Northward subduction of a spreading ridge within the Bangong Co–Nujiang Tethys Ocean: Evidence from Early Cretaceous mafic dykes in the Duolong porphyry Cu–Au deposit, western Tibet

Wei Xu^a, Cai Li^{a,*}, Ming Wang^a, Jian-jun Fan^a, Hao Wu^a, Xin Li^b

Abstract: The intrusion of mafic dykes into a near-trench accretionary prism, and continental margin magmatism with characteristics that differ from those of adjacent arc magmatism, are direct manifestations of the subduction of a spreading ridge and the formation of a slab window. In this paper, we investigated mafic dykes intruded into the accretionary prism that hosts the Duolong porphyry Cu–Au deposit (DCAD) of western Tibet. LA–ICP–MS analysis of U–Pb in zircon indicates that the dykes formed during the Early Cretaceous (126–127 Ma). The dykes are characterized by $\epsilon_{\text{Hf}}(t)$ values from +2.44 to +11.8. Twenty-nine mafic dyke samples were divided into three groups based on their locations and geochemical compositions: group I has Nb = 8.31–10.2 ppm, Nb/La = 0.71–1.20, and Nb/U = 21.4–37.9; group II has Nb = 40.5–52.6 ppm, Nb/La = 0.84–1.58, and Nb/U = 18.8–47.8; and group III has Nb =

65.7–105 ppm, Nb/La = 1.35–2.08, and Nb/U = 36.5–73.8. Group I is classified as Nb-enriched basalts (ENBs), whereas groups II and III are classified as high-Nb basalts (HNBs). Both the ENBs and HNBs were derived from an adakite-metasomatized mantle wedge that subsequently underwent crystallization of olivine and clinopyroxene. The compositional variations of the studied dykes resulted mainly from mantle source heterogeneity. The volume of the slab melts that reacted the mantle wedge gradually increases from group I (ENBs) to group II (HNBs) and group III (HNBs), leading to their gradually increasing incompatible element concentrations. Considering their geochemical characteristics and field relationships, as well as the unique characteristics of continental margin magmatism in the DCAD, we propose that the dykes were emplaced in an extensional accretionary prism that formed during the northward subduction of a spreading ridge in the Bangong Co–Nujiang Tethys Ocean during the Early Cretaceous. The ridge subduction event was also responsible for the generation of coeval adakites, intermediate–felsic intrusions, and the Maierze bimodal volcanic rocks, and for the metallogensis of the DCAD.

38

Key words: Mafic dykes, High-Nb basalts, Duolong Cu–Au porphyry deposit, Ridge subduction, Early Cretaceous, Tibet

41

42

43

44

1. Introduction

Mafic dykes are generated by the crystallization of basaltic melt from the mantle (Qiu, 1985; Elthon, 1987). Such dykes that form along faults under an extensional regime can provide important geological information about the composition of mantle material, the nature of crust–mantle interactions, the regional tectonic evolution, and supercontinent assemblage and dispersion (Halls, 1982; Parker et al., 1990; Ernst et al., 1995; Hoek et al., 1995; Li et al., 1997; Liu et al., 2008; Hou et al., 2008; Maurice et al., 2009; Cai et al., 2010; Xu et al., 2012; Tang et al., 2012a; Srivastava and Gautam, 2014; Wang et al., 2015; Xu et al., 2015a). These dykes are found in continental and oceanic settings, and in the ocean–continent transition zone. The mechanisms responsible for the formation of mafic dykes can be summarized as follows: (1) upwelling of a mantle plume and generation of a hot spot (Ernst et al., 1997; Zhang and Zou, 2012; Fan et al., 2014; Wang et al., 2015; Xu et al., 2015a); (2) mid-ocean ridge spreading (Lissenberg et al., 2004); (3) slab roll-back (Tang et al., 2012a); (4) slab break-off (Xu et al., 2008; Song et al., 2011); and (5) post-orogenic collapse and delamination (Liu et al., 2008; Xu et al., 2012; Dai et al., 2015). An increasing number of studies indicate that interaction between a spreading ridge and a trench, known as ridge subduction, can also generate mafic dykes with various geochemical characteristics, including boninites, depleted mid-ocean ridge basalts (MORBs), Nb-enriched basalts (ENBs), high-Nb basalts (HNBs), enriched ocean island basalts (OIBs), and transitional basalts, which can intrude into the near-trench accretionary prism, fore-arc, arc, and back-arc (Hole et al., 1991; Guivel et al., 1999,

2006; AguilloÂn-Robles et al., 2001; Benoit et al., 2002; Sisson et al., 2003; Espinozaa et al., 2005; Schoonmaker and Kidd, 2006; Cole et al., 2006; Windley et al., 2007; Pallares et al., 2007; Viruete et al., 2007; Cole and Stewart, 2009; Cai et al., 2010; Thorkelson et al., 2011; Tang et al., 2012b).

The Bangong Co–Nujiang suture zone (BNSZ) of the central Tibetan Plateau consists mainly of ophiolitic fragments and Late Triassic–Early Cretaceous flysch sediments. The zone is bounded by multiple volcanic belts to the north and south, and the Nierong and Jiayuqiao microcontinents to the east (Pan et al., 2004, 2006, 2012; Li et al., 2014a, 2014b; Chen et al., 2014, 2015; Zhang et al., 2015; Fan et al., 2015a; Xu et al., 2015b). The role of the BNSZ in the formation and early evolution of the Tibetan Plateau, including its temporal and spatial evolution, opening and closing times, and subduction polarity, has long been debated (Fan et al., 2014; Chen et al., 2014, 2015; Zhang et al., 2014; Xu et al., 2014). The magmatic rocks and ophiolites of the western BNSZ (Liu et al., 2014a, 2014b; Zhou et al., 2014; Li et al., 2014a), especially the numerous Early Cretaceous intrusions in the Duolong Cu–Au porphyry deposit (DCAD) (Li et al., 2012, 2013, 2014b, 2015; Lv, 2012; Duan et al., 2013; Chen et al., 2013; Zhu et al., 2015), have recently attracted considerable attention (Fig. 1c). However, the tectonic setting of the Early Cretaceous magmatism, the petrogenesis of the intrusions, and the ore-forming processes of the DCAD remain controversial. Two competing viewpoints have been proposed to explain the magmatism: a post-collisional setting (Qu et al., 2006), and an arc setting related to slab subduction (Li et al., 2008, 2011, 2012, 2013, 2014b, 2015; Zhu et al., 2011,

2015; Lv, 2012; Chen et al., 2013).

Previous studies mainly focused on the intermediate–felsic intrusions and the Cu–Au deposits; however, the mafic dykes, which can provide more reliable information regarding the tectonic setting than intermediate–felsic rocks, have yet to be systematically studied. In this paper, we present detailed petrological data, whole-rock geochemical analyses, U–Pb dating on zircon, and Lu–Hf isotope analyses of newly discovered mafic dykes in the DCAD. The aims are to (1) determine the crystallization age of the mafic dykes, (2) shed light on their petrogenesis, and (3) understand the extensional event in which the dykes formed in order to establish a geodynamic model for the Early Cretaceous magmatism in the DCAD.

2. Geological background and petrology

The Tibetan Plateau, located in the eastern part of the Tethys tectonic domain (Fig. 1a), is divided into the Songpan–Ganzi flysch complex, the northern Qiangtang Terrane, the southern Qiangtang Terrane, the Lhasa Terrane, and the Himalaya Terrane by the Jinsha suture zone (JSSZ), the Longmu Co–Shuanghu suture zone (LSSZ), the Bangong Co–Nujiang suture zone (BNSZ), and the Indus–Yarlung Zangbo suture zone (IYZSZ), respectively (Fig. 1b) (Li, 1987; Zhu et al., 2013). The Lhasa Terrane is further divided into the northern, central, and southern sub-terrane by the Shiquan River–Yongzhu–Jiali ophiolitic mélange belt (SYJMB) and the Luobadui–Milashan Fault (LMF), respectively (Fig. 1b) (Zhu et al., 2013; Xu et al., 2014).

The BNSZ, extending over 2000 km from Bangong Co in the west to the

Nujiang River in the east, is the tectonic collision zone between the northern Lhasa subterrane and the southern Qiangtang terrane, and is also an important polymetallic metallogenic belt in Tibet (Fig. 1b) (Li, 1987, 2008; Geng et al., 2011; Pan et al., 2012). The DCAD, which is located in the southern Qiangtang terrane, to the north of the western BNSZ, is the largest porphyry copper deposit in the Bangong Co–Nujiang metallogenic belt (Fig. 1c) (Li et al., 2011). The DCAD is composed mainly of the Duobuza, Bolong, Nadun, Naruo, Tiegelong, Dibaomamugang, and Gaerqin deposits (Fig. 2) (Duan et al., 2013). Carboniferous–Permian strata, which are the oldest sediments in the DCAD, are part of the southern Qiangtang stratigraphic region. The Late Triassic Riganpeico Group consists mostly of shallow marine limestones that formed in the Bangong Co–Nujiang Tethys Ocean (Wang and Zhong, 2002). The Jurassic strata, including the Quse and Sewa formations, which were previously considered to be bathyal to deep-sea flysch sediments (Fig. 1c), are now acknowledged as the metamorphic base of the accretionary prism that formed in response to northward subduction of the Bangong Co–Nujiang Tethys Ocean crust (Fig. 2) (Duan et al., 2013). The Early Cretaceous volcanic–sedimentary strata, known as the Meiriquieco Group, consist mainly of volcanic rocks with island-arc affinities, and minor volcanoclastic rocks. The Late Cretaceous Abushan Group, which consists of conglomerates and sandstones, represents post-collisional molasse deposits of the BNSZ.

Many felsic intrusions (porphyritic granites, porphyritic granodiorites, granodiorites, and monzonitic granites) and minor intermediate intrusions (diorites

and porphyritic diorites) have been reported in the accretionary prism in the DCAD (Fig. 2) (Qu et al., 2006; Li et al., 2008, 2011, 2012, 2013, 2014b, 2015; Lv, 2012; Chen et al., 2013; Zhu et al., 2015). The ore-forming rocks are mainly porphyritic granodiorites. All intermediate–felsic intrusions with the characteristics of volcanic-arc rocks, including ore-bearing and barren intrusions, have similar emplacement ages (116–128 Ma) (Fig. 2). Furthermore, some ore-bearing porphyritic granodiorites with adakitic geochemical characteristics in the Duobuza deposit also formed during the Early Cretaceous, yielding a U–Pb zircon age of 121.6 ± 1.9 Ma (Fig. 2) (Li et al., 2008). The mineralization ages of the DCAD are consistent with the estimated ages of the intrusions, as follows: (1) molybdenite from the Duobuza deposit yields a Re–Os age of 118 ± 1.5 Ma (Fig. 2) (She et al., 2009); and (2) molybdenite from the Bolong deposit yields a Re–Os age of 119.4 ± 1.3 Ma (Fig. 2) (Zhu et al., 2011, 2015).

