86°E are consistent with previous interpretations (Fig. 3E, F). More importantly, both the mafic and felsic Paleocene-Eocene igneous rocks show similar spatial isotopic variations with their $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$ values increasing from ~84° to ~92°E and then decreasing toward ~95°E (Fig. 3E, F). These spatial trends are also exhibited by the Miocene (~21–13 Ma) mineralizing and barren granitoids (Fig. 3G, H), but not the precollisional Triassic-Cretaceous intrusions (Fig. 3A-D). Given that the precollisional arc rocks at ~88° to 95°E have depleted Nd-Hf isotopes (Fig. 3A-D), the more unradiogenic Nd-Hf isotopes of the Paleocene to Miocene rocks most likely reflect the involvement of the subducted Indian continental materials with low $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$ values (Chu et al., 2011). This interpretation is supported by geophysical results showing a N-dipping subducted Indian continental lithosphere and transport of Indian crust north of the Yarlung Zangbo suture (Repumaz et al., 2010; Gao et al., 2016). In addition, the contributions of subducted Indian components to collisional magmas along the Gangdese belt probably decreased from ~84° to ~92°E and then increased from ~92° to ~95°E, in keeping with the spatial isotopic variations of the Paleocene to Miocene igneous rocks (Fig. 3E-H).

**Genesis of Miocene porphyry copper-related intrusions**

The origin of Miocene ore-related intrusions in the Gangdese belt remains highly controversial, but it is generally accepted that either subduction-modified juvenile Tibetan lower crust or metasomatized mantle-derived mafic magmas played major roles in their formation (Hou et al., 2004, 2015a; Lu et al., 2015; Yang et al., 2015, 2016a; Sun et al., 2018; Wang et al., 2018). The Paleocene-Eocene intrusions crop out within or nearby all known Miocene porphyry copper deposits (Fig. 4A) and have more juvenile Nd and Hf isotope compositions than the Miocene mineralizing granitoids at individual deposits when all data are recalculated to 15 Ma (Fig. 4B, C). It suggests the Miocene rocks involved a less radiogenic component, which is most likely the subducted Indian continental materials with unradiogenic Nd and Hf isotopes (Guo et al., 2013; Yang et al., 2016a; Sun et al., 2018). The Miocene mineralizing intrusions have large variations in zircon oxygen isotope ratios, which range from mantle-like (5.3 ± 0.6‰, 2σ; Valley et al., 1998) to supracrustal δ18O values (up to 8‰; Fig. 5), consistent with involvement of mantle and supracrustal components in their genesis (Kemp et al., 2006).

We propose a three-component mixing model to explain the large variations of Sr-Nd isotopes of the Miocene mineralizing intrusions ([87Sr/86Sr]t = 15 Ma) = 0.7048–0.7091; $\varepsilon_{\text{Nd}}(t = 15$ Ma) = −6.9 to 2.4; Figs. 6, 7). The three components include Indian plate-released fluids, subduction-modified Tibetan lower crust, and mafic magmas derived from mantle metasomatized by Indian continental materials (Fig. 7). Given the subduction-modified Tibetan lower crust is heterogeneous, as shown by the spatial isotopic variations of Paleocene-Eo-
Fig. 3. Longitudinal variations of bulk-rock $\varepsilon_{\text{Nd}}(t)$ values and zircon $\varepsilon_{\text{Hf}}(t)$ values for Triassic-Jurassic (A, B), Cretaceous (C, D), Paleocene-Eocene (E, F), and Miocene (G, H) igneous rocks along the Gangdese belt. Nd-Hf isotope data are shown in Appendix Tables A3 and A4.
cene igneous rocks (Fig. 3E, F), the local Paleocene-Eocene gabbros were chosen to represent Tibetan lower crustal end member at different localities (Table 3; Fig. 7). The modeling results show that the proportion of Indian plate-released fluids increased from Qulong, Jiama, and Lakange (0–10%) in the east to other deposits (Dabu, Chongjiang, Tinggong, and Zhunuo; 10–25%) in the west. Similarly, the proportion of metasomatized mantle-derived magmas also increased from Qulong, Jiama, Lakange, and Dabu (mostly <5%) in the east to Chongjiang, Tinggong, and Zhunuo (mostly 10–25%) in the west (Fig. 7). This westward-increasing contribution of Indian continental components during Miocene mineralization could reflect increasingly shallower angle of subducted Indian lithosphere from east (Qulong) to west (Zunuo) as imaged by geophysical data (Zhao et al., 2010; Chen et al., 2015; Guo et al., 2018). Along-strike variation of subduction angle during the Miocene could have led to slab tearing (Chen et al., 2015; Guo et al., 2018; Li and Song, 2018; Liu et al., 2020), leading to formation of five distinct porphyry copper districts in the Gangdese belt (Fig. 8).

