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U–Pb zircon chronology, geochemical and Sr–Nd isotopic composition of Mesozoic–Cenozoic granitoids in the SE Lhasa terrane: Petrogenesis and tectonic implications

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ABSTRACT

Whole-rock geochemistry, Sr–Nd isotope and zircon U–Pb isotope data are reported for seven granitoid intrusions from the eastern Lhasa terrane. Our zircon U–Pb data exhibit three periods of magmatism: 164–125 Ma, 83 Ma, and 71–45 Ma. Granitoids from the Middle Jurassic to Early Cretaceous (164–125 Ma) display evolved Nd isotope composition, with $\varepsilon_{Nd}(t) = -8.6$ to -15.5 and $T_{2DM} = 1.6$ to 2.2 Ga. In contrast, the Late Cretaceous (83 Ma) granitoids with adakitic characteristics (high Sr/Y ratios) display less evolved Nd isotopic composition, with $\varepsilon_{Nd}(t) = -0.3$ to -3.0 and $T_{2DM} = 0.9$ to 1.1 Ga. Geochemical and Sr–Nd isotopic data indicate that the Middle Jurassic to Early Cretaceous granitoids were derived from partial melting of Proterozoic crustal basement and the Late Cretaceous adakitic granitoids were derived from partial melting of over-thickened lower crust. Geochemical and Sr–Nd isotopic data of granitoids from the Latest Cretaceous to Eocene period (71–45 Ma) reveal that they result from diverse magma sources including both juvenile and reworked mature crustal materials. Our compilation of new and published data from the eastern Lhasa terrane show a marked variation in Sr/Y ratios and a step change in Sr–Nd isotope compositions during the Late Cretaceous. We suggest that the Middle Jurassic to Early Cretaceous granitoids resulted from the northward Neo-Tethyan ocean slab subduction. The increasing Sr/Y ratios from the Middle Jurassic to Late Cretaceous granitoids and northeastward migration of arc magmatism in the eastern Lhasa terrane during the interval *ca.* 125–95 Ma are attributed to the shallowing angle of subduction of the Neo-Tethyan ocean slab. The Late Cretaceous magmatism in the eastern Lhasa terrane probably resulted from the Neo-Tethyan mid-ocean ridge subduction and subsequent delamination of the arc root. The Latest Cretaceous to Eocene granitoids could be interpreted as a magmatic response to roll-back and/or break-off of the subducted Neo-Tethyan slab.

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1. Introduction

The protracted period of convergence between the India and Eurasia plates was concomitant with the continuous subduction of the Neo-Tethyan slab and culminated in continent–continent collision (Allegre et al., 1984; Chung et al., 2005; Guo et al., 2011; Harris et al., 1988a; Ji et al., 2009a; Wen et al., 2008b). The Mesozoic–Cenozoic magmatic rocks of the southern margin of Eurasia provide a record of these geological events and are extensively exposed in the southern Lhasa terrane (Gangdese belt), southern Tibet (Coulon et al., 1986; Xu et al., 1985). Hence they offer a unique insight into the tectonic evolution of the Neo-Tethyan slab subduction and the subsequent India–Eurasia collision. The geochronological data for the Gangdese magmatic rocks suggest that the Neo-Tethyan ocean slab subduction began as early as *ca.* 205 Ma and the collision between the India and Eurasia continents was initiated before 55 Ma (Chung et al., 2009; Ji et al., 2009a; Mo et al., 2007; Wen et al., 2008b). Many studies suggest that the Cretaceous consumption of the Neo-Tethyan ocean in the central Gangdese was characterized by flat (low-angle) slab subduction (Chung et al., 2009; Coulon et al., 1986; DeCelles et al., 2007; Kapp et al., 2007; Leier et al., 2007; Wen et al., 2008a; Zhang et al., 2012).

In the eastern Gangdese belt, Guo et al. (2011) described three magmatic phases (165 Ma, 81 Ma and 61–50 Ma) associated with the Neo-Tethyan slab subduction. However, their detailed magma generation mechanism during Mesozoic–Cenozoic remains poorly constrained. These authors identified the presence of a mature lower crustal basement in the eastern Gangdese belt, which is distinct from the juvenile lower crust of the central Gangdese belt (Chu et al., 2011; Harris et al., 1988b; Ji et al., 2009a; Mo et al., 2008). The Late Cretaceous granitoids (*ca.* 90–80 Ma) from the eastern Gangdese belt show adakitic geochemical signatures, suggesting that they were derived from partial melting of a thickened crust (Guan et al., 2010; Wen et al., 2008a; Zhang et al., 2010b). In contrast, the Latest Cretaceous–Paleocene granitoids

