Late Early Cretaceous magmatic rocks (118-113 Ma) in the middle segment of the Bangong–Nujiang suture zone, Tibetan Plateau: Evidence of lithospheric delamination

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1. Introduction

Magmatic rocks from continental collision zones offer important insights into mantle–crust interactions and the tectonic evolution of ocean closure (e.g., Mo et al., 2007; Zhao et al., 2012; Holm et al., 2015). The Tibetan Plateau holds a geological record of several continental collision events since the early Paleozoic (Kapp et al., 2007; Yin and Harrison, 2000; Zhu et al., 2009, 2011, 2013). The Bangong–Nujiang suture zone (BNSZ) lies in the central part of the Tibetan Plateau and marks the remnants of the Bangong–Nujiang Tethyan Ocean (Yin and Harrison, 2000). This ocean existed between the Qiangtang terrane to the north and the Lhasa terrane to the south (Yin and Harrison, 2000). Generally, the Bangong–Nujiang Tethyan Ocean is thought to have opened during the Late Triassic and closed during the Late Jurassic–Cretaceous (Yin and Harrison, 2000; Zhang et al., 2004; Kapp et al., 2005, 2007; Leier et al., 2007; Xu et al., 2014). The Cretaceous magmatic rocks of the BNSZ therefore offer an opportunity to understand the magmatic processes that operated during the closure of the Bangong–Nujiang Tethyan Ocean and associated continental collision.

The northern margin of the Lhasa terrane contains a magmatic belt that is thought to have been generated during a period of intense magmatism towards the end of the Early Cretaceous (ca. 113 Ma) (Zhu et al., 2009). The magmatism may have been caused by the intrusion of mantle-derived fluids and/or melts into the Lhasa terrane after slab breakoff of the southward-subducted oceanic lithosphere (Zhu et al., 2009, 2011; Qu et al., 2012; Sui et al., 2013; Chen et al., 2014; Wu et al., 2015). It should be pointed out that the slab breakoff model was originally proposed based on the assumption that coeval magmatism was poorly developed within the BNSZ and along the southern margin of the South Qiangtang terrane. Recently, however, numerous late Early Cretaceous magmatic (both volcanic and plutonic)

rocks were found within and on the north side of the BNSZ (Zhu et al., 2011; Kapp et al., 2007; Qu et al., 2012; Chang et al., 2011; Li et al., 2011, 2013, 2014; Qu and Xin, 2006; this study). Thus, the Early Cretaceous geodynamic evolution of the BNSZ remains an enigma.

In this contribution, we present our new zircon U–Pb geochronologic and Hf-isotopic, and whole-rock geochemical data for the late Early Cretaceous magmatic rocks (118–113 Ma) of the middle part of the BNSZ. These new data will be used to discuss the Early Cretaceous geodynamic evolution of the BNSZ.

2. Geologic background and sample descriptions

The Tibetan Plateau forms the eastern end of the Himalayan–Alpine orogenic belt and comprises five E–W trending terranes (from north to south): the Kunlun, North Qiangtang, South Qiangtang, Lhasa, and Himalaya terranes. These terranes are separated by the Jinsha, Longmu Co–Shuanghu, Bangong–Nujiang, and Indus–Yarlung Zangbo suture zones, respectively (Yin and Harrison, 2000) (Fig. 1a). The BNSZ extends for over 2000 km from Bangong Co in the west to Dengqen in the east, where it turns south towards the Nujiang River (Pan et al., 2004). In the southeastern Asia, the BNSZ is connected with the Longling–Ruili suture zone (Liu et al., 2002; Mao et al., 2014; Xie et al., 2016) which separates the Tengchong and Baoshan terranes (Fig. 1a).

Ophiolite fragments are distributed irregularly along the BNSZ (Xu et al., 2014; Zhou et al., 1997; Xia et al., 2008; Chen et al., 2006). The Amdo basement, which is commonly considered to be a micro-continent of the Lhasa terrane (Dewey et al., 1988; Xu et al., 1985; Yin and Harrison, 2000), is located in the middle segment of the BNSZ (Fig. 1b). Recent studies indicate that the Amdo basement has Precambrian rocks (Guynn et al., 2012; Wang

et al., 2012) whereas the northern Lhasa terrane mainly contains juvenile crust (Zhu et al., 2011), suggesting that the Amdo basement and the northern Lhasa terrane have different tectonic histories (Zhu et al., 2011).

The Jiang Co and Zigetang Co areas are located in the middle segment of the BNSZ (Fig. 1a). The main outcrops in these areas are Paleozoic sedimentary sequences, Jurassic sandstones and limestones, Early Cretaceous volcanic rocks and granites, Late Cretaceous conglomerates, and ophiolite fragments (Fig. 1b). The ophiolite fragments are thought to represent the remnants of the Bangong–Nujiang Tethyan Ocean (Zhou et al., 1997; Xia et al., 2008; Chen et al., 2006). The Early Cretaceous volcanic rocks unconformably overlie Jurassic sandstones and limestones and are unconformably overlain by Late Cretaceous conglomerates. These Early Cretaceous volcanic rocks can be further divided into two groups: the Duoni Formation from the northern part of the Lhasa terrane (Liu et al., 2011a; Zhu et al., 2011; Huang et al., 2012; Peng et al., 2011) and the Qushenla Formation in the BNSZ (this study; Zhang et al., 2010). Early Cretaceous granitoids were also reported in this area (Chen et al., 2010; Zhu et al., 2011).

In this study, we focus on the Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas within the BNSZ (Fig. 1b). All of these magmatic rocks are extensively altered, but the original textures remain preserved. The volcanic rocks of the Qushenla Formation widely occur in the Jiang Co area and mainly comprise andesite (Fig. 2a), dacite, rhyolite (Fig. 2b), felsic tuff, and volcanic breccia. They overlie the Jurassic sandstones and ophiolite fragments but are overlain by the Cenozoic rocks. We sampled the andesites and rhyolites in the Jiang Co area. The andesite samples are porphyritic, comprising plagioclase (35–55 vol.%) and quartz (~5 vol.%) phenocrysts in a cryptocrystalline groundmass (Fig. 2e). The rhyolite samples are cryptocrystalline (80–85 vol.%) with quartz phenocrysts

(15–20 vol.%) (Fig. 2f). To the north of the Jiang Co area, the Early Cretaceous magmatic rocks from the Zigetang Co area mainly comprise andesites (Fig. 2c) and granodiorites (Fig. 2d). The andesites are also considered as part of the Qushenla Formation. These andesites are porphyritic, with plagioclase phenocrysts (15–25 vol.%) in a cryptocrystalline groundmass (Fig. 2g). The granodiorite dikes intruded into the Jurassic sandstones (Fig. 2d). They display granitic textures and consist of plagioclase (50–60 vol.%), hornblende (20–30 vol.%), quartz (20–30 vol.%), and minor biotite (~5 vol.%) (Fig. 2h).

3. Analytical methods

Thirty-one samples were collected for whole-rock geochemical analyses while six ones (Table 1) were selected for zircon U–Pb dating and Hf-isotope analyses.

3.1. Zircon U–Pb analyses

Zircons were separated by conventional heavy-liquid and magnetic techniques at the Special Laboratory of the Geological Team of Hebei Province, Langfang, China. Cathodoluminescence (CL) images were taken using a HITACH S-3000N scanning electron microscope fitted with a Gatan Chroma cathodoluminescence imaging system at the SHRIMP Center, Chinese Academy of Geological Sciences, Beijing, China.

Zircon U–Pb analyses were undertaken by secondary ion mass spectrometry (SIMS) and laser-ablation–inductively coupled plasma–mass spectrometry (LA–ICP–MS). SIMS zircon U–Pb analyses were undertaken using a CAMECA IMS-1280 ion microprobe at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China. U–Th–Pb ratios and absolute abundances were determined relative to zircon reference material 91500 (Wiedenbeck et al., 1995), using operating and data processing procedures similar to those described by Li et al. (2009). The mass resolution used to measure U–Pb

isotopes was 5400, and isotopic compositions were corrected for common Pb using measured ^{204}Pb values. Corrections were sufficiently small to be insensitive to the choice of common-Pb composition, and an average of present-day crustal composition (Stacey and Kramers, 1975) was used, assuming that the common Pb is largely surface contamination or from the gold coating introduced during sample preparation. Data reduction was performed using Isoplot/Ex v. 3.0 (Ludwig, 2003). Analytical uncertainties are reported at the 1σ level and mean ages for pooled U/Pb analyses are quoted at the 95% confidence interval.

LA-ICP-MS zircon U-Pb analysis was conducted on a Bruker M90 ICP-MS equipped with a 193 nm laser, at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. The crater diameter was 32 μm and helium was used as the carrier gas. Zircon reference material 91500 (Wiedenbeck et al., 1995) and NIST610 (^{29}Si) were used for calibration and as the internal standard, respectively. The details of this method are described by Yuan et al. (2004). Common Pb was corrected following Anderson (2002). Uncertainties in the geochronologic data are given as 1σ values, with weighted mean ages quoted at the 95% confidence level. The isotopic data were processed using the programs GLITTER (version 4.4) and Isoplot/Ex (version 3.0) (Ludwig, 2003).

3.2. *In situ* zircon Hf-isotope analysis

In situ zircon Hf-isotopic analyses were performed at the same sites, or in the same age domains (identified using CL images), in the zircons used for U-Pb analyses. Hf-isotopic analyses were undertaken using a Geolas-193 laser-ablation microprobe attached to a Neptune multi-collector ICP-MS at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. The ablation time was ~26 s for each measurement, the beam diameter was ~50 μm , the repetition rate was 8–10 Hz, and the

beam energy was 100 mJ. Instrument set-up and data acquisition processes followed Griffin et al. (2000) and the zircon standard Mud Tank was analyzed to evaluate accuracy and precision. During the analysis period, a $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282496 ± 9 (2σ , $n = 276$) was obtained for the Mud Tank standard, which is consistent with the values obtained by Goolaerts et al. (2004), Woodhead and Hergt (2005), and Griffin et al. (2006).

3.3. Major and trace element analyses

Major and trace element analyses were performed at the National Research Center for Geoanalysis, Beijing, China. The weathered surfaces of samples were removed prior to washing with de-ionized water and crushing to powder in an agate mill. Major element analyses were undertaken using X-Ray Fluorescence (XRF) on sample powders fused with lithium tetraborate. Analytical uncertainty was between 0.2% and 1%. Loss on ignition (LOI) was calculated from the weight lost from sample powders after they were heated at 1000 °C for 1 h. Trace elements were measured by inductively coupled plasma-mass spectrometry (ICPMS) following Dulski (1994). The analytical uncertainty is <5%. Before the spectrometric analysis, the preparation of sample solution is as follows. Fifty mg of each powdered sample was dissolved in equal mixture of sub-boiling distilled HF and HNO₃ in a high-pressure Teflon bomb on a hot-plate for 24 h. This was done to ensure complete digesting/dissolution. The procedure was repeated using smaller amounts of acids for additional 12 h. After complete digestion, sample solution was evaporated to incipient dryness, refluxed with 6 N HNO₃, and heated again to incipient dryness to remove organic matter. The sample was then dissolved in 2 ml of 3 N HNO₃ and diluted with Milli-Q water (18 MX) to a final dilution factor of 2000.

4. Results

4.1. Zircon U–Pb geochronology

Zircon grains from six samples are similar, with lengths of 200–300 μm and aspect ratios of $\sim 3:1$. Most zircon grains are transparent, colorless, and euhedral. The zircon grains from sample 12T036 were analyzed by SIMS (Table 2), while the other five samples were analyzed by LA–ICP–MS (Table 3).

The zircons in andesite sample 12T036 from the Jiang Co area display oscillatory zoning and high Th/U ratios (0.65–1.94), suggesting an igneous origin (Hoskin and Schaltegger, 2003). Their $^{206}\text{Pb}/^{238}\text{U}$ ages are 111–116 Ma ($N = 19$), yielding a weighted mean age of 112.9 ± 0.8 Ma (Fig. 3a), which probably reflects the crystallization age of the rock. An older age of ca. 167 Ma (measured at spot 18) (Fig. 3a) is interpreted as representing earlier magmatic activity.

U and Th contents of zircons from an andesitic sample (13T034) and a rhyolitic sample (13T046) from the Jiang Co area are 2376–7034 ppm and 1215–13441 ppm, respectively. As a result of the high U contents, the CL images of these zircons are so dark that the oscillatory zoning is not clear. The high Th/U ratios (0.37–2.37; i.e., >0.1), together with the euhedral shapes of the crystals, indicate a magmatic origin (Hoskin and Schaltegger, 2003). Twenty U–Pb analyses of zircons from sample 13T034 gave weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 116.8 ± 0.7 Ma (Fig. 3b), which is probably the crystallization age. The older $^{206}\text{Pb}/^{238}\text{U}$ age of 126 Ma measured at Spot 8 in sample 13T034 is interpreted to represent earlier magmatic activity. Seventeen analyses of zircons from sample 13T046 yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 116.3 ± 1.2 Ma (Fig. 3c), which represents the time of eruption of the rhyolite.