Previous studies have proposed various interpretations of the geological setting of the ore-forming processes in the DCAD. For example, Qu and Xin (2006) suggested that the DCAD was generated at shallow depths during a post-collisional crustal uplift. Duan et al. (2013) and Zhu et al. (2011, 2015) concluded that the DCAD is an island-arc porphyry copper deposit that formed in an accretionary prism. She et al. (2009) suggested that the formation of the DCAD was related to ridge subduction. The majority of researchers agree that the DCAD is an island-arc or continental arc porphyry copper deposit related to the northward subduction (i.e., non-ridge) of the Bangong Co–Nujiang Tethys Ocean crust during the Early

Cretaceous (Li et al., 2008, 2011, 2012, 2013, 2014b, 2015; Chen et al., 2013).
Outcrops of the Maierze bimodal volcanic rocks (MZBVR), which yield U–Pb zircon
ages of 120 Ma (dacites) and 122 Ma (basalts), were recently discovered in the
northern part of the DCAD and are considered to represent a back-arc basin that
resulted from slab roll-back of the Bangong Co–Nujiang Tethys Ocean crust (Fig. 2)
(Fan et al., 2015b).

In contrast to the widely distributed granitoids in the DCAD, mafic rocks are
relatively sparse (Fig. 2). ENBs (basalts and porphyritic diabases) of unknown age
have been reported, and were proposed to have been derived from the
adakite-metasomatized mantle wedge during the Early Cretaceous (Li et al., 2008).
However, based on field observations, Duan et al. (2013) argued that all the mafic
rocks in the area are fragments of oceanic crust. Based on recent geological data, the
mafic rocks in the DCAD can be divided into mafic dykes, related basalts, and
fragments of oceanic crust (Fig. 2). The latter, including ocean islands and ophiolitic
fragments, have been tectonically emplaced in the accretionary prism (Fig. 2). The
mafic dykes have arc-type characteristics (Fig. 2) and commonly intrude the
accretionary prism with obvious intrusive boundaries (Fig. 3A, B and C). Enclaves of
sandstone occur at the margin of one of mafic dykes (10–15 m long and 3–4 m wide)
(Fig. 3D). The mafic dykes typically show a gabbroic texture comprising platy
plagioclase (50%) and euhedral to subhedral pyroxene (45%), both 0.5–2.0 mm in
size (Fig. 3E, F). Some pyroxene crystals have been replaced by chlorite, and the
plagioclase crystals, which contain polysynthetic twins and typical Carlsbad–albite

compound twins, are weakly altered to clay (Fig. 3E, 3F). The mafic dykes variably carbonated and contain variable amounts of opaque minerals (Fig. 3E, F). The surrounding rocks are strongly deformed and consist of interbedded sandstone and shale (Fig. 3A, B, G and H). Cast structures are apparent on the undersides of bedding planes (Fig. 3I). These rocks were originally continental-margin flysch sediments that were incorporated into the metamorphic base of the accretionary prism that resulted from the northward subduction of the Bangong Co–Nujiang Tethys Ocean crust (Duan et al., 2013).

3. Analytical methods

3.1. Major and trace elemental analyses

Whole-rock geochemical analyses were carried out at the ICP–OES and laser ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS) laboratories at China University of Geoscience, Beijing, China. Major element abundances were determined using PS-950 X-ray fluorescence spectrometry (XRF) and trace element compositions were determined using an Agilent 7500 inductively coupled plasma–emission mass spectrometer (ICP–MS). Analytical accuracy is generally better than 1 wt% for all major elements. The analytical results for the AGV-2 (US Geological Survey) and GSR-3 (National Geological Standard Reference Materials of China) standards indicate that the accuracy is better than 5% for trace elements. Details of the analysis and reference materials are reported in Yu (2011).

3.2. LA–ICP–MS zircon U–Pb analyses

Zircon grains were separated using heavy-liquid and magnetic methods in the

Laboratory of the Geological Team of Hebei Province, Langfang, China. To reveal the internal structures, cathodoluminescence (CL) images were obtained at the Institute of Physics, Peking University, China. Based on the CL images, distinct domains within the zircons were selected for U–Pb analysis by LA–ICP–MS at the Geological Laboratory Centre, China University of Geosciences, Beijing, China. Uncertainties for the age analyses are given as 1σ values, and weighted mean ages are provided along with the 95% confidence level. Isotopic data were processed using the GLITTER (version 4.4) and Isoplot/Ex (version 3.0) programs (Ludwig et al. 2003). Common Pb was corrected following Andersen (2002). Analytical details of reference materials are reported in Yuan et al. (2004).

3.3. Zircon Hf analyses

In situ Hf isotope analyses were conducted using a Neptune Plus multi-collector ICP–MS (MC–ICP–MS) (Thermo Fisher Scientific, Germany) in combination with a Geolas 2005 excimer ArF laser ablation system (193 nm) at the Institute of Tibetan Plateau, Chinese Academy of Sciences, Beijing, China. Details of the operating conditions for the laser ablation system and the MC–ICP–MS instrument, as well as the analytical method, are given in Hu et al. (2012). The measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratio for the analyzed zircon standard (91500) was 0.282299 ± 31 ($2\sigma_n$, $n = 40$), which is similar to $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282302 ± 8 and 0.282306 ± 8 (2σ) determined by the solution method. Off-line selection and integration of analyte signals and mass bias calibrations were performed using the ICPMSDataCal program.

4. Results

Whole-rock geochemical data, U–Pb analyses and Hf isotopic compositional data from the mafic dykes are listed in Supplementary Tables 1–3, respectively. Petrographic observations and loss-on-ignition (LOI) values of 3.07–9.08 wt% show that most of the samples have undergone weak to moderate alteration. Previous studies have shown that large ion lithophile elements (LILEs; e.g., Rb, K, and Sr) are mobile during metamorphism and alteration (Polat and Hofmann, 2003). Conversely, the high field strength elements (HFSEs; e.g., Nb, Ta, Zr, Hf, and Ti), rare earth elements (REEs; e.g., La, Ce, and Sm), and Th are largely immobile during post-magmatic processes (Polat and Hofmann, 2002). Therefore, only relatively immobile elements are considered in the following geochemical analysis.

4.1. Geochemistry

4.1.1. Geochemical classification

To determine the petrogenesis of the mafic dykes from the DCAD, 29 samples from three locations (DCT18, DCT10 and DCT27) were selected for whole-rock geochemical analyses. Although they have basaltic compositions, the mafic dykes are compositionally diverse and were divided into three groups based on their locations and geochemical compositions (Supplementary Material 1): group I (DCT18) with 8.31–10.2 ppm Nb, group II (DCT10) with 40.5–52.6 ppm Nb, and group III (DCT27) with 65.7–105 ppm Nb. In the Nb/Y versus Zr/TiO₂ classification diagram (Fig. 4a), groups II and III are alkaline basalts and group I is sub-alkaline basalts. Furthermore, the TFe₂O₃/MgO versus SiO₂ diagram indicates that the group I dykes are tholeiitic

(Fig. 4b).

ENBs and HNBS which are commonly associated with high-Mg andesites and adakites are different rock types from island arc basalts, OIBs and other intraplate lavas (Hastie et al., 2011). According to Sajona et al. (1993, 1996), Castillo et al. (2007) and Hastie et al. (2011), ENBs are enriched in LILEs, LREEs, and HFSEs (Nb = 5–20 ppm), and have weakly negative or positive primitive mantle-normalized Nb and Ta anomalies. Conversely, HNBS are more enriched in LILEs, LREEs, and HFSEs (Nb > 20 ppm) than NEBs and can have trace element compositions similar to OIBs, continental alkaline basalts, and alkaline basalts. The dykes from group I are classified as NEBs based on their high Nb concentrations (Nb = 8.31–10.2 ppm) and enriched LREEs, whereas those from groups II and III are classified as HNBS based on their even higher Nb concentrations (Nb = 40.5–52.6 and 65.7–105 ppm, respectively) and LREE contents. These classifications are supported by the Nb/La and Nb/U ratios of group I (Nb/La = 0.71–1.20 and Nb/U = 21.4–37.9), group II (Nb/La = 0.84–1.58 and Nb/U = 18.8–47.8), and group III (Nb/La = 1.35–2.08, and Nb/U = 36.5–73.8) (Fig. 4c, d). The HNBS from groups II and III also show characteristics of OIBs, intraplate basalts and continental flood basalts on various tectonic discrimination diagrams (Fig. 5).

4.1.2. Major elements

Group I, II, and III dykes all have similar SiO₂ contents of 46.2–54.1 wt%, 44.1–53.1 wt%, and 44.2–53.7 wt%, respectively. Group I dykes have narrow range of Mg numbers (Mg[#] = 55.1–60.9), while group II dykes have a wider range of Mg

numbers ($Mg^\# = 48.2\text{--}62.0$) and the $Mg^\#$ of group **III** dykes extends to lower values (47.3–53.9) than groups **I** and **II**. The Mg numbers of these samples are lower than those of primary basalts, indicating that they have undergone fractional crystallization. However, plots of major element oxides versus $Mg^\#$ show a wide scatter (Fig. 6), suggesting that the compositional variations between the groups cannot be ascribed to fractional crystallization.

4.1.3. Compatible trace elements

The concentrations of compatible elements (Ni and Cr) in the studied dykes are low compared with primary basalts (Ni = 300–400 ppm, Cr = 300–500 ppm; Frey et al., 1978), indicating that the dykes have undergone fractional crystallization. However, the relatively large scatter on the Cr and Ni versus $Mg^\#$ plots shows that the studied dykes were not generated from a homogeneous melt through simple fractionation (Fig. 6). The well-defined positive correlations between Cr, Ni, and $Mg^\#$ suggest that the magmas that formed the group **I** and **II** dykes underwent fractionation of olivine and pyroxene. Group **III** dykes have the lowest concentrations of Ni and Cr, and the lowest $Mg^\#$ of the studied dykes, which we interpret to reflect the extensive fractionation of olivine and pyroxene, although Cr and Ni versus $Mg^\#$ plots show no obvious linear relationships.

