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Geochronology, geochemistry and Sr-Nd-Pb-Hf isotopes of the Early Paleogene gabbro and granite from Central Lhasa, southern Tibet: petrogenesis and tectonic implications

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ABSTRACT
The Tibetan Plateau is a composite orogenic belt that has experienced prolonged subduction, obduction, and collisional processes, during the opening and closure of successive Tethyan oceans. We present new zircon U-Pb ages and Hf isotopes, and whole-rock geochemical and Sr-Nd-Pb isotopic data from the Early Paleogene Longge’er gabbro and Qingduxiang granite of Central Lhasa, southern Tibet. Together these allow us to refine existing models for widespread magmatic activity associated with the subduction of the Neo-Tethyan Ocean. The Longge’er gabbro (53.5 ± 1.6 Ma) belongs to the low-K tholeiitic to medium-K and metaluminous series, while the Qingduxiang granite (54.5 ± 0.9 Ma) is characterized as high-K, calc-alkaline, metaluminous, and of I-type affinity. Both intrusions are enriched in the LREE and depleted in the HREE with negative Eu, Ba, Nb, Ta, Sr, and Ti anomalies. Trace elements characteristics and enriched whole-rock Sr-Nd-Pb and zircon Hf isotopic compositions demonstrate that the gabbro was derived from partial melting of enriched lithosphere mantle metasomatized by Central-Lhasa ancient crustal materials, while the I-type granite was generated by partial melting of Central-Lhasa ancient lower crust combined with magmas derived from Southern-Lhasa juvenile crust. Geochemical compositions of the gabbro and granite reveal the Early Paleogene magmatism was emplaced in a shallow extensional setting related to slab break off following the closure of the Neo-Tethyan Ocean. Combined with previous studies, we can infer slab rollback occurred from Late Cretaceous (~69 Ma) to Early Eocene (55 Ma), while slab break off was shortly lived at ca. 55–49 Ma. Consequently, the India-Asia collision must not have started later than ca. 55 Ma.

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1. Introduction

The Tibetan Plateau is a composite orogenic belt that has experienced prolonged episodes of subduction, obduction, and collisional processes, during the opening and closure of successive Tethyan oceans (including the Paleo-, Meso-, and Neo-Tethyan oceans) (Pan et al. 2012; Hou et al. 2015; Cao et al. 2016; Zhu et al. 2016, 2017a; Wang et al. 2016b). The Neo-Tethyan Ocean was open and northwardly subducted beneath the Asian plate during the Late Triassic to Early Paleogene, and was finally closed during the India-Asia collision (Gardiner et al. 2015; Zhu et al. 2015; Cao et al. 2017b, 2018). During the Late Mesozoic to Cenozoic, southern Tibet was an active continental margin closely associated with the subduction of the Neo-Tethyan Ocean, accompanied by intense and widespread magmatic activity (Jiang et al. 2014, 2015; Zheng et al. 2015; Zhu et al. 2015; Huang et al. 2016; Wang et al. 2017a).

As a constituent part of southern Tibet, the Lhasa terrane is composed of Northern Lhasa, Central Lhasa and Southern Lhasa (Zhu et al. 2011). Due to the subduction of the Neo-Tethyan Ocean, myriad Early Paleogene magmatic rocks were produced in Central and Southern Lhasa, including a series of abundant mafic and felsic intrusive rocks, and volcanic rocks (Lee et al. 2009, 2012; Zhao et al. 2012, 2014, 2016; Zhu et al. 2015; Chen et al. 2015b). Since latest several years, amounts of mafic intrusive rocks (e.g. diorite and gabbro) have been discovered on Central Lhasa and the exact metasomatic mechanism forming these mafic rocks has not come to an agreement. While a few studies have regarded the partial melting of the Neo-Tethyan Oceanic slab as the source of crustal material (Mo et al. 2007; Gao et al. 2010; Xu et al. 2014), other scholars have held the view that it was derived from Indian continental ancient sediments (Mo et al. 2009; Chu et al. 2011; Ma et al. 2017a). Recently, Zhu et al. (2011) have reported that ancient crust occurs in Central Lhasa. As such, a number of researches have maintained that partial melting of this ancient crust may have been involved (Guan et al. 2012; Huang et al. 2015; Pan et al. 2016; Liu et al. 2017a). To clarify the metasomatic mechanism, the petrogenesis of mafic rocks has yet to be constraint by systemic analysis.

Integrated study of mafic-felsic intrusive rocks has been proven to be useful in unravelling the geodynamic history of various regions (Zhao et al. 2011; Yang et al. 2018; Yin et al. 2018). Although the abundant studies concerning the Early Paleogene magmatism in southern Tibet (Ji et al. 2009, 2012, 2014; Jiang et al. 2014, 2015; Ma et al. 2016, 2017a, 2017b), however, the majority was concentrated on the on a couple of felsic or mafic intrusive rocks (Table 1), whereas the combined analysis for mafic-felsic intrusive rocks has been scarcely conducted. This imbalance severely hampers a reliable and comprehensive explanation for the Early Paleogene tectonic evolution. In addition, the timing of the India-Asia collision is

<table>
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<th>No.</th>
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<th>Method</th>
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still considerably debated, with ages ranging from 65 Ma to 35 Ma (Jaeger et al. 1989; Ding et al. 2005; Ali and Aitchison 2007; Chen et al. 2010b; Zhu et al. 2015; Hu et al. 2016a). For this reason, the well-preserved Early Paleogene igneous rocks exposed on southern Tibet can provide a sensible window for addressing the disputed timing of the India-Asia collision.

To help resolve these issues, we present new detailed zircon U-Pb ages and Hf isotopic data, mineral chemical compositions, whole-rock geochemistry, and Sr-Nd-Pb isotopes for the Early Paleogene Longge’er gabbroic pluton and Qinduxiang granitic pluton from Central Lhasa. Compared with existing data, moreover, the comprehensive analyses of the Early Paleogene magmatism allow us to better understand the tectono-magmatic evolution in Central Lhasa. Finally, we have an attempt to preliminarily constrain the controversial timing for the India-Asia collision, based on multi-disciplinary studies (e.g. magmatism, stratigraphy, structural geology, etc.).

2. Geological background and petrography

2.1. Geological background

The Tibet area is located in southwestern China and consists of several terranes, including the Himalaya, Lhasa, Qiangtang, and Songpan-Ganzi terranes (Figure 1(a)) (Pan et al. 2012). The Lhasa terrane, which extends for more than 2000 km, is a major constituent of southern Tibet. It occurs between the Indus-Yarlung Tsangpo suture (IYTS) in the south and Bangong-Nujiang suture (BNS) to the north, and is composed of Northern Lhasa, Central Lhasa, and Southern Lhasa. These are bounded by the Shiquanhe-Nam Tso Mélange zone (SNMZ) and Luobadui-Milashan fault (LMF), respectively (Figure 1(b)) (Zhu et al. 2011).