The U and Th contents of zircons in samples 13T091 (andesite), 13T109

(granodiorite), and 13T118 (granodiorite) from the Zigetang Co area are 172–1099 ppm and 97.2–1311 ppm, respectively. The Th/U ratios (0.62–2.30; i.e., >0.1), together with the presence of oscillatory zoning, indicates an igneous origin (Hoskin and Schaltegger, 2003). Weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages for samples 13T091, 13T109, and 13T118 are 114.3 ± 0.8 Ma (N = 23) (Fig. 3d), 118.4 ± 0.8 Ma (N = 23) (Fig. 3e), and 116.7 ± 0.6 Ma (N = 25) (Fig. 3f), respectively, which most likely reflect the formation ages of the samples.

4.2. Zircon Hf-isotope analyses

The zircon Hf-isotope data for the six U–Pb dated samples are given in Table 4 and shown in Fig. 4. Most of the zircons from the Jiang Co andesites (samples 12T036 and 13T034) yield variable $\epsilon_{\text{Hf}}(t)$ values of -9.1 to $+0.5$ and old T_{DM}^{C} model ages of 1137–1750 Ma. Nine analyses of the ca. 116 Ma zircons from the Jiang Co rhyolite (sample 13T046) yielded negative and positive $\epsilon_{\text{Hf}}(t)$ values between -6.4 and $+2.3$, corresponding to T_{DM}^{C} model ages of 1025–1580 Ma. The zircons in the other three samples (13T091, 13T109, and 13T118) from the Zigetang Co area have consistent positive $\epsilon_{\text{Hf}}(t)$ values ($+0.9$ to $+6.8$, with the exception of one analysis) and T_{DM}^{C} model ages (749–1415 Ma).

4.3. Whole-rock major and trace element data

4.3.1 Jiang Co andesites

The andesite samples from the Jiang Co area have constant SiO_2 (59.59–61.47 wt.%), Al_2O_3 (16.39–16.84 wt.%), and MgO (3.13–4.03 wt.%) contents (hereafter, all whole-rock major element data have been normalized to an anhydrous basis) and high $\text{Mg}^{\#}$ [$=\text{Mg}/(\text{Mg} + \text{Fe}_{\text{T}})$] values (54–58) (Table 5). The samples plot in the andesite field on the SiO_2 –Zr/Ti classification diagram (Fig. 5a) which is especially effective for altered

volcanic rocks (Winchester and Floyd, 1977). In the chondrite-normalized rare earth element (REE) patterns (Fig. 6a), light REE (LREE) are enriched ($\text{La}_N/\text{Sm}_N = 3.59\text{--}4.29$ and $\text{La}_N/\text{Yb}_N = 8.30\text{--}9.50$; hereafter, N denotes normalized to the chondrite values of Sun and McDonough (1989)). The Eu anomalies are generally moderate ($\text{Eu}/\text{Eu}^* = 0.65\text{--}0.75$). In primitive-mantle-normalized multi-element diagrams (Fig. 6b), all samples are depleted in Nb, Ta, P, and Ti, and enriched in Th, U, Zr, and Hf.

4.3.2 Jiang Co rhyolite

The rhyolite samples from the Jiang Co area exhibit distinguished high SiO_2 contents (80.42–81.55 wt.%) as well as low TFe_2O_3 (0.53–0.88 wt.%) and MgO (0.24–0.26 wt.%) contents (Table 5). On the Th–Co classification diagram (Fig. 5b) (Hastie et al., 2007), all six samples plot in the high-K calc-alkaline and shoshonite fields. All samples have similar $(\text{La}/\text{Sm})_N$ (5.22–5.50) and $(\text{La}/\text{Yb})_N$ (14.0–18.0) ratios, and negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.66\text{--}0.77$; Fig. 6a). In primitive-mantle-normalized multi-element diagrams (Fig. 6b), all the samples are depleted in Nb, P, and Ti, and enriched in Th, U, Zr, and Hf.

4.3.3 Zigetang Co andesites

The andesite samples from the Zigetang Co area have variable SiO_2 (62.73–65.24 wt.%) and relatively high Al_2O_3 (15.85–16.32 wt.%) and K_2O (2.95–3.58 wt.%) concentrations (Table 5). Their high MgO (2.50–3.31 wt.%) and Sr (439–610 ppm) contents and $\text{Mg}^\#$ values (58–59) and low Y (15.1–16.3 ppm) and Yb (1.45–1.65 ppm) contents are comparable to those of the high-Mg adakitic andesites (HMAA) (Gao et al., 2004; Xu et al., 2002). On the Th–Co classification diagram (Fig. 5b) (Hastie et al., 2007), the samples are classified as high-K calc-alkaline and shoshonite series. Chondrite-normalized rare earth element (REE) patterns obtained for the andesites (Fig.

6c) slope towards the right and show obvious fractionation between the light REEs (LREEs) and heavy REEs (HREEs). Eu does not exhibit an obvious negative anomaly ($\text{Eu}/\text{Eu}^* = 0.75\text{--}0.85$; Fig. 6c). On the primitive mantle-normalized spidergram (Fig. 6d), all samples exhibit similar trace element patterns. They are enriched in Th, U, Zr, and Hf, but depleted in Nb, Ta, P, and Ti. In addition, these samples have high Cr (66.5–81.1 ppm) and Ni (25.4–39.4 ppm) contents.

4.3.4 Zigetang Co granodiorites

The granodiorites from the Zigetang Co area display relatively higher SiO_2 contents (64.18–69.17 wt.%) than those of the nearby andesites (62.73–65.24 wt.%). The granodiorite samples have variable $\text{Fe}_2\text{O}_3\text{t}$ (2.58–6.29 wt.%), MgO (0.72–2.21 wt.%), and K_2O (2.94–4.30 wt.%) contents. On the $\text{SiO}_2\text{--Zr/Ti}$ classification diagram (Fig. 5a) (Winchester and Floyd, 1977), most samples plot in the rhyodacite/dacite field. They fall within the high-K calc-alkaline and shoshonite fields on the Th–Co diagrams (Fig. 5b) (Hastie et al., 2007). All samples are enriched in LREE, with $(\text{La}/\text{Sm})_{\text{N}} = 4.48\text{--}6.33$ and $(\text{La}/\text{Yb})_{\text{N}} = 12.0\text{--}20.3$, and they show variable Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.55\text{--}0.81$; Fig. 6c). On primitive-mantle-normalized multi-element diagrams (Fig. 6d), Nb, Ta, P, and Ti are depleted in all samples.

5. Discussion

5.1. The timing of the Lhasa–Qiangtang collision

The timing of the Lhasa–Qiangtang collision can help determine the tectonic setting and petrogenesis of the magmatic rocks in this study. In the past few decades, the timing of the Lhasa–Qiangtang collision has long been disputed. Two contrasting hypotheses are (1) that the collision occurred in the Late Cretaceous (e.g., Zhang, 2004; Zhu et al., 2006;

Fan et al., 2014; Liu et al., 2014), and (2) that the collision initiated in the Late Jurassic and terminated in the Early Cretaceous (e.g., Yin and Harrison, 2000; Zhu et al., 2016).

A key evidence of the former hypothesis is the presence of 120–108 Ma OIB-type basaltic rocks and interbedded limestones within the BNSZ (Fan et al., 2014; Liu et al., 2014; Zhang et al., 2014; Zhu et al., 2006). These basaltic rocks have been interpreted to indicate the presence of oceanic islands, and thus the Bangong–Nujiang Tethyan Ocean was still open during the end of the Early Cretaceous (Fan et al., 2014; Liu et al., 2014; Zhang et al., 2014). However, this hypothesis is inconsistent with paleomagnetic data. Lippert et al. (2014) suggested that the southern margin of the Lhasa terrane remained at latitude $\sim 20 \pm 4^\circ\text{N}$ during ca. 110–50 Ma. Given that the Lhasa terrane was probably approximately 600 km wide in the Early Cretaceous (Kapp et al., 2007; Leier et al., 2007), this would imply a paleolatitude for the northern margin of ca. $\sim 26 \pm 4^\circ\text{N}$. Such a paleolatitude is virtually indistinguishable from that of the southern margin of the South Qiangtang terrane as indicated by the new paleomagnetic data ($29.3 \pm 5.7^\circ\text{N}$) of the ca. 110–104 Ma volcanic rocks from NE Gerze (Chen et al., 2015). The results of stratigraphic and structural studies also allow us to argue that the Lhasa terrane may have already collided with the South Qiangtang terrane prior to ca. 110 Ma (Kapp et al., 2007; Raterman et al., 2014). Moreover, Zhu et al. (2016) suggested that the geochemistry data of the 120–108 Ma basaltic rocks within the BNSZ point to a mixed mantle source involving a shallow N-MORB source and a deep depleted source. Such mixed characteristic of magma source region is analogous to that documented by the Iron King volcanic rocks from west-central Arizona involving arc and oceanic plateau components (Condie et al., 2002); and thus these basaltic rocks were probably derived from the decompression melting of asthenospheric materials after the Lhasa–Qiangtang collision,

but are not indicative of the presence of oceanic crust as previously interpreted (Zhu et al., 2016).

The later hypothesis was upheld by Yin and Harrison (2000), who argued that the Lhasa terrane collided with Qiangtang to the north in the late Jurassic near Amdo (Long, 91°E) (Dewey et al., 1988) and in the early Cretaceous near Shiquanhe (Long, 80°E) (Matte et al., 1996). Subsequent stratigraphic and structural studies along the BNSZ also support this hypothesis. Structural mapping and detrital zircon U–Pb dating in the Domar area of the South Qiangtang terrane identified a significant Late Jurassic–Early Cretaceous shortening rather than significant Cenozoic shortening in response to the India–Asia collision (Raterman et al., 2014). Stratigraphic and sedimentology studies of rocks in the Nyima area along the BNSZ indicate a transition from marine to nonmarine conditions at ca. 125–118 Ma (Kapp et al., 2007). Further to the east, the ophiolites from the Tsige Dartso area are unconformably overlain by the Lower Cretaceous Dongqiao Formation, which consists of a lower succession of ophiolitic-derived sandstone and conglomerate (Aptian–Albian; 125–100 Ma) (Wang and Dong, 1984; Yin et al., 1988). Moreover, the presence of ca. 115–114 Ma anorogenic felsic (A2-type) rocks that point to a post-collisional setting (Eby, 1992) was identified in the northern Lhasa terrane (Chen et al., 2014) and BNSZ (Qu et al., 2012). Finally, the well-developed Upper Cretaceous terrestrial molasse sedimentary rocks, such as the Jingzhushan Formation on the northern Lhasa terrane and the Abushan Formation on the South Qiangtang terrane (Pan et al., 2004), suggest that the two terranes had collided by this time.

In summary, the lithotectonic evidences for deformation and crustal thickening, the stratigraphic evidences for angular unconformities and accumulation of non-marine successions, and the presence of ca. 115–114 Ma anorogenic felsic (A2-type) rocks that

point to a post-collisional setting, suggest that the Lhasa–Qiangtang collision took place in the Late Jurassic to Early Cretaceous and the late Early Cretaceous magmatic rocks of this study formed after the closure of the BNSZ.

5.2. Origin of the andesites and granodiorites from the Zigetang Co area

Field and petrographical investigations indicate that the magmatic rocks underwent extensive alteration, which probably accounts for the variable LOI values of 1.17–5.04 wt.%. The abundances of immobile (e.g., REEs, high-field-strength elements (HFSEs), Ti, and P) and transition (e.g., V, Ni, Cr, and Fe) elements, their corresponding ratios, and zircon Hf isotopic compositions were essentially unaffected by the alteration processes (e.g., [Zhu et al., 2012](#); [Hu et al., 2013](#); [Zhai et al., 2013](#)); thus, these parameters can be used to classify the rocks and investigate their petrogenesis. Generally, the alteration processes should have modified the concentrations of mobile elements (e.g., Na, K, Ca, Cs, Rb, Ba, and Sr) (e.g., [Zhu et al., 2012](#); [Hu et al., 2013](#); [Zhai et al., 2013](#)). However, we note clear correlations between several mobile elements (e.g., K, Ca, and Sr) and SiO₂ from the andesites and granodiorites of the Zigetang Co area, suggesting that these mobile elements were barely modified during the alteration processes and can be used to investigate petrogenesis.

The andesites (114 Ma, +2.7 to +6.4) and granodiorites (117 and 118 Ma, +0.9 to +6.8) from the Zigetang Co area share the similar zircon U–Pb ages and $\varepsilon_{\text{Hf}}(t)$ values, suggesting that they were probably derived from the same magma source. The variable SiO₂ contents of these andesites (62.73–65.24 wt.%) and granodiorites (64.18–69.17 wt.%) suggest that crystal fractionation played an important role in their petrogenesis. Several evolution trends were recognized in [Fig. 7](#). The negative correlation between TiO₂ and

SiO₂ is interpreted as the result of the fractionation of Ti-bearing phases such as ilmenite and titanite (Fig. 7b). The decrease in TFe₂O₃ and MgO during magmatic evolution (Fig. 7c) indicates separation of ferromagnesian minerals (e.g., biotite) during crystallization. The decreased contents of P₂O₅ (Fig. 7e) are probably related to apatite fractionation and this is an important feature of I-type magma (Wolf and London, 1994). The Al₂O₃ (Fig. 7a), Sr (Fig. 7f), Eu/Eu* (Fig. 7g), and CaO (Fig. 7i) decreases with increasing SiO₂, suggesting the contribution of the fractionation of plagioclase. The positive correlation between K₂O and SiO₂ (Fig. 7h) suggests the absence of K-feldspar fractionation. These clear trends indicate that the andesites and granodiorites from the Zigetang Co area probably represent the melts generated by low- and high-degree fractional crystallization respectively.