4.1.4. Rare earth and other incompatible trace elements

Incompatible elements concentration significantly increases during fractional crystallization. The non-linear relationships between $Mg^\#$ and La and Nb contents further indicate that the compositional variations among the studied dykes cannot be

explained by fractional crystallization (Fig. 6). Each group of dykes shows sub-parallel and right-sloping chondrite-normalized REE patterns with negligible Eu anomalies (Fig. 7). The (La/Sm)_N ratios gradually increase from group I (1.34–1.51) to group II (2.74–3.21) and group III (3.24–3.67), and the (Gd/Yb)_N ratios gradually decrease from group II (3.42–3.72) to group III (2.44–3.17) and group I (2.09–2.18). On primitive-mantle-normalized multi-element diagrams (Fig. 7), group I dykes are characterized by negative or positive Nb anomalies and weakly negative Zr and Hf anomalies, group II dykes have significantly negative Zr, Hf and Ti anomalies that are typical of island-arc magmas, and group III dykes show positive Nb anomalies and negligible Zr, Hf, and Ti anomalies.

4.2. Geochronology

Three mafic dykes (DCT10, DCT18 and DCT27) were selected for LA–ICP–MS analysis on zircon (Fig. 2). Only samples from DCT10 and DCT18 yielded concordant ages. Although the ages from DCT27 are not concordant, the ages of the three youngest zircons are similar to the concordant ages obtained from DCT10 and DCT18. The zircons from DCT10 are mostly hypidiomorphic laths, 60–120 μm in size, with wide concentric oscillatory zoning, and high length-to-width ratios (Fig. 8). All the zircons have relatively high Th/U ratios (0.32–1.13; average, 0.61) (Supplementary Material 2). The zircons from DCT18 are also mostly hypidiomorphic laths with wide concentric oscillatory zoning, high length-to-width ratios (Fig. 8), and high Th/U ratios (0.30–0.60; average, 0.38) (Supplementary Material 2), although they have a larger grain size (200–300 μm) than those from

DCT10 (Fig. 8). The three youngest zircons from DCT27 are irregular in shape and 80–180 μm in size (Fig. 8), with wide concentric oscillatory zoning and high Th/U ratios of 0.51, 0.48, and 0.74 (Supplementary Material 2). These characteristics indicate that the zircons from both DCT10 and DCT18 are magmatic and formed during the crystallization of the mafic dykes (Hoskin and Schaltegger, 2003).

A total of 19 zircon analyses from DCT10 yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 126.6 ± 1.8 Ma (95% confidence level; MSWD = 2.0) (Fig. 8), and 22 zircon analyses from DCT18 yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 126.2 ± 1.0 Ma (95% confidence level; MSWD = 0.92) (Fig. 8). These ages are interpreted as the crystallization ages of the mafic dykes. In addition, the three youngest zircons from DCT27 formed at 110 ± 2 , 122 ± 3 , and 133 ± 4 Ma (Fig. 8), suggesting that the three mafic dykes have same emplacement ages.

4.3. Lu–Hf isotope analysis

Thirteen dated zircon grains from DCT10 and 14 from DCT18 were selected for Hf isotope analysis. The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of DCT10 varied from 0.282769 to 0.283023, and the $\epsilon_{\text{Hf}}(t)$ values and single-stage Hf model ages (TDM1) ranged from +2.44 to +11.6 and from 326 to 697 Ma, respectively (Supplementary Material 3). The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of DCT18 varied from 0.282875 to 0.283030, and the $\epsilon_{\text{Hf}}(t)$ values and single-stage Hf model ages (TDM1) ranged from +6.26 to +11.8 and from 319 to 547 Ma, respectively (Supplementary Material 3).

5. Discussion

5.1. Crustal contamination

Since the mafic dykes of the present study intruded sediments, it is necessary to evaluate if their parental magmas were contaminated by crustal material during ascent. All the mafic dykes have low SiO₂ and elevated Mg[#] values (Supplementary Material 1), indicating negligible crustal contamination. Crustal materials are rich in LILE, Zr and Hf, and depleted in Nb and TiO₂ (Nb = 8 ppm; Rudnick and Gao, 2003). Therefore, minor crustal contamination will result in negative Nb-Ta anomalies relative to LILEs and LREEs, and positive Zr-Hf anomalies (Rudnick and Gao, 2003; Zhao and Zhou, 2007). The negative and negligible Zr-Hf anomalies observed in the primitive-mantle-normalized multi-element diagrams for the studied dykes support crustal contamination was insignificant (Fig. 7). All dyke samples (except for the DCT10H1) plot within or near the field of most oceanic basalts on the (Th/Nb)_{PM} versus (La/Nb)_{PM} diagram (Fig. 9), also suggesting the continental crust input is insignificant (Frey et al., 2002).

5.2. Mantle source heterogeneity or partial melting

Each group of dykes displays sub-parallel REE patterns and primitive-mantle-normalized trace-element spidergrams, indicating that each group was generated from a common magma source (Fig. 7). As discussed above, crustal contamination was insignificant for the studied dykes, and fractional crystallization cannot produce their observed geochemical diversity. Therefore, it is necessary to consider whether this compositional variation was caused by mantle source

heterogeneity or by variable degrees of partial melting from a common mantle source (Zhu et al., 2008). The Th/Ta versus Th/Tb diagram is an effective method to characterize the mantle source and the effects of partial melting, and can minimize the effects of magmatic differentiation (Saunders et al., 1988; Rollinson, 1993). With the exception of the assimilated sample (DCT10H1), three distinct mantle sources are identified for the studied dykes in Fig. 10a. The Sm/Yb-La/Sm diagram supports the three groups were derived from different mantle sources (Fig. 10b). The higher incompatible element concentrations of group II and group III dykes suggest that they were derived from a more enriched mantle source than those in group I.

5.3. Mantle source

The petrogenesis of HNBs and NEBs remains debated. Generally, they are regarded as forming either from: (1) mixing between an enriched or OIB-like mantle and depleted MORB-type upper mantle (Reagan and Gill, 1989; Castillo et al., 2007; Castillo, 2008); or (2) a mantle wedge metasomatized by slab melt (Sajona et al., 1993, 1996; Kepezhinskas et al., 1996). Massive Early Cretaceous intermediate–felsic intrusions in the DCAD have compositions with arc magma affinities, indicating the interaction of slab-derived fluids and a mantle wedge (Li et al., 2008, 2015; Chen et al., 2013). Early Cretaceous adakites with U–Pb zircon ages of 121.6 ± 1.9 Ma have been reported in the DCAD (Fig. 2) (Li et al., 2008), and these slab melts could have interacted with the mantle wedge during ascent. Most of the HNBs and ENBs in the present study plot above the MORB–OIB array in Th/Yb and Nb/Yb diagram (Fig. 11) (Pearce, 2008), suggesting that the source region of the ENBs and HNBs was

contaminated with minor melts of subducted sediments. The variable zircon $\epsilon_{\text{Hf}}(\text{t})$ values (+2.44 to +11.8) also suggest that the mafic dykes were derived from a depleted mantle source that was contaminated by minor subduction-related material. Therefore, we suggest that the NEBs and HNBs in the present study were formed through metasomatism of the mantle wedge by slab-derived melts.

Partial melting of the subducting altered oceanic crust may have produced melts of adakitic composition that reacted with the mantle wedge, forming Ti-enriched phases (phlogopite, rutile, and amphibole) when the melts intruded the accretionary prism through the wedge (Sen and Dunn, 1994; Sajona et al., 1996; Kepezhinskas et al., 1996; Rapp et al., 1999; Prouteau et al., 2001; Benoit et al., 2002). The Ti-enriched phases would have been unstable and would have melted along with the mantle wedge, leading to the formation of Nb-enriched and high-Nb basaltic magmas (Arculus and Powell, 1986; Ryerson and Watson, 1987; Kepezhinskas et al., 1996; Sajona et al., 1996; Benoit et al., 2002). The interaction between different volumes of the slab melts and the mantle wedge would have been important in producing the heterogeneity in the mantle source (Rapp et al., 1999). Therefore, more incompatible element-enriched dykes were derived from a mantle wedge contaminated with larger volumes. In other words, the volume of the slab melts that reacted the mantle wedge gradually increases from group I (ENBs) to group II (HNBs) and group III (HNBs).

5.4. Unique characteristics of magmatism in the DCAD

The well-defined U–Pb zircon ages of 126 ± 1 and 127 ± 2 Ma obtained for the mafic dykes in this study indicate that the mafic component of Early Cretaceous

magmatism in the DCAD is greater than previously thought. Comparative studies suggest that the Early Cretaceous magmatism in the DCAD has characteristics that differ from those of adjacent arc magmatism (the adjacent area includes the Rutog–Caima–Fuye magmatic belt, Qingcaoshan, Liqunshan, and Rena Co), as follows. (1) The magmatism in the DCAD is developed on the basis of an Jurassic accretionary prism, whereas adjacent arc magmatism intruded into Carboniferous–Late Triassic strata. (2) The DCAD is characterized by voluminous Early Cretaceous magmatism, with minor or no Jurassic magmatism, whereas the adjacent areas contain widespread Jurassic intrusions and minor Early Cretaceous intrusions (Fig. 1c). (3) The Early Cretaceous magmatism of the DCAD is manifested as mafic–intermediate–felsic rocks (Fig. 2), whereas no mafic dykes crop out in the adjacent areas (Fig. 1c). (4) The intermediate–felsic intrusions and enclaves in the adjacent areas have zircon $\epsilon_{\text{Hf}}(t)$ values from -19.4 to $+4.1$ (Fig. 12), whereas the intermediate–felsic intrusions in the DCAD have positive values ($+3.5$ to $+11.2$) (Fig. 12). (5) The intrusions in the near-trench accretionary prism in the DCAD exhibit bimodal characteristics with a minor intermediate component (Fig. 2). (6) Finally, the intermediate–felsic intrusions in the DCAD are mostly rounded to ellipsoidal in horizontal cross-section (Fig. 2), which is unusual in a typical subduction setting and therefore indicates an extensional tectonic regime (Cole et al., 2006; Cole and Stewart, 2009; Tang et al., 2010).