Northern Lhasa is inferred to consist of a juvenile crust, with overlying Middle Triassic to Cretaceous sedimentary rocks and abundant Early Cretaceous medium-K calc-alkaline arc volcanic rocks and granitoids (Zhu et al. 2013). Central Lhasa is characterized by ancient crust representing a possible microcontinent that experienced multi metamorphic events during the Neoproterozoic (Dong et al. 2011; Guynn et al. 2012). The overlying strata include Carboniferous-Permian and Upper Jurassic-Lower Cretaceous sedimentary rocks. Southern Lhasa is dominated by juvenile crust (with local ancient crust), covered by the Cretaceous-Tertiary Gangdese batholith and Paleogene Linzizong volcanic succession with minor sedimentary rocks (Zhu et al. 2011).

Prolonged and intense Late Mesozoic-Cenozoic magmatic events were triggered by the northward Andean-style continental subduction of the Neo-Tethyan Ocean,
which is characterized by the >1600 km E–W-trending magmatic belt (Chen et al. 2010a, 2017; Jiang et al. 2014, 2015; Zhu et al. 2015; Huang et al. 2016; Cao et al. 2017a; Fang et al. 2018). The subduction of the Neo-Tethyan Ocean gave birth to the Jurassic to Paleogene Gangdese batholith and Paleogene Linzizong volcanic succession with a small number of Jurassic-Cretaceous arc volcanic rocks (Figure 1(b)). Within ongoing subduction of the Neo-Tethyan Ocean, oceanic slab rollback and break-off occurred and induced the upwelling of hot asthenosphere, generating mafic and felsic intrusive rocks and Linzizong volcanic rocks with a magmatic flare-up at ca. 51 Ma (Zhu et al. 2015, 2017a, 2017b). After a magmatic quiescence of ca. 40–30 Ma, abundant post-collisional Oligocene-Miocene potassic and ultrapotassic volcanic rocks, with accompanying adakitic rocks, were extensively exposed in the western segment of central Tibet (Liu et al. 2017a; Zhang et al. 2017a).

2.2. Petrography and mineralogy

The Longge’er gabbroic pluton is situated in the western segment of the Gangdese batholith (Figure 1(b)), which is a newly discovered dike intruded into Early Cretaceous granodiorite. A Late Cretaceous diorite and Permian limestones are located in the eastern and western parts of the study area (Figure 2(a)). A skarn occurs at the contact zone between the granodiorite and limestone, with iron bodies developed in both the granodiorite and skarn (Figure 3(a)). The Longge’er gabbroic pluton is characterized by a massive and fine- to medium-grained texture and is composed of clinopyroxene (10–15%), plagioclase (30–35%), biotite (10–15%), and hornblende (25–30%) with accessory minerals of zircon, Fe-Ti oxides and titanite (Figure 3(c)). The samples of Longge’er gabbroic pluton are clarified as gabbro in the Total Alkali-Silica (TAS) diagram (Figure 4(a)).

Chemical compositions of feldspar, hornblende, pyroxene, and biotite analyzed from the Longge’er gabbro are provided in Supplementary Table 1. Plagioclase crystals from the Longge’er gabbro are prismatic and have An contents of 44.93–46.90%, classified as andesine (Figure 5(a)). Biotites are subhedral and are characterized by low Mg# values of 34–43, belonging to magnesio-biotite (Figure 5(b)). In addition, the biotite compositions suggest a mixture source between crustal- and mantle-derived magmas (Figure 5(c)) (Zhou 1986). Clinopyroxenes contain variable compositions of \( \text{FeO} \) (11.58–15.76 wt.%), \( \text{MgO} \) (13.29–15.72 wt.%), and \( \text{Cr}_2\text{O}_3 \) (0.03–0.27 wt.%) and are plotted in the augite fields of the \( \text{CaSiO}_3–\text{MgSiO}_3–\text{FeSiO}_3 \) diagram (Figure 5(d)). Hornblendes have high CaB values of 1.81–1.92 (>1.5), low (Na + K)A values of 0.32–0.75 (mean = 0.52, >0.5), and low Ti values of 0.00–0.11 (< 0.5), indicating these are mainly classified as edenite (Figure 5(e)).

The Qingduxiang granitic pluton is located in the south of the Qingduxiang County and belongs to the middle part of the Gangdese batholith (Figures 1(b) and 2(b)). A series of Permian, Early Cretaceous,
Figure 3. Field geological characteristics and petrography of the Longge'er gabbro and Qingduxiang granite. (a) Field crop of the Longge'er gabbro pluton and (b) Qingduxiang granitic pluton; microscope photos for (c) the Longge'er gabbro and (d) Qingduxiang granite. Primary minerals include Pl = plagioclase; Cpx = clinopyroxene; Hb = hornblende; Bt = biotite; Qtz = Quartz; Kfs = K-feldspar.

Figure 4. (a) (Na<sub>2</sub>O + K<sub>2</sub>O) versus SiO<sub>2</sub> diagram (Middlemost 1994); (b) K<sub>2</sub>O versus SiO<sub>2</sub> diagram, (Peccerillo and Taylor 1976); (c) Al<sub>2</sub>O<sub>3</sub>/(Na<sub>2</sub>O + K<sub>2</sub>O) molar versus Al<sub>2</sub>O<sub>3</sub>/(CaO + Na<sub>2</sub>O + K<sub>2</sub>O) molar diagram (Maniar and Piccoli 1989); (d) P<sub>2</sub>O<sub>5</sub> versus SiO<sub>2</sub> diagram for the Longerger gabbro and Qingduxiang granite.

and Paleogene sedimentary rocks are exposed in the studied area, intruded by Late Cretaceous and Early Paleogene magmatism. The Qingduxiang granitic pluton locally intrudes the Paleogene Dianzhong Formation (Figure 3(b)) and consists of K-feldspar (20–25%), plagioclase (25–30%), quartz (30–35%), hornblende (5–10%), biotite (<5%), with a medium-grained granitic texture and massive structure (Figure 3(d)). Accessory minerals include apatite, zircon, Fe-Ti oxides, and titanite. The samples of the Qingduxiang granitic pluton are classified as a granite in the TAS diagram (Figure 4(a)).

Chemical compositions of feldspar, hornblende, and biotite analyzed from the Qingduxiang granite are provided in Supplementary Table 1. K-feldspars from the Qingduxiang granite are prismatic and have Or contents of 86.28–93.89%, belonging to orthoclase classification. Plagioclase crystals have tabular and prismatic forms, and contain variable An contents of 25.20–41.80%, classified as andesine and labradorite (Figure 5(a)). Biotites consist of 35.40–36.34% SiO₂ and 8.24–9.43% MgO, and are characterized as ferro-biotite from a crustal-derived source (Figure 5(b, c)). Hornblendes with subhedral to euhedral crystals have high Ca₉ values of 1.70–1.90

Figure 5. Geochemical characteristics of minerals for the Longge’er gabbro and Qingduxiang granite. (a) Ab-Or-An triangle diagram for feldspar (Pan et al. 1994). Ab = albite, Or = potassium feldspar, An = anorthite; (b) (Al⁺ newList + Fe²⁺ + Ti)–Mg–(Fe²⁺ + Mn) triangle diagram for biotite (Foster 1960); (c) ²FeO/MgO (Fe+Mg) versus MgO diagram (Zhou 1986); (d) CaSiO₃ (Wo)–MgSiO₃ (En)–FeSiO₃ (Fs) triangle diagram showing the compositions of pyroxene (Morimoto 1988); (e) and (f) Hornblende classification diagrams (Leake et al. 1997). QDX = Qingduxiang, LGR = Longge’er.
values of 0.32 in situ.

