Lithos 245 (2016) 223–242

Contents lists available at ScienceDirect

Lithos

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

Underplating of basaltic magmas and crustal growth in a continental arc: Evidence from Late Mesozoic intermediate–felsic intrusive rocks in southern Qiangtang, central Tibet

Lu-Lu Hao [a,b], Qiang Wang [a,c,*], Derek A. Wyman [d], Quan Ou [a,b], Wei Dan [a], Zi-Qi Jiang [a,e], Fu-Yuan Wu [f], Jin-Hui Yang [f], Xiao-Ping Long [a], Jie Li [a]

[a] State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
[b] University of Chinese Academy of Sciences, Beijing 10069, China
[c] CAS Center for Excellence in Tibetan Plateau Earth Sciences, China
[d] School of Geosciences, The University of Sydney, NSW 2006, Australia
[e] School of Earth Science, Guilin University of Technology, Guilin 541004, China
[f] Institute of Geology and Geophysics, Chinese Academy of Science, Beijing 100029, China

ARTICLE INFO

Article history:
Received 8 April 2015
Accepted 16 September 2015
Available online 28 September 2015

Keywords:
Crustal growth
Underplating
Adakites
Late Mesozoic
Qiangtang
Tibet

ABSTRACT

Phanerozoic growth of continental crust has widely been considered as an important geological phenomenon and mainly occurs in an arc setting. However, the crustal growth models (mantle-derived basalt underplating or accretion of island or intra-oceanic arc complexes or oceanic plateau) have been disputed. Here we present new zircon LA–ICPMS U–Pb age, whole-rock major and trace element, Sr–Nd and zircon Hf isotopic data for Late Mesozoic intermediate–felsic intrusive rocks in the Rena Co area in southern Qiangtang, central Tibet. LA–ICP–MS zircon U–Pb dating for two granodiorite and three diorite samples and one granodiorite porphyry sample gives ages of ca. 150 Ma, ca. 112 Ma, respectively, indicating they were generated in the Late Jurassic–Early Cretaceous. All rocks are sub-alkaline in composition and belong to the high-K cal-alkaline series. The ~150 Ma diorites ($SiO_2 = 57.9$–61.2 wt.%) exhibit relatively high MgO (3.13–3.88 wt.%) and Cr (52.4–282 ppm) contents and $Mg^\#$ (47–51) values, similar to magnesian diorites. They are geochemically characterized by uniformly low $\varepsilon_{Nd}(t)$ (−5.5 to −5.2), high $(^{87}Sr/^{86}Sr)_i$ (0.7071 to 0.7078) and Th/La (0.22–0.32), and variable zircon $\varepsilon_{Hf}(t)$ (−8.7 to +4.8) values. They were probably generated by melting of oceanic sediment diapirs, followed by interaction with the surrounding mantle during the northward subduction of Bangong–Nujiang Oceanic lithosphere. The ~150 Ma granodiorites and ~112 Ma granodiorite porphyries are characterized by low MgO (<3 wt.%) contents and $Mg^\#$ (<45) values, high Al_2O_3 (>15% wt.%) and Sr (>400 ppm) and low Y (<18 ppm) and Yb (<1.9 ppm) contents, and high Sr/Y and La/Yb ratios, which are similar to those of typical adakites. The granodiorites have low $\varepsilon_{Nd}(t)$ (−7.6 to −3.7) and zircon $\varepsilon_{Hf}(t)$ (−9.8 to +0.2) and high $(^{87}Sr/^{86}Sr)_i$ (0.7069 to 0.7086) values, and were likely produced by partial melting of a thickened and heterogeneous ancient lower continental crust. The relatively depleted isotope compositions [$(^{87}Sr/^{86}Sr)_i = 0.7054$–0.7065; $\varepsilon_{Nd}(t) = -0.61$ to +0.25; zircon $\varepsilon_{Hf}(t) = +4.7$ to +9.7] of the granodiorite porphyries indicate that they were most probably generated by partial melting of newly underplated and thickened basaltic lower crust. Taking into account ophiolites in the Bangong–Nujiang Suture and Late Mesozoic magmatic rocks in the southern Qiangtang sub-block, we suggest that this area was located in a continental arc setting. Moreover, from the Late Jurassic to Early Cretaceous, the ancient lower crust in the southern Qiangtang sub-block was gradually replaced by mantle-derived juvenile materials. The crustal evolution indicates that, in a continental arc, basaltic magma underplating plays a key role in vertical crustal growth.