Implications for exploration
The along-strike isotopic variation along the Gangdese belt is consistent with new geophysical evidence suggesting a seg-

Fig. 4. Longitudinal variations of zircon U-Pb ages (A), bulk-rock $\varepsilon_{Nd}(t)$ values (B), and zircon $\varepsilon_{Hf}(t)$ values (C) for Miocene and older (Paleocene-Eocene or Jurassic) igneous rocks within or adjacent to porphyry Cu deposits along the Gangdese belt. The zircon U-Pb ages (Ma) of pre-Miocene intrusions (Wen, 2007; Yang et al., 2009; Zheng et al., 2014; Huang et al., 2015; Wu et al., 2016; Sun et al., 2018) are labeled on (A). Nd-Hf isotope data for igneous rocks within and nearby deposits are recalculated to 15 Ma and are shown in Appendix Tables A3 and A4. Abbreviations: BR = Bairong, CJ = Chongjiang, DB = Dabu, GJ = Gangjiang, JM = Jiama, JR = Juju, LKE = Lakange, QD = Qiangdui, QL = Qulong, TG = Tinggong, ZN = Zhunuo.
mented subducting Indian slab (Figs. 3E, F; Li and Song, 2018; Liu et al., 2020). The segment between ~86° and ~92°E hosts all known Gangdese Miocene porphyry copper deposits, which are found above a steeper Indian slab segment that was less metasomatized by Indian continental materials than other segments (Figs. 3E, F, 8). By contrast, the segments to the west of ~86°E and east of ~92° to ~95°E were strongly metasomatized by Indian continental components above flatter slabs—these segments do not host any Miocene porphyry deposits. The lack of porphyry deposits above flatter Indian slab is at odds with previous observations that young giant porphyry deposits coincide with domains of flat slab subduction in circum-Pacific arcs (Cooke et al., 2005). We speculate that this discrepancy is due to the continental nature of the subducting Indian slab, which likely contains less chlorine, sulfur, and water than subducting oceanic slab.

The Nd-Hf isotopes are effective in imaging large-scale lithospheric architecture through time (Hou et al., 2015b). Previous studies have proposed that isotopic values of ore-related intrusions are correlated with metal endowment of porphyry copper deposits in collisional zones (Hou et al., 2013; Asadi, 2018; Deng et al., 2018). However, our larger Nd-Hf isotope data show that there are no obvious positive correlations between copper metal tonnage and bulk-rock $\varepsilon_{\text{Nd}}(t)$ and zircon $\varepsilon_{\text{Hf}}(t)$ values on a global scale (Fig. 9). We advise caution when using Nd-Hf isotopes for predicting metal endowment of porphyry deposits, because other factors such as tectonic setting, crustal thickening, magma differentiation,
Table 3. Sr-Nd Isotope Compositions of Three End Members of Mixing Model for Porphyry Copper Deposits in the Gangdese Belt