2 et al. 176 146 (51.63 Hf isotopic 0.58 (mean = 0.48, 2009 2004 0.05 (<0.5), belong to values of 0.00 5.95 wt.%), Ni (66.4 2006 51.78 wt.%), MgO 175 2010 74.8 ppm) and Cr (142 n crops of the Longge

A total of 30 samples were collected from fresh outcrops of the Longge’er gabbro and Qingduxiang granite. Samples LGR-0 (Longge’er gabbro) and QDX-0 (Qingduxiang granite), larger than 5 kg, were used for LA-ICP-MS U-Pb zircon dating and in situ Hf isotopic analysis. Twelve samples were chosen for mineral chemical analysis of biotite, hornblende, feldspar, and pyroxene. Ten samples were selected for whole-rock major- and trace-element geochemistry, while six samples were determined for whole-rock Sr-Nd-Pb isotopes.

Mineral compositions were acquired using a JXA-8100 Microprobe at Chang’an University, China. The electron beam was 5 μm in diameter, with an accelerating voltage of 15 kV at 10 nA beam current. The peak counting times for all elements were set to 10 s. Well-characterized natural silicate minerals were used as standards for calibration. The data reduction was carried out using ZAF correction.

Whole-rock geochemistry was determined at the Beijing Research Institute of Uranium Geology. The weathered surfaces of the samples were removed, and fresh portions of the rocks were chipped and powdered to 200 mesh. The details of the analytical procedures are similar to those in Feng et al. (2016). Analyses were performed using an Axios MAX X-ray Fluorescence Spectrometer (PANalytical B.V., Netherlands) with precision better than 5%. Trace element concentrations were determined using a Perkin-Elmer NexIon 300D ICP-MS (Perkin Elmer, Branford, CT, U.S.A.). National rock standards of the GBW series were analyzed together with samples, yielding analytical precision better than 5% for major elements and better than 10% for trace elements, respectively. The Chinese National standards GBW07105 and GBW07312 were used to calibrate the element concentrations of the unknowns.

Whole-rock Sr-Nd-Pb isotopic compositions were determined using an ISOPYROBE-T thermal ionization mass spectrometer (TIMS) at the Analytical Laboratory of Beijing Research Institute of Uranium Geology. Detailed procedures for the chemical separation and isotopic analyses were described in Ding et al. (2016). Mass fractionation corrections for Sr and Nd isotopic ratios were based on 86Sr/88Sr and 146Nd/144Nd values of 0.1194 and 0.7219, respectively. The reported 87Sr/86Sr and 143Nd/144Nd ratios were adjusted to the Standard NBS SRM 987 87Sr/86Sr = 0.710234 ± 0.000006 (2σ) and the Standard JMC = 0.512113 ± 0.000004 (2σ), respectively. Over the period of analytical work, repeat analyses yielded 208Pb/204Pb, 207Pb/204Pb, and 206Pb/204Pb ratios of the Standard NBS 981 of 36.605 ± 0.015 (2σ), 15.458 ± 0.007 (2σ), and 16.913 ± 0.002 (2σ), respectively.

Zircons for U-Pb dating were separated from crushed whole-rock samples using conventional magnetic and heavy liquid separation methods, and then handpicked under a binocular microscope. Zircons were subsequently mounted on epoxy resin discs. Their internal morphology and texture were examined by cathodoluminescence (CL) prior to zircon U-Pb and Lu-Hf isotopic analyses.

U-Pb dating and trace element analyses for selected zircon were conducted at the Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) microanalysis laboratory, affiliated with the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing. Laser sampling was conducted by Coherent GeoLasPro-193 nm system. A Thermo Fisher X-Series 2 ICP-MS was used to acquire ion-signal intensities. Helium was applied as a carrier gas. Zircon 91,500 was used as an external standard for U-Th-Pb isotopic ratios (Wiedenbeck et al. 2004). Off-line selection and integration of background and analysis signals and time-drift correction and quantitative calibration of trace element analyses and U-Pb dating were performed using ICPMSDataCal (Liu et al. 2010). Data reduction and concordia diagram creation were performed using Isoplot 3.7 software (Gao et al. 2009). The errors of the individual LA-ICP-MS analyses were quoted at the 95% (1σ) confidence level.

Zircon Hf isotope analyses were conducted by LA-MC-ICP-MS at the Laboratory of Continental Tectonics and Dynamics, Chinese Academy of Geological Sciences, Beijing. Experimental instruments used for analysis were a Thermo Finnigan Neptune MC-ICP-MS and the Coherent UP193 ultraviolet laser ablation system. Helium was used as the carrier gas. The GJ-1 zircon standard was used to monitor the accuracy. The specific analytical techniques are as described by Hou et al. (2007). The 176Hf/177Hf ratios for the GJ-1 standard were 0.282015 ± 8 (2σ, n = 10), corresponding to the recommended values from Elhlou et al. (2006).

4. Analytical results

4.1. Whole-rock geochemistry

The whole-rock geochemical data for the analyzed samples are listed in Supplementary Table 2.

4.1.1. Longge’er gabbro

The Longge’er gabbro samples are characterized by restricted contents of SiO2 (51.63–51.78 wt.%), MgO (5.84–5.95 wt.%), Ni (66.4–74.8 ppm) and Cr (142–175
ppm), with Mg$^4$ values of 64–65. They are plotted in the field of low-K tholeiitic to medium-K and metaluminous magmatic rocks with A/CNK \([\text{molar } \text{Al}_2\text{O}_3/(\text{CaO + Na}_2\text{O + K}_2\text{O})]\) ratios of 0.59–0.60 (Figure 4(b, c)). On chondrite-normalized rare earth element (REE) diagrams, all gabro samples are characterized by gently rightward sloping patterns and slightly negative Eu anomalies, comparable to OIB (Oceanic island basalt) (Figure 6(a)). N-MORB-normalized trace element curves display enrichments in large ion lithophile elements (LILEs; e.g. Rb, Th, U), and depletions in high field strength elements relative to OIB (HFSEs; e.g. Zr, Hf, Nb, Ta) (Figure 6(b)).

### 4.1.2. Qingduxiang granite

The samples analyzed from the Qingduxiang granite have high contents of SiO$_2$ of 71.11–71.87 wt.%, K$_2$O of 3.84–4.56 wt.%, and alkaline elements (Na$_2$O+K$_2$O) (7.34–7.96 wt. %), moderate Al$_2$O$_3$ concentrations of 14.16–14.68 wt.%, but low contents of MgO (0.60–0.67 wt.%), CaO (2.06–2.25 wt.%), and P$_2$O$_5$ (0.08–0.09 wt.%). They are characterized as high-K, calc-alkaline and of metaluminous affinity with the A/CNK ratios of 1.01–1.03, similar to other Early Paleogene granitoids in southern Tibet (Figure 4(b, c)).

