***Tectonic shortening and crustal thickening in subduction zones: Evidence from
Middle–Late Jurassic magmatism in Southern Qiangtang, China***

Hao Wu, Chaoming Xie*, Cai Li, Ming Wang, Jianjun Fan, Wenliang Xu

College of Earth Sciences, Jilin University, Changchun, 130061, P.R. China

Postal address: 2199 Jianshe Street, College of Earth Sciences, Jilin University,

Changchun 130061, China. Tel.: +86-431-88502046; Fax: +86-431-88584422

Corresponding author: Email: xcmxcm1983@126.com

Tectonic shortening and crustal thickening in subduction zones: Evidence from Middle–Late Jurassic magmatism in Southern Qiangtang, China

Abstract

We report new zircon U–Pb geochronologic and Hf-isotopic data, and whole-rock major and trace element data, for the Labuco granitoids of the southern margin of the Southern Qiangtang terrane (SQ), Tibet. Five intermediate–felsic samples yielded zircon U–Pb ages of 169–156 Ma, making the Labuco granitoids contemporaneous with Middle–Late Jurassic magmatism in the SQ. The granitoids exhibit a range of zircon $\epsilon\text{Hf}(t)$ values from -7.3 to -0.6 . The samples from Labuco can be divided into low-Sr/Y granitoids (LSG) and high-Sr/Y granitoids (HSG). The LSG are normal calc-alkaline I-type granitoids, characterized by varying major and trace element contents indicative of partial melting of ancient mafic lower crust. The HSG are characterized by high Sr/Y ratios (64–75), $(\text{La}/\text{Yb})_{\text{N}}$ (chondrite-normalized) ratios of 57–76, and $(\text{Gd}/\text{Yb})_{\text{N}}$ ratios of 6.6–8.9. These signatures indicate that the HSG were derived by partial melting of garnet-bearing thickened lower crust. The across-arc variation in magma geochemistry in the SQ was caused by tectonic shortening and crustal thickening, which occurred as a result of the northward subduction of the Bangong–Nujiang Ocean lithosphere during the Middle–Late Jurassic. These results have important implications for our understanding of tectonic shortening, crustal thickening, and the geometry of modern and ancient subduction zones.

Key words: Bangong–Nujiang Ocean; Middle–Late Jurassic magmatism; Subduction zone; Tectonic shortening; Crustal thickening

1 Introduction

Subduction zones can be considered “factories” that have contributed significantly to the geochemical evolution of the Earth, as they produce volcanic arc magmas, plutonic rocks that solidified from the magmas, and, ultimately, continental crust (Tatsumi, 2005). This recycling mechanism has important consequences for global geochemical cycling and the geodynamics of the deep Earth. In contrast, physical processes occurring during subduction, such as tectonic shortening caused by extrusion, play an important role in controlling the thickness of continental crust. For example, the Central Andes has one of the thickest continental crusts on Earth, in excess of 70 km (Giambiagi et al., 2012; Mcquarrie et al., 2005; Wigger et al., 1994; Zandt et al., 1994), and this great thickness is thought to have resulted from tectonic shortening of the South American Plate during the Neogene (Sempere et al., 1990; Sheffels, 1990). Much of the work to date concerned with understanding the coupling between subduction zone magmatism, tectonic shortening, and crustal thickening has concentrated on currently active subduction zones, such as the Central Andes and the Himalayan–Tibetan orogens. This may reflect the fact that paleo-subduction zones are typically weathered and deformed, thereby making it difficult to determine their structural and geochemical evolution. As “petrogenetic records” of paleo-geotectonic events, ancient subduction-related magmatic rocks provide important petrogenetic windows into the evolution of deep crustal magma sources and subduction zone geodynamics.

The Southern Qiangtang terrane (SQ) of Tibet contains many irregularly

distributed Middle–Late Jurassic intrusive bodies (Fig. 1a, b). Previous studies have presented zircon U–Pb geochronology and whole-rock trace element data from the Larelaxin, Caima, Qingcaoshan, and Renaco granitoid plutons in the SQ (e.g., Hao et al., 2016; Li et al., 2014a,b; Liu et al., 2014; Zhang et al., 2011). Various lithologies have been identified, and different source magmas proposed, based on the diverse geochemistry of the plutons (Li et al., 2014a,b; Liu et al., 2014). The presence of Late Jurassic adakitic granodiorites in the Renaco area, derived from thickened lower crust, indicates that this crustal thickening had already occurred by the time the Bangong–Nujiang oceanic lithosphere was subducted beneath the SQ (Hao et al., 2016). The specific processes relating to magma origin and petrogenesis can be further constrained using petrological, geochemical, and geochronological data.

In this paper, we report zircon U–Pb age data, Hf isotopic data, and whole-rock major and trace element data for the Labuco granitoids of the southern margin of the SQ. Our results, together with existing geochemical and structural data, are used to propose a new petrogenetic model for subduction zone magmatism in the SQ, which shows that tectonic shortening and crustal thickening occurred along the southern margin of the SQ in response to northward subduction of the Bangong–Nujiang Ocean lithosphere.

2 Geological background and field observations

From south to north, the Tibet Plateau consists of the Himalaya, Lhasa, Central Qiangtang, Southern Qiangtang, and Northern Qiangtang terranes, together with the Songpan–Ganzi flysch complex. These terranes are separated by the Indus–Yarlung

Zangbo suture zone (IYZSZ), the Bangong–Nujiang suture zone (BNSZ), the Longmu Tso–Shuanghu suture zone (LSSZ) and the Jinsha suture zone (JSSZ) (Fig. 1a), respectively (Zhu et al., 2011). The BNSZ represents the remnants of the Bangong–Nujiang Ocean crust, and is characterized by ophiolitic fragments consisting of thick sequences of Jurassic flysch, *mélange*, and volcanic rocks (Kapp et al., 2003). Based on the age of the ophiolites, and radiolarian ages from this zone, the Bangong–Nujiang Ocean is inferred to have existed from at least the Triassic to the Early Cretaceous (Yin and Harrison, 2000; Zhu et al., 2011).