The Zigetang Co andesites have high Sr contents (439–610 ppm) and Sr/Y ratios (27–40), and low Y (15.1–16.3 ppm) and Yb (1.45–1.65 ppm) contents. Because the Sr contents were reduced during the crystal fractionation of plagioclase, the primary magma of the Zigetang Co andesites probably has even higher Sr contents and Sr/Y ratios. These chemical features are comparable to those of modern adakites (Chung et al., 2003; Defant and Drummond, 1990; Hou et al., 2004; Martin et al., 2005). The adakitic affinities were originally interpreted to represent melts derived by partial melting of descending oceanic slabs with garnet dominant and plagioclase poor (or absent) residual phases (Defant and Drummond, 1990). Later adakite-like melts also have been widely reported in continental settings, generally being interpreted as partial melts of the thickened (e.g., Atherton and Petford 1993; Hou et al., 2004), subducted (e.g., Wang et al., 2008a), or delaminated eclogitic lower continental crust (e.g. Xu et al., 2002; Gao et al., 2004). Several recent studies suggest that the high Sr/Y signature can also be produced by high-pressure

fractional crystallization of basaltic magmas (e.g. Macpherson et al., 2006; Castillo, 2012; Li et al., 2013), magma mixing (e.g. Guo et al., 2007), melting of a high Sr/Y source at low pressure (e.g. Moyen, 2009; Ma et al., 2012; Qian and Hermann, 2013), or melting of the metasomatized lithospheric mantle (e.g. Martin et al., 2005; Jiang et al., 2006).

Although the Zigetang Co andesites have positive zircon $\varepsilon_{\text{Hf}}(t)$ values (+2.7 to +6.4), they have higher K₂O (Fig. 8a) and Th (Fig. 8b) contents than those of the Pacific adakites whose sources were the basaltic oceanic crust. Martin et al. (2005) identifies two distinct types of adakites: the high-SiO₂ adakites (HSA) and low-SiO₂ adakites (LSA). The Zigetang Co andesites have relatively high SiO₂ contents (> 60 wt.%) and are plotted in the HSA fields on the Sr/Y-Y (Fig. 8c) and Cr/Ni-TiO₂ (Fig. 8d) diagrams. Melting of metasomatized lithospheric mantle is expected to produce mainly LSA rather than HSA like the andesites studied here (Martin et al., 2005). Adakitic rocks derived from high-pressure fractional crystallization will generally display distinct geochemical trends (Macpherson et al., 2006); their La contents decrease with increasing SiO₂ contents, whereas Dy/Yb and Sr/Y ratios increase with increasing SiO₂ contents. The Zigetang Co andesites do not show such trends (Fig. 7j, k, and l). Mixing of basaltic (ultra) potassic rocks and rhyolitic magmas to explain the genesis of these andesites seems unlikely either. The andesites and granodiorites from the Zigetang Co area display consistent positive $\varepsilon_{\text{Hf}}(t)$ values and mafic microgranular enclaves are absent among these rocks. Adakite-like melts have also been interpreted as being produced by partial melting of thickened lower crust at high pressure (>12.5 kbar) (Wang et al., 2007, 2008b) or a high Sr/Y crustal source at relatively lower pressure (10–12.5 kbar) (Ma et al. 2012; Qian and Hermann, 2013). The adakitic melts derived from pure crustal sources generally have low compatible element abundances (e.g., Cr, Ni) and Mg[#] values (Wang et al., 2007; Qian

and Hermann, 2013), but the geochemical features of the Zigetang Co andesites (Fig. 8e, f) are not consistent with this genesis model.

Besides the adakitic affinity, the HMAA displays high-Mg features as a result of melt-peridotite interaction (Xu et al., 2002; Wang et al., 2008a, 2008b; Polat and Kerrich, 2001). We note that the Zigetang Co andesites have high MgO contents (2.50–3.31 wt.%) and $Mg^\#$ values (58–59) and thus are geochemically similar to the HMAA (Polat and Kerrich, 2001; Xu et al., 2002; Calmus et al., 2003; Gao et al., 2004; Wang et al., 2008a, 2008b) (Fig. 8). On $Mg^\#$ - SiO_2 diagram (Fig. 8e), these andesites were plotted in the field of the metabasaltic and experimental melts hybridized by peridotite. Therefore, the primary magma of the Zigetang Co andesites should have traversed mantle peridotites (Xu et al., 2002; Gao et al., 2004; Wang et al., 2004a, 2004b, 2006a, 2006b).

After excluding the other possibilities, both of the remaining continental subduction and delamination models can generate the Zigetang Co andesites of this study. This is supported by their high K_2O (Fig. 8a) and Th (Fig. 8b) contents and $Mg^\#$ values (Fig. 8e) and low TiO_2 contents (Fig. 8d) which are comparable to those of the HMAA related to either continental subduction or delamination. Of these two alternatives, we prefer the latter because of the presence of the coeval A-type granites (ca. 114–110 Ma) in the middle segment of the BNSZ (Qu et al., 2012; Chen et al., 2014). These A-type granites suggest a post-orogenic extension setting while the continental subduction process requires an orogenic compression environment.

Studies have indicated that the northern Lhasa terrane is characterized by the presence of juvenile crust (Zhu et al., 2011) while the Amdo basement within the BNSZ and the South Qiangtang terrane have ancient crust (Liu et al., 2010, 2011b; Zhu et al., 2011). Considering the Zigetang Co andesites and granodiorites have positive zircon $\varepsilon_{Hf}(t)$ values

(+2.7 to +6.4), we propose that their sources were delaminated juvenile lower continental crust of the northern Lhasa terrane. As discussed above, varying-degree fractional crystallization was important in the evolution of the adakitic magma after it formed.

5.3. Origin of the volcanic rocks from the Jiang Co area

5.3.1. Andesites

By contrast to the Zigetang Co andesites, the andesites from the Jiang Co area have low Sr (278–423 ppm) and high Y (20.8–24.5 ppm) contents with low Sr/Y ratios (12–20), indicating a different origin. Generally, there is an agreement that magmas experienced some degree of crustal contamination during ascent and/or residence within crustal magma chambers. However, the Jiang Co andesites have a narrow range of La/Nb ratio (3.2–3.5) and display no positive correlation on the La/Nb-La/Sm diagram (Fig. 7m), suggesting that crustal contamination was insignificant in these rocks (Liu et al., 2012; Huang et al., 2012). Moreover, for the studied andesite samples, SiO₂ shows negative correlations with TiO₂, Fe₂O₃, and MgO, probably related to the fractionation of clinopyroxene, hornblende, and Ti-bearing phases (rutile, ilmenite, titanite, etc.) (Liu et al., 2012). Both the partial melting and fractional crystallization trends are recognized on the La/Sm-La diagram (Fig. 7n), further supporting the fractionation processes after the generation of the parental magma of the Jiang Co andesites.

The petrogenesis of intermediate rocks is complex and several hypotheses have been proposed (Kuno, 1968; Boettcher, 1973; Grove and Kinzler, 1986; Grove et al., 2002). The existing models for the generation of intermediate rocks include: (1) partial melting of mantle wedge peridotite contaminated by fluid or melt from a subducting slab (e.g., Tatsumi, 1982; Parman and Grove, 2004); (2) fractional crystallization of mantle-derived basalt or basaltic andesite in a shallow crustal magma chamber (e.g., Grove et al., 1997;

Sisson and Grove, 1993); (3) mixing between mafic and silicic magma (e.g., Heiken and Eichelberger, 1980; Annen et al. 2006); (4) dehydration partial melting of meta-basalt in the crust, induced by mantle-derived magma (e.g., Petford and Atherton, 1996; Smith and Leeman, 1987; Wang et al., 2014); and (5) partial melting of subduction-modified lithospheric mantle (Wang et al., 2010; Lan et al., 2012; Huang et al., 2012).

As discussed above, the Lhasa terrane collided with the South Qiangtang terrane in the late Jurassic near Amdo. This indicates the absence of oceanic subduction in the study area in late Early Cretaceous, and thus the Jiang Co andesites cannot be interpreted to be produced by partial melting of a mantle wedge peridotite that was metasomatized by subduction-derived components. The Early Cretaceous mantle-derived basaltic andesite near the BNSZ (ca. 131–115 Ma) all display large positive zircon $\varepsilon_{\text{Hf}}(t)$ values (+6.3 to +18.8) (Zhu et al., 2011; Xu et al., 2015a, 2015b) which are obviously different to those of the Jiang Co andesites (-9.1 to +0.5), so the fractional crystallization origin can be ruled out. We rule out the possibility of magma mixing origin either, because of the lack of magma mixing trend on the FeOt–MgO diagram (Fig. 7o) and petrological evidences (such as mafic micro-granular enclaves) for magma mixing observed on the outcrops. Given the interpretation above, the primary magma of the Jiang Co andesites should possess higher MgO contents and $\text{Mg}^\#$ values than the present-day samples ($\text{MgO} = 3.13\text{--}4.03$ wt.%; $\text{Mg}^\# = 54\text{--}58$), so the Jiang Co andesites could not be derived from partial melting of a mafic crust, which would produce magmas with low $\text{Mg}^\#$ (< 40 ; Atherton and Petford, 1993; Martin et al., 2005).

We suggest that partial melting of ancient heterogeneous subduction-modified lithospheric mantle is the most likely origin for the andesites, for three reasons. (1) Ancient lithospheric mantle, which had been modified by the subduction processes of the

Bangong–Nujiang Tethyan Ocean, has been recognized from the Amdo basement and the South Qiangtang terrane (Zhu et al., 2011; Huang et al., 2012; Li et al., 2014). (2) Most of the zircons from the andesites have variable and negative $\varepsilon_{\text{Hf}}(t)$ values. (3) These andesites are enriched in Th, U, and LREE, but depleted in Nb, Ta, P, and Ti, suggesting that their magma source has been modified by the subduction fluids (Wang et al., 2010; Huang et al., 2012).

5.3.2. Rhyolite

Rhyolites can be generated by extensive fractional crystallization of basaltic-andesitic magmas, and various source materials could have contributed to the rhyolitic magmas investigated here, including enriched mantle, depleted mantle, and felsic crust (Civetta et al., 1998; Lustrino et al., 2000; Ronga et al., 2010). In such cases, the isotopic composition of the magmas would not have been altered during the process of closed-system fractional crystallization. The magmas could also have been produced by crustal anatexis induced by underplating of mantle-derived basaltic magma (Clemens, 2003; Kemp et al., 2006, 2007). This type of process has been considered to generate most of the late Mesozoic silicic igneous rocks recognized along the BNSZ (Zhu et al., 2011).

The possibility that the Jiang Co rhyolites were produced by fractional crystallization of basaltic-andesitic magmas can be ruled out, for two main reasons. (1) The zircons of these rhyolites exhibit small negative to positive $\varepsilon_{\text{Hf}}(t)$ values (-6.4 to +2.3), which are considerably different from those of the coeval basaltic rocks recognized within or along the both sides of the BNSZ (ca. 115 Ma, $\varepsilon_{\text{Hf}}(t) = +13.1$ to +15.0, Xu et al., 2015a; ca. 126 Ma, $\varepsilon_{\text{Hf}}(t) = +6.3$ to +10.7, Xu et al., 2015b; ca. 117 and 131 Ma, $\varepsilon_{\text{Hf}}(t) = +12.3$ to +18.8, Zhu et al., 2011). (2) There are no fractional crystallization trends between the rhyolites and andesites in Fig. 7. Therefore, partial melting of crustal materials is the most likely

origin for the rhyolites. Moreover, given the negative and positive $\varepsilon_{\text{Hf}}(t)$ values, a heterogeneous source is required.

These rhyolites exhibit distinguished high SiO_2 contents (80.42–81.55 wt.%) as well as low Fe_2O_3 (0.53–0.88 wt.%) and MgO (0.24–0.26 wt.%) contents. These geochemical features are similar to those of highly-differentiated granites (e.g., Hu et al., 2013, 2014; Jiang et al., 2011), suggesting the extensive fractional crystallization processes after the partial melting. This is further supported by the clear trend of fractional crystallization on the La/Sm–La diagram (Fig. 7n).