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(*ca.* 70–50 Ma) both from this area, and from the eastern side of the eastern Himalayan syntaxis, lack such geochemical signatures (Booth et al., 2004; Guo et al., 2011; Li et al., 2012; Lin et al., 2012; Liu et al., 2011). This could be indicative of significant crustal thinning of the eastern Lhasa terrane during the Late Cretaceous (*ca.* 80–70 Ma), that is distinct from the central Gangdese belt (Ji et al., 2009b). If such crustal thinning in the eastern Lhasa terrane took place, it raises an important question regarding the tectonic mechanism responsible for this process.

Mesozoic–Cenozoic granitoids are widespread in the eastern side of the eastern Himalayan syntaxis (Chiu et al., 2009; Geng et al., 2006; Pan et al., 2012). However, the geodynamic setting for these granitoids is still ambiguous (Chiu et al., 2009). To address this question, in this paper we have carried out an integrated study of zircon U–Pb dating combined with Sr–Nd isotopic analyses for seven granitoid intrusions from the eastern side of the eastern Himalayan syntaxis (Motuo area). Our main aims are: (1) to constrain their petrogenesis and secular tectonic evolution in the eastern Lhasa terrane; (2) to explore the Mesozoic–Cenozoic geodynamic process along the central and eastern parts of the southern Lhasa terrane.

2. Geological setting

The Tibetan Plateau comprises four continental terranes: from north to south these are termed the Songpan-Gangze, Qiangtang, Lhasa and Himalaya terranes, separated by the Jinsha, Bangong-Nujiang and Yarlung-Tsangpo suture zones, respectively (Yin and Harrison, 2000). The Lhasa terrane is mainly composed of Paleozoic to Paleogene sedimentary cover and widespread Mesozoic to Neogene igneous rocks (Chung et al., 2003; Harris et al., 1988a, 1990; Ji et al., 2009a; Miller et al., 1999; Pearce and Houjun, 1988; Wen et al., 2008b; Williams et al., 2004; Xu et al., 1985; Zhu et al., 2011). The supracrustal cover overlies the Precambrian crystalline basement [e.g. Amdo gneiss in the north (Dewey et al., 1988; Guynn et al., 2006; Xu et al., 1985); and to the south the Nyainqentanglha Group (Dong et al., 2011; Kapp et al., 2005a), Nyingchi and Bomi Group (Dong et al., 2010; Xu et al., 2013; Zhang et al., 2008)]. The Mesozoic to Neogene igneous rocks can be divided into two belts: the southern Gangdese belt dominated by Cenozoic juvenile crust-derived magmas (Harris et al., 1988b; Ji et al., 2009a; Wen et al., 2008b) and the northern plutonic belt dominated by Mesozoic mature crust-derived magmas (Harris et al., 1988b; Xu et al., 1985; Zhu et al., 2009). Recently, a few juvenile crust-derived magmas were reported in the northern part of the northern plutonic belt (Zhu et al., 2011).

The southeastern Lhasa terrane around the eastern Himalayan syntaxis is separated from the Namche Barwa Group (High Himalayan unit) by the Yarlung-Tsangpo suture zone (Fig. 1a and b), representing the remnants of the Neo-Tethyan ocean slab (Booth et al., 2004; Burg et al., 1998; Ding et al., 2001; Geng et al., 2006; Seward and Burg, 2008; Xu et al., 2012). The terrane is transected by a major tectonic feature, the Jiali fault (Fig. 1a and b) (Guo et al., 2011). To the northeast of the Jiali fault, Paleozoic to Mesozoic sedimentary cover is intruded by Cretaceous–Paleocene granitoids (Booth et al., 2004; Chiu et al., 2009; Geng et al., 2006; Lin et al., 2012). The negative $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values of the Cretaceous–Paleocene granitoids suggest that these magmas were mainly derived from partial melting of mature crustal material, indicating that this region is the eastward prolongation of the northern plutonic belt in the Lhasa terrane (Booth et al., 2004; Chiu et al., 2009; Lin et al., 2012; Zhu et al., 2009, 2011).

