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Subduction of Indian continent beneath southern Tibet in the latest Eocene (~35 Ma): Insights from the Quguosha gabbros in southern Lhasa block

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ABSTRACT

Geophysical data illustrate that the Indian continental lithosphere has northward subducted beneath the Tibet Plateau, reaching the Bangong–Nujiang suture in central Tibet. However, when the Indian continental lithosphere started to subduct, and whether the Indian continental crust has injected into the mantle beneath southern Lhasa block, are not clear. Here we report new results from the Quguosha gabbros of southern Lhasa block, southern Tibet. LA-ICP-MS zircon U–Pb dating of two samples gives a ca. 35 Ma formation age (i.e., the latest Eocene) for the Quguosha gabbros. The Quguosha gabbro samples are geochemically characterized by variable SiO_2 and MgO contents, strongly negative Nb–Ta–Ti and slightly negative Eu anomalies, and uniform initial $^{87}Sr/^{86}Sr$ (0.7056–0.7058) and $\varepsilon_{Nd}(t)$ (−2.2 to −3.6). They exhibit Sr–Nd isotopic compositions different from those of the Jurassic–Eocene magmatic rocks with depleted Sr–Nd isotopic characteristics, but somewhat similar to those of Oligocene–Miocene K-rich magmatic rocks with enriched Sr–Nd isotopic characteristics. We therefore propose that an enriched Indian crustal component was added into the lithospheric mantle beneath southern Lhasa by continental subduction at least prior to the latest Eocene (ca. 35 Ma). We interpret the Quguosha mafic magmas to have been generated by partial melting of lithospheric mantle metasomatized by subducted continental sediments, which entered continental subduction channel(s) and then probably accreted or underplated into the overlying mantle during the northward subduction of the Indian continent. Continental subduction likely played a key role in the formation of the Tibetan plateau at an earlier date than previously thought.

1. Introduction

Continental subduction is a common process in collisional orogenic belts and has important implications for the recycle of crustal materials (e.g., Yin and Harrison, 2000; Wang et al., 2001, 2008a, 2008b; Zheng, 2012; Guo et al., 2014b). The subduction of continental crustal rocks to mantle depths of over 100 km has been demonstrated by the discoveries of coesite (Smith, 1984; Chopin, 1984) and diamond (Sobolev and Shatsky, 1990; Xu et al., 1992) in metamorphic supracrustal rocks, but the continental subduction process is still poorly understood. For instance, as the largest and highest topographic feature on Earth, the Tibetan Plateau was considered to have been created by the Cenozoic collision between Indian and Asian continents and subsequent continental subduction (Harrison et al., 1992; Yin and Harrison, 2000; Tapponnier et al., 2001; Wang et al., 2001; Ding et al., 2003; Yin and Taylor, 2011; Xu et al., 2013a; 2013b; Jiang et al., 2014). Geophysical data also show that the current Indian continental lithosphere has subducted northward beneath the continental lithosphere to close to the Bangong–Nujiang suture (BNS) in central Tibet (Zhao and Nelson, 1993; Owens and Zandt, 1997; Kosarev et al., 1999; Tilmann and Ni, 2003; Schulte-Pelkum et al., 2005; Li et al., 2008; Nábělek et al., 2009). However, it has been unclear when the Indian continental lithosphere began to subduct and whether the Indian continental crust was ever subducted into the lithospheric mantle beneath the southern Lhasa block. Mantle-derived magmas have a potential to address this issue.

Post-collisional (ca. 24–8 Ma) ultrapotassic–potassic lavas widely distributed within the Lhasa block of southern Tibet are characterized by relatively high contents of large ion lithophile elements (LILE) and