The Jurassic intermediate–felsic intrusions in the areas adjacent to the DCAD display geochemical characteristics typical of volcanic arc rocks and are

believed to have formed in a continental arc setting during northward subduction of the Bangong Co–Nujiang Ocean crust (Li et al., 2014a, 2014b). This observation is consistent with the data from Jurassic SSZ-type ophiolitic fragments in the western BNSZ. For example, gabbros and basaltic andesites from the Bangong Co ophiolite have zircon U–Pb ages of 167.0 ± 1.4 and 163.9 ± 0.7 Ma, respectively (Shi et al., 2007; Zhou et al., 2014), and gabbros from the Rebang Co ophiolite yield a zircon U–Pb age of 161.5 ± 1.5 Ma (Liu et al., 2014a) (Fig. 1c). Many different interpretations of the Early Cretaceous tectonic regime in the DCAD have been presented. Here we propose an extensional tectonic regime based on the characteristics of Early Cretaceous magmatism and the mafic dykes, as described above.

5.5. Tectonic significance

Many researchers have considered the Early Cretaceous intermediate–felsic intrusions in the DCAD to be the result of northward subduction (i.e., non-ridge) of the Bangong Co–Nujiang Ocean crust (Li et al., 2008, 2011, 2012, 2013, 2014b, 2015; Zhu et al., 2011, 2015; Lv, 2012; Duan et al., 2013; Chen et al., 2013). However, this model cannot explain the extensional tectonic setting indicated by the coeval mafic dykes described in this paper. Any proposed geodynamic model for interpreting the formation of the Early Cretaceous magmatism in the DCAD must consider the following points: (1) the unique characteristics of magmatism in the DCAD; (2) the existence of an extensional tectonic regime; (3) interaction between the mantle wedge and slab melts; and (4) the formation of a large gold-rich porphyry copper deposit. An

explanation invoking a mantle plume and the generation of a hot spot cannot explain the arc-like geochemical signatures and the diversity of the Early Cretaceous magmatism in the DCAD. Post-orogenic collapse, delamination, and slab break-off might explain the generation of the mafic dykes; however, recent studies on ophiolites and ocean islands suggest that the Bangong Co–Nujiang Ocean basin was still of significant size during the Early Cretaceous (Zhu et al., 2006; Bao et al., 2007; Zhang, 2007; Fan et al., 2014, 2015a; Xu et al., 2014, 2015b; Liu et al., 2014a). Furthermore, slab break-off is commonly triggered by continental subduction and can hardly account for the great diversity of near-trench magmatism in the DACD (Benoit et al., 2002; Chen et al., 2014; Chung et al., 2005). Slab roll-back is also an unlikely mechanism because this process usually results in a linear zone of magmatism in the back-arc region (Tang et al., 2012a ; Li et al., 2014c; Fan et al., 2015b). Instead, we support a model in which the intrusion of mafic dykes into a near-trench accretionary prism and the generation of continental margin magmas with different characteristics from adjacent arc magmas are direct manifestations of the subduction of a spreading ridge and the formation of a slab window (Sisson et al., 2003; Schoonmaker and Kidd, 2006; Windley et al., 2007; Cole and Stewart, 2009).

6. Ridge subduction model

Ridge subduction is a reasonably common geological event and appears to play an important role in modern orogenesis, such as in Alaska, California, Japan, the western USA, Canada, Chile, Patagonia, Mexico, and the Caribbean (Hole et al., 1991; Guivel et al., 1999, 2006; Aguillo-Ân-Robles et al., 2001; Benoit et al., 2002;

Kinoshita, 2002; Espinoza et al., 2005; Cole et al., 2006; Pallares et al., 2007; Jolly et al., 2008; Cole and Stewart, 2009; Boutonnet et al., 2010; Thorkelson et al., 2011). It has also been reported in ancient orogenic belts, such as the Central Asian Orogenic Belt and the Yarlung–Tsangpo suture zone (Windley et al., 2007; Geng et al., 2009; Cai et al., 2010; Tang et al., 2010, 2012b; Zhang et al., 2010; Zheng et al., 2014). Ridge subduction along a continental margin may result in the development of a slab window and related asthenospheric upwelling, thereby having a strong influence on magmatism, metamorphism, and mineralization on the continental margin (Cole and Stewart, 2009; Tang et al., 2012b). Asthenospheric upwelling through a slab window would lead to the generation and emplacement of magmas with unique geochemical characteristics within arc-front, forearc, and accretionary prism settings (Cole and Stewart, 2009). Moreover, ridge subduction would result in the waning of, or a complete hiatus in, adjacent arc magmatism (Cole and Stewart, 2009).

The DCAD examined in this study may have been the site of Early Cretaceous ridge subduction and the formation of a slab window (Fig. 13). When the spreading ridge of the Bangong Co–Nujiang Ocean reached the trench of southern Qiangtang terrane during the Early Cretaceous, upwelling of asthenospheric mantle material through the slab window meant that the accretionary prism entered an extensional setting (Fig. 13). Adakitic magmas were generated from partial melting of the oceanic crust at the edges of the slab window due to heat transfer from the upwelling mantle (Fig. 13). Partial melting of adakite-metasomatized mantle wedge in the slab window produced the mafic dykes with the characteristics of NEBs and HNBs (Fig. 13). The

intermediate–felsic intrusions which have positive zircon $\epsilon_{\text{Hf}}(t)$ values (+3.5 to +11.2) most likely have originated from partial melting of juvenile crust or magma mixing between mantle-derived and crust-derived melts. The coeval MZBVR are also consistent with ridge subduction, similar to the volcanism in the northeastern Puerto Rican Virgin Islands (Jolly et al., 2008). Finally, ridge subduction and the development of a slab window may also have been responsible for the formation of the DCAD, given the genetic link between ridge subduction and Cu–Au porphyry deposits (Haeussler et al., 1995; Sun et al., 2010; Tang et al., 2012b).

7. Conclusion

Early Cretaceous mafic dykes that intrude the near-trench accretionary prism in the DACD yield zircon U–Pb emplacement ages of 126–127 Ma, which are similar to those of intermediate–felsic intrusions, adakites, and the MZBVR, and are consistent with the age of formation of Cu–Au porphyry deposits in the DCAD. The mafic dykes are classified as Nb-enriched and high-Nb basalts, and were derived from the adakite-metasomatized mantle wedge in an extensional tectonic setting. The Early Cretaceous magmatism in the DACD has different characteristics from adjacent arc magmatism, which may reflect the subduction of a spreading ridge and the formation of a slab window. Such a model also explains the generation of the Cu–Au porphyry deposits in the DCAD.

Acknowledgements

We thank Mr Xie Chaoming, Mr Peng Hu, Mr Jiang Qingyuan, for their help in the field. We also thank reviewers and Dr. Zhang Zeming for their comments and

suggestions. This research was supported by the National Science Foundation of China (Grant No. 41072166, 41272240, 41273047) and China Geological Survey project (Grant No. 1212011221093, 1212011121248, 12120113036700).

References

AguilloÂn-Robles, A., Calmus, T., Benoit, M., Bellon, H., Maury, R.C., Cotton, J., Bourgois, J., Michaud, F., 2001. Late Miocene adakites and Nb-enriched basalts from Vizcaino Peninsula, Mexico: Indicators of East Pacific Rise subduction below southern Baja California? *Geology* 29, 531–534.

Aldanmaz, E., Pearce, J.A., Thirlwall, M.F., Mitchell, J.G., 2000. Petrogenetic evolution of late Cenozoic, post-collision volcanism in western Anatolia, Turkey. *Journal of Volcanology and Geothermal Research* 102, 67–95.

Anderson, T., 2002. Correction of common lead in U–Pb analyses that do not report ²⁰⁴Pb. *Chemical Geology* 192, 59–79.

Arculus, R.J., Powell, R., 1986. Source component mixing in the regions of arc magma generation. *Journal of Geophysical Research* 91(B6), 5913–5926.

Bao, P.S., Xiao, X.C., Su, L., Wang, J., 2007. Petrological, geochemical and chronological constraints for the tectonic setting of the Dongco ophiolite in Tibet. *Science in China Series D. Earth Sciences* 50, 660–671 (in Chinese with English abstract).

Benoit, M., AguilloÂn-Robles, A., Calmus, T., Maury, R.C., Bellon, H., Cotton, J., Bourgois, J., Michaud, F., 2002. Geochemical Diversity of Late Miocene

Volcanism in Southern Baja California, Mexico: **Implication of mantle and**
crustal sources during the opening of an Asthenospheric window. The Journal of
Geology 110, 627–648.

Boutonnet, E., Arnaud, N., Guivel, C., Lagabrielle, Y., Scalabrino, B., Espinoza, F.,
2010. Subduction of the South Chile active spreading ridge: A 17 Ma to 3 Ma
magmatic record in central Patagonia (western edge of Meseta del Lago Buenos
Aires, Argentina). Journal of Volcanology and Geothermal Research 189,
319–339.

Cai, K.D., Sun, M., Yuan, C., Zhao, G.C., Xiao, W.J., Long, X.P., Wu, F.Y., 2010.
Geochronological and geochemical study of mafic dykes from the northwest
Chinese Altai: Implications for petrogenesis and tectonic evolution. Gondwana
Research 18, 638–652.

Castillo, P.R., 2008. Origin of the adakite–high-Nb basalt association and its
implications for postsubduction magmatism in Baja California, Mexico.
Geological Society of America Bulletin **120**, 451–462.

Castillo, P.R., Rigby, S.J., Solidum, R.U., 2007. Origin of high field strength element
enrichment in volcanic arcs: geochemical evidence from the Sulu Arc, southern
Philippines. Lithos 97, 271–288.

Chen, H.A., Zhu, X.P., Ma, D.F., Huang, H.X., Li, G.M., Li, Y.B., Li, Y.C., Wei, L.J.,
Liu, C.Q., 2013. Geochronology and Geochemistry of the Bolong Porphyry
Cu-Au Deposit, Tibet and Its Mineralizing Singnificance. Acta Geologica Sinica
87, 1593–1611 (in Chinese with English abstract).