5.4. Tectonic interpretation: a lithospheric delamination model

As shown in Fig. 9, the Late Jurassic to Early Cretaceous magmatic rocks along the both sides of and within the BNSZ show similar temporal distributions. The late Early Cretaceous magmatic rocks have clearly larger scale than that of the Jurassic magmatic rocks (Fig. 9), indicating a magmatic flare-up which initiated at ca. 125 Ma (slight earlier in the northern Lhasa terrane at ca. 135 Ma) and terminated at ca. 105 Ma. The slab breakoff of the southward-subducting oceanic lithosphere cannot account for this magmatic flare-up on both sides of and within the BNSZ. Moreover, although the magmatic flare-up overlaps the timing of northward subduction of Neo-Tethyan Ocean lithosphere beneath the southern margin of the Lhasa Terrane (Zhu et al., 2011, 2013), this is unlikely to be the geodynamic driver of the magmatic flare-up as the BNSZ was some 600 km from the southern margin of the Lhasa Terrane (Kapp et al., 2007; Leier et al., 2007). The magmatic flare-up would require low angle subduction (Coulon et al., 1986; Kapp et al., 2005, 2007; Zhang, 2004) which could not then account for coeval calc-alkaline magmatism along the southern margin of the Lhasa terrane (Zhu et al., 2011,

2013). Therefore, we propose a two-stage lithospheric delamination model (Fig. 10) for the Early Cretaceous evolution of the BNSZ.

Stage I (135–125 Ma): As discussed above, the Lhasa–Qiangtang collision took place during the Late Jurassic to Early Cretaceous. The Lhasa–Qiangtang collision zone would have experienced lithospheric stacking or crustal thickening as a result of the oceanic subduction and continental collision by the Early Cretaceous (Wu et al., 2016). The resulting thickened lithospheric keel (i.e., the lithospheric mantle and lowermost crust) would have progressed from amphibolite- to eclogite-facies conditions (Arndt and Goldstein, 1989) and become denser than the underlying mantle. Some parts of this dense keel would rupture and detach due to gravitational instability (Krystopowicz and Currie, 2013). As shown in Fig. 9, the Early Cretaceous magmatic flare-up of the northern Lhasa terrane (135–105 Ma) overlaps but is a little older than that of the South Qiangtang terrane and the BNSZ (125–105 Ma), suggesting that the rupture of lithospheric keel most likely initiated beneath the northern Lhasa terrane at ca. 135 Ma (Fig. 10a). This rupture would induce invasion of the deep asthenosphere into the mantle wedge, causing mantle decompression melting (Dilek and Altunkaynak, 2007, 2009; Lustrino, 2005). This phase is represented by the ca. 131 Ma basaltic andesite of the Yanhu area of the northern Lhasa terrane ($\varepsilon_{\text{Hf}}(t)=+12.3$ to $+18.8$; Zhu et al., 2011). Moreover, the mantle-derived melt would also cause crustal anatexis of northern Lhasa terrane that generated the 134–130 Ma granitoids in the Baingoin Batholith (Zhu et al., 2016).

Stage II (125–105 Ma): Continued sinking of the dense keel would lead to the rupture propagating from the south to the north, eventually resulting in its complete detachment from the overlying crust (Krystopowicz and Currie, 2013). Such processes would create a gap that is filled with upwelling hot asthenosphere (Fig. 10b),

consequently resulting in partial melting of the asthenosphere and the overriding metasomatized lithosphere to produce mafic magmatism that continues for a few millions of years (e.g., Fan et al., 2014; Zhu et al., 2006, 2011; Xu et al., 2015a, 2015b; Chen et al., 2006) and anatexis of continental crust and lithospheric mantle (this study; Zhu et al., 2011, 2016; Li et al., 2014) to produce andesitic-rhyolitic magmatism that can proceed over a considerably longer period (Krystopowicz and Currie, 2013). As a result, magmatism occurs throughout the collision zone (this study; Zhu et al., 2011, 2016; Li et al., 2014), explaining the magmatic flare-up at 125–105 Ma in the northern Lhasa terrane, the BNSZ, and the South Qiangtang terrane (Fig. 9). Moreover, the Zigetang Co adakitic andesites were generated by partial melting of the delaminated juvenile lower continental crust of the northern Lhasa terrane. Their high $Mg^{\#}$ values (58–59) and Cr (66.5–81.1 ppm) and Ni (25.4–39.4 ppm) contents were probably related to the melt-peridotite interaction processes in the gap above the delaminated crust (Fig. 10b).

Notably, coeval magmatism was also recognized on the both sides of the Longling–Ruili suture zone (e.g., the Tengchong and Baoshan terranes; Fig. 9) (Xie et al., 2016; Tao et al., 2010), which marks the extension of the BNSZ in the southeastern Asia. Therefore, the late Early Cretaceous lithospheric delamination may also occur along the Longling–Ruili suture zone, although further investigations and more data on the Early Cretaceous geological records are required for the testing of this hypothesis.

6. Conclusions

- (1) Zircon U–Pb dating indicates that magmatic rocks from the Jiang Co and Zigetang Co areas formed at 118–113 Ma.
- (2) The Zigetang Co andesites have adakitic index ratios and are characterized by high

K₂O (2.95–3.58 wt.%), Th (12.5–15.0 ppm), MgO (2.50–3.31 wt.%), and Mg[#] (58–59), and relatively juvenile $\epsilon_{\text{Hf}}(t)$ (+2.7 to + 6.4) isotopic compositions. These observations suggest that these rocks were derived from partial melting of the delaminated juvenile lower continental crust of the northern Lhasa terrane. The Zigetang Co granodiorites represent the melts generated by high-degree fractional crystallization of the adakitic magma.

(3) The Jiang Co andesites display no adakitic geochemical features and have variable and mostly negative $\epsilon_{\text{Hf}}(t)$ values (-9.1 to +0.5). Geochemical and isotopic data indicate that these andesites were probably derived from partial melting of ancient heterogeneous subduction-modified lithospheric mantle. Some fractionation processes occurred after the generation of their parental magma.

(4) The Jiang Co rhyolites exhibit distinguished high SiO₂ contents (80.42–81.55 wt.%) and negative to positive $\epsilon_{\text{Hf}}(t)$ values (-6.4 to +2.3). Partial melting of crustal materials in a heterogeneous source is the most likely origin for the rhyolites. Extensive fractional crystallization processes may occur after the partial melting.

(5) Coeval Early Cretaceous magmatism was extensive in on both sides of and within the BNSZ. They are related to the post-collisional delamination of thickened lithosphere following collision of the Lhasa and South Qiangtang terranes. This lithospheric delamination process may also affect the Longling–Ruili suture zone in the southeastern Asia.

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Figure captions

Fig. 1. (a) Tectonic framework of the Tibetan Plateau and southeastern Asia (modified from Chung et al. 2005). (b) Simplified geologic map of the Jiang Co and Zigetang Co areas in the middle segment of the BNSZ showing the sample locations of this study. Age data sources: 110, 111, and 118 Ma, Zhu et al., 2011; 113 Ma, Huang et al., 2012; 117 Ma, Peng et al., 2011; 116 Ma, Liu et al., 2011a; 114 and 115 Ma, Zhang et al., 2010; 122 Ma, Chen et al., 2010.

Fig. 2. Field photographs (a-d) and photomicrographs (e-h) of the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the BNSZ. Q = quartz; Pl = plagioclase; Hbl = hornblende; and Bt = biotite.

Fig. 3. Cathodoluminescence (CL) images of representative zircon grains, and LA-ICP-MS zircon U–Pb concordia diagrams of the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the BNSZ. Solid and dashed circles show the locations of U–Pb dating and Hf analyses, respectively. The scale bar on the CL images is 100 μm .

Fig. 4. Histograms of zircon $\varepsilon_{\text{Hf}}(t)$ for the late Early Cretaceous magmatic rocks of the Jiang Co and Zigetang Co areas of the BNSZ.

Fig. 5. (a) Plots of SiO_2 vs. Zr/Ti (Winchester and Floyd, 1977) and (b) Th vs. Co (Hastie et al., 2007) for the late Early Cretaceous magmatic rocks of the Jiang Co and Zigetang Co

1049 areas of the BNSZ.

Fig. 6 Chondrite-normalized REE patterns (a and c) and primitive-mantle-normalized spider diagrams (b and d) for the late Early Cretaceous magmatic rocks of the Jiang Co and Zigetang Co areas of the BNSZ. The REE data for chondrites and trace element data for primitive mantle are after [Sun and McDonough \(1989\)](#).

Fig. 7. Plots of selected major and trace elements of the late Early Cretaceous magmatic rocks of the Jiang Co and Zigetang Co areas of the BNSZ. The evolution trends are after [Wolf and London \(1994\)](#), [Wang et al., 2010](#), [Huang et al., 2012](#), and [Zorpi et al., 1991](#).

Fig. 8. Plots of selected major and trace elements of the Zigetang Co andesites of the BNSZ. Data sources of adakites from the circum-Pacific Ocean are from [Kepezhinskas et al. \(1997\)](#), [Prouteau et al. \(2000\)](#) and [Volynets \(1994\)](#). North Tibetan adakites are from [Wang et al. \(2005, 2008a, 2008b\)](#). HAS and LSA fields are from [Martin et al. \(2005\)](#). The metabasaltic and eclogite experimental melts are from [Rapp et al. \(1999, 2003\)](#) and references therein. The field of Late Mesozoic delaminated lower crust-derived adakitic rocks in the eastern Yangtze Block is from [Xu et al. \(2002\)](#) and [Wang et al. \(2004a, 2004b, 2006a, 2006b\)](#). The field of Early Cretaceous thickened lower crust-derived adakitic granites in the northern Dabie Complex is from [Wang et al. \(2007\)](#). Data of different types of HMAA are from [Polat and Kerrich, 2001](#); [Xu et al., 2002](#), [Calmus et al., 2003](#), [Gao et al., 2004](#), and [Wang et al., 2008a, 2008b](#).

Fig. 9. Plots of zircon $\varepsilon_{\text{Hf}}(t)$ vs. U–Pb ages for the Jurassic–Early Cretaceous magmatic

rocks of the northern Lhasa terrane (Zhu et al., 2011, 2015; Xu et al., 2015b), Tengchong terrane (Xie et al., 2016, and the references therein), the BNSZ (Zhu et al., 2011; Xu et al., 2015a; this study), the South Qiangtang terrane (Li et al., 2014), and the Baoshan terrane (Tao et al., 2010).

Fig. 10. Schematic diagrams illustrating the two-stage lithospheric delamination model for the Early Cretaceous evolution of the BNSZ. See text for explanation. OLC=ancient lower crust; JLC=juvenile lower crust; FC=fractional crystallization; ①=northern Lhasa Baingoin Batholith (134–130 Ma; $\epsilon_{\text{Hf}}(\text{t})=+2.2$ to $+11.0$; Zhu et al., 2015); ② = MORB-like basaltic andesite of the northern Lhasa terrane (131 Ma; $\epsilon_{\text{Hf}}(\text{t})=+12.3$ to $+18.8$; Zhu et al., 2011); ③=Jiang Co andesite (this study); ④=Jiang Co rhyolite (this study); ⑤=Zigetang Co andesite (this study); ⑥=Zigetang Co granodiorite (this study); ⑦ = MORB-like basaltic andesite of the northern Lhasa terrane (117 Ma; $\epsilon_{\text{Hf}}(\text{t})=+13.5$ to $+18.4$; Zhu et al., 2011); ⑧ = MORB-like basaltic rocks within the BNSZ (115 Ma; $\epsilon_{\text{Hf}}(\text{t})=+13.1$ to $+15.0$; Xu et al., 2015a); ⑨ = MORB-like basaltic rocks of the South Qiangtang terrane (126 Ma; $\epsilon_{\text{Hf}}(\text{t})=+6.3$ to $+11.8$; Xu et al., 2015b)

Table captions

Table 1. Locations, zircon U–Pb ages, and mineral assemblages of the Late Early Cretaceous magmatic rocks in the middle segment of the Bangong–Nujiang suture zone, Tibetan Plateau

Table 2. SIMS U–Pb data for zircon grains from the late Early Cretaceous andesite (12T036) of the Jiang Co area of the Bangong–Nujiang suture zone, Tibet.

Table 3. LA-ICP-MS U–Pb data for zircon grains from the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

Table 4. Hf isotopic compositions of zircons from the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

Table 5. Whole-rock major and trace element data of the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

Figure1

Figure2

Figure3

Figure 4

Figure5

Figure6

Figure 7

Figure 8

Figure9

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Table1

Table 1 Locations, zircon U–Pb ages, and mineral assemblages of the Late Early Cretaceous magmatic rocks in the middle segment of the Bangong–Nujiang suture zone, Tibetan Plateau

Sample	GPS data	Location	Lithology	Zircon U-Pb age	Mineral assemblage
12T036	N: 31°40.019' E: 90°37.020'	Jiang Co	Andesite	112.9±0.8 Ma	Plagioclase and Quartz phenocrysts, and cryptocrystalline groundmass
13T034	N: 31°43.010' E: 90°54.030'	Jiang Co	Andesite	116.8±0.7 Ma	
13T046	N: 31°55.080' E: 90°51.993'	Jiang Co	Rhyolite	116.3±1.2 Ma	Quartz phenocrysts and cryptocrystalline groundmass
13T091	N: 32°03.798' E: 90°43.418'	Zigetang Co	Andesite	114.3±0.8 Ma	Plagioclase phenocrysts and cryptocrystalline groundmass
13T109	N: 32°06.164' E: 90°41.098'	Zigetang Co	Granodiorite	118.4±0.8 Ma	Plagioclase, hornblende, quartz, and minor biotite
13T118	N: 32°06.045' E: 90°44.725'	Zigetang Co	Granodiorite	116.7±0.6 Ma	

Table2

Table 2 SIMS U–Pb data for zircon grains from the late Early Cretaceous andesite (12T036) of the Jiang Co area of the Bangong–Nujiang suture zone, Tibet.