| Deposit      | End member 1 | End member 2 | End member 3 |
|--------------|--------------|--------------|--------------|
| Qulong, Jiama, Lakange | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7042, \varepsilon_{\text{Nd}}(t) = 3.4$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7424, \varepsilon_{\text{Nd}}(t) = -17.8$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7089, \varepsilon_{\text{Nd}}(t) = -11.3$ |
|              | (~64 Ma quartz gabbro from Qulong; Wen, 2007) | (Guo et al., 2013) | (lamprophyre from Dabu; S. Wu, unpub. data, 2020) |
| Dabu         | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7039, \varepsilon_{\text{Nd}}(t) = 5.7$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7424, \varepsilon_{\text{Nd}}(t) = -17.8$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7089, \varepsilon_{\text{Nd}}(t) = -11.3$ |
|              | (~54 Ma gabbro from Quxu; Wang et al., 2019) | (Guo et al., 2013) | (lamprophyre from Dabu; S. Wu, unpub. data, 2020) |
| Chongjiang   | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7039, \varepsilon_{\text{Nd}}(t) = 4.6$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7424, \varepsilon_{\text{Nd}}(t) = -17.8$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7089, \varepsilon_{\text{Nd}}(t) = -11.3$ |
| Tinggong     | (~57 Ma gabbro from Nyemo; Wang et al., 2019) | (Guo et al., 2013) | (lamprophyre from Dabu; S. Wu, unpub. data, 2020) |
| Zhunuo       | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7056, \varepsilon_{\text{Nd}}(t) = -2.4$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7424, \varepsilon_{\text{Nd}}(t) = -17.8$ | Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7089, \varepsilon_{\text{Nd}}(t) = -11.1$ |
|              | (~50 Ma gabbro from Xiani; this study) | (Guo et al., 2013) | (high-Mg diorite from Zhunuo; Sun et al., 2018) |

Fig. 7. Three-component modeling of Sr-Nd isotope compositions for the Miocene mineralizing intrusions from Qulong, Jiama, and Lakange (A), Dabu (B), Chongjiang, Tinggong, and Bairong (C), and Zhunuo (D). The compositions of three end members (Tibetan lower crust, Indian plate-released fluids, and metasomatized mantle-derived mafic magmas) are listed in Table 3. The dashed and solid curves are magma mixing curves with percentage of fluids and mantle-derived magmas labeled as numbers. All data are recalculated to 15 Ma and are listed in Appendix Table A4.
Fig. 8. Schematic illustration (not to scale) of collision-related porphyry Cu mineralization in the Gangdese belt of southern Tibet (modified after Li and Song, 2018). Indian slab tearing, probably due to variations of the subduction angle along the Gangdese arc, induced asthenospheric mantle upwelling and local mantle convection, which in turn caused fluid-fluxed melting of the metasomatized subcontinental lithospheric mantle and part of the Tibetan lower crust and resulted in the emplacement of mineralizing Miocene intrusions. The extensional stress coupled to the crust and resulted in extension and rifting in the upper crust. The slab tears may not have one-to-one relationships with near-surface fault systems. All known porphyry copper deposits in the Gangdese belt are located in the region with steeper slab dips. Abbreviations for suture zone and rifts: CR = Comei rift, IYZSZ = Indus-Yarlung Zangbo suture zone, LGR = Lunggar rift, PXR = Punqu-Xianza rift, TYR = Tangra Yuro Co rift, YGR = Yadong-Gulu rift, YRR = Yari rift. Abbreviations for porphyry copper deposits: BR = Bairong, CJ = Chongjiang, DB = Dabu, GJ = Gangjiang, JM = Jiama, JR = Jiru, LKE = Lakange, QL = Qulong, TG = Tinggong, ZN = Zhunuo.

Fig. 9. $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ values versus Cu metal tonnage (Mt) for porphyry copper deposits. Data for zircon Hf and bulk-rock Nd isotopes and metal tonnage for deposits are listed in Appendix A5. The line and symbol (circle, square, triangle) for each deposit denote the range and average of $\varepsilon_{\text{Hf}}(t)$ and $\varepsilon_{\text{Nd}}(t)$ values (note that some symbols are not in the middle of lines because the lines represent the range of value rather than $2\sigma$).
fluid exsolution, and ore-forming processes all play roles in determining Cu endowment and grades (Tosdal and Richards, 2001; Chiariadha, 2014; Zhang and Audetâé, 2017).

Conclusions

Gangdese Paleocene-Eocene igneous rocks and Miocene granitoids have systematic along-arc isotopic variations, characterized by bulk-rock εHf(t) and zircon εHf(t) values increasing from −84° to −92°E and decreasing from −92° to −95°E. The amounts of subducted Indian continental materials involved in mantle metasomatism decreased from −84° to −92°E and then increased from −92° to −95°E during the Paleocene-Eocene due to variations in the subduction angle of the segmented Indian slab. The Miocene porphyry Cu deposits are located above a steeper Indian slab segment, and their genesis involved Indian plate-released fluids, metasomatized mantle-derived magmas, and Tibetan lower crust. Our results highlight that caution must be taken when using Nd-Hf isotopes for predicting metal endowment of porphyry deposits.

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