- 548 Chen, S.S., Shi, R.D., Gong, X.H., Liu, D.L., Huang, Q.S., Yi, G.D., Wu, K., Zou,
549 H.B., 2015. A syn-collisional model for Early Cretaceous magmatism in the
550 northern and central Lhasa subterrane. *Gondwana Research*, DOI:
551 <http://dx.doi.org/10.1016/j.gr.2015.04.008>.
- 552 Chen, Y., Zhu, D.C., Zhao, Z.D., Meng, F.Y., Wang, Q., Santosh, M., Wang, L.Q.,
553 Dong, G.C., Mo, X.X., 2014. Slab breakoff triggered ca. 113 Ma magmatism
554 around Xainza area of the Lhasa Terrane, Tibet. *Gondwana Research* 26,
555 449–463.
- 556 Chung, S.L., Chu, M.F., Zhang, Y.Q., Xie, Y.W., Lo, C.H., Lee, T.Y., Lan, C.Y., Li,
557 X.H., Zhang, Q., Wang, Y.Z., 2005. Tibetan tectonic evolution inferred from
558 spatial and temporal variations in post-collisional magmatism. *Earth-Science*
559 *Reviews* 68 (3–4), 173–196.
- 560 Cole, R., Nelson, S.E., Layer, P.W., Oswald, P.J., 2006. Eocene volcanism above a
561 depleted mantle slab window in southern Alaska. *Geology Society of America*
562 *Bulletin* 118, 140–158.
- 563 Cole, R.B., Stewart, B.W., 2009. Continental margin volcanism at sites of spreading
564 ridge subduction: Examples from southern Alaska and western California.
565 *Tectonophysics* 464, 118–136.
- 566 Dai, L.Q., Zhao, Z.F., Zheng, Y.F., 2015. Tectonic development from oceanic
567 subduction to continental collision: Geochemical evidence from postcollisional
568 mafic rocks in the Hong'an–Dabie orogens. *Gondwana Research* 27, 1236–1254.
- 569 Du, D.D., Qu, X.M., Wang, G.H., Xin, H.B., Liu, Z.B., 2011. Bidirectional

subduction of the Middle Tethys oceanic basin in the west segment of
Bangonghu–Nujiang suture, Tibet: evidence from zircon U–Pb LA–ICP–MS
dating and petrogeochemistry of arc granites. *Acta Petrologica Sinica* 27(7),
1993–2002 (in Chinese with English abstract).

Duan, Z.M., Li, G.M., Zhang, H., Duan, Y.Y., 2013. The formation and its geologic
significance of Late Triassic–Jurassic accretionary complexes and constraints on
metallogenic and geological settings in Duolong porphyry copper gold ore
concentration area, northern Bangong Co–Nujiang suture zone, Tibet. *Geological
Bulletin of China* 32(5), 742–750 (in Chinese with English abstract).

Elthon, D., 1987. Petrology of Gabbroic Rocks From the Mid-Cayman Rise Spreading
Center. *Journal of Geophysical Research* 92(B1), 658–682.

Ernst, R.E., Buchan, K.L., 1997. Giant radiating dyke swarms: their use in identifying
preMesozoic large igneous provinces and mantle plumes. In: Mahoney, J., Coffin,
M. (Eds.), *Large igneous provinces: continental, oceanic, and planetary
volcanism*. Geophysical Monograph Series, American Geophysical Union 100,
297–333.

Ernst, R.E., Head, J.W., Parfitt, E.A., Grosfils, E., Wilson, L., 1995. Giant radiating
dyke swarms on Earth and Venus. *Earth-Science Reviews* 39(1–2), 1–58.

Espinozaa, F., Morataa, D., Pelleterb, E., Maury, R.C., Suárez, M., Lagabriell, Y.,
Polvé, M., Bellonb, H., Cottenb, J., Cruzc, R.D.L., Guivel, C., 2005.
Petrogenesis of the Eocene and Mio–Pliocene alkaline basaltic magmatism in
Meseta Chile Chico, southern Patagonia, Chile: Evidence for the participation of

two slab windows. *Lithos* 82, 315–343.

Fan, J.J., Li, C., Xie, C.M., Wang, M., 2014. Petrology, geochemistry, and geochronology of the zhonggang ocean island, gaize county, northern Tibet: implications for the evolution of the Bangongco-Nujiang ocean. *International Geology Review* 56, 1504–1520.

Fan, J.J., Li, C., Liu, Y.M., Xu, J.X., 2015a. Age and nature of the late Early Cretaceous Zhaga Formation, northern Tibet: constraints on when the Bangong–Nujiang Neo-Tethys Ocean closed. *International Geology Review*, 57(3), 342–353.

Fan, J.J., Li, C., Xie, C.M., Wang, M., Chen, J.W., 2015b. Petrology and U-Pb zircon geochronology of bimdal volcanic rocks from the Maierze Group, northern Tibet: Constraints on the timing of closure of the Bangong–Nujiang Ocean. *Lithos* 277, 148–160

Frey, F.A., Green, D.H., Roy, S.D., 1978. Integrated models of basalt petrogenesis: A study of quartz tholeiites to olivine melilitites from South Eastern Australia utilizing geochemical and experimental petrological data. *Journal of Petrology* 19, 463–513.

Frey, F.A., Weis, D., Borisova, A.Y., Xu, G., 2002. Involvement of continental crust in the formation of the Cretaceous Kerguelen Plateau: new perspectives from ODP Leg 120 sites. *Journal of Petrology* 43, 1207–1239.

Geng, H.Y., Sun, M., Yuan, C., Xiao, W.J., Xian, W.S., Zhao, G.C., Zhang, L.F., Wong, K., Wu, F.Y., 2009. Geochemical, Sr–Nd and zircon U–Pb–Hf isotopic studies

614 of Late Carboniferous magmatism in the West Junggar, Xinjiang: Implications
615 for ridge subduction? *Chemical Geology* 266, 364–389.

616 Goolaerts, A., Mattielli, N., Jong, J.D., Weis, D., Scoates, J.S., 2004. Hf and Lu
617 isotopic reference values for the zircon standard 91500 by MC–ICP–MS.
618 *Chemical Geology* 206, 1–9.

619 Geng, Q.R., Pan, G.T., Wang, L.Q., Peng, Z.M., Zhang, Z., 2011. Tethyan evolution
620 and metallogenic geological background of the Bangong Co–Nujiang belt and the
621 Qiangtang massif in Tibet. *Geological Bulletin of China* 30(8), 1261–1274 (in
622 Chinese with English abstract).

623 Guivel, C., Lagabriele, Y., Bourgois, J., Maury, R.C., Fourcade, S., Martin, H.,
624 Arnaud, H., 1999. New geochemical constraints for the origin of
625 ridge-subduction-related plutonic and volcanic suites from the Chile Triple
626 Junction (Taitao Peninsula and Site 862, LEG ODP141 on the Taitao Ridge).
627 *Tectonophysics* 311, 83–111.

628 Guivel, C., Morata, D., Pelleter, E., Espinoza, F., Maury, R.C., Lagabriele, Y., Polvéf,
629 Y., Bellon, H., Cotten, J., Benoit, M., Suárezh, M., Cruz, R.D.L., 2006. Miocene
630 to Late Quaternary Patagonian basalts (46–478S): Geochronometric and
631 geochemical evidence for slab tearing due to active spreading ridge subduction.
632 *Journal of Volcanology and Geothermal Research* 149, 346–370.

633 Haeussler, P.J., Bradley, D.C., Goldfarb, R.J., Snee, L.W., Taylor, C.D., 1995. Link
634 between ridge subduction and gold mineralization in Southern Alaska. *Geology*
635 23, 995–998.

- 636 Halls, H.C., 1982. The importance and potential of mafic dyke swarms in studies of
637 geodynamic process. *Geoscience Canada* 3, 145–154.
- 638 Hastie, A.R., Mitchell, S.F., Kerr, A.C., Minifie, M.J. Millare, I.L., 2011.
639 Geochemistry of rare high-Nb basalt lavas: Are they derived from a mantle
640 wedge metasomatised by slab melts? *Geochimica et Cosmochimica Acta* 75,
641 5049–5072.
- 642 Hoek, J.D., Seitz, H.M., 1995. Continental mafic dyke swarms as tectonic indicators:
643 an example from the Vestfold Hills, East Antarctica. *Precambrian Research*
644 75(3–4), 121–139.
- 645 Hole, M.J., Rogers, G., Saunders, A.D., Storey, M., 1991. Relation between alkalic
646 volcanism and slab-window formation. *Geology* 19, 657–660.
- 647 Hoskin, P.W.O., Schaltegger, U., 2003. The Composition of Zircon and Igneous and
648 Metamorphic Petrogenesis. *Reviews in Mineralogy and Geochemistry* 53,
649 27–62.
- 650 Hou, G.T., Santosh, M., Qian, X.L., Lister, G.S., Li, J.H., 2008. Configuration of the
651 Late Paleoproterozoic supercontinent Columbia: Insights from radiating mafic
652 dyke swarms. *Gondwana Research* 14, 395–409.
- 653 Hu, Z.C., Liu, Y.S., Gao, S., Liu, W.G., Zhang, W., Tong, X.R., Lin, L., Zong, K.Q.,
654 Li, M., Chen, H.H., Zhou, L., Yang, L., 2012. Improved in situ Hf isotope ratio
655 analysis of zircon using newly designed X skimmer cone and Jet sample cone in
656 combination with the addition of nitrogen by laser ablation multiple collector
657 ICP–MS. *Journal of Analytical Atomic Spectrometry* 27, 1391–1399.