Spot	Pb	Th	U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U	
	ppm	ppm	ppm		Ratio	±1σ (%)	Ratio	±1σ (%)	Ratio	±1σ (%)	Age (Ma)	±1σ	Age (Ma)	±1σ	Age (Ma)	±1σ
12T036	Andesite															
1	7	415	272	1.53	0.04976	2.75	0.11531	3.76	0.01744	1.55	96.6	79.2	110.8	4.0	111.5	1.7
2	5	275	206	1.33	0.04818	2.28	0.11779	2.83	0.01773	1.68	108.2	53.0	113.1	3.0	113.3	1.9
3	5	290	210	1.38	0.04705	2.28	0.11414	2.76	0.01760	1.55	51.7	53.5	109.7	2.9	112.4	1.7
4	10	291	448	0.65	0.04828	1.53	0.11855	2.18	0.01781	1.55	113.1	35.7	113.8	2.3	113.8	1.7
5	10	600	376	1.60	0.04895	1.67	0.11592	2.69	0.01763	1.56	84.0	51.1	111.4	2.8	112.7	1.7
6	6	297	233	1.27	0.04795	2.17	0.11479	2.67	0.01736	1.55	96.6	50.6	110.3	2.8	111.0	1.7
7	6	302	223	1.35	0.05016	2.16	0.11573	3.57	0.01750	1.55	97.1	74.6	111.2	3.8	111.9	1.7
8	13	478	551	0.87	0.04844	1.81	0.11395	2.89	0.01765	1.62	40.4	56.3	109.6	3.0	112.8	1.8
9	38	2441	1258	1.94	0.04773	0.91	0.11958	1.78	0.01817	1.52	86.1	21.5	114.7	1.9	116.1	1.8
10	12	552	461	1.20	0.04822	1.75	0.11960	2.32	0.01799	1.52	110.0	40.8	114.7	2.5	114.9	1.7
11	24	923	1000	0.92	0.04939	1.30	0.11926	2.10	0.01779	1.50	129.6	34.1	114.4	2.3	113.7	1.7
12	4	187	188	1.00	0.04822	2.39	0.11726	2.86	0.01763	1.57	110.3	55.5	112.6	3.0	112.7	1.7
13	6	220	243	0.91	0.04929	2.09	0.10990	4.18	0.01747	1.77	-22.0	89.3	105.9	4.2	111.6	2.0
14	3	104	122	0.85	0.04879	2.96	0.10049	7.90	0.01762	1.65	-264.6	185.3	97.2	7.3	112.6	1.8
15	5	195	189	1.03	0.04853	2.39	0.11914	2.86	0.01780	1.57	125.4	55.4	114.3	3.1	113.8	1.8
16	2	79	97	0.82	0.05032	3.28	0.10473	7.85	0.01734	1.63	-121.6	179.3	101.1	7.6	110.8	1.8
17	8	502	306	1.64	0.04767	2.10	0.11524	2.60	0.01753	1.53	82.8	49.2	110.7	2.7	112.0	1.7
18	16	514	431	1.19	0.04959	1.29	0.17796	2.06	0.02625	1.51	156.1	32.6	166.3	3.2	167.0	2.5
19	7	346	271	1.28	0.04781	2.36	0.11576	2.82	0.01756	1.55	90.0	54.9	111.2	3.0	112.2	1.7
20	19	978	735	1.33	0.04823	1.21	0.11913	1.95	0.01791	1.53	110.7	28.3	114.3	2.1	114.5	1.7

Table3

Table 3 LA-ICP-MS U–Pb data for zircon grains from the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

Spot	Th	U	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U		²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U	
	ppm	ppm		Ratio	±1σ	Ratio	±1σ	Ratio	±1σ	Age (Ma)	±1σ	Age (Ma)	±1σ	Age (Ma)	±1σ
13T034	Andesite														
1	9754	4209	0.43	0.04936	0.00242	0.12340	0.00595	0.01813	0.00023	165	88	118	5	116	1
2	12751	5136	0.40	0.04827	0.00121	0.12135	0.00298	0.01823	0.00018	113	39	116	3	116	1
3	10178	5131	0.50	0.04989	0.01232	0.12479	0.03050	0.01814	0.00067	190	383	119	28	116	4
4	10109	5579	0.55	0.04846	0.00144	0.12364	0.00361	0.01850	0.00018	122	50	118	3	118	1
5	13441	6401	0.48	0.04847	0.00146	0.12282	0.00358	0.01837	0.00021	122	47	118	3	117	1
6	9886	5022	0.51	0.04779	0.00799	0.12028	0.01996	0.01825	0.00040	89	278	115	18	117	3
7	9366	5189	0.55	0.04675	0.00464	0.11987	0.01177	0.01859	0.00031	36	184	115	11	119	2
8	10413	5188	0.50	0.04918	0.00600	0.13344	0.01616	0.01967	0.00033	156	238	127	14	126	2
9	7258	3673	0.51	0.04889	0.00611	0.12427	0.01540	0.01843	0.00035	143	240	119	14	118	2
10	6484	3584	0.55	0.05753	0.01119	0.14470	0.02789	0.01824	0.00051	512	369	137	25	117	3
11	8407	4608	0.55	0.05247	0.00357	0.13070	0.00862	0.01806	0.00034	306	116	125	8	115	2
12	7155	5205	0.73	0.04847	0.00206	0.12061	0.00504	0.01804	0.00021	122	75	116	5	115	1
13	10433	4840	0.46	0.04699	0.00475	0.11929	0.01190	0.01841	0.00034	49	187	114	11	118	2
14	9874	7034	0.71	0.04848	0.00261	0.12185	0.00648	0.01822	0.00021	123	98	117	6	116	1
15	11539	6463	0.56	0.04869	0.00364	0.12401	0.00912	0.01847	0.00030	133	135	119	8	118	2
16	9892	5276	0.53	0.04915	0.00536	0.12176	0.01309	0.01796	0.00036	155	204	117	12	115	2
17	9972	5969	0.60	0.05079	0.01431	0.12618	0.03487	0.01802	0.00104	231	409	121	31	115	7
18	9188	4333	0.47	0.05053	0.00763	0.12641	0.01889	0.01814	0.00043	219	277	121	17	116	3
19	12148	5319	0.44	0.04849	0.00623	0.12236	0.01548	0.01830	0.00045	123	232	117	14	117	3
20	8361	4592	0.55	0.04826	0.00089	0.12367	0.00219	0.01858	0.00018	112	24	118	2	119	1

21	10346	5734	0.55	0.04916	0.00544	0.12461	0.01349	0.01838	0.00046	155	196	119	12	117	3
13T046	Rhyolite														
1	1215	2622	2.16	0.04867	0.00336	0.12235	0.00836	0.01823	0.00025	132	128	117	8	116	2
2	4655	4263	0.92	0.04869	0.01770	0.12268	0.04348	0.01827	0.00153	133	476	117	39	117	10
3	1291	2376	1.84	0.05454	0.01138	0.13352	0.02725	0.01775	0.00081	393	347	127	24	113	5
4	3227	3351	1.04	0.04969	0.01245	0.12390	0.03068	0.01808	0.00072	181	382	119	28	116	5
5	2128	3261	1.53	0.04896	0.00421	0.12236	0.01040	0.01812	0.00028	146	162	117	9	116	2
6	1556	2514	1.62	0.04929	0.00688	0.12212	0.01642	0.01797	0.00071	162	225	117	15	115	4
7	2167	3375	1.56	0.04979	0.00777	0.12460	0.01926	0.01815	0.00042	185	280	119	17	116	3
8	4927	4111	0.83	0.04766	0.02111	0.12088	0.05325	0.01839	0.00087	82	666	116	48	117	6
9	1472	2788	1.89	0.04845	0.00618	0.12299	0.01528	0.01841	0.00058	121	216	118	14	118	4
10	2649	3470	1.31	0.05639	0.01218	0.14112	0.02958	0.01815	0.00099	468	356	134	26	116	6
11	1333	2394	1.80	0.04948	0.00678	0.12349	0.01667	0.01810	0.00046	171	250	118	15	116	3
12	1899	3097	1.63	0.04799	0.00514	0.12122	0.01272	0.01832	0.00043	99	190	116	12	117	3
13	1338	3174	2.37	0.04882	0.00168	0.12361	0.00413	0.01836	0.00022	139	56	118	4	117	1
14	1449	2998	2.07	0.04793	0.01729	0.12038	0.04264	0.01821	0.00128	96	489	115	39	116	8
15	1478	2964	2.01	0.04840	0.00324	0.11830	0.00782	0.01772	0.00025	119	121	114	7	113	2
16	2406	2873	1.19	0.04973	0.00896	0.12408	0.02193	0.01809	0.00066	182	294	119	20	116	4
17	1995	3373	1.69	0.05541	0.00859	0.14295	0.02188	0.01871	0.00049	429	297	136	19	119	3
13T091	Andesite														
1	400	403	1.01	0.05266	0.00209	0.13118	0.00502	0.01806	0.00025	314	62	125	5	115	2
2	107	172	1.61	0.04872	0.00562	0.12037	0.01373	0.01792	0.00036	134	215	115	12	114	2
3	332	367	1.10	0.05081	0.00293	0.12598	0.00708	0.01798	0.00027	232	102	120	6	115	2
4	248	303	1.22	0.04788	0.00542	0.11517	0.01291	0.01744	0.00031	93	214	111	12	111	2
5	430	587	1.36	0.04836	0.00184	0.11954	0.00441	0.01793	0.00023	117	62	115	4	115	1
6	336	322	0.96	0.04855	0.01216	0.12000	0.02986	0.01792	0.00054	126	387	115	27	114	3

7	225	255	1.13	0.04940	0.01208	0.12355	0.03004	0.01814	0.00049	167	392	118	27	116	3
8	160	269	1.68	0.04830	0.00860	0.12195	0.02151	0.01831	0.00047	114	290	117	19	117	3
9	174	255	1.46	0.04856	0.00669	0.12209	0.01657	0.01823	0.00047	127	244	117	15	116	3
10	198	298	1.50	0.04706	0.01520	0.11826	0.03802	0.01822	0.00058	52	484	113	35	116	4
11	162	266	1.64	0.04961	0.01273	0.12675	0.03222	0.01853	0.00068	177	398	121	29	118	4
12	348	395	1.13	0.04845	0.00279	0.12200	0.00687	0.01826	0.00026	121	100	117	6	117	2
13	123	227	1.85	0.04842	0.00997	0.11734	0.02359	0.01758	0.00078	120	366	113	21	112	5
14	356	527	1.48	0.04975	0.00552	0.12276	0.01350	0.01789	0.00031	183	215	118	12	114	2
15	450	627	1.39	0.04864	0.00281	0.11946	0.00677	0.01781	0.00026	131	101	115	6	114	2
16	177	284	1.61	0.05709	0.00534	0.13594	0.01254	0.01727	0.00030	495	175	129	11	110	2
17	165	301	1.83	0.05664	0.00619	0.14312	0.01504	0.01832	0.00058	478	177	136	13	117	4
18	246	345	1.40	0.04751	0.00957	0.12096	0.02421	0.01846	0.00043	75	321	116	22	118	3
19	245	424	1.73	0.04941	0.00578	0.12330	0.01425	0.01810	0.00037	167	222	118	13	116	2
20	217	288	1.33	0.04782	0.00814	0.12070	0.02032	0.01830	0.00049	90	279	116	18	117	3
21	97	199	2.04	0.05208	0.01336	0.13115	0.03348	0.01826	0.00050	289	428	125	30	117	3
22	310	499	1.61	0.05083	0.00229	0.12235	0.00539	0.01746	0.00022	233	78	117	5	112	1
23	163	291	1.79	0.04820	0.00305	0.11929	0.00735	0.01795	0.00030	109	106	114	7	115	2
13T109	Granodiorite														
1	238	370	1.55	0.05156	0.00211	0.13159	0.00515	0.01851	0.00027	266	63	126	5	118	2
2	419	490	1.17	0.04844	0.00494	0.12603	0.01262	0.01887	0.00041	121	183	121	11	121	3
3	643	589	0.92	0.04921	0.00509	0.12870	0.01318	0.01896	0.00033	158	197	123	12	121	2
4	400	568	1.42	0.04814	0.00255	0.12378	0.00640	0.01864	0.00027	106	89	118	6	119	2
5	102	234	2.30	0.04838	0.00748	0.12375	0.01877	0.01855	0.00060	118	256	118	17	118	4
6	470	568	1.21	0.04615	0.00341	0.12070	0.00883	0.01897	0.00024	5	136	116	8	121	2
7	277	459	1.66	0.04918	0.00314	0.12422	0.00769	0.01832	0.00029	157	145	119	7	117	2
8	323	314	0.97	0.04860	0.01755	0.12617	0.04506	0.01882	0.00104	129	521	121	41	120	7