To the southwest of the Jiali fault, the Motuo tectono-magma belt (Fig. 1c) consists of Precambrian metamorphic basement (e.g. Bomi Group) overlain by Paleozoic sedimentary cover (CIGMR, 2003; Geng et al., 2006; Xu et al., 2013). The Bomi Group comprises banded migmatite, amphibolite, biotite felsic gneiss and garnet–muscovite–biotite gneiss (CIGMR, 2003; Geng et al., 2006; Xu et al., 2013). The Paleozoic sedimentary cover consists of biotite paragneiss, sandstones and limestones. Both of the Bomi Group and the Paleozoic sedimentary cover were intruded by abundant granitoids. Regional mapping and interpretation of magnetic and gravity data suggest that these granitoid plutons represent around 50% of the belt (CIGMR, 2003). These granitoids mainly consist of granodiorite, monzogranites, biotite granite and two-mica granite. The Motuo tectono-magma belt is considered to represent an eastward prolongation of the Gangdese belt (Pan et al., 2012).

3. Field relations and petrology

The Motuo tectono-magmatic belt is located along the eastern margin of the east Himalayan syntaxis. Seven granitoid intrusions along the road from Motuo to Bomi between ~95°10′–95°45′ E and ~29°10′–29°45′ N have been sampled for this study (Fig. 1c). Both the Bomi Group and these granitoids are locally intruded by Oligocene two-mica granite (Pan et al., 2012). All collected samples are fresh, without visible alteration (see Supplementary Fig. 1).

The Beibeng pluton (>200 km^2 in outcrop area), located to the south of Motuo town (Fig. 1c), is composed of biotite granite and two-mica granite. The pluton has sharp contact with its wall-rocks (the Bomi Group). The biotite granite, the major phase of the Beibeng pluton, is intruded by the two-mica granite of presumed Oligocene age. Detailed petrography of this pluton has been described in Pan et al. (2012). The biotite granite was sampled for this study.

The Meiri pluton is located ~5 km north of Motuo town (Fig. 1c). This intrusion consists of massive granodiorite to granite. It mainly contains quartz (15–20%), plagioclase (30–35%), K-feldspar (15–20%), biotite (~12%) and hornblende (~10–15%). Zircon, apatite and Fe–Ti oxides are present as accessories. Mafic magmatic enclaves (MMEs) are abundant in the pluton. Typical modal compositions for the enclaves are plagioclase (~30–40%), hornblende (~50–60%) and biotite (~0–5%). The MMEs occur as lenses with sharp contacts against the host granitoid.

The Bolonggong#1 pluton is a foliated granodiorite–granite stock. The granodiorite and granite are porphyritic with augen-shaped K-feldspar (10–30 mm in length, most <15 mm) which form 10–35% of the bulk rock; the matrix (grain size 0.5–2 mm) contains K-feldspar (20–25%), plagioclase (25–40%), quartz (20–25%) and biotite (10–15%), with accessory zircon, muscovite, apatite and Fe–Ti oxides.

The Bolonggong#2 pluton is a gray granite stock, with weak foliation. This granite is generally fine-grained (0.5–1.5 mm) and consists mainly of quartz (25–30%), plagioclase (35–40%), K-feldspar (20–25%), and biotite (5–8%), with accessory minerals of muscovite, zircon, garnet, and Fe–Ti oxides.

The Bolonggong#3 is an epidote-bearing granodiorite stock. The granodiorite generally shows fine-grained (1–2 mm) and equigranular in texture. It consists mainly of quartz (15–20%), plagioclase (35–40%), K-feldspar (20–25%), biotite (~10%) and hornblende (~15%). Epidote, muscovite, calcite, zircon, apatite and Fe–Ti oxides are present as accessories. Mafic microgranular enclaves are abundant in this intrusion. These are mainly composed of quartz (~5%), plagioclase (~5%), biotite (30–40%) and hornblende (45–55%).

The Bolonggong#4 pluton is a foliated porphyritic granodiorite–granite stock. The K-feldspar phenocrysts are augen-shaped with 10–30 mm (mostly >15 mm) in crystal length making up 30–50% of the bulk volume. The matrix (0.5–4 mm) is composed of K-feldspar (25–30%), plagioclase (35–40%), quartz (20–25%) and biotite (5–10%), with accessory titanite, zircon, muscovite, apatite, and Fe–Ti oxides.

The 52K pluton is composed of fine-grained (0.5–1 mm) biotite granite and porphyritic granodiorite. The biotite granite consists mainly of quartz (25–35%), plagioclase (35–40%), K-feldspar (15–25%) and biotite (~5%), with accessory minerals of zircon, muscovite, titanite, and Fe–Ti oxides. The phenocrysts of the porphyritic granodiorite are euhedral feldspar (5–20 mm) forming 5–15% of the bulk volume; the matrix (0.5–2 mm) contains K-feldspar (10–20%), plagioclase

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