- 658 Jolly, W.T., Lidiak, E.G., Dickin, A.P., 2008. Bimodal volcanism in northeast Puerto
659 Rico and the Virgin Islands (Greater Antilles Island Arc): Genetic links with
660 Cretaceous subduction of the mid-Atlantic ridge Caribbean spur. *Lithos* 103,
661 393–414.
- 662 Kapp, P., Yin, A., Harrison, T.M., Ding, L., 2005. Cretaceous–Tertiary shortening,
663 basin development, and volcanism in central Tibet. *Geological Society of
664 America Bulletin* 117 (7–8), 865–878.
- 665 Kepezhinskas, P.K., Defant, M.J., Drummond, M.S., 1996. Progressive enrichment of
666 island arc mantle by melt-peridotite interaction inferred from Kamchatka
667 xenoliths. *Geochimica et Cosmochimica Acta* 60, 1217–1229.
- 668 Kinoshita, O., 2002. Possible manifestations of slab window magmatisms in
669 Cretaceous southwest Japan. *Tectonophysics* 344, 1–13.
- 670 Li, C., 1987. The Longmucuo-Shuanghu-Langcangjiang Plate Suture and the North
671 Boundary of Distribution of Gondwana Facies Permo-Carboniferous System in
672 Northern Xizang, China. *Journal of Changchun College of Geology* 17, 155–166
673 (in Chinese with English Abstract).
- 674 Li, J.H., He, W.Y., Qian, X.L., 1997. Genetic mechanism and tectonic setting of
675 Proterozoic mafic dyke swarm: its implication for paleoplate reconstruction.
676 *Geological Journal of China Universities* 3, 272–281 (in Chinese with English
677 abstract).
- 678 Li, J.X., Li, G.M., Qin, K.Z., Xiao, B., 2008. Geochemistry of porphyries and
679 volcanic rocks and ore-forming geochronology of Duobuza gold-rich porphyry

680 copper deposit in Bangonghu belt, Tibet: constraints on metallogenic tectonic
 681 settings. *Acta Petrologica Sinica* 24, 531–543 (in Chinese with English abstract).
 682 Li, J.X., Li, G.M., Qin, K.Z., Xiao, B., Chen, L., Zhao, J.X., 2012. Mineralogy and
 683 mineral chemistry of the Cretaceous Duolong gold-rich porphyry copper deposit
 684 in the Bangongco arc, northern Tibet. *Resource Geology* 62, 19–41.
 685 Li, J.X., Qin, K.Z., Li, G.M., Xiao, B., Zhao, J.X., Cao, M.J., Chen, L., 2013.
 686 Petrogenesis of ore-bearing porphyries from the Duolong porphyry Cu–Au
 687 deposit, central Tibet: evidence from U–Pb geochronology, petrochemistry and
 688 Sr–Nd–Hf–O isotope characteristics. *Lithos* 160–161, 216–227.
 689 Li, J.X., Qin, K.Z., Li, G.M., Xiao, B., Zhao, J.X., Chen, L., 2011.
 690 Magmatic-hydrothermal evolution of the Cretaceous Duolong gold-rich
 691 porphyry copper deposit in the Bangongco metallogenic belt, Tibet: evidence
 692 from U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Journal of Asian Earth Sciences* 41,
 693 525–536.
 694 Li, S.M., Zhu, D.C., Wang, Q., Zhao, Z.D., Sui, Q.L., Liu, S.A., Liu, D., Mo, X.X.,
 695 2014a. Northward subduction of Bangong–Nujiang Tethys: Insight from Late
 696 Jurassic intrusive rocks from Bangong Tso in western Tibet. *Lithos* 205,
 697 284–297.
 698 Li, J.X., Qin, K.Z., Li, G.M., Xia, B., Zhao, J.X., Cao, M.J., Chen, L., 2014b.
 699 Geochronology, geochemistry, and zircon Hf isotopic compositions of Mesozoic
 700 intermediate–felsic intrusions in central Tibet: Petrogenetic and tectonic
 701 implications. *Lithos* 198–199, 77–91.

- Li, Z., Qiu, J.S., Yang, X.M., 2014c. A review of the geochronology and geochemistry of Late Yanshanian (Cretaceous) plutons along the Fujian coastal area of southeastern China: Implications for magma evolution related to slab break-off and rollback in the Cretaceous. *Earth-Science Reviews* 128, 232–248.
- Li, X.K., Li, C., Sun, Z.M., Wu, H., 2015. Geochronology and Geochemistry of the diorite in Saijiao Cu–Au Deposit, Tibet, and Its Mineralizing Significance. *Geological Bulletin of China* (5)34, 908–918 (in Chinese with English abstract).
- Lissenberg, C.J., Bédard, J.H., van Staal, C.R., 2004. The structure and geochemistry of the gabbro zone of the Annieopsquotch ophiolite, Newfoundland: implications for lower crustal accretion at spreading ridges. *Earth and Planetary Science Letters* 229, 105–123.
- Liu, W.L., Xia, B., Zhong, Y., Cai, J.X., Li, J.F., Liu, H.F., Cai, Z.R., Sun, Z.L., 2014a. Age and composition of the Rebang Co and Julu Ophiolites, Central Tibet: implication for evolution of the Bangong Meso-Tethys. *International Geology Review* 56, 430–447.
- Liu, D.L., Huang, Q.S., Fan, S.Q., Zhang, L.Y., Shi, R.D., Ding, L., 2014b. Subduction of the Bangong–Nujiang Ocean: constraints from granites in the Bangong Co area, Tibet. *Geological Journal* 49, 188–206.
- Liu, S., Hu, R.Z., Gao, S., Feng, C.X., Qi, L., Zhong, H., Xiao, T.F., Qi, Y.Q., Wang, T., Coulson, I.M., 2008. Zircon U–Pb geochronology and major, trace elemental and Sr–Nd–Pb isotopic geochemistry of mafic dykes in western Shandong Province, east China: Constrains on their petrogenesis and geodynamic

significance. *Chemical Geology* 255, 329–345.

Liu, Y.S., Gao, S., Hu, Z.C., Gao, C.G., Zong, K.Q., Wang, D.B., 2010. Continental and oceanic crust recycling–induced melt–peridotite interactions in the Trans–North China Orogen: U–Pb dating, Hf isotopes and trace elements in zircons from mantle xenoliths. *Journal of Petrology* 51, 537–571.

Ludwig, K.J., 2003. *ISOPLOT 3.0*. Berkeley Geochronology Center Special Publication 4, 70.

Lv, L.N., 2012. *Metallogenic Model of Rich Iron and Copper (Gold) Deposits in Western Part of Bangong Co–Nujiang Metallogenic Belt, Tibet* [Master dissertation]. China University of Geosciences (Beijing) (in Chinese with English abstract).

Maurice, C., David, J., O’Neil, J., Francis, D., 2009. Age and tectonic implications of Paleoproterozoic mafic dyke swarms for the origin of 2.2 Ga enriched lithosphere beneath the Ungava Peninsula, Canada. *Precambrian Research* 174, 163–180.

McKenzie, D., O’Nions, R.K., 1991. Partial melt distribution from inversion of rare earth element concentrations. *Journal of Petrology* 32, 1021–1091.

Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental margins. *American Journal of Science* 274, 321–355.

Pallares, C, Maury, R.C., Bellon, H., Royer, J.Y., Calmus J., Aguilón-Robles, A., Cotton, J., Benoit, M., Michaud, F., Bourgois, J., 2007. Slab-tearing following ridge-trench collision: Evidence from Miocene volcanism in Baja California,

- 746 México. *Journal of Volcanology and Geothermal Research* 161, 95–117.
- 747 Pan, G.T., Ding, J., Yao, D.S., Wang, L.Q., 2004. Guidebook of 1: 1,500,000 geologic
748 map of the Qinghai–Xizang (Tibet) plateau and adjacent areas. Chengdu,
749 Cartographic Publishing House 1–148 (in Chinese).
- 750 Pan, G.T., Mo, X.X., Hou, Z.Q., Zhu, D.C., Wang, L.Q., Li, G. M., Zhao, Z.D., Geng,
751 Q.R., Liao, Z.L., 2006. Spatial–temporal framework of the Gangdese Orogenic
752 Belt and its evolution. *Acta Petrologica Sinica* 22, 521 (in Chinese with English
753 abstract).
- 754 Pan, G.T., Wang, L.Q., Li, R.S., Yuan, S.H., Ji, W.H., Yin, F.G., Zhang, W.P., Wang,
755 B.D., 2012. Tectonic evolution of the Qinghai–Tibet Plateau. *Journal of Asian
756 Earth Sciences* 53, 3–14.
- 757 Parker, A.J., Rickwood, R.C., Tucker, D.H., 1990. *Mafic Dykes and Emplacement
758 Mechanisms*. Rotterdam, Netherlands (A. A. Balkema).
- 759 Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to
760 ophiolite classification and the search for Archean oceanic crust. *Lithos* 100,
761 14–48.
- 762 Pearce, J.A., Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb
763 variations in volcanic rocks. *Contribution to Mineralogy and Petrology* 69,
764 33–47.
- 765 Polat, A., Hofmann, A.W., 2003. Alteration and geochemical patterns in the 3.7–3.8
766 Ga Isua greenstone belt, West Greenland. *Precambrian Research* 126, 197–218.
- 767 Polat, A., Hofmann, A.W., Rosing, M.T., 2002. Boninite-like volcanic rocks in the

- 768 3.7–3.8 Ga Isua greenstone belt, West Greenland: geochemical evidence for
769 intra-oceanic subduction zone processes in the early Earth. *Chemical Geology*
770 184, 231–254.
- 771 **Prouteau, G.**, Scaillet, B., Pichavant, M., Maury, R., 2001. Evidence for mantle
772 metasomatism by hydrous silicic melts derived from subducted oceanic crust.
773 *Nature* 410, 197–200.
- 774 Pullen, A., Kapp, P., Gehrels, G.E., Ding, L., Zhang, Q.H., 2011. Metamorphic rocks
775 in central Tibet: lateral variations and implications for crustal structure.
776 *Geological Society of America Bulletin* 123 (3–4), 585–600.
- 777 Qiu, J.X., 1985. *Magmatic petrology*. Beijing: Geological Publishing House 185–189
778 (in Chinese).
- 779 Qu, X.M., Wang, R.J., Xin, H.B., Zhao, Y.Y., Fan, X.T., 2009. Geochronology and
780 geochemistry of igneous rocks related to the subduction of the Tethys oceanic
781 plate along the Bangong Lake arc zone, the western Tibetan Plateau. *Geochimica*
782 38 (6), 523–535 (in Chinese with English abstract).
- 783 Qu, X.M., Xin, H.B., 2006. Ages and tectonic environment of the Bangong Co
784 porphyry copper belt in weatern Tibet, China. *Geological Bulletin of China* 25(7),
785 792–799 (in Chinese with English abstract).
- 786 Rapp, R.P., Shimizu, N., **Norman, M.C.**, **Applegate, G.S.**, 1999. Reaction between
787 slab-derived melts and peridotite in the mantle wedge: experimental constraints
788 at 3.8 GPa. *Chemical Geology* 160, 335–356.
- 789 Reagan, M.K., Gill, J.B., 1989. Coexisting calcalkaline and high-niobium basalts

from Turrialba volcano, Costa Rica: implications for residual titanites in arc
magma sources. *Journal of Geophysical Research* 94, 4619–4633.