9	216	288	1.34	0.05772	0.01927	0.15038	0.04946	0.01889	0.00112	519	539	142	44	121	7
10	397	634	1.60	0.05094	0.00408	0.12869	0.01022	0.01832	0.00024	238	156	123	9	117	2
11	359	500	1.39	0.04874	0.00243	0.12321	0.00596	0.01833	0.00023	135	114	118	5	117	1
12	279	269	0.97	0.04634	0.00732	0.12137	0.01905	0.01899	0.00036	15	258	116	17	121	2
13	493	977	1.98	0.04922	0.00257	0.12520	0.00647	0.01844	0.00020	158	98	120	6	118	1
14	146	252	1.72	0.04711	0.01172	0.12306	0.03046	0.01894	0.00052	55	379	118	28	121	3
15	619	733	1.18	0.05218	0.00273	0.13241	0.00674	0.01841	0.00022	293	122	126	6	118	1
16	359	349	0.97	0.05206	0.00210	0.13264	0.00511	0.01848	0.00027	288	61	126	5	118	2
17	303	341	1.12	0.04862	0.00565	0.12387	0.01431	0.01848	0.00029	130	227	119	13	118	2
18	289	285	0.99	0.05031	0.00274	0.12873	0.00686	0.01855	0.00027	209	96	123	6	118	2
19	418	385	0.92	0.05045	0.00553	0.12720	0.01366	0.01829	0.00041	216	247	122	12	117	3
20	159	259	1.63	0.04680	0.00910	0.12123	0.02322	0.01878	0.00067	39	291	116	21	120	4
21	389	477	1.23	0.05225	0.00227	0.13462	0.00557	0.01868	0.00030	296	65	128	5	119	2
22	681	912	1.34	0.04664	0.00259	0.12059	0.00646	0.01875	0.00032	31	83	116	6	120	2
23	268	275	1.03	0.04786	0.00784	0.12406	0.02008	0.01879	0.00051	92	276	119	18	120	3
13T118	Granodiorite														
1	664	824	1.24	0.04837	0.00099	0.12114	0.00236	0.01816	0.00019	117	27	116	2	116	1
2	485	590	1.22	0.05138	0.00165	0.12858	0.00401	0.01815	0.00021	258	50	123	4	116	1
3	409	466	1.14	0.04889	0.00597	0.12183	0.01476	0.01807	0.00032	143	236	117	13	115	2
4	468	651	1.39	0.05003	0.00129	0.12669	0.00310	0.01836	0.00021	196	36	121	3	117	1
5	235	315	1.34	0.05112	0.01114	0.12775	0.02768	0.01812	0.00047	246	364	122	25	116	3
6	591	891	1.51	0.04792	0.00258	0.12158	0.00647	0.01840	0.00022	95	96	117	6	118	1
7	381	445	1.17	0.05042	0.01162	0.12626	0.02875	0.01816	0.00068	214	363	121	26	116	4
8	454	516	1.14	0.04903	0.00529	0.12195	0.01299	0.01804	0.00035	149	203	117	12	115	2
9	510	720	1.41	0.05293	0.00423	0.13344	0.01057	0.01828	0.00025	326	156	127	9	117	2
10	304	288	0.95	0.04836	0.01225	0.12409	0.03126	0.01861	0.00053	117	394	119	28	119	3

11	1311	811	0.62	0.04856	0.00139	0.12141	0.00339	0.01813	0.00018	127	47	116	3	116	1
12	417	498	1.20	0.04881	0.00418	0.12419	0.01051	0.01845	0.00029	139	160	119	9	118	2
13	323	463	1.43	0.04741	0.00234	0.11778	0.00567	0.01802	0.00024	70	81	113	5	115	2
14	465	381	0.82	0.04774	0.00549	0.12221	0.01392	0.01856	0.00033	86	219	117	13	119	2
15	408	549	1.35	0.04886	0.00770	0.12276	0.01910	0.01822	0.00049	141	269	118	17	116	3
16	319	472	1.48	0.04902	0.00513	0.12126	0.01260	0.01794	0.00027	149	205	116	11	115	2
17	460	770	1.67	0.04819	0.00147	0.11993	0.00354	0.01804	0.00020	109	49	115	3	115	1
18	229	291	1.27	0.04828	0.00630	0.12013	0.01514	0.01804	0.00064	113	212	115	14	115	4
19	374	450	1.20	0.04839	0.00179	0.12283	0.00438	0.01840	0.00024	118	59	118	4	118	2
20	417	655	1.57	0.05212	0.00139	0.13199	0.00335	0.01836	0.00022	291	36	126	3	117	1
21	751	1099	1.46	0.05290	0.00224	0.13448	0.00548	0.01844	0.00021	325	98	128	5	118	1
22	358	445	1.24	0.05271	0.01073	0.13439	0.02722	0.01848	0.00041	316	371	128	24	118	3
23	310	625	2.02	0.04759	0.00570	0.12095	0.01408	0.01842	0.00056	79	199	116	13	118	4
24	471	525	1.11	0.04737	0.00405	0.12164	0.01022	0.01861	0.00035	68	150	117	9	119	2
25	172	272	1.58	0.04961	0.00488	0.12445	0.01186	0.01818	0.00048	177	165	119	11	116	3

Table 4

Table 4 Hf isotopic compositions of zircons from the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

[illegible]

1	116	0.0892	0.0005	0.0024	0.0000	0.282600	0.000030	0.282594	-6.1	-3.7	1.1	960	1411	-0.93
2	116	0.0978	0.0019	0.0026	0.0000	0.282562	0.000027	0.282556	-7.4	-5.1	1.0	1021	1497	-0.92
3	116	0.1105	0.0005	0.0029	0.0000	0.282631	0.000028	0.282625	-5.0	-2.7	1.0	927	1343	-0.91
4	118	0.1112	0.0021	0.0030	0.0001	0.282557	0.000029	0.282551	-7.6	-5.2	1.0	1040	1508	-0.91
5	117	0.1017	0.0003	0.0029	0.0000	0.282540	0.000030	0.282533	-8.2	-5.9	1.0	1062	1547	-0.91
6	117	0.1162	0.0010	0.0033	0.0000	0.282664	0.000025	0.282657	-3.8	-1.5	0.9	889	1270	-0.90
7	119	0.1006	0.0013	0.0028	0.0000	0.282538	0.000025	0.282532	-8.3	-5.9	0.9	1061	1549	-0.92
8	126	0.1053	0.0015	0.0027	0.0000	0.282587	0.000032	0.282581	-6.5	-4.0	1.1	987	1436	-0.92
9	118	0.1173	0.0020	0.0030	0.0000	0.282543	0.000027	0.282536	-8.1	-5.8	1.0	1060	1540	-0.91
10	117	0.1192	0.0010	0.0032	0.0000	0.282582	0.000031	0.282575	-6.7	-4.4	1.1	1009	1453	-0.90
11	115	0.1043	0.0014	0.0027	0.0000	0.282666	0.000031	0.282660	-3.8	-1.4	1.1	870	1264	-0.92
12	115	0.1336	0.0008	0.0039	0.0000	0.282608	0.000047	0.282600	-5.8	-3.6	1.7	988	1399	-0.88
13	115	0.0692	0.0007	0.0017	0.0000	0.282595	0.000027	0.282591	-6.3	-3.9	1.0	950	1420	-0.95
14	110	0.1039	0.0007	0.0027	0.0000	0.282613	0.000031	0.282607	-5.6	-3.4	1.1	949	1386	-0.92
15	118	0.1167	0.0011	0.0033	0.0000	0.282516	0.000040	0.282509	-9.0	-6.7	1.4	1110	1601	-0.90
16	116	0.1029	0.0026	0.0029	0.0001	0.282622	0.000047	0.282616	-5.3	-3.0	1.7	941	1363	-0.91
17	118	0.1253	0.0009	0.0032	0.0000	0.282634	0.000034	0.282627	-4.9	-2.5	1.2	930	1336	-0.90
18	116	0.1280	0.0007	0.0038	0.0000	0.282627	0.000039	0.282618	-5.1	-2.9	1.4	956	1357	-0.89
19	110	0.1011	0.0013	0.0028	0.0000	0.282573	0.000028	0.282567	-7.0	-4.8	1.0	1011	1476	-0.92
20	115	0.1247	0.0018	0.0036	0.0001	0.282578	0.000029	0.282571	-6.8	-4.6	1.0	1025	1464	-0.89
21	115	0.1206	0.0016	0.0035	0.0000	0.282600	0.000034	0.282593	-6.1	-3.8	1.2	988	1415	-0.90
13T046	Rhyolite													
1	116	0.1080	0.0010	0.0033	0.0001	0.282701	0.000022	0.282693	-2.5	-0.2	0.8	834	1188	-0.90
2	117	0.1687	0.0027	0.0059	0.0001	0.282778	0.000036	0.282765	0.2	2.3	1.3	773	1025	-0.82
3	113	0.1358	0.0003	0.0046	0.0000	0.282755	0.000033	0.282745	-0.6	1.5	1.2	780	1074	-0.86
4	116	0.1034	0.0005	0.0032	0.0000	0.282704	0.000025	0.282697	-2.4	-0.1	0.9	825	1180	-0.90

5	116	0.1456	0.0014	0.0047	0.0000	0.282733	0.000031	0.282723	-1.4	0.8	1.1	817	1122	-0.86
6	115	0.1576	0.0019	0.0055	0.0001	0.282702	0.000037	0.282690	-2.5	-0.4	1.3	885	1195	-0.83
7	116	0.1822	0.0016	0.0065	0.0001	0.282532	0.000075	0.282518	-8.5	-6.4	2.7	1193	1580	-0.80
8	117	0.1423	0.0016	0.0052	0.0001	0.282709	0.000087	0.282698	-2.2	-0.1	3.1	867	1178	-0.84
9	118	0.1594	0.0016	0.0056	0.0001	0.282602	0.000048	0.282590	-6.0	-3.8	1.7	1048	1418	-0.83
13T091	Andesite													
1	115	0.041803	0.000259	0.001584	0.000012	0.282813	0.000030	0.282809	1.4	3.8	1.1	633	928	-0.95
2	114	0.023007	0.000334	0.000821	0.000012	0.282853	0.000023	0.282851	2.8	5.3	0.8	564	835	-0.98
3	115	0.023686	0.000414	0.000837	0.000011	0.282830	0.000024	0.282828	2.0	4.5	0.8	596	885	-0.97
4	112	0.047393	0.000246	0.001668	0.000009	0.282887	0.000026	0.282883	4.1	6.4	0.9	527	762	-0.95
5	115	0.036889	0.000314	0.001292	0.000011	0.282787	0.000025	0.282784	0.5	2.9	0.9	665	985	-0.96
6	114	0.039611	0.000310	0.001356	0.000011	0.282826	0.000025	0.282823	1.9	4.3	0.9	610	898	-0.96
7	116	0.051775	0.000823	0.001748	0.000028	0.282846	0.000025	0.282843	2.6	5.0	0.9	587	852	-0.95
8	117	0.045061	0.000308	0.001739	0.000012	0.282878	0.000024	0.282874	3.7	6.2	0.8	541	780	-0.95
9	116	0.035438	0.000252	0.001234	0.000006	0.282819	0.000025	0.282817	1.7	4.1	0.9	618	911	-0.96
10	116	0.032313	0.000429	0.001174	0.000014	0.282844	0.000026	0.282841	2.5	5.0	0.9	582	855	-0.96
11	118	0.044235	0.000709	0.001595	0.000021	0.282855	0.000028	0.282851	2.9	5.4	1.0	573	831	-0.95
12	117	0.023741	0.000064	0.000767	0.000002	0.282686	0.000022	0.282685	-3.0	-0.5	0.8	797	1208	-0.98
13	118	0.028811	0.000391	0.001003	0.000014	0.282807	0.000025	0.282805	1.2	3.7	0.9	632	936	-0.97
14	114	0.049140	0.000338	0.001694	0.000008	0.282859	0.000028	0.282855	3.1	5.5	1.0	568	824	-0.95
15	114	0.041441	0.000107	0.001462	0.000006	0.282810	0.000030	0.282807	1.4	3.7	1.1	635	934	-0.96
16	110	0.027455	0.000311	0.000978	0.000012	0.282846	0.000026	0.282844	2.6	5.0	0.9	576	853	-0.97
17	117	0.026905	0.000163	0.000948	0.000005	0.282846	0.000025	0.282844	2.6	5.1	0.9	575	848	-0.97
18	118	0.027584	0.000081	0.000981	0.000002	0.282809	0.000024	0.282807	1.3	3.8	0.8	629	932	-0.97
19	116	0.029234	0.000602	0.001016	0.000020	0.282827	0.000024	0.282825	2.0	4.4	0.8	603	892	-0.97
20	117	0.021381	0.000251	0.000726	0.000010	0.282823	0.000025	0.282822	1.8	4.3	0.9	604	899	-0.98

