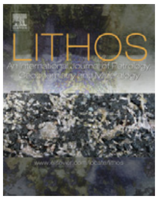
Lithos 196–197 (2014) 321–338

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos



Petrogenesis of the Early Eocene adakitic rocks in the Napuri area, southern Lhasa: Partial melting of thickened lower crust during slab break-off and implications for crustal thickening in southern Tibet

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ARTICLE INFO

Article history:
Received 5 October 2013
Accepted 16 February 2014
Available online 24 February 2014

Keywords:
Adakitic rocks
Lower crustal melting
Crustal thickening
Slab breakoff
Tibet

ABSTRACT

Cenozoic adakitic rocks in the Lhasa block (southern Tibet) have been widely used to trace the lateral extent of crustal thickening. However, their petrogenesis remains controversial. Here, we report geochronological and geochemical data for the Napuri intrusive rocks in the core area of the Quxu batholith, southern Lhasa. Zircon U–Pb dating suggests that they were generated at approximately 48 Ma. The studied samples show significant geochemical variations, manifested by the coexistence of three types of igneous rocks. Groups I and II rocks exhibit variable and high SiO_2 (66.4–73.9 wt.%), high Al_2O_3 (14.0–17.4 wt.%), K_2O (3.9–5.3 wt.%), Sr (273–718 ppm) and Sr/Y (18.3 to 81.3) values, and low Y (3.6 to 16 ppm), heavy rare earth element (REE) (e.g., Yb = 0.48 to 1.8 ppm), MgO (0.4–1.0 wt.%), Cr (2.9–7.4 ppm) and Ni (1.6–4.5 ppm) contents, which are similar to those of thickened lower crust-derived adakitic rocks. The Group I rocks show higher Sr/Y (77.5–81.3) ratios and lower total REE (55.5–63.2 ppm) contents with clearly positive Eu and Sr anomalies, whereas the Group II rocks have relatively lower Sr/Y (18.3–65.7) ratios and higher total REE (115–375 ppm) contents with negligible or slightly negative Eu and Sr anomalies. Group III rocks have the highest SiO_2 (74.5–76.0 wt.%), Y (17.0–23.7 ppm) and Yb (2.91–3.30 ppm) contents, and the lowest Al_2O_3 (12.5–13.2 wt.%), Sr (81.3–141 ppm) and Sr/Y (4.8–5.9) values with distinctly negative Eu and Sr anomalies. Compared with the Jurassic–Cretaceous granitoids in southern Lhasa, the relative enrichment in Sr–Nd–Hf isotopic compositions ($(^{87}Sr/^{86}Sr)_i = 0.7049$–$0.7055$, $\varepsilon_{Nd}(t) = -0.3 \pm 0.7$ and $\varepsilon_{Hf}(t)_{zircon} = +3.6 \pm 11.4$) for the Napuri intrusive rocks indicates that they likely contained Indian continental components. The Group I and Group II rocks most probably originated from thickened mafic lower crust (amphibolite eclogites or garnet amphibolites) with garnet + rutile ± plagioclase as residual minerals in the source at >1.5 GPa, corresponding to depths of >50 km, and Group III rocks were probably generated by fractional crystallization of plagioclase from the adakitic magmas. Taking into account the narrow linear nature of the Eocene magmatic belt and reported synchronous asthenosphere-derived basaltic rocks in southern Lhasa, we suggest that upwelling asthenosphere triggered by the break-off of subducted Neo-Tethyan slab probably provided the required thermal conditions for lower crustal melting. The identification of Indian continental components in the Napuri intrusive rocks probably indicates that the Asia–India collision had taken place prior to their emplacement. The dramatic changes in the $(La/Yb)_N$ ratios and $\varepsilon_{Nd}(t)$ and $\varepsilon_{Hf}(t)$ values of magmatic rocks in the Gangdese area at ca. 51–46 Ma indicate that the Cenozoic crustal thickening associated with the indentation of the Indian continent began in the Early Eocene (ca. 51–46 Ma) at the latest.

1. Introduction

The Tibetan Plateau has the thickest continental crust on Earth. Various models have been proposed in the past decades to account for the formation of the plateau, which can be roughly summarized as

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http://dx.doi.org/10.1016/j.lithos.2014.02.011

crustal/lithospheric thickening models (e.g., Tapponnier et al., 2001; Wang et al., 2008; Yin and Harrison, 2000), convective removal or delamination of the lower lithosphere models (e.g., Chung et al., 1998, 2009; Turner et al., 1996) and crustal flow models (e.g., Royden et al., 1997; Wang et al., 2012). The timing and mechanism of the continental crustal thickening are pivotal factors that all such models need to reconcile.