Rollinson, H.R., 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman Group UK Ltd., New York, pp. 1–352.

Rudnick, R.L., Gao, S., 2003. The composition of the continental crust. In: Rudnick, R.L., Holland, H.D., Turekian, K.K. (Eds.), *The Crust Treatise on Geochemistry* vol. 3. Elsevier, Oxford, pp. 1–64.

Ryerson, F.J., Watson, E.B., 1987. Rutile saturation in magmas: implications for Ti-Nb-Ta depletion in island-arc basalts. *Earth and Planetary Science Letters* 86, 225–239.

Sajona, F.G., Maury, R.C., Bellon, H., Cotton, J., Defant, M.J., 1996. High field strength element enrichment of Pliocene–Pleistocene island arc basalts, Zamboanga Peninsula, Western Mindanao (Philippines). *Journal of Petrology* 37, 693–726.

Sajona, F.G., Bellon, H., Maury, R.C., Pubellier, M., Cotton, J., Rangin, C., 1994. Magmatic response to abrupt changes in tectonic setting: Pliocene–Quaternary calc-alkaline lavas and Nb-enriched basalts of Leyte and Mindanao (Philippines). *Tectonophysics* 237, 47–72.

Sajona, F.G., Maury, R.C., Bellon, H., Cotton, J., Defant, M.J., Pubellier, M., 1993. Initiation of subduction and the generation of slab melts in western and eastern Mindanao, Philippines. *Geology* 21, 1007–1010.

Saunders, A.D., Norry, M.J., Tarney, J., 1988. Origin of MORB and chemically

812 depleted mantle reservoirs: trace element constraints. *Journal of Petrology*,
 813 415–445 (Special Issue).
 814 Schoonmaker, A., Kidd, W.S.F., 2006. Evidence for a ridge subduction event in the
 815 Ordovician rocks of north-central Maine. *Geological Society of America Bulletin*
 816 118, 897–912.
 817 Sen, C., and Dunn, T. 1994. Experimental modal metasomatism of a spinel lherzolite
 818 and the production of amphibole-bearing peridotite. *Contributions to Mineralogy*
 819 and *Petrology* 119, 394–409.
 820 She, H.Q., Li, J.W., Ma, D.F., Li, G.M., Zhang, D.Q., Feng, C.Y., Qu, W.J., Pan, G.T.,
 821 2009. Molybdenite Re-Os and SHRIMP zircon U- Pb dating of Duobuza
 822 porphyry copper deposit in Tibet and its geological implications. *Mineral*
 823 *Deposits* 28(6), 737–746 (in Chinese with English abstract).
 824 Shervais, J.W., 1982. Ti–V plots and the petrogenesis of modern and ophiolitic lavas.
 825 *Earth and Planetary Science Letters* 59, 101–118.
 826 Shi, R.D., 2007. SHRIMP dating of the Bangong Lake SSZ-type ophiolite:
 827 Constraints on the closure time of ocean in the Bangong Lake–Nujiang River,
 828 northwestern Tibet. *Chinese Science Bulletin* 52, 936–941 (in Chinese with
 829 English abstract).
 830 Shi, R.D., Yang, J.S., Xu, Z.Q., Qi, X.X., 2008. The Bangong Lake ophiolite (NW
 831 Tibet) and its bearing on the tectonic evolution of the Bangong–Nujiang suture
 832 zone. *Journal of Asian Earth Sciences* 32, 438–457.
 833 Sisson, V.B., Pavlis, T.L., Roeske, S.M., Thorkelson, D.J., 2003. Introduction: an

overview of ridge–trench interactions in modern and ancient settings. In: Sisson, V.B., Pavlis, T.L., Roeske, S.M., Thorkelson, D.J. (Eds.), *Geology of a Transpressional Orogen Developed During Ridge–trench Interaction Along the North Pacific Margin*. Geological Society of America (Special Paper), 1–18.

Song, X.Y., Xie, W., Deng, Y.F., Crawford, A.J., Zheng, W.Q., Zhou, G.F., Deng, G., Cheng, S.L., Li, J., 2011. Slab break-off and the formation of Permian mafic–ultramafic intrusions in southern margin of Central Asian Orogenic Belt, Xinjiang, NW China. *Lithos* 127, 128–143.

Srivastava, R.K., Gautam, C.C., 2015. Geochemistry and petrogenesis of Paleo–Mesoproterozoic mafic dyke swarms from northern Bastar craton, central India: Geodynamic implications in reference to Columbia supercontinent. *Gondwana Research* 28, 1061–1078.

Sun, S.S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: *Magmatism in the Ocean Basins* (Saunders A D and Norry M J, eds.). Geological society special Publication 42, 313–345.

Sun, W.D., Ling, M.X., Yang, X.Y., Fan, W.M., Ding, X., Liang, H.Y., 2010. Ridge subduction and porphyry copper-gold mineralization: An overview. *Science China Earth Sciences* 53, 475–484.

Tang, G.J., Wang, Q., Wyman, D.A., Li, Z.X., Xu, Y.G., Zhao, Z.H., 2012a. Metasomatized lithosphere–asthenosphere interaction during slab roll-back: Evidence from Late Carboniferous gabbros in the Luotugou area, Central

- 856 Tianshan. *Lithos* 155, 67–80.
- 857 Tang, G.J., Wyman, D.A., Wang, Q., Li, J., Li, Z.X., Zhao, Z.H., Sun, W.D., 2012b.
- 858 Asthenosphere– lithosphere interaction triggered by a slab window during ridge
- 859 subduction: Trace element and Sr–Nd–Hf–Os isotopic evidence from Late
- 860 Carboniferous tholeiites in the western Junggar area (NW China). *Earth and*
- 861 *Planetary Science Letters* 329–330, 84–96.
- 862 Tang, G.J., Wang, Q., Wyman, D.A., Li, Z.X., Zhao, Z.H., Jia, X.H., Jiang, Z.Q., 2010.
- 863 Ridge subduction and crustal growth in the Central Asian Orogenic Belt:
- 864 Evidence from Late Carboniferous adakites and high-Mg diorites in the western
- 865 Junggar region, northern Xinjiang (west China). *Chemical Geology* 277,
- 866 281–300.
- 867 Thorkelson, D.J., Madsen, J.K., Slaggett, C.L., 2011. Mantle flow through the
- 868 Northern Cordilleran slab window revealed by volcanic geochemistry. *Geology*
- 869 39, 267–270.
- 870 Viruete, J.E., Contreras, F., Stein, G., Urien, P., Joubert, M., Pérez-Estaún A.,
- 871 Friedman R., Ullrich T., 2007. Magmatic relationships and ages between adakites,
- 872 magnesian andesites and Nb-enriched basalt-andesites from Hispaniola: Record
- 873 of a major change in the Caribbean island arc magma sources. *Lithos* 99,
- 874 151–177.
- 875 Wang, G.M., Zhong, J.H., 2002. Tectonic sedimentary evolution of the west segment
- 876 of the Bangong Co-Nujiang structural belt in the Triassic and Jurassic.
- 877 *Geological Review* 48, 297–303 (in Chinese with English abstract).

- Wang, W., Liu, S.W., Santosh, M., Zhang, L.F., Bai, X., Zhao, Y., Zhang, S.H., Guo, R.G., 2015. 1.23 Ga mafic dykes in the North China Craton and their implications for the reconstruction of the Columbia supercontinent. *Gondwana Research* 27, 1047–1418.
- Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology* 20, 325–343.
- Windley, B.F., Alexeiev, D., Xiao, W., Kroner, A., Badarch, G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *Journal of the Geological Society* 164, 31–47.
- Woodhead, J., Hergt, J., Shelley, M., Eggins, S., Kemp, R., 2004. Zircon Hf–isotope analysis with an excimer laser, depth profiling, ablation of complex geometries, and concomitant age estimation. *Chemical Geology* 209, 121–135.
- Xu, H.J., Ma, C.Q., Song, Y.R., Zhang, J.F., Ye, K., 2012. Early Cretaceous intermediate-mafic dykes in the Dabie orogen, eastern China: Petrogenesis and implications for crust–mantle interaction. *Lithos* 154, 83–99.
- Xu, M.J., Li, C., Xu, W., Hu, P.Y., Wang, M., 2014. Petrology, Geochemistry and Geochronology of Gabbros from the Zhongcang Ophiolitic Mélange, Central Tibet: Implications for an Intra-Oceanic Subduction Zone within the Neo-Tethys Ocean. *Journal of Earth Science* 25(2), 224–240.
- Xu, W., Dong, Y.S., Zhang, X.Z., Deng, M.R., Zhang, L., 2015a. Petrogenesis of high-Ti mafic dykes from Southern Qiangtang, Tibet: Implications for a ca. 290

- Ma large igneous province related to the early Permian rifting of Gondwana. Gondwana Research, DOI: <http://dx.doi.org/10.1016/j.gr.2015.07.016>.
- Xu, W., Xu, M.J., Wu, Y.W., Fan, J.J., Wu, H., 2015b. Petrology, Geochemistry and Geochronology of Boninitic Dykes from the Kangqiong Ophiolite: Implications for the Early Cretaceous evolution of Bangong–Nujiang Neo-Tethys Ocean in Tibet. *International Geology Review* 57(26), 2028–2043.
- Xu, Y.G., Lan, J.B., Yang, Q.J., Huang, X.L., Qiu, H.N., 2008. Eocene break-off of the Neo-Tethyan slab as inferred from intraplate-type mafic dykes in the Gaoligong orogenic belt, eastern Tibet. *Chemical Geology* 255, 439–453.
- Yu, H.Q., Li, J.W., Ma, D.F., Li, G.M., Zhang, D.Q., Feng, C.W., Qu, W.J., Pan, G.T., 2009. Molybdenite Re–Os and SHRIMP zircon U–Pb dating of Duobuza porphyry copper deposit in Tibet and its geological implications. *Mineral Deposits* 28, 737–746 (in Chinese with English abstract).
- Yuan, H.L., Gao, S., Liu, X.M., Li, H.M., Günther, D., Wu, F.Y., 2004. Accurate U–Pb age and trace element determinations of zircon by laser ablation-inductively coupled plasma mass spectrometry. *Geostandards and Geoanalytical Research* 28, 353–370.
- Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., Shen, K., 2010. Late Cretaceous charnockite with adakitic affinities from the Gangdese batholith, southeastern Tibet: Evidence for Neo-Tethyan mid-ocean ridge subduction? *Gondwana Research* 17, 615–631.
- Zhang, C.L., Zou, H.B., 2012. Comparison between the Permian mafic dykes in Tarim

and the western part of Central Asian Orogenic Belt (CAOB), NW China:

Implications for two mantle domains of the Permian Tarim Large Igneous Province. *Lithos* 174, 15–27.