21	117	0.022639	0.000129	0.000801	0.000004	0.282777	0.000024	0.282775	0.2	2.7	0.9	670	1003	-0.98
22	112	0.026999	0.000228	0.000934	0.000006	0.282863	0.000028	0.282861	3.2	5.6	1.0	550	812	-0.97
23	115	0.029620	0.000346	0.001031	0.000010	0.282842	0.000023	0.282840	2.5	4.9	0.8	582	859	-0.97
13T109	Granodiorite													
1	118	0.029825	0.000096	0.001046	0.000005	0.282781	0.000022	0.282779	0.3	2.8	0.8	669	995	-0.97
2	121	0.033030	0.000768	0.001115	0.000026	0.282794	0.000024	0.282792	0.8	3.4	0.8	651	963	-0.97
3	121	0.028055	0.000250	0.000932	0.000009	0.282836	0.000027	0.282834	2.3	4.8	1.0	590	869	-0.97
4	119	0.031417	0.000244	0.001082	0.000011	0.282817	0.000021	0.282814	1.6	4.1	0.7	619	914	-0.97
5	118	0.030435	0.000439	0.000990	0.000012	0.282786	0.000028	0.282784	0.5	3.0	1.0	660	983	-0.97
6	121	0.034114	0.000093	0.001216	0.000003	0.282775	0.000024	0.282773	0.1	2.7	0.9	680	1007	-0.96
7	117	0.024017	0.000286	0.000773	0.000008	0.282846	0.000025	0.282844	2.6	5.1	0.9	573	849	-0.98
8	120	0.026890	0.000105	0.000871	0.000004	0.282854	0.000023	0.282852	2.9	5.5	0.8	563	829	-0.97
9	121	0.037522	0.000163	0.001201	0.000004	0.282883	0.000024	0.282881	3.9	6.5	0.8	526	763	-0.96
10	117	0.036141	0.000112	0.001219	0.000006	0.282842	0.000022	0.282839	2.5	4.9	0.8	585	859	-0.96
11	117	0.028276	0.000261	0.000937	0.000007	0.282818	0.000022	0.282815	1.6	4.1	0.8	615	913	-0.97
12	121	0.032587	0.000053	0.001135	0.000002	0.282799	0.000023	0.282796	1.0	3.5	0.8	645	953	-0.97
13	118	0.028768	0.000112	0.000960	0.000004	0.282810	0.000021	0.282807	1.3	3.8	0.7	627	930	-0.97
14	121	0.025133	0.000323	0.000811	0.000012	0.282853	0.000025	0.282851	2.9	5.5	0.9	563	829	-0.98
15	118	0.038698	0.000278	0.001258	0.000007	0.282728	0.000023	0.282725	-1.6	0.9	0.8	749	1117	-0.96
16	118	0.061435	0.000421	0.001962	0.000013	0.282792	0.000026	0.282788	0.7	3.1	0.9	670	975	-0.94
17	118	0.042912	0.001238	0.001394	0.000039	0.282811	0.000023	0.282808	1.4	3.9	0.8	632	928	-0.96
18	118	0.028467	0.000219	0.000943	0.000007	0.282805	0.000023	0.282803	1.2	3.7	0.8	634	941	-0.97
19	117	0.029371	0.000073	0.000957	0.000003	0.282818	0.000026	0.282816	1.6	4.1	0.9	615	912	-0.97
20	120	0.036538	0.000109	0.001155	0.000004	0.282765	0.000026	0.282762	-0.2	2.3	0.9	694	1031	-0.97
21	119	0.028725	0.000081	0.000949	0.000001	0.282815	0.000021	0.282813	1.5	4.1	0.7	619	917	-0.97
22	120	0.030714	0.000326	0.001030	0.000011	0.282871	0.000021	0.282869	3.5	6.1	0.8	541	790	-0.97

23	120	0.030845	0.000264	0.001021	0.000008	0.282835	0.000023	0.282833	2.2	4.8	0.8	592	871	-0.97
13T118	Granodiorite													
1	116	0.041155	0.000154	0.001368	0.000004	0.282867	0.000023	0.282864	3.4	5.8	0.8	551	803	-0.96
2	116	0.111389	0.002207	0.003357	0.000070	0.282828	0.000029	0.282821	2.0	4.3	1.0	641	901	-0.90
3	115	0.030098	0.000706	0.001003	0.000024	0.282783	0.000023	0.282781	0.4	2.8	0.8	665	992	-0.97
4	117	0.033130	0.000176	0.001076	0.000006	0.282798	0.000022	0.282795	0.9	3.4	0.8	646	958	-0.97
5	116	0.041204	0.000197	0.001347	0.000005	0.282818	0.000025	0.282815	1.6	4.1	0.9	622	915	-0.96
6	118	0.033961	0.000056	0.001169	0.000001	0.282831	0.000023	0.282829	2.1	4.6	0.8	599	882	-0.96
7	116	0.036613	0.000462	0.001172	0.000013	0.282802	0.000022	0.282799	1.1	3.5	0.8	641	950	-0.96
8	115	0.025924	0.000084	0.000876	0.000003	0.282789	0.000023	0.282787	0.6	3.1	0.8	655	978	-0.97
9	117	0.032980	0.000513	0.001105	0.000018	0.282875	0.000021	0.282872	3.6	6.1	0.8	537	784	-0.97
10	119	0.033811	0.000609	0.001131	0.000020	0.282805	0.000020	0.282803	1.2	3.7	0.7	636	941	-0.97
11	116	0.114185	0.001345	0.003418	0.000038	0.282899	0.000028	0.282891	4.5	6.8	1.0	536	742	-0.90
12	118	0.028030	0.000543	0.000914	0.000016	0.282777	0.000020	0.282775	0.2	2.7	0.7	672	1004	-0.97
13	115	0.021373	0.000110	0.000728	0.000003	0.282826	0.000028	0.282825	1.9	4.4	1.0	600	893	-0.98
14	119	0.071583	0.000096	0.002243	0.000007	0.282846	0.000028	0.282841	2.6	5.0	1.0	596	855	-0.93
15	116	0.030126	0.000464	0.000980	0.000013	0.282848	0.000024	0.282846	2.7	5.2	0.8	573	845	-0.97
16	115	0.027235	0.000240	0.000907	0.000007	0.282773	0.000023	0.282771	0.0	2.5	0.8	677	1014	-0.97
17	115	0.043644	0.000311	0.001404	0.000007	0.282822	0.000024	0.282819	1.8	4.2	0.8	617	906	-0.96
18	115	0.030535	0.000533	0.001006	0.000015	0.282798	0.000025	0.282796	0.9	3.4	0.9	644	958	-0.97
19	118	0.033713	0.000750	0.001101	0.000023	0.282821	0.000020	0.282818	1.7	4.2	0.7	614	906	-0.97
20	117	0.024608	0.000187	0.000844	0.000005	0.282837	0.000022	0.282835	2.3	4.8	0.8	587	868	-0.97
21	118	0.045753	0.000100	0.001535	0.000002	0.282803	0.000021	0.282799	1.1	3.6	0.8	646	948	-0.95
22	118	0.032277	0.000169	0.001067	0.000004	0.282794	0.000024	0.282791	0.8	3.3	0.8	651	966	-0.97
23	118	0.030231	0.000613	0.000977	0.000019	0.282822	0.000024	0.282820	1.8	4.3	0.8	609	902	-0.97
24	119	0.029639	0.000253	0.001001	0.000009	0.282806	0.000022	0.282804	1.2	3.7	0.8	632	937	-0.97

25	116	0.029806	0.000103	0.001000	0.000003	0.282856	0.000026	0.282854	3.0	5.4	0.9	562	827	-0.97
Note: $\epsilon_{\text{Hf}}(t) = 10,000 \times \left[\frac{\left((^{176}\text{Hf}/^{177}\text{Hf})_S - (^{176}\text{Lu}/^{177}\text{Hf})_S \times (e^{\lambda t} - 1) \right)}{\left[(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} \times (e^{\lambda t} - 1) \right] - 1} \right]$, $T_{\text{DM}} = 1/\lambda \times \ln \{ 1 + [(^{176}\text{Hf}/^{177}\text{Hf})_S - (^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}}] / [(^{176}\text{Lu}/^{177}\text{Hf})_S - (^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}}] \}$, $T_{\text{DM}}^{\text{C}} = T_{\text{DM}} - (T_{\text{DM}} - t) \times [(f_{\text{cc}} - f_s)/(f_{\text{cc}} - f_{\text{DM}})]$, $f_{\text{Lu/Hf}} = (^{176}\text{Lu}/^{177}\text{Hf})_S / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} - 1$, where, $\lambda = 1.867 \times 10^{-11} \text{ year}^{-1}$ (Soderlund et al., 2004); $(^{176}\text{Lu}/^{177}\text{Hf})_S$ and $(^{176}\text{Hf}/^{177}\text{Hf})_S$ are the measured values of the samples; $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}} = 0.0332$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{CHUR},0} = 0.282772$ (Blichert-Toft and Albarede, 1997); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} = 0.0384$ and $(^{176}\text{Hf}/^{177}\text{Hf})_{\text{DM}} = 0.28325$ (Griffin et al., 2000); $(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}} = 0.015$; $f_{\text{cc}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{mean crust}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$; $f_s = f_{\text{Lu/Hf}}$; $f_{\text{DM}} = [(^{176}\text{Lu}/^{177}\text{Hf})_{\text{DM}} / (^{176}\text{Lu}/^{177}\text{Hf})_{\text{CHUR}}] - 1$; t =crystallization time of zircon.														

Table 5. Whole-rock major and trace element data of the late Early Cretaceous magmatic rocks from the Jiang Co and Zigetang Co areas of the Bangong–Nujiang suture zone, Tibet.

Sample	12T031	12T032	12T033	12T034	12T035	12T036	14T127	14T128
Lithology	Andesite	Andesite	Andesite	Andesite	Andesite	Andesite	Andesite	Andesite
Locality	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co
Major element (wt.%)								
SiO ₂	59.98	59.49	58.85	59.47	59.52	58.84	58.21	58.68
TiO ₂	0.70	0.67	0.71	0.69	0.72	0.70	0.73	0.74
Al ₂ O ₃	16.15	16.20	16.17	16.16	16.35	16.10	16.32	16.17
Fe ₂ O _{3t}	6.28	6.05	6.14	6.21	6.04	6.43	6.57	6.72
MnO	0.11	0.11	0.11	0.11	0.11	0.12	0.09	0.12
MgO	3.16	3.03	3.64	3.17	3.55	3.32	3.64	3.42
CaO	3.88	4.12	4.58	4.11	3.93	4.78	4.64	4.80
Na ₂ O	4.08	4.14	3.33	4.17	3.82	4.34	3.21	3.99
K ₂ O	3.07	3.00	3.08	3.10	3.45	2.74	3.33	2.80
P ₂ O ₅	0.16	0.15	0.16	0.15	0.16	0.16	0.16	0.16
LOI	2.75	3.32	2.85	2.81	2.82	3.21	3.21	2.62
Total	100.32	100.28	99.62	100.15	100.47	100.74	100.11	100.22
Mg#	54	54	58	54	58	55	56	54
Trace element (ppm)								
Li	24.0	25.8	37.5	29.0	32.9	23.5	35.4	26.2
Be	2.26	2.24	2.26	2.47	2.42	2.39	1.80	1.81
P	790	741	790	741	790	790	790	790
Sc	16.6	16.5	18.1	16.9	17.3	16.9	19.1	18.4
Ti	4312	4214	4534	4313	4466	4327	4379	4385
V	128	126	134	131	131	128	141	140
Cr	19.7	20.2	27.9	17.8	24.7	22.9	20.5	18.8
Co	16.4	16.5	17.4	16.9	16.7	17.2	18.8	18.4
Ni	10.4	10.8	11.8	9.79	9.70	9.47	12.0	11.1
Ga	17.8	18.1	17.9	18.6	17.8	17.9	16.7	16.6
Rb	122	135	131	127	143	112	137	100
Sr	296	324	323	288	328	305	299	278
Zr	156	149	159	162	159	159	150	156
Nb	9.15	9.52	9.07	9.52	8.97	8.89	9.12	8.89
Cs	2.29	2.75	3.16	2.27	3.03	2.22	4.04	1.56
Ba	458	503	607	518	652	436	535	410
Ta	1.04	1.01	0.91	0.97	0.88	0.85	0.75	0.72
Pb	31.2	43.3	21.0	25.5	42.2	29.4	8.40	21.0
Th	17.7	16.8	16.3	17.6	17.0	16.7	15.8	16.6
U	3.25	3.15	3.27	3.44	3.34	3.26	2.85	2.76
Y	23.8	23.4	24.5	24.4	24.4	23.5	21.2	21.9
La	32.2	30.7	31.2	32.5	31.2	31.3	30.1	31.1
Ce	63.4	60.0	61.9	64.5	62.3	62.8	62.6	64.8
Pr	7.16	6.77	7.02	7.21	7.03	7.18	6.49	6.72
Nd	28.0	26.1	27.2	27.9	27.7	27.2	24.5	25.2
Sm	4.85	4.73	4.93	5.04	4.78	4.81	5.33	5.30
Eu	1.11	1.08	1.11	1.10	1.11	1.12	1.14	1.16
Gd	4.37	4.16	4.53	4.36	4.44	4.36	5.04	5.16
Tb	0.67	0.62	0.68	0.65	0.70	0.64	0.71	0.77
Dy	4.23	4.07	4.09	4.19	4.30	4.22	4.45	4.41
Ho	0.83	0.83	0.85	0.86	0.89	0.85	0.90	0.90
Er	2.35	2.34	2.37	2.42	2.42	2.34	2.61	2.63
Tm	0.41	0.37	0.40	0.41	0.41	0.38	0.37	0.38
Yb	2.43	2.43	2.61	2.50	2.42	2.48	2.49	2.57
Lu	0.40	0.39	0.39	0.40	0.39	0.38	0.39	0.41
Hf	4.54	4.21	4.34	4.37	4.46	4.37	4.27	4.32