Cenozoic adakitic rocks are widely distributed in a 1500 km-long E–W trending magmatic belt in southern Lhasa, the southern Tibetan Plateau (e.g., Chung et al., 2003, 2005, 2009; Gao et al., 2010; Guo et al., 2007; Hou et al., 2004, 2012 and references therein) and have been widely used for tracing crustal thickening processes in the region (e.g., Chung et al., 2003, 2009; Guan et al., 2012; Hou et al., 2012; Ji et al., 2012; Zeng et al., 2011). Nonetheless, their petrogenesis remains a highly controversial issue. Various magmatic sources have been proposed to account for the generation of these adakitic rocks, including a thickened mafic lower continental crust (e.g., Chung et al., 2003; Guan et al., 2012; Guo et al., 2007; Hou et al., 2004; Ji et al., 2012), subducted Indian continental crust (e.g., Xu et al., 2010), upper mantle metasomatized by slab-derived melts (e.g., Gao et al., 2007, 2010), and Jurassic–Eocene Gangdese intermediate intrusive rocks and basement metasedimentary rocks (e.g., King et al., 2007; Pan et al., 2012; Zhang et al., 2010a).

The Cenozoic adakitic rocks in southern Lhasa were mainly emplaced between the Late Oligocene and the Late Miocene (ca. 26–9 Ma; Chung et al., 2003; Guo et al., 2007; Hou et al., 2004). More recently, Eocene–Oligocene (ca. 51–30 Ma) adakitic rocks have also been reported (e.g., Chung et al., 2009; Guan et al., 2012; Hou et al., 2012; Ji et al., 2012; Jiang et al., 2011; Zeng et al., 2011). In this study, we present detailed petrology, geochronology, mineral composition, and major and trace element and Sr–Nd–Hf isotopic data for the Napuri adakitic intrusive rocks at the hinterland of the Quxu batholith in southern Lhasa (Fig. 1). New SHRIMP (Sensitive High Resolution Ion Microprobe) and LA-ICPMS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry) zircon U–Pb dating results indicate that they were generated in the early Eocene (49–46 Ma). Owing to the wide occurrence of Early Cenozoic adakitic rocks in southern Tibet, a better understanding of their petrogenesis has importance for delineating the processes of Cenozoic crustal thickening and plateau uplift in southern Tibetan.

2. Geological background and rock characteristics

From south to north, Tibet consists of the Himalaya, Lhasa, Qiangtang, Songpan-Ganze, and Kunlun-Qaidam blocks (Yin and Harrison, 2000). The Lhasa block is bounded by the Indus–Yarlung Tsangpo suture (IYTS) to the south and the Bangong–Nujiang suture (BNS) to the north (Fig. 1a) (Yin and Harrison, 2000). It is generally accepted that the BNS developed during the Late Jurassic–Middle Cretaceous (Yin and Harrison, 2000). The IYTS marks the closure of the Tethys, and lies on the southern boundary of an east–west-trending Andean arc-type calc-alkaline magmatic zone (including the Yeba, Sangri, Linzizong volcanic successions and the Gangdese batholith) in the Lhasa block (Fig. 1a) (e.g., Coulon et al., 1986; Mo et al., 2007; Zhu et al., 2008).

The Gangdese batholith, consisting of the Latest Triassic–Late Miocene intermediate–felsic intrusive rocks, is one of the most important geologic units of southern Lhasa (e.g., Chu et al., 2006; Chung et al., 2003, 2009; Ji et al., 2009, 2012; Wen et al., 2008a,b). The adakitic intrusive rocks within the Gangdese batholith are considered to have been generated in two main stages, the Jurassic–Cretaceous (160–77 Ma) and Paleocene–Miocene (62–10 Ma): (1) Jurassic–Cretaceous adakitic rocks generated in an arc setting were related to Neo-Tethyan subduction processes, by melting of either subducted oceanic slabs (e.g., Jiang et al., 2012; Ma et al., 2013a; Wei et al., 2007; Zhang et al., 2010b; Zhu et al., 2009) or thickened mafic continental lower crust (e.g., Guan et al., 2010; Wen et al., 2008b); (2) Cenozoic adakitic rocks occurring 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 Lhasa (Fig. 1b) (e.g., Chung et al., 2003, 2005, 2009; Gao et al., 2007, 2010; Guan et al., 2012; Guo et al., 2007; Hou et al., 2004, 2012; Ji et al., 2012; Jiang et al., 2011, 2014; Pan et al., 2012; Xu et al., 2010; Zhang et al., 2010a).