Zhang, X.R., Shi, R.D., Huang, Q.S., Liu, D.L., Gong, X.H., Chen, S.S., Wu, K., Yi, G.D., Sun, Y., Ding, L., 2014. Early Jurassic high-pressure metamorphism of the Amdo terrane, Tibet: Constraints from zircon U–Pb geochronology of mafic granulites. *Gondwana Research* 26, 975–985.

Zhang, Y.X., 2007. Tectonic evolution of the middle-western Bangong–Nujiang suture, Tibet [Doctor dissertation]. Graduate School of the Chinese Academy of Sciences (in Chinese with English abstract).

Zhao, J.H., Zhou, M.F., 2007. Geochemistry of Neoproterozoic mafic intrusions in the Panzihua district (Sichuan Province, SW China): implications for subduction-related metasomatism in the upper mantle. *Precambrian Research* 152, 27–47.

Zheng, Y.C., Hou, Z.Q., Gong, Y.L., Liang, W., Sun, Q.Z., Zhang, S., Fu, Q., Huang, K.X., Li, Q.Y., Li, W., 2014. Petrogenesis of Cretaceous adakite-like intrusions of the Gangdese Plutonic Belt, southern Tibet: Implications for mid-ocean ridge subduction and crustal growth. *Lithos* 190–191, 240–263.

Zhou, T., Chen, C., Liang, S., Chen, G.F., Li, H.L., and Li, D.W., 2014. Zircon U–Pb Geochronology and Geochemical Characteristics of Volcanic Rocks in the Ophiolite Mélange at the Bangong Lake, Tibet. *Geotectonica et Metallogenia* 38, 157–1678 (in Chinese with English abstract).

- Zhu, D.C., Pan, G.T., Mo, X.X., Wang, L.Q., Zhao, Z.D., Liao, Z.L., Geng, Q.R., and
Dong, G.C., 2006. Identification for the mesozoic OIB-type basalts in Central
Qinghai–Tibetan plateau: Geochronology, geochemistry and their tectonic setting.
Acta Geologica Sinica 80, 1312–1328 (in Chinese with English abstract).
- Zhu, D.C., Pan, G.T., Chung, S.L., Liao, Z.L., Wang, L.Q., Li, G.M., 2008. SHRIMP
Zircon Age and Geochemical Constraints on the Origin of Lower Jurassic
Volcanic Rocks from the Yeba Formation, Southern Gangdese, South Tibet.
International Geology Review 50, 442–471.
- Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin
and pre-Cenozoic evolution of the Tibetan Plateau. Gondwana Research 23,
1430–1455.
- Zhu, X.P., Chen, H.A., Ma, D.F., Huang, H.X., Li, G.M., Li, Y.B., Li, Y.C., 2011.
Re–Os dating for the molybdenite from Bolong porphyry copper-gold deposit in
Tibet, China and its geological significance. Acta Petrologica Sinica 27(7),
2159–2164 (in Chinese with English abstract).
- Zhu, X.P., Li, G.M., Chen, H.A., Ma, D.F., Huang, H.X., 2015. Zircon U–Pb,
Molybdenite Re–Os and K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ Dating of the Bolong Porphyry
Cu–Au Deposit, Tibet, China. Resource Geology 65, 122–135.

Figure captions

Fig. 1. (a) Geographic map and (b) tectonic framework of the Tibetan Plateau (Li,
1987), and (c) Geological sketch map of the southern Qiangtang terrane, western

Tibet. Modified after [Li et al. \(2014b\)](#). Published age data shown for intermediate-felsic intrusions and ophiolitic fragments are from [Kapp et al. \(2005\)](#), [Shi \(2007\)](#), [Qu et al. \(2009\)](#), [Pullen et al. \(2011\)](#), [Du et al. \(2011\)](#), [Li et al. \(2013, 2014a, 2014b\)](#), [Liu et al. \(2014a, 2014b\)](#) and [Zhou et al. \(2014\)](#).

Fig. 2. Simplified geological map of the study area, western Tibet. Modified after [Fan et al. \(2015b\)](#). Sample localities are indicated. Published age data are from [Li et al. \(2008, 2011, 2013, 2014b, 2015\)](#), [She et al. \(2009\)](#), [Zhu et al. \(2011\)](#), [Lv \(2012\)](#), [Chen et al. \(2013\)](#) and [Fan et al. \(2015b\)](#).

Fig. 3. Field photographs and photomicrographs of the representative mafic dykes and their wall rocks. *Abbreviations*: Pl = plagioclase, Px = pyroxene, Chl = chlorite, Cal = calcite.

Fig. 4. Geochemical classification and association for studied dykes in the DCAD, western Tibet. (a) $Zr/(TiO_2 \times 0.0001)$ -Nb/Y diagram of [Winchester and Floyd \(1977\)](#). (b) SiO_2 -FeOT/MgO diagram, the boundary line between tholeiitic and calc-alkaline rock types is from [Miyashiro \(1974\)](#). (c) Nb/La-MgO and (d) Nb/U-Nb diagrams ($SiO_2 < 54$ wt.%), the fields of island arc basalts, HNBS and NEBS (high Nb basalts and Nb-enriched basalts) are from [Kepezhinskis et al. \(1996\)](#).

Fig. 5. Tectonic discrimination diagrams for studied dykes in the DCAD, western

1 988 Tibet. (a) V vs. Ti/1000 diagram of [Shervais \(1982\)](#). (b) Ti/1000-Y*3-Zr diagram of
2
3 989 [Pearce and Norry \(1979\)](#). (c) Zr/Y vs. Zr diagram of [Pearce and Norry \(1979\)](#);
4
5
6 990 A-islandarc tholeiite, B-MORB island-arc tholeiite and calc-alkali basalt,
7
8
9 991 C-calc-alkaline basalt, D-intraplate basalt. (d) TiO₂ vs. Zr diagram of [Pearce and](#)
10
11
12 992 [Norry \(1979\)](#). Symbols as in Fig. 4.

13
14
15 993

16
17 994 Fig. 6. Representative major and trace elements plotted against Mg[#] of studied dykes
18
19
20 995 in the DCAD, western Tibet. Symbols as in Fig. 4.

21
22
23 996

24
25 997 Fig. 7. Chondrite-normalized rare-earth element distributions and primitive mantle
26
27
28 998 normalized multi-element diagrams for the mafic dykes in the DCAD, western Tibet.
29
30
31 999 The normalized values for chondrite, primitive mantle, OIB (Ocean Island Basalt),
32
33
34 1000 E-MORB (Enriched Mid-Ocean Ridge Basalt) are from [Sun and McDonough \(1989\)](#).

35
36
37 1001

38
39 1002 Fig. 8. CL images of representative zircon grains and U–Pb concordia diagrams for
40
41
42 1003 zircons from DCT10, DCT18 and DCT27.

43
44
45 1004

46
47 1005 Fig. 9. (La/Nb)_{PM} vs. (Th/Nb)_{PM} diagram for testing crustal contamination of the
48
49
50 1006 studied mafic dykes in the DCAD, western Tibet. The normalized values for primitive
51
52
53 1007 mantle are from [Sun and McDonough \(1989\)](#). Middle crust and crust data are from
54
55
56 1008 [Rudnick and Gao \(2003\)](#). Symbols as in Fig. 4.

57
58
59 1009

Fig. 10. Plots of Th/Ta vs. Th/Tb (DMM, McKenzie and O’Nions, 1991) (a) and Sm/Yb vs. La/Sm (b) for the studied dykes in the DCAD, western Tibet. Mantle array (heavy line) defined by depleted MORB mantle (DMM, McKenzie and O’Nions, 1991) and primitive mantle (PM, Sun and McDonough, 1989); Melting curves for spinel lherzolite and garnet peridotite with both DMM and PM compositions are after Aldanmaz et al. (2000). Numbers along lines represent the degree of the partial melting. Symbols as in Fig. 4.

Fig. 11. Th/Yb vs. Ta/Yb diagram of Pearce (2008). Symbols as in Fig. 4.

Fig. 12. Zircon $\epsilon_{\text{Hf}}(t)$ values versus age for magmatic rocks from the southern Qiangtang terrane. Zircon Hf isotopic data for the intermediate–felsic intrusions are from Li et al. (2013, 2014a and 2014b).

Fig. 13. A sketch map showing the formation mechanism of the Early Cretaceous magmatism in the DCAD, western Tibet. Modified after Cole and Stewart (2009).

Figure 1

Figure 1

Figure 2

Figure 6

Figure 3

Figure 2

Figure 4

Figure 3

Figure 5

Figure 4

Figure 6

Figure 5

Figure 7

Figure 7

Figure 8

Figure 8

Figure 9

Figure 9

Figure 10 consists of two panels. Panel (a) is a scatter plot of Th/Ta versus Th/Tb. The y-axis (Th/Ta) ranges from 0 to 4, and the x-axis (Th/Tb) ranges from 0 to 10. Data points are categorized by color and shape: pink circles (enclosed in an ellipse), blue diamonds (enclosed in an ellipse), and green crosses (enclosed in an ellipse). A single blue diamond labeled 'DCT10H1' is located at approximately (9.0, 4.2). Panel (b) is a scatter plot of Sm/Yb versus La/Sm on a log-log scale. The y-axis (Sm/Yb) ranges from 0.1 to 10, and the x-axis (La/Sm) ranges from 0.1 to 10. Data points are pink circles, blue diamonds, and green crosses. Several dashed curves represent REE patterns for 'Garnet lherzolite' and 'Spinel lherzolite', with numerical labels (1, 5, 10, 30, 50) indicating specific patterns. A solid line represents the 'PM' (primitive mantle) pattern. A horizontal line at Sm/Yb = 1 is labeled 'DM' (depleted mantle) and 'N-MORB'. A horizontal arrow at the bottom indicates 'Depletion' to the left and 'Enrichment' to the right.

Figure 10

Figure 11

Figure 11

Figure 12

Figure 12

Figure 13

Figure 13