Chondrite normalized REE patterns of the Qingduxiang granite are characterized by the enrichment of light rare earth elements (LREEs) and depletion of heavy rare earth elements (HREEs) with moderately negative Eu anomalies and (La/Yb)$_N$ ratios of 5.62–8.21. These REE element characteristics are almost identical to upper continental crust (Figure 6(c)). On the N-MORB-normalized spider diagram, all samples are enriched in Rb, Th, U, Pb, and depleted in Ba, Nb, Ta, Sr, Zr, and Ti (Figure 6(d)).

### 4.2. Whole-rock Sr-Nd-Pb isotopic compositions

The analytical results of whole-rock Sr-Nd-Pb isotopes of the Longer’er gabbro and Qingduxiang granite samples are listed in Supplementary Table 3 and illustrated in Figure 7. The $^{87}\text{Sr}/^{86}\text{Sr}$, $\varepsilon_{\text{Nd}}(t)$, $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ values are calculated using their zircon U-Pb ages of 54 and 55 Ma (see Section 4.3), respectively.

In the samples from the Longer’er gabbro, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.708290 to 0.708331 and $\varepsilon_{\text{Nd}}(t)$ values range from $-5.4$ to $-3.5$ with older Nd model ages ranging from 1059 Ma to 1232 Ma. The calculated initial ratios of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ are 18.703–18.714, 15.621–15.623, and 39.035–39.050, respectively.

In the samples from the Qingduxiang granite, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.706471 to 0.706494 and $\varepsilon_{\text{Nd}}(t)$ values range from $-4.1$ to $-3.1$, and Nd model ages range from 1003 to 1126 Ma. They
Figure 7. Plot diagrams of (a) $\varepsilon_{\text{Nd}}(t)$ versus $^{87}\text{Sr}/^{86}\text{Sr}$, (b) $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$, (c) $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the Longer'er gabbro and Qingduxiang granite.

QDX = Qingduxiang, LGR = Longer’er, the hypothetical ancient lower crust of Central Lhasa (Miller et al. 1999), ancient upper crust of Central Lhasa (Zhu et al. 2012), Yarlung-Tsangpo ophiolite (200–120 Ma) (Zhang et al. 2005), potassic-ultrapotassic volcanic rocks (Liu et al. 2014; Wang et al. 2014a; Tian et al. 2017), Linzizong volcanic rocks (Yu et al. 2010; Lee et al. 2012), Indian continental sediments (Zhao et al. 2009), GLOSS (Plank and Langmuir 1998), and Early Paleogene granitoids, gabbro and diorite (Jiang et al. 2014; Xin et al. 2015; Zheng et al. 2015; Chen et al. 2015b; Wang et al. 2015b; Zhao et al. 2016) are illustrated shown for comparison. Bulk Silicate Earth (BSE), enriched mantle components (EMI and EMII) and prevalent mantle (PREMA) are from (Zindler and Hart 1986). Northern Hemisphere Reference Line (NHRL): $^{207}\text{Pb}/^{204}\text{Pb} = 0.1084 \times ^{206}\text{Pb}/^{204}\text{Pb} + 13.491$; $^{208}\text{Pb}/^{204}\text{Pb} = 1.209 \times ^{206}\text{Pb}/^{204}\text{Pb} + 15.627$. $^{87}\text{Sr}/^{86}\text{Sr}$, $\varepsilon_{\text{Nd}}(t)$ and $^{207}\text{Pb}/^{204}\text{Pb}$ are corrected to ca. 55 and ca. 54 Ma, respectively.
have homogeneous Pb isotope compositions of $^{206}_{\text{Pb}}/^{204}_{\text{Pb}} = 18.672 - 18.675$, $^{207}_{\text{Pb}}/^{204}_{\text{Pb}} = 15.663 - 15.669$, and $^{208}_{\text{Pb}}/^{204}_{\text{Pb}} = 38.958 - 39.010$.

All samples analyzed from both lithologies plot in similar positions in terms of their Sr-Nd and Pb isotopic compositions (Figure 7). In terms of their $^{87}_{\text{Sr}}/^{86}_{\text{Sr}}$ and $\varepsilon_{\text{Nd}}(t)$ values these samples are most similar to the Linzizong volcanic rocks (Figure 7(a)), whereas in Pb isotope space they plot within and adjacent to the field of S-type granites and gneisses of the Lhasa terrane (Figure 7(b, c)).

4.3. Zircon U-Pb geochronology, trace elements, and Hf isotopes

Results of LA-ICP-MS U-Pb zircon dating, zircon trace element analysis, and Hf isotopes are listed in Supplementary Tables 4–6 and illustrated in Figures 8 and 9.

Most zircon grains from sample LGR-0 and QDX-0 exhibit similar morphological and trace-element characteristics. Zircons have euhedral and prismatic forms with crystal lengths from 100 to 250 μm, and length-to-width ratios from 1.5:1 to 3:1 (Figure 8(a, b)). The zircon grains are mainly colourless and transparent, and display oscillatory zoning under CL. Their Th/U ratios of 0.6–2.1 indicate a magmatic origin (Corfu et al. 2003), consistent with the plots in Figure 9(a). Samples from the latter also plot in the I-type field of a number of discrimination diagrams (e.g. Figure 9(b), see Discussion). Zircons from both the Longge’er gabbro and Qingduxiang granite plot within the continental arc field of a number of tectonic discrimination diagrams according to their trace element characteristics (Figure 9(c, d)).

Fourteen analyses were conducted on the zircon grains from sample LGR-0. Five zircon grains have a concordia U-Pb age of ca. 53.5 ± 1.6 Ma (Figure 8(a)), and 10 zircon grains have an older concordia U-Pb age of ca. 112.5 ± 1.9 Ma, similar with the emplacement ages of the Early granodiorite intruded by the Longge’er gabbro (ca. 113 Ma, from Hua-wen Cao unpublished data). Therefore, we proposed the Longge’er gabbro formed at ca. 53.5 ± 1.6 Ma, while the older zircon grains of ca. 112.5 Ma were incorporated during magma ascent, and are inherited xenocrysts. Eleven Hf isotopic analyses were corrected to the magmatic crystallization age of ca. 54 Ma, and yield relatively negative $\varepsilon_{\text{Hf}}(t)$ values of...
−1.2 to +1.0 with ancient two-stage model ages (TDm2(Hf)) of ca. 1005–1197 Ma.

Twenty-three zircon grains from sample QDX-0 yield 206Pb/238U ages ranging from ca. 52 to ca. 59 Ma, with a weighted mean age of ca. 54.5 ± 0.9 Ma (MSWD = 1.5; Figure 8(b)). Sixteen analyses for the QDX-0 present relatively negative εHf(t) (calculated at ca. 55 Ma) of −2.6 to −0.6 with ancient TDm2(Hf) values of ca. 1091–1217 Ma. Therefore, we can infer the Longge’er gabbro and Qingduxiang granite were formed during ca. 55–54 Ma, a little earlier to the magmatic flare-up (ca. ~51 Ma) in southern Tibet (Figure 8(c)).