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light rare earth element (LREE) (Fig. 5) and high $(^{87}Sr/^{86}Sr)_i$ and low $(^{143}Nd/^{144}Nd)_i$ (Fig. 6). This indicates that their parental magmas were mainly derived from an enriched mantle source (Williams et al., 2004; Ding et al., 2003; Zhao et al., 2009; Guo et al., 2013; Hébert et al., 2014; Liu et al., 2014b; Guo et al., 2015; Huang et al., 2015). Understanding the petrogenesis of the most primitive K-rich magmatic rocks can provide important constraints on mantle characteristics and deep geodynamic processes in such continent–continent collision zones (e.g., Arnaud et al., 1992; Turner et al., 1993). For more than 20 years, numerous studies on Cenozoic K-rich magmatic rocks in Tibet have been carried out in order to trace the mantle enrichment and deep geodynamic processes (e.g., Turner et al., 1996; Williams et al., 2001; Ding et al., 2003; Nomade et al., 2004; Mo et al., 2006; Gao et al., 2007; Zhao et al., 2009; Chen et al., 2010, 2012; Guo et al., 2013; Liu et al., 2014a; Wang et al., 2014a; Liu et al., 2014b; Guo et al., 2015; Huang et al., 2015; Tian et al., 2015). Three main genetic models have been proposed to account for their formation: (1) convective removal of previously thickened lithospheric mantle (e.g., Turner et al., 1993, 1996; Williams et al., 2001, 2004; Chung et al., 2005; Zhao et al., 2009; Liu et al., 2014b); (2) subduction of Indian continental lithosphere (e.g., Pearce and Mei, 1988; Arnaud et al., 1992; Tapponnier et al., 2001; Ding et al., 2003; Guo et al., 2013); and (3) break off of the subducted Indian continental lithosphere slab (e.g., Miller et al., 1999; DeCelles et al., 2002; Mahéo et al., 2002; Replumaz et al., 2010, 2013, 2014; Huang et al., 2015; Tian et al., 2015) or slab roll-back (e.g., Guo et al., 2013, 2015). However, how and when the enriched mantle source of post-collisional ultrapotassic rocks was formed remains highly controversial. Thus, understanding the relationship between the subduction of the Indian continent and the formation of an enriched mantle source beneath southern Tibet is critical to address the above issues.

A large number of Paleocene–Eocene granitoids are found in southern Tibet, but few contemporary gabbros or basaltic rocks have been reported. In this study, we present detailed petrological, geochronological, and major and trace element, and Sr–Nd–Hf isotopic data for the Quguosha gabbros from the southern Gangdese batholith. Our zircon U–Pb analyses of the gabbros give a latest Eocene (~35 Ma) age, which is within the Late Eocene to Early Oligocene (ca. 40–30 Ma) magmatic gap in the Lhasa block (Chung et al., 2005). Moreover, their geochemical data show enriched Sr–Nd isotopic compositions different from those of the Jurassic to Eocene Gangdese magmatic rocks. Therefore, these gabbros provide a rare opportunity to examine a possible earlier subduction of the Indian continent and details of the continental subduction process.

2. Geologic background and petrographic characteristics

The Tibetan plateau primarily consists of three Gondwana-derived continental fragments: from south to north, the Lhasa, Qiangtang and Songpan-Ganze–Hoh Xil blocks. They are separated from each other by the Bangong–Nujiang and the Jinsha sutures, representative of the relicts of the Meso- and Paleo-Tethys, respectively (e.g., Yin and Harrison, 2000). The Lhasa block was the last of a series of continental fragments to accrete onto southern Asia during the Phanerozoic before the collision of India and Asia (e.g., Yin and Harrison, 2000). Along the southern margin of the Lhasa block, Cretaceous–Paleogene subduction of Neo-Tethyan oceanic crust produced the Cretaceous–Early Tertiary Gangdese magmatic arc (e.g., Allégre et al., 1984; Coulon et al., 1986; Chung et al., 2005). The Indus–Yarlung Tsangpo suture (IYTS) marks the southern boundary of the Lhasa block (e.g., Klootwijk et al., 1992; Yin and Harrison, 2000; Ding et al., 2005; Cai et al., 2011; Chu et al., 2011; Yi et al., 2011; Hu et al., 2012; Decelles et al., 2014; Jiang et al., 2014; Wu et al., 2014; Zhang et al., 2014c; Hu et al., 2015;) (Fig. 1a).