1. Introduction

One of the Earth's unique features when compared with other planets in our Solar System is the presence of the continental crust (Rudnick, 1995). However, the growth and evolution of the continental crust remains the topic of considerable debate (e.g., Hawkesworth and Kemp, 2006; Jahn, 2004). It is widely accepted that the formation of

* Corresponding author at: Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China.
E-mail address: wqiang@gig.ac.cn (Q. Wang).

http://dx.doi.org/10.1016/j.lithos.2015.09.015
0024-4937/

the continental crust was essentially complete in the Precambrian (Condie, 1998; Taylor and McLennan, 1995). However, in recent decades, this idea was challenged by isotope investigations in western North America (Sierra Nevada, Peninsular Range, and Canadian Cordillera) (Lee et al., 2007; Samson et al., 1989), South America (Andean) (Mišković and Schaltegger, 2009), eastern Australia (Lachlan and New England Fold belts) (Collins, 1998; McCulloch and Chappell, 1982), the central Asian Orogenic Belt (also known as the Altaid Tectonic Collage) (e.g., Jahn, 2004; Kröner et al., 2014; Sengör et al., 1993) and south Tibet (Gangdese belt) (e.g., Chu et al., 2006; Ji et al., 2009; Ma et al., 2013a; Mo et al., 2008; Zhang et al., 2014c; Zhu et al., 2011), which revealed that a substantial proportion of Phanerozoic crust is juvenile. Phanerozoic continental crustal growth primarily occurs in subduction zones by lateral accretion of island or intra-oceanic arc complexes and oceanic plateaus or by vertical addition by underplating of basaltic magmas in the crust–mantle interface (Chen and Arakawa, 2005; Jahn, 2004; Rudnick, 1995).

Numerous studies in southern Tibet indicate that Jurassic–Early Eocene Gangdese granitoids with high and positive εNd(t) have important implications for Gangdese crustal growth (e.g., Chu et al., 2006; Ji et al., 2009; Ma et al., 2013a; Zhang et al., 2014c). Geochemical investigations of Early Cretaceous igneous rocks along an east–west traverse in central and northern Lhasa sub-block reveal basalt underplating-related vertical crustal growth, plausibly triggered by break-off in a continent–continent collision setting in central Tibet (e.g., Sui et al., 2013; Zhu et al., 2009, 2011). Recently, however, Zhang et al. (2014a) reported the occurrence of a Meso-Tethyan oceanicplateau in the Bangong–Nujiang Ocean, in the Late Mesozoic (193–173 Ma and 128–104 Ma), indicating lateral crustal growth by accretion of oceanic plateau. Therefore, we suggest that the mechanism and tectonic setting for Late Mesozoic crustal growth in central Tibet remains unclear.

Granitoids are the main components of continental crust. Much work has been done on their Sr–Nd isotopic compositions to better understand their genesis and thus the origin and evolution of the continental crust (e.g., Jahn, 2004). Phanerozoic granitoids that originated from juvenile crust have rather different initial Sr–Nd isotopic compositions compared to those derived from ancient crust because juvenile crust (middle oceanic ridge basalt (MORB), oceanic island basalt (OIB), and newly underplated basalts) have positive $\varepsilon_{Nd}(t)$ and low $(^{87}Sr/^{86}Sr)_i$, while old continental crustal rocks generally have negative $\varepsilon_{Nd}(t)$ and high $(^{87}Sr/^{86}Sr)_i$ (e.g., Chen and Arakawa, 2005). Recently, Hf isotope analyses on zircons have been widely used to trace the source regions of their host magmas. Due to the mineral's physiochemical resistance, the isotopic data can readily distinguish the involvement of newly derived mantle melts from the remelting of old mature crust (Griffin et al., 2002; Kemp et al., 2007; Yang et al., 2007; Zhu et al., 2011).

Mesozoic intermediate–felsic intrusive rocks are widely distributed in the southern Qiangtang, central Tibet (e.g., Kapp et al., 2005; Li et al., 2014a). In this study, we report zircon LA–ICPMS U–Pb age, whole-rock major and trace element, Sr–Nd and zircon Hf isotopic data for Late Jurassic granodiorites and diorites and Early Cretaceous granodiorite porphyries in the Rena Co area, north of Gerze County in southern Qiangtang. We systematically investigate their petrogenesis and tectonic setting and trace the temporal variations of their source regions, with important implications for crustal growth in central Tibet.