5. Discussion
5.1. Petrogenesis of the longge’er gabbro
5.1.1. Fractional crystallization and/or accumulation
The Longge’er gabbro is characterized by relatively low SiO2 (51.63–51.78 wt.%) and high MgO (5.84–5.95 wt.%) and 7Fe2O3 (6.37–6.61 wt.%) contents, remarkably different to crustal material and crustally derived magmas (Rudnick and Gao 2003). This suggests the Longge’er magmas were derived from a mantle source. The Longge’er gabbro samples have lower Mg# values (64–65), Ni (66.4–74.8 ppm) and Cr (142–175 ppm) contents than primary mantle-derived magmas, implying they formed from mantle-derived melts that have undergone a certain degree of fractional crystallization and/or crystal accumulation (Perfit et al. 1980). As it is known that Ni is compatible in olivine, and Cr is compatible in clinopyroxene and spinel, the positive correlations between Cr and Ni against MgO indicate fractional crystallization of olivine, clinopyroxene and spinel (Figure 10(a, b)). Plagioclase fractionation is supported by slightly negative Eu and Sr anomalies.

Although the restricted contents of SiO2, MgO, Ni, and Cr may be the result of crystal accumulation, this model can be excluded based on following lines of evidence: (1) neither layered structures in outcrop, nor textural evidence for crystal accumulation in thin section has been observed; (2) the plagioclase in the Longge’er gabbro is of andesine composition (An45-47), inconsistent with typical cumulative gabbros of An-rich (>An60; Beard 1986) (Figure 5(a)); (3) the chondrite-normalized profiles of the Longge’er gabbro show moderate negative Eu anomalies (Figure 6(a)), unlike positive Eu anomalies from typical cumulative gabbros (Beard 1986; Turner 1996).

Figure 9. Zircon trace-element diagrams for the Longge’er gabbro and Qingduxiang granite. (a) Ce/Ce* versus (Sm/La)N diagram (Hoskin and Schaltegger 2003); (b) Th versus Pb diagram (Wang et al. 2012b); (c) U/Yb versus Y (Grimes et al. 2007); and (d) Nb/Yb versus U/Yb diagrams (Grimes et al. 2015). QDX = Qingduxiang, LGR = Longge’er, Ce/Ce* = 2*w(Ce)/[w(La)+w(Pr)]. N denotes the normalized to chondritic values from Sun and McDonough (1989).
5.1.2. Mechanism of enriched lithosphere mantle

The enrichment in LILs and LREE concentrations, and depletion of HFSEs (Nb, Ta, Zr, Hf, Ti) in the Longge’er gabbro, together with a positive Pb anomaly (Figure 6(a, b)), collectively suggest that either the mantle from which the primary melts were derived was enriched, or the mafic magmas were contaminated by crustal material on ascent. Three mechanisms may be invoked to explain these geochemical features: (1) binary mixing between mantle- and crustal-derived magmas (Cheng et al. 2012; Manya 2014), (2) crustal contamination, i.e. mantle-derived melts contaminated by wall rocks during magma ascent (Ma et al. 2013b; Hu et al. 2016b), and (3) metasomatism by an older source material within specific tectonic settings, such as subduction or thickened crustal delamination (Pan et al. 2016; Ma et al. 2017a).

The magma mixing model is not favoured in the present case because the Longge’er gabbro is characterized by uniform geochemical features with low SiO$_2$ and high MgO contents, as well as homogeneous Sr-Nd-Pb-Hf isotopic compositions. Mixing curves in the plots between isotopic ratios and certain elements (e.g. MgO) are absent in the Longge’er gabbro (Figure 10(c, d)). Moreover, evidence for magma mixing, such as the presence of mafic microgranular enclaves and disequilibrium textures, are not observed in the Longge’er gabbro.

It is almost inevitable that crustal contamination occurs where mantle-derived basaltic magmas intrude continental felsic crust (Castillo et al. 1999). Significant crustal contamination would modify both major-trace elements and radiogenic isotope compositions of mantle-derived basaltic melts (Castillo et al. 1999). Involvement of crustal components will commonly cause $^{87}$Sr/$^{86}$Sr ratios to increase and $\varepsilon_{Nd}(t)$ values to decrease towards continental crustal values (Cheng et al. 2012). Therefore, the relationship between major elements versus radiogenic isotopes can be used to evaluate the effect of crustal contamination on basaltic rocks (Ma et al. 2013b, 2017a). The poor linear relationships of $^{87}$Sr/$^{86}$Sr and $\varepsilon_{Nd}(t)$ against MgO content (Figure 10(c, d)) would rule out significant crustal contamination of mantle-derived magma. Whole-rock Sr-Nd isotopes would indicate the final isotopic compositions of magmas, whereas zircons can preserve Hf isotopic compositions more compatible to that of the parental magma (Griffin et al. 2002). The relatively homogeneous zircon $\varepsilon_{Hf}(t)$ values (~−1.2 to +1.0) of the Longge’er gabbro argue for little or no crustal contamination involved in the parental magma. Despite fractional crystallization or accumulation of olivine, clinopyroxene, and plagioclase can modify both major and trace element contents, but ratios of highly incompatible trace elements remain unaltered. As such, the low Th/ Ce (0.048–0.054) and Th/La (0.101–0.113) ratios of...
the Longge’er gabbro suggest insignificant crustal contamination was involved in the formation of the magmas, because continental crust contains relatively high Th/Ce (~0.15, Taylor and McLennan 1995) and Th/La (~0.30, Plank 2005), while mantle-derived magmas have low Th/Ce (0.02–0.05) and Th/La (~0.12) (Sun and McDonough 1989). Meanwhile, the Longge’er gabbro samples collectively display negative Nb-Ta anomalies in the N-MORB-normalized trace element diagram (Figure 6(b)), suggesting the parental magmas of these rocks might have undergone crustal contamination (Jahn et al. 1999). However, crustal assimilation during emplacement would also result in positive Zr-Hf anomalies (Zhou et al. 2004), inconsistent with the negative Zr-Hf anomalies in Figure 6(b). In spite of the existence of ancient zircon xenocrysts (ca. 112.5 Ma), it is proposed that the Longge’er gabbro underwent only limited crustal contamination on ascent/emplacement, identical with other contemporary gabbros in the eastern Lhasa and Tengchong terranes (Pan et al. 2016; Ma et al. 2017a).

Both subduction and thickened crustal delamination trigger metasomatism in lithospheric mantle (Aulbach 2012; Gu et al. 2018). During the Early Paleogene, southern Tibet was in an active continental margin setting related with the southward subduction of the Neo-Tethyan Ocean (Mo et al. 2008; Zhu et al. 2015; Zhang et al. 2017b). Previous studies have proposed that thickened crustal delamination occurred in southern Tibet during the Late Cretaceous (Ji et al. 2014), earlier than the formation of the Longge’er gabbro. Meanwhile, thickened crustal delamination would generate abundant adakitic rocks (Castillo et al. 1999; Chiaradia 2009), however, which have scarcely been discovered in southern Tibet during Early Paleogene (Figure 12(a, b)).