The southern Lhasa sub-block (the Gangdese area) represents the southernmost part of the Asian continent and is characterized by extensive Mesozoic–Cenozoic intrusive and volcanic rocks associated with Neo-Tethyan subduction and subsequent India–Asia continental collision. Based on their temporal–spatial distribution and different geochemical characteristics, these magmatic rocks can be divided into three types. (1) The Mesozoic–Paleocene calc-alkaline rock suites, including the Late Triassic–Early Tertiary (205–43 Ma) gabbros and granitoids (Debon et al., 1986; Harris et al., 1990; Chung et al., 1998; Chung et al., 2005; Wen et al., 2008; Ji et al., 2009; Ma et al., 2013a; 2013b, Ma et al., 2013c, Zhang et al., 2013; Zhu et al., 2013; Ji et al., 2014; Zhang et al., 2014b; Ma et al., 2015), the Early Jurassic (190–174 Ma) Yeba Formation volcanic rocks (Zhu et al., 2008; Guo et al., 2014a), the Late Jurassic–Late Cretaceous (136–93 Ma) Sangri Group volcanic rocks (Zhu et al., 2009; Kang et al., 2010), and the Cretaceous–Tertiary (69–43 Ma) Linzizong Group terrestrial volcanic sequence (Coulon et al., 1986; Pearce and Mei, 1988; Mo et al., 2003, 2007, 2008; Lee et al., 2009, 2012). These magmatic rocks typically show depleted Nd–Hf isotope compositions ($\varepsilon_{Nd}(t)$ up to +5.5 and $\varepsilon_{Hf}(t)$ up to +16.5) and arc-like geochemical characteristics with the enrichment in large ion lithophile elements (LILE) relative to high field strength elements (HFSE) and the strongly negative Ta–Nb–Ti anomalies. (2) The Oligocene–Miocene adakitic rocks (30–10 Ma) and (3) ultrapotassic rocks (25–8 Ma). These latter two types of rocks were developed after an apparent magmatic gap between ca. 40 and ca. 30 Ma in the Lhasa block (Chung et al., 2005). The adakitic rocks occur as small-volume plugs or dikes/sills, which intrude or crosscut the Gangdese batholith, the Linzizong volcanic successions and associated sedimentary formations, and extend ~1300 km across nearly the entire southern Tibet (Fig. 1). They display intermediate to silicic composition (SiO_2 = 56–72 wt.%) and were interpreted to have been generated by partial melting of thickened lower crust (e.g., Chung et al., 2003; Hou et al., 2004; Guo et al., 2007; Chung et al., 2009; Hou et al., 2012; Ji et al., 2012; Ma et al., 2014; Zhang et al., 2014a) or subducted Indian continental crust (Xu et al., 2010; Jiang et al., 2014) or low-degree melting of enriched mantle (Gao et al., 2010). The ultrapotassic rocks crop out as small-volume lava flows, plugs and dike swarms within a series of north–south-trending rifts bounded by normal faults (e.g., Chung et al., 2005; Zhao et al., 2009; Guo et al., 2013, 2015) (Fig. 1). They have extremely radiogenic Sr ($^{87}Sr/^{86}Sr_{(i)}$ = 0.7107 to 0.7365) and Pb isotopes ($^{206}Pb/^{204}Pb$ = 18.45–19.35, $^{207}Pb/^{204}Pb$ = 15.72–15.80, $^{208}Pb/^{204}Pb$ = 39.44–40.17) with Nd isotopes ($\varepsilon_{Nd}(0)$ = −7.6 to −15) and old Nd model ages (T_{DM} = 2.1–1.3 Ga), which were considered to have originated from enriched mantle (Williams et al., 2004; Ding et al., 2003; Chung et al., 2005; Zhao et al., 2009; Guo et al., 2013, 2015; Huang et al., 2015).

The Quguosha area is located in the Sangri County of Tibet and is only 10 km away from the Indus–Yarlung Zangbo suture zone. The Quguosha gabbro pluton intrudes the Eocene gneiss that was traditionally believed to be of Proterozoic (1290 Ma) age (Xie et al., 2007) (Fig. 1b). It consists of non-deformed amphibole gabbros (Fig. 2a). The gabbros are mainly of massive and medium- to fine-grained textures (Fig. 2a), and contain plagioclase (~30–35 vol.%), amphibole (~30–35 vol.%), clinopyroxene (~5–20 vol.%) and biotite (~10–15 vol.%) with Fe–Ti oxides, titanite, apatite and calcite. Amphiboles in the Quguosha gabbros consist of pargasites, magnesiohornblendes and tremolites. The pargasite grains are subhedral and exhibit variable colors, from dark-puce, dark-blue to opaque (Fig. 2f). The magnesiohornblende grains are xenomorphic and show light green to light yellow colors (Fig. 2e and f). Most of the xenomorphic magnesiohornblende grains surround coarse grains of pargasite, clinopyroxene and biotite where there are no reaction rims between them (Fig. 2c, e and f). Tremolites often occur within clinopyroxene grains (Fig. 2h). There are at least two types of feldspar crystals in the Quguosha gabbros (Fig. 2c–h). Some plagioclases are embedded in biotites (Fig. 2d). The other plagioclases are associated with clinopyroxene, amphibole and biotite grains (Fig. 2c–f and h). No reaction rims occur between plagioclase and clinopyroxene grains, indicating that they crystallized contemporaneously (Fig. 2c and h). Some plagioclase grains show the crystallization zonation and apatite grains cut across the crystallization zonation of the plagioclase grains (Fig. 2g). On the basis of textural relationships, the mineral crystallization sequence

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