2. Geological setting and petrographical characteristics

The Tibetan plateau consists of five blocks (from north to south: Qaidam, Songpan–Ganze–Hoh Xil, Qiangtang, Lhasa, and Himalaya), mainly separated by four sutures (Anyimaqin–Kunlun–Muztagh, Jinsha, Bangong–Nujiang and Indus–Yalu Sutures, respectively. Fig. 1a) (Chung et al., 2005; Yin and Harrison, 2000). The Qiangtang block is located in central Tibet, and is bounded by the Jinsha Suture (JS) to the north and the Bangong–Nujiang Suture (BNS) to the south (Yin and Harrison, 2000). It is divided into southern and northern Qiangtang sub-blocks by Longmu–Shuanghu suture (Li et al., 2006; Pan et al., 2004).

The Bangong–Nujiang Suture Zone (BNSZ), which extends over 2000 km across central Tibet, is characterized by mainly Jurassic–Cretaceous flysch, mélange and scattered ophiolitic fragments representing remnants of the Bangong–Nujiang ocean basin (Kapp et al., 2003; Pan et al., 2004). The main strata exposed in southern Qiangtang sub-block consist of Carboniferous and Permian interbedded sandstone and shale, Triassic limestone, and Jurassic sandstone (Pan et al., 2004) (Fig. 1c). Late Mesozoic magmatic rocks are widely distributed in the southern Qiangtang from the Rotug to Amdo area (Fig. 1b). These rocks are dominated by intermediate–felsic magmatic rocks and currently available geochronological data (e.g., Chang et al., 2011; Guynn et al., 2006; Kapp et al., 2005; Li et al., 2011, 2013, 2014a,b; Liu et al., 2012, 2014; Zhang et al., 2012a) indicate that they were emplaced between 183 and 101 Ma.

The Rena Co (lake) area, approximately 40 km north of Gerze County, is located in the southern Qiangtang sub-block (Fig. 1b) and includes five unnamed intermediate-felsic plutons. As numbered in Fig. 2, plutons ① and ②, ③ and ④, and ⑤ consist of granodiorites, diorites and granodiorite porphyries, respectively.

Granodiorites contain amphibole (5–10 vol.%), biotite (10–15 vol.%), plagioclase (60–65 vol.%), and quartz (10–15 vol.%) with accessory zircon, apatite and Fe–Ti oxides (Fig. 2a–d). Diorites contain amphibole (10–15 vol.%), biotite (20–25 vol.%), plagioclase (55–60 vol.%), and quartz (~5 vol.%) with accessory zircon, apatite, titanite, and Fe–Ti oxides (Fig. 2e–h). Granodiorite porphyries are typically porphyritic, with 40–50 vol.% phenocrysts of plagioclase, biotite and quartz and matrix composed mainly of K-feldspar and quartz (Fig. 2i–j).

3. Analytical methods

The samples used for geochemical analyses were powdered to ~200-mesh size in an agate mortar. Major element oxides were analyzed on fused glass beads using a Rigaku RIX 2000 X-ray fluorescence spectrometer at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (SKLaBIG, GIGCAS). Calibration lines used in quantification were produced by bivariate regression of data from 36 reference materials encompassing a wide range of silicate compositions (Li et al., 2004). Analytical uncertainties are between 1% and 5%. Trace elements were analyzed using an Agilent 7500a ICP–MS at GIGCAS. Analytical procedures were similar to those described by Li et al. (2004). A set of USGS and Chinese national rock standards, including BHVO-2, GSR-1, GSR-2, GSR-3, AGV-2, W-2 and SARM-4 were chosen for calibration. Analytical precision typically is better than 5%. The major and trace element data are listed in Table 1.

Sr and Nd isotope analyses were performed using a Micromass Isoprobe multi-collector mass spectrometer (MC–ICPMS) at SKLaBIG, GIGCAS. Analytical procedures are described by Li et al. (2004). The $^{87}Sr/^{86}Sr$ ratio of the NBS987 standard and $^{143}Nd/^{144}Nd$ ratio of the Shin Etsu JNdi-1 standard measured were 0.710251 ± 6 (n = 19, 2σ) and 0.512087 ± 3 (n = 11, 2σ), respectively. All measured $^{143}Nd/^{144}Nd$ and $^{86}Sr/^{88}Sr$ ratios are fractionation corrected to $^{146}Nd/^{144}Nd = 0.7219$ and $^{86}Sr/^{88}Sr = 0.1194$, respectively. The Sr–Nd isotope data are presented in Table 1.

Zircon crystals were separated from six rock samples using standard density and magnetic separation techniques. Zircon grains were handpicked and mounted in an epoxy resin disk, and then polished and coated with gold. Cathodoluminescence (CL) images were taken at SKLaBIG, GIGCAS with a JEOL JXA-8100 Superprobe for inspecting