We suggest that metasomatism of the enriched lithospheric mantle during the formation of the Longge’er gabbro was due to the subduction of the Neo-Tethyan Ocean. Zircon REE contents are a useful tool to constrain the magma nature and origins of magmas, in addition to processes during magma emplacement (Grimes et al. 2015). For instance, plots of U/Yb versus Y and Nb/Yb are an effective way to distinguish continental zircons from those from oceanic crust (Grimes et al. 2007). In Figure 9(c,d), zircons from the Longge’er gabbro are predominantly distributed in the field of continental zircon, suggesting it was emplaced in a continental margin. Moreover, Pearce (2008) proposed that whole-rock Th and Nb elements are useful indicators for crustal input because they are immobile during weathering and metamorphism up to lower amphibolite facies, and they perform analogous behaviours during most petrogenetic processes. Consequently, the Nb/Yb versus Th/Yb

![Figure 11. Th/Yb versus Nb/Yb discrimination diagram for Early Paleogene gabbro (Dilek and Furnes 2011; Pearce 2014). OIB = Oceanic island basalt, E-MORB = Enriched mid-ocean ridge basalt, N-MORB = Normal mid-ocean ridge basalt. Data for the OIB, E-MORB, and N-MORB are from McDonough and Sun (1995) and Sun and McDonough (1989).](image-url)

**5.1.3. Origin of ancient crustal signature**

Based on the information above, we propose the Longge’er gabbro formed from partial melting of the enriched mantle wedge metasomatized by ancient crustal melts and/or fluids in a subduction setting. As mentioned previously, possible three potential sources of ancient crustal melts and/or fluids have been linked to the formation of mafic rocks in Central Lhasa: (1) the Neo-Tethyan Oceanic slab (Mo et al. 2007; Gao et al. 2010; Xu et al. 2014), (2) Indian continental crust (Mo et al. 2009; Chu et al. 2011; Ma et al. 2017a), and (3) ancient Central-Lhasa crust (Guan et al. 2012; Zhu et al. 2013; Huang et al. 2015; Pan et al. 2016; Liu et al. 2017a).

The lithospheric mantle metasomatized by melts from subducted oceanic crust generally display relatively low 87Sr/86Sr ratios, high εNd(t) values and HFSE enrichment (Defant and Drummond 1990; Yang et al. 2008), distinguished from those of the Longge’er gabbro. It is noted that partial melting of subducted oceanic crust would result in formation of adakitic rocks (Defant and Drummond 1990). However, an adakitic
affinity has not been identified for most of the contemporary granitoids in southern Tibet (Figure 12(a, b)). Taken together, the Neo-Tethyan oceanic sediments can be excluded.

Ancient crust has been identified in both the Indian terrane and Central Lhasa (Ding et al. 2003; Zhu et al. 2011; Guo et al. 2015). Due to the similar Sr-Nd isotopic compositions of the Indian continental sediments and Lhasa upper crust (Figure 7(a)), it would be fairly difficult to distinguish between the two potential candidates for the ancient crustal source of the Longge’er gabbro. It is noted that the Longge’er gabbro is characterized by similar Pb isotopic compositions to S-type granites and gneiss in the Lhasa terrane (Figure 7(b, c)). Positive and negative zircon εHf(t) values are attributed to juvenile and ancient crustal sources, respectively (Iizuka et al. 2017). In Figure 13, we have summarized zircon Hf isotopic data of the Late Mesozoic to Cenozoic magmatic rocks in Central Lhasa and Southern Lhasa, respectively (Figure 13). These results show zircon εHf(t) values gradually decreased at ca. 60 Ma in Central Lhasa and at ca. 30 Ma in Southern Lhasa, respectively, implying the asynchronous inputs of ancient crustal components. For example, the Eocene Quguosha gabbro (ca. ~35 Ma) was suggested to be generated by partial melting of lithospheric mantle metasomatized by about 5% Indian continental sediments, marking the initial time of mantle-enriched process (Ma et al. 2017a). Subsequent Oligocene-Miocene post-collisional potassic and ultrapotassic volcanic rocks and adakitic intrusions are further characterized by increasing involvements of Indian continental sediments, marking the initial time of mantle-enriched process (Ma et al. 2017a). Hence, the Indian continental sediments had not been added into lithospheric mantle until ca. 35 Ma, failing to account for the ca. 54 Ma Longge’er gabbro. Therefore, the crustal contribution of the Longge’er gabbro is most likely to be derived from partial melting of the Central-Lhasa ancient crust.
A-type granites are characterized by the presence of high-temperature anhydrous minerals (e.g. pyroxene, fayalite and late-crystallized biotite and hornblende) and enrichment in the HFSE (Whalen et al. 1987), which are absent in the Qingduxiang granite (Figure 3). Moreover, most samples plot in the field of highly fractionated felsic granite in the $^{1}$FeO/MgO versus Zr+Nb+Ce+Y discrimination diagram (Figure 12(c)). Moreover, Zr saturation temperatures of the Qingduxiang granite range from 612 to 675°C (calculated based on Boehnke et al. 2013), lower than those of A-type granites (>800°C) (King et al. 1997).

Al-rich minerals (e.g. muscovite and cordierite) have been considered as the critical feature of S-type granites (Clemens 2003), which have not been identified in the Qingduxiang granite. Meanwhile, the presence of hornblende is more consistent to I-type granites (Figure 3(d)). Furthermore, A/NCNK ratio of 1.1 is the boundary between the S-type and I-type granites (Chappell 1999). The Qingduxiang granite samples show metaluminous features with A/NCNK ratios less than 1.1, atypical of S-type granites (Figure 4(c)). The plots follow I-type liner trends in the $^{3}P_{2}O_{5}$ versus SiO$_{2}$ (Figure 4(d)) and Th versus Rb diagrams (Figure 12(d)), while I-type affinity of the Qingduxiang granite is further confirmed by the plots in the zircon trace elements diagram (Th vs. Pb) (Figure 9(b)). In addition, The Qingduxiang I-type granite samples are enriched in Rb, Th, U, Pb, and depleted in Eu, Ba, Sr, Zr, and Ti, implying fractional crystallization of mineral phases, such as plagioclase, feldspar, ilmenite, and titanite (Figures 6(c, d) and 12(b)).

5.2. Petrogenesis of the qingduxiang granite

5.2.1. Genetic type
Granitic rocks can be classified as I-, S-, A-, and M-types by geochemical and mineralogical parameters (Whalen et al. 1987; Clemens 2003; Gao et al. 2016). The samples from the Qingduxiang granite show higher SiO$_{2}$ contents and lower MgO, Cr, and Ni contents compared to rocks that originated from mantle-derived sources. Correspondingly, the Qingduxiang granite is characterized by high $^{12}$Sr/$^{60}$Sr ratios (0.706471–0.706494), and negative $\varepsilon_{Nd}(t)$ (~4.1 to –3.1) and $\varepsilon_{Hf}(t)$ values (~1.5 to +0.5), indicative of crustally-derived magmas. Hence, the Qingduxiang granite samples do not possess the isotopic features of M-type granites.

The origin of I-type granites can be attributed to three genetic models as follows: (1) advanced fractional crystallization of mantle-derived parental magmas, with or without crustal assimilation (Soesoo 2000; Chiaradia 2009); (2) reworking of supracrustal sedimentary rocks, modified by mantle-derived magmas (Kempton et al. 1997; Yang et al. 2007; Zhu et al. 2009); and (3) partial melting of mafic to intermediate meta-igneous lower crustal rocks, with or without mantle-derived magma input (Roberts and Clemens 1993; Griffin et al. 2002; Yang et al. 2004).