Table 5. (continued)

Sample	14T129	14T130	14T131	14T132	14T133	14T134	13T045	13T047
Lithology	Andesite	Andesite	Andesite	Andesite	Andesite	Andesite	Rhyolite	Rhyolite
Locality	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co	Jiang Co
Major element (wt.%)								
SiO ₂	57.72	58.74	58.91	58.72	57.95	59.35	78.17	77.93
TiO ₂	0.75	0.75	0.75	0.74	0.76	0.74	0.08	0.08
Al ₂ O ₃	15.84	16.24	16.16	16.27	15.94	16.24	14.17	14.51
Fe ₂ O ₃ t	6.98	6.79	6.83	6.63	7.11	6.66	0.51	0.52
MnO	0.12	0.11	0.11	0.09	0.12	0.12	0.01	0.01
MgO	3.89	3.58	3.82	3.55	3.64	3.54	0.24	0.23
CaO	4.85	3.76	4.12	4.28	5.02	4.56	0.20	0.17
Na ₂ O	3.29	3.75	3.16	3.19	3.82	3.38	0.01	0.01
K ₂ O	3.00	3.28	3.67	3.32	2.73	2.86	2.44	2.41
P ₂ O ₅	0.16	0.16	0.16	0.16	0.16	0.16	0.02	0.02
LOI	3.30	3.08	2.82	3.19	3.03	2.66	3.65	3.72
Total	99.90	100.24	100.51	100.14	100.28	100.27	99.50	99.61
Mg#	56	55	57	55	54	55	52	51
Trace element (ppm)								
Li	36.5	31.7	33.3	35.2	27.0	30.2	18.9	16.2
Be	1.81	1.76	1.78	1.74	1.75	1.67	2.92	2.79
P	790	790	790	790	790	790	87.3	87.3
Sc	21.2	18.4	19.5	17.8	19.9	18.2	1.89	1.48
Ti	4564	4403	4547	4431	4492	4370	432	423
V	148	138	141	140	147	137	2.73	1.58
Cr	24.4	20.3	21.5	18.8	20.8	19.9	13.5	10.1
Co	20.0	18.7	19.3	19.0	20.1	18.3	0.19	0.13
Ni	11.5	11.3	9.94	11.0	10.4	10.2	1.38	1.64
Ga	16.9	16.5	17.0	16.3	17.0	16.6	14.9	15.0
Rb	136	117	154	110	108	128	119	116
Sr	325	293	346	282	283	423	9.87	11.9
Zr	151	152	155	150	154	154	60.7	61.1
Nb	8.91	9.16	9.16	8.99	9.04	9.19	11.2	11.1
Cs	3.12	3.96	3.51	4.04	1.53	3.82	3.25	2.93
Ba	543	440	574	459	429	626	110	160
Ta	0.73	0.77	0.78	0.74	0.75	0.75	1.03	1.04
Pb	11.9	13.2	10.8	7.28	19.6	13.4	2.98	3.14
Th	15.7	16.2	16.9	15.7	16.6	16.7	21.1	21.8
U	2.91	2.82	3.14	2.85	2.90	3.24	2.69	2.72
Y	22.3	21.2	21.9	20.8	21.8	21.5	5.04	5.91
La	30.7	29.5	31.3	29.3	30.3	31.7	15.6	19.5
Ce	63.0	62.2	64.6	61.8	63.7	65.1	27.6	34.6
Pr	6.61	6.50	6.66	6.51	6.61	6.69	2.96	3.55
Nd	25.8	25.8	27.0	25.4	26.9	26.7	9.97	12.6
Sm	5.36	5.30	5.46	5.18	5.42	5.48	1.89	2.29
Eu	1.17	1.19	1.14	1.12	1.14	1.17	0.37	0.46
Gd	5.31	5.21	5.17	4.94	5.28	5.08	1.54	2.01
Tb	0.75	0.74	0.75	0.71	0.75	0.73	0.20	0.28
Dv	4.53	4.58	4.47	4.32	4.50	4.34	1.12	1.31
Ho	0.96	0.92	0.93	0.87	0.94	0.93	0.19	0.24
Er	2.75	2.69	2.71	2.60	2.72	2.67	0.57	0.63
Tm	0.41	0.40	0.40	0.38	0.40	0.39	0.12	0.13
Yb	2.54	2.50	2.55	2.44	2.62	2.43	0.63	0.83
Lu	0.40	0.41	0.39	0.39	0.39	0.40	0.11	0.13
Hf	4.29	4.37	4.40	4.43	4.37	4.43	2.33	2.38

Table 5. (continued)

Sample	13T048	13T049	13T050	13T086	13T087	13T089	13T090	13T091
Lithology	Rhyolite	Rhyolite	Rhyolite	Andesite	Andesite	Andesite	Andesite	Andesite
Locality	Jiang Co	Jiang Co	Jiang Co	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co
Major element (wt.%)								
SiO ₂	78.05	77.69	76.57	62.40	59.98	60.07	59.25	60.28
TiO ₂	0.07	0.08	0.07	0.64	0.77	0.78	0.79	0.78
Al ₂ O ₃	14.31	14.52	14.33	15.16	15.36	15.53	15.39	15.57
Fe ₂ O ₃ t	0.53	0.85	0.54	4.11	4.93	4.95	5.00	5.02
MnO	0.00	0.01	0.01	0.07	0.09	0.08	0.07	0.08
MgO	0.23	0.25	0.24	2.39	3.08	3.08	3.12	3.05
CaO	0.22	0.21	1.01	3.74	4.17	3.88	4.06	3.76
Na ₂ O	0.01	0.01	0.01	3.51	4.12	4.25	3.61	3.98
K ₂ O	2.28	2.47	2.40	3.42	2.86	2.82	2.76	3.05
P ₂ O ₅	0.02	0.03	0.03	0.21	0.26	0.26	0.26	0.27
LOI	3.82	3.83	4.41	3.71	3.99	4.11	5.04	4.16
Total	99.54	99.95	99.62	99.36	99.61	99.81	99.35	100.00
Mg#	50	41	51	58	59	59	59	59
Trace element (ppm)								
Li	18.2	24.9	24.8	38.9	42.7	44.2	59.6	45.9
Be	2.67	2.68	2.96	2.48	2.30	2.39	2.00	2.16
P	87.3	131	131	917	1135	1135	1135	1179
Sc	1.47	2.14	2.45	9.73	11.6	11.3	12.0	11.3
Ti	417	425	450	3982	4756	4725	4828	4780
V	2.56	2.26	1.15	78.0	94.1	94.8	94.6	92.3
Cr	5.40	4.86	9.00	72.0	81.1	66.5	70.3	66.8
Co	0.16	0.33	0.31	12.6	15.9	15.7	15.9	15.1
Ni	2.70	2.28	1.94	25.4	38.3	36.8	39.4	37.3
Ga	13.9	15.9	16.5	17.2	17.1	17.3	16.9	16.9
Rb	104	127	120	135	106	128	125	120
Sr	33.6	17.5	17.4	610	590	494	439	549
Zr	57.4	57.5	56.7	172	181	174	178	178
Nb	10.8	11.9	11.9	12.2	13.3	12.8	13.0	12.7
Cs	2.42	4.73	4.67	6.20	4.81	5.35	6.26	6.44
Ba	931	324	239	549	556	447	488	513
Ta	1.01	1.05	1.03	1.11	1.07	1.10	1.09	1.07
Pb	3.67	11.0	9.97	103	15.2	17.8	15.8	18.6
Th	23.0	24.4	25.8	15.0	13.9	12.6	12.5	12.9
U	2.47	2.61	2.81	4.06	3.26	3.44	3.3	3.26
Y	5.23	7.11	10.2	15.1	16.3	15.7	16.0	15.8
La	17.8	18.4	21.5	30.4	34.4	31.7	32.2	31.8
Ce	30.9	28.1	37.0	54.6	63.1	57.3	58.7	57.5
Pr	3.43	3.42	4.10	5.94	6.75	6.37	6.46	6.43
Nd	11.7	12.1	14.1	22.3	25.7	23.9	24.8	24.7
Sm	2.11	2.17	2.66	4.07	4.43	4.17	4.23	4.40
Eu	0.49	0.52	0.59	0.97	1.12	1.15	1.06	1.11
Gd	1.80	1.99	2.51	3.84	4.35	4.15	4.13	4.01
Tb	0.24	0.30	0.37	0.56	0.61	0.61	0.62	0.63
Dv	1.15	1.48	1.90	3.02	3.37	3.11	3.38	3.39
Ho	0.20	0.29	0.35	0.58	0.62	0.62	0.62	0.62
Er	0.59	0.81	0.96	1.45	1.58	1.64	1.67	1.65
Tm	0.12	0.16	0.17	0.28	0.30	0.30	0.31	0.29
Yb	0.71	0.94	1.01	1.45	1.57	1.62	1.63	1.65
Lu	0.10	0.14	0.15	0.22	0.24	0.24	0.24	0.24
Hf	2.23	2.34	2.37	4.09	4.11	3.99	4.21	4.22

Table 5. (continued)

Sample	13T110	13T111	13T113	13T114	13T116	13T117	13T118
Lithology	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite	Granodiorite
Locality	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co	Zigetang Co
Major element (wt.%)							
SiO ₂	67.95	65.00	63.17	63.13	62.86	65.04	65.00
TiO ₂	0.47	0.53	0.68	0.70	0.69	0.61	0.49
Al ₂ O ₃	15.85	14.53	16.18	16.09	16.10	14.88	14.42
Fe ₂ O _{3t}	2.53	3.32	5.98	6.18	6.11	3.65	3.28
MnO	0.04	0.06	0.09	0.09	0.09	0.09	0.06
MgO	0.71	1.90	1.22	1.24	1.21	1.64	2.12
CaO	2.37	3.15	3.11	2.99	3.19	2.55	3.00
Na ₂ O	3.99	4.09	4.20	4.20	4.17	4.57	4.33
K ₂ O	4.22	2.81	3.40	3.32	3.25	3.83	3.07
P ₂ O ₅	0.11	0.15	0.28	0.29	0.28	0.17	0.14
LOI	1.17	3.90	1.35	1.43	1.25	2.80	3.24
Total	99.41	99.44	99.66	99.66	99.20	99.83	99.15
Mg#	40	57	32	32	32	51	60
Trace element (ppm)							
Li	12.3	30.5	26.6	27.3	25.4	24.9	30.6
Be	3.36	2.02	3.52	3.46	3.44	3.56	2.54
P	480	655	1223	1266	1223	742	611
Sc	8.18	7.54	11.9	12.4	12.1	9.29	7.81
Ti	2716	3321	4229	4310	4214	3857	3067
V	30.0	57.2	27.9	27.7	27.7	58.4	56.8
Cr	0.27	41.7	12.2	2.61	2.34	25.7	66.2
Co	4.20	10.6	7.77	6.74	8.04	8.22	11.4
Ni	12.5	28.3	7.33	6.58	5.85	21.9	32.6
Ga	19.9	17.7	22.3	21.3	21.6	18.1	16.5
Rb	143	145	104	90.8	93.8	158	160
Sr	281	254	496	444	456	407	352
Zr	312	166	591	601	581	246	148
Nb	19.3	12.7	21.4	21.6	20.8	17.5	11.9
Cs	3.61	7.59	2.76	2.01	2.31	3.93	6.22
Ba	682	468	765	736	744	625	479
Ta	1.45	1.19	1.52	1.52	1.52	1.72	1.16
Pb	30.2	9.12	34.3	36.8	29.5	16.1	30.3
Th	24.5	21.6	19.1	19.1	17.9	31.2	21.5
U	4.70	3.80	4.51	4.74	4.26	4.98	3.47
Y	22.4	14.1	28.1	28.1	27.2	20.6	13.3
La	75.6	27.3	53.6	51.9	52.4	43.2	31.3
Ce	134	61.8	101	100	97.4	84.0	57.7
Pr	14.0	5.84	11.3	11.1	10.8	8.23	5.89
Nd	49.6	21.9	42.3	42.2	41.3	29.5	21.2
Sm	7.71	3.93	7.73	7.40	7.3	5.06	3.70
Eu	1.34	0.85	1.97	1.89	1.89	1.10	0.87
Gd	7.31	3.75	7.28	7.06	6.96	5.26	3.55
Tb	1.02	0.53	1.04	1.09	1.02	0.76	0.52
Dv	5.15	2.85	5.86	5.77	5.56	4.16	2.74
Ho	0.98	0.56	1.16	1.10	1.06	0.85	0.51
Er	2.46	1.44	2.96	2.83	2.64	2.08	1.28
Tm	0.47	0.28	0.55	0.52	0.52	0.41	0.23
Yb	2.67	1.53	2.96	3.11	2.95	2.17	1.33
Lu	0.40	0.21	0.44	0.48	0.44	0.32	0.21
Hf	7.33	4.18	11.0	11.0	10.5	5.77	3.64

Note: LOI = loss on ignition.