The Napuri area of Doilungdeqen County (Fig. 1c) is difficult to access due to the high altitudes (4800–5700 m). Large-scale granitic intrusive bodies, being parts of the Quxu batholith, are found in the area (Fig. 1b, c). These intrusive rocks are composed mainly of porphyritic granites, and minor quartz monzonites with a heterogeneous granular texture. A total of 12 samples were collected for this study, including 10 granites and 2 quartz monzonites. The granite is composed of plagioclase (15–25 vol.%), alkali feldspar (25–35 vol.%), quartz (30–40 vol.%), biotite (5–10 vol.%), and titanite (1–2 vol.%) with minor epidote, magnetite and titaniferous magnetite (Fig. 2a, b, e and f). The quartz monzonite consists of plagioclase (35–45 vol.%), alkali feldspar (30–40 vol.%), quartz (10–15 vol.%), biotite (5–10 vol.%), and titanite (1–2 vol.%) with minor epidote, magnetite and titaniferous magnetite (Fig. 2c and d).

3. Analytical methods

All silicate mineral analyses were carried out at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (SKLaBIG GIG CAS) using a JXA-8100 electron microprobe. An accelerating voltage of 15 kV, a specimen current of 2.0×10^{-8} A, and a beam size of 1–2 μm were employed. The analytical errors are generally less than 2%. The analytical procedures were described in detail in Huang et al. (2007).

Zircons were separated using standard density and magnetic separation techniques. Zircon grains were handpicked and mounted in an epoxy resin disc, and then polished and coated with gold. Cathodoluminescence (CL) images were taken at SKLaBIG GIG CAS with a JEOL JXA-8100 Superprobe for inspecting the internal morphology of individual zircons and for selecting positions for U–Pb and Lu–Hf isotope analyses. U–Pb isotope compositions of zircon grains from two samples (D175 and D182) were analyzed using the SHRIMP at the John de Laeter Centre of Mass Spectrometry of Curtin University of Technology in Perth, Western Australia. Both unknown zircon grains and zircon standards, TEMORA (for calibrating the U–Th–Pb ratios; ^{206}Pb/^{238}U $=0.0668$, corresponding to 417 Ma; Black et al., 2003) and CZ3 (for calibrating absolute U abundances; U = 551 ppm; Pidgeon et al., 1994) were analyzed under the following conditions: cycles of 7 scans, primary O^{2-} beam of ~2 nA, spot size of ~25 μm with a mass resolution of about 5000. The data have been reduced following the procedure described by Williams (1998) using the software SQUID (Ludwig, 2001). U/Pb ratios and U concentrations of the samples have been normalized to the TEMORA and CZ3 standards, respectively. Common Pb was determined using measured ^{204}Pb and by applying a composition after Stacey and Kramers (1975) appropriate to the age of the zircon. LA-ICPMS zircon U–Pb dating for sample PIII-02 were conducted at the MC-ICPMS laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG CAS) in Peking, China. Detailed operating conditions for the laser ablation system and the ICP-MS instrument and data reduction were the same as described by Xie et al. (2008). An Agilent 7500a quadruple (Q)-ICPMS and a Neptune multi-collector (MC)-ICPMS with a 193 nm excimer ArF laser-ablation system (GeoLas Plus) attached were used for simultaneous determination of zircon U–Pb ages. In situ Hf isotope measurements were subsequently done using LA-ICPMS with a beam size of 60 μm and laser pulse frequency of 8 Hz with age determinations at the MC-ICPMS laboratory of IGG CAS. Details of instrumental conditions and data acquisition were given in Wu et al. (2006). The isobaric interference of ^{176}Lu on ^{176}Hf is negligible due to the extremely low ^{176}Lu/^{177}Hf in zircon (normally <0.002).

Rock samples were examined by optical microscopy and selected whole-rock samples were sawed into small chips and ultrasonically cleaned in distilled water with <3% HNO_3 and then in distilled water alone and subsequently dried and handpicked to remove visible alteration. The rocks were powdered in a chrome ring mill, and the resulting