Magma derived from direct melting of the mantle have high Mg$^{+}$ values and are typically no more silicic than andesitic compositions (Chiaradia 2009). In contrast, the Qingduxiang granite samples represent highly siliceous (71.11–71.87 wt.%), calc-alkaline, LREEs, and HREE enrichment, low Mg$^{+}$ (31–33), Cr (0.9–2.0 ppm) and Ni (0.7–5.9 ppm) contents, incompatible with typical mantle-derived magmas. Additionally, the low Nb/U (1.3–5.7), and Ce/Pb (2.7–3.8) ratios of the Qingduxiang I-type granite suggest a crustal origin (Rudnick and Gao
High $^{87}\text{Sr}/^{86}\text{Sr}_i$ and negative $\varepsilon_{\text{Nd}}(t)$ and $\varepsilon_{\text{Hf}}(t)$ values, as well as ancient $T_{\text{DM2}}$ ages are consistent with parental magmas derived from partial melting of ancient crustal rocks. In addition, the Pb isotopic compositions of the Qingduxiang granite reveal a significant crustal affinity of Lhasa terrane (Figure 8(b), c). Thus, the Qingduxiang I-type granite was not sourced from primary mantle melts.

Partial melting of supracrustal sedimentary rocks generally produce peraluminous granites with A/CNK ratios $>1$ and Al-rich minerals (e.g. muscovite and cordierite) (Chappell and White 2001), which is inconsistent with what we observe from the Qingduxiang granite. Moreover, the $^{86}\text{Sr}/^{87}\text{Sr}_i$ values of the Qingduxiang I-type granite distinguish the crustal source from the supracrustal sediments, similar to the lower crust of Central Lhasa (Figure 8(a)). Magma derived from reworking of supracrustal sedimentary rocks would have pretty wide range of zircon $\varepsilon_{\text{Hf}}(t)$ values (up to 10-ε units) (Kemp et al. 2007), significantly distinguished from the Qingduxiang I-type granite's uniform $\varepsilon_{\text{Hf}}(t)$ values of $-2.6$ to $-0.6$. As such, the second genetic model is not eligible for the Qingduxiang I-type granite. The upper-crustal-type characteristics of the chondrite-normalized REE and N-MORB-normalized trace-element patterns probably are the results of fractional crystallization (Figure 6(c, d)).

Previous studies have revealed that I-type granites can be produced by partial melting of the mafic to intermediate lower crust based on geochemistry (Petford and Gallagher 2001) and experimental constraints (Chappell 1999). $^{87}\text{Sr}/^{86}\text{Sr}_i$ and Mg$^{	ext{8}}$ values of most I-type granites that originate from meta-igneous lower crustal rocks are lower than 0.708 and 45 (Chappell and Stephens 1988), similar to those of the Qingduxiang granite. The Qingduxiang granite samples yield the relatively negative whole-rock $\varepsilon_{\text{Nd}}(t)$ values ($-4.1$ to $-3.1$) and zircon $\varepsilon_{\text{Hf}}(t)$ values ($-1.5$ to $+0.5$) with ancient Nd isotope two-stage model ages (1003–1126 Ma) and zircon Hf isotope crustal model ages (1091–1217 Ma). Together this suggests the Qingduxiang granite was derived from partial melting of an ancient crustal source. Interestingly, the binary mixing modelling results of Sr-Nd isotopes show the Qingduxiang granite was generated by 50–60% ancient crustal material and 40–50% juvenile materials (Figure 8(a)), while the zircon $\varepsilon_{\text{Hf}}(t)$ values ($-1.5$ to $+0.5$) of the Qingduxiang granite are much higher than those of the ancient crust in Central Lhasa (up to $-22$) (Zhu et al. 2011), implying significant inputs of juvenile material. Coupled the high SiO$_2$ content and low MgO, Cr, and Ni contents it is unlikely that significant volumes of mantle-derived magmas were involved. Correspondingly, absence of mafic micro-granular enclaves and low crystallization temperatures (612–675°C) are not consistent with large contribution of mantle-derived magmas. It is noteworthy that the Qingduxiang granite was exposed in the transition area between Central Lhasa of ancient crust and Southern Lhasa of juvenile crust (Figure 1(b)). Considering this, partial melting of Southern-Lhasa juvenile crust would join the formation of the Qingduxiang granite, accounting for the significant juvenile magmas. Therefore, Qingduxiang I-type granite is believed to be generated by a combination of anatexis of Central-Lhasa ancient lower crust, combined with Southern-Lhasa juvenile crustally derived magmas.

5.3. Tectonic setting of the Paleogene magmatism in Central Lhasa

Paleogene magmatic rocks of Central Lhasa formed in an active continental margin associated with the prolonged subduction of the Neo-Tethyan Ocean (Ji et al. 2012; Ma et al. 2014; Jiang et al. 2015; Chen et al. 2015a, 2015b; Wang et al. 2015b). Geochemical compositions of magmatic rocks have been considered as a robust tool to interpret corresponding tectonic setting (Pearce and Cann 1973; Pearce et al. 1984; Meschede 1986; Pearce 1996). Therefore, it is plausible to investigate the tectonic setting of the Early Paleogene magmatism in Central Lhasa based on the geochemical data of the Longge’er gabbro and Qingduxiang granite. REE fractionation patterns can be used to constrain the melting depths of gabbro (George et al. 2003). For instance, La and Sm are incompatible in garnet, whereas Yb is compatible, implying that the La/Sm and Sm/Yb ratios will be intensely fractionated in melts originated from low melting degree of garnet Iherzolite (D’Orazio et al. 2001). By contrast, the La/Sm and Sm/Yb ratios are only slightly fractionated during melting in the spinel stability field. From our data the proportion between clinopyroxene and garnet was approximately 6:1 (Figure 14(a)), while less than 2% residual garnet was present (Figure 14b). Considering the depth of the transition from spinel to garnet at the peridotite solidus should be ~75–80 km, the Longge’er gabbro is interpreted to be formed in a relatively shallow environment (<80 km), mostly within the spinel stability field. Furthermore, the geochemical compositions of the Longge’er gabbro samples, as well as other contemporay gabbros, have a within-plate extensional affinity in Figure 14(c, d). In addition, the Chondrite-normalized curves of the Longge’er gabbro are typical of OIB-like mantle-derived magmas that was produced by slab break-off (Figure 6(a)).

The Qingduxiang I-type granite samples are enriched in LREEs and LILEs and depleted in Sr, P, and Ti, with flat
HREE patterns and negative Eu anomalies (Figure 6(c, d)), suggesting that hornblende and plagioclase were important residual phases in the source region (Chappell et al. 1987; Rapp and Watson 1995). Meanwhile, the low (La/Yb)_N and Sr/Y ratios indicate the parental magmas were generated under low pressure, without residual garnet present during the partial melting (Watt and Harley 1993) (Figure 12(a, b)). Accordantly, the emplacement pressures of the Qingduxiang granite range from 0.94 to 1.70 kPa (based on the hornblende T_Al thermobarometer from Mutch et al. (2016)). Geochemical characteristics totally suggest a relatively low-pressure and shallow chamber for formation. However, some plots of the Early Paleogene granitoids are clarified as syn-collisional and volcanic arc granites in the tectonic discrimination diagrams (Figure 14(e, f)). This conflict is probably produced by the geochemical components of highly fractionated granites that are not suitable for the tectonic discrimination (Wu et al. 2003).

In conclusion, we take this as evidence that the Early Paleogene magmatism in Central Lhasa was developed in extensional environment. Previous studies have suggested...
that Neo-Tethyan oceanic slab break-off was associated with an extensional tectonic environment (von Blanckenburg and Davies 1995; Xu et al. 2008; Zhu et al. 2015, 2017b), whereas slab rollback and India-Asia collision would lead to compression in southern Tibet (Stadler et al. 2010; Ma et al. 2013a; Jiang et al. 2014). Considering this, the Early Paleogene magmatism in Central Lhasa is believable to be generated during the slab break-off associated with the closure of the Neo-Tethyan Ocean.

5.4. Implication for the India-Asia collision

The subduction of the Neo-Tethyan Ocean and subsequent India-Asia collision led to intense and widespread magmatic activity, including the Jurassic to Paleogene Gangdese batholith (Ji et al. 2009, 2014; Li et al. 2011; Guan et al. 2012; Leng et al. 2016), Paleogene Linzizong volcanic rocks (Mo et al. 2008; Chen et al. 2010b, 2016; Lee et al. 2012; Zhu et al. 2015), Miocene potassic, and ultrapotassic rocks (Xu et al. 2010, 2017; Cheng and Guo 2017; Tian et al. 2017; Liu et al. 2017a; Zhang et al. 2017a). Although the timing of the India-Asia collision has been debated for a long time, it is still not resolved with estimates ranging from 65 Ma to 35 Ma (Jaeger et al. 1989; Ding et al. 2005; Ali and Aitchison 2007; Chen et al. 2010b; Zhu et al. 2015; Hu et al. 2016a). Previous studies have contended the subduction of the Neo-Tethyan Ocean was proceeding, with subsequent slab rollback, India-Asia collision (oceanic closure) and slab break-off (Metcalf 2013; Zhu et al. 2015, 2017a; Zhang et al. 2017b). As the India-Asia collision was occurred amid slab rollback and break off of the Neo-Tethyan Ocean, using slab rollback and break-off is feasible to constrain the preliminary collisional timing.

One of the most recent studies in this field focused on abundant Paleocene-Eocene intrusive and volcanic rocks of the Gangdese batholith and constructed a basic geo-chronological framework for Neo-Tethyan slab rollback (~69–53 Ma) and slab breakoff (53–49 Ma) (Zhou et al. in press). Slab rollback of the Neo-Tethyan Ocean is believed to be responsible for the crustal deformation and shorten occurred after ca. 64 Ma in central Tibet (Kapp et al. 2005). Hodges (2000) illustrated that sedimentary facies changed from marine to non-marine deposition at Early Eocene (ca. 54–50 Ma), constraining the upper limit of the slab rollback. Southward migration of the Late Cretaceous to Early Paleogene magmatic rocks in southern Tibet has been linked to slab rollback (Zhu et al. 2015, 2017b) and the ca. 51 Ma magmatic flare-up in southern Tibet is interpreted by the upwelling of the asthenosphere through ‘slab window’ generated by slab break-off (Mo et al. 2009; Lee et al. 2012; Zhu et al. 2015). Consistently, the subduction velocity of the Indian plate was decreased rapidly at ca. 51 Ma without the drag force of the dense Neo-Tethyan Oceanic slab (Zhu et al. 2015). When the depth of slab break-off is in the range of 35–200 km, slab break-off would not last more than several million years (Duretz et al. 2012; Zhu et al. 2015). Considering the crustal thickness of 30–60 km (calculated by Zhu et al. (2017a)), slab break-off of the Neo-Tethyan Ocean should be a short duration, lasting several million years since ca. 51 Ma. As numerical simulations have documented that the intense magmatic activity would have occurred less than 2 million years after slab break-off (Zedde and Wortel 2001), slab break-off was most likely to end at ca. 49 Ma. On the other hand, the Early Paleogene igneous rocks in this study (ca. 55–54 Ma) emplaced in an extensional tectonic setting, probably marking the lower-limit timing for slab break-off.

The Linzizong volcanism with an age range from 60.2 Ma to 52.3 Ma is extensively exposed in southern Tibet and is characterized by isotopically similar magmas to those described in our study (Figure 7(a)). The geochemistry of the Dianzhong (60.2–58.3 Ma) and Nianbo (55.4–52.6 Ma) formations are indicative of arc magmatism related to the subduction of the Neo-Tethyan Ocean (Zhu et al. 2015) (Figure 6(c)). The thin Nianbo Formation (~850m) is indicative of weak volcanism in southern Tibet and is regarded as syn-collisional magmatism (Lee et al. 2009, 2012). On the other hand, slab break-off would trigger heating of the overriding lithospheric mantle by rising asthenosphere, melting of overlying enriched crust, and thus produce heterogeneous magmatism (von Blanckenburg and Davies 1995). Dramatically, high zircon saturation temperatures of the Pan’na Formation (52.6–52.3 Ma) may have resulted from hot rising asthenosphere, while the compositional heterogeneity of this formation could be attributed to mantle-crustal interaction, suggesting it was developed during slab break-off (Lee et al. 2009). Therefore, the Linzizong volcanic succession suggests slab rollback was terminated before the Nianbo Formation (55.4–52.6 Ma), while slab break-off occurred not later than the upper limit of the Panna Formation (52.6–52.3 Ma).

Taken together with all the evidence discussed above, slab roll back of the Neo-Tethyan Ocean occurred from Late Cretaceous (~69 Ma) to Early Eocene (55 Ma) (Figure 15(a)), while slab break-off was most likely initiated at ca. 55–54 Ma, peaked at ca. 51 Ma and lasted several million years till ca. 49 Ma (Figure 15(b)). Consequently, the India-Asia collision
must have occurred prior to slab break-off, and thus started no later than ca. 55 Ma.

6. Conclusions

Our comprehensive geochronological and geochemical studies of the Early Paleogene Longge’er gabbro and Qingduxiang granite in Central Lhasa have reached the following conclusions:

(1) New LA-ICP-MS zircon U-Pb data demonstrate the Longge’er gabbro and Qingduxiang granite were formed at 55 Ma and 54 Ma, respectively.

(2) Geochemical and Sr-Nd-Pb-Hf isotopic compositions indicate that the Longge’er gabbro was derived from partial melting of the enriched mantle wedge metasomatism by Central-Lhasa ancient crust-derived magmas, while the Qingduxiang granite with I-type affinity was produced by partial melting of Central-Lhasa ancient lower crust combined with magmas derived from Southern Lhasa juvenile crust.

(3) Slab rollback of the Neo-Tethyan Ocean was a prolonged process during Late Cretaceous (~69 Ma) to Early Eocene (55 Ma), whereas slab break-off was of short duration during Early Eocene (ca. 55–49 Ma), respectively. The India-Asia collision must have started no later than ca. 55 Ma.

- The Qingduxiang granite was generated by partial melting of ancient and juvenile crust.
- Early Paleogene (55–54 Ma) magmatism formed in an extensional setting relate to the Neo-Tethyan oceanic slab break off.

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