Jurassic intrusions are exposed along the southern margin of the SQ and are thought to be related to the northward subduction of the Bangong–Nujiang oceanic lithosphere beneath the SQ (e.g., Cao et al., 2016; Li et al., 2014a,b; Liu et al., 2014, 2015; Zhang et al., 2011). These intrusives are dominated by intermediate–felsic rocks, including gabbroic diorites, diorites, granodiorites, and granites. Zircon U–Pb geochronological data indicate that these rocks were emplaced during the Middle–Late Jurassic (e.g., Hao et al., 2016; Li et al., 2014a,b; Liu et al., 2014, 2015; Zhang et al., 2011). The granitoid samples investigated in this study were collected from the Labuco plutons and sample locations are shown in Fig. 1c. The Labuco plutons are typically composed of diorite (sample DT17), granodiorite (DT14, DT18, and DT30), and granite (DT15). The granodiorite of sample DT14 and granite of sample DT15 intruded limestone and sandstone units of the Upper Triassic Riganpeicuo Group (Fig. 1d). The diorite of sample DT17 and granodiorite of samples DT18 and DT30 intruded chert and metamorphic peridotite, respectively, of

the Labuco ophiolite mélange (Fig. 1e–g).

The diorites (DT17) have an aphyric texture and consist primarily of plagioclase (40%–45%) and biotite (20%–25%; the biotite is locally partially altered to chlorite) along with minor quartz (5%–10%) and amphibole (5%) (Fig. 1h). The granodiorites (DT14, DT18 and DT30) and granites (DT15) are fine- to medium-grained and have a mineral assemblage of quartz (30%–35%), zoned plagioclase (50%–60%), and biotite (10%–15%), with accessory zircon, apatite, and Fe–Ti oxides (Fig. 1i, j).

3 Analytical methods

3.1. LA–ICP–MS zircon U–Pb dating

Five samples (DT14, DT15, DT17, DT18 and DT30) from different plutons were selected for the zircon U–Pb analyses (Fig. 1c). Zircons were separated from each sample using heavy-liquid and magnetic methods in the Laboratory of the Geological Team of Hebei Province, China. Cathodoluminescence (CL) images were taken at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China in order to observe the internal structures of individual zircons. Zircon U–Pb dating was performed by LA–ICP–MS at the Geological Laboratory Centre, China University of Geosciences, Beijing, using an Agilent 7500a ICP–MS (Agilent Technologies Inc., USA). Zircon crystals from the sample rocks were ablated via ArF laser ablation (UP193SS, New Wave, Inc., USA) operating at a wavelength of 193 nm, a spot diameter of 36 μm , and using helium as the carrier gas. Isotopic compositions of the zircon trace elements (U, Pb, Si) were calibrated to the zircon reference material

91500 and determined relative to the standard zircons TEM (417 Ma) and NIST 610 as the reference and internal standards, respectively. NIST 612 and NIST 614 standards were used to optimize the instrument. The isotope data were processed using the programs Isoplot (version 3.0) and Glitter (version 4.4) (Ludwig 2003). The operating conditions for the laser ablation system, the ICP–MS instrument, and the data reduction methods are identical to those described by Yuan et al. (2004).

3.2. Whole-rock geochemical analyses

Forty samples were collected for major and trace element analyses. Fresh whole-rock samples were sawn into chips and ultrasonically cleaned using distilled water with <5% HNO₃ and then using distilled water only. Subsequently, the samples were dried and handpicked to avoid visible contamination. The chosen samples were then crushed and ground in an agate ring mill, and the resulting powders were analyzed for major and trace elements. The major elemental compositions of the whole-rock samples were analyzed using a Leeman Prodigy inductively coupled plasma–optical emission spectroscopy system with high-dispersion Echelle optics at the China University of Geosciences, Beijing. Loss on ignition was determined by placing 1 g of sample in a furnace at 1000 °C for several hours, cooling the sample in a desiccator, and then reweighing the sample. The analytic uncertainties for the major elements were less than 5%. Trace element analyses were performed using an Agilent-7500a inductively coupled plasma–mass spectrometer at the China University of Geosciences, Beijing. The rock reference materials AGV-2 (USGS) and GSR-3

(National Geological Standard Reference Materials of China) were used to monitor analytic accuracy and precision. Analytic accuracy, as indicated by the relative difference between the measured and recommended values, was better than 5% for most of the elements. The results of the analyses of the international standards (AGV-2 and GSR-3) were in good agreement with their accepted values (Govindaraju 1994).

3.3. Zircon Hf isotope analyses

Hf isotope measurements were performed on the same spots or the same age domains that had been used for age determinations of the concordant grains, as guided by CL images. In situ zircon Hf isotope analyses were conducted using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany), coupled with a Geolas 2005 excimer ArF laser ablation system (193 nm) that was hosted at the state Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences in Wuhan. We used a simple Y junction downstream from the sample cell to add small amounts of nitrogen (4 ml min^{-1}) to the argon makeup gas flow (Hu et al., 2008a,b). Compared with the standard arrangement, the addition of nitrogen in combination with the use of a newly designed X skimmer cone and Jet sample cone in Neptune Plus, improved the signal intensities of Hf, Yb, and Lu by factors of 5.3, 4.0, and 2.4, respectively. All data were acquired on zircon in single spot ablation mode with a spot size of $44 \text{ }\mu\text{m}$. Each measurement consisted of 20 s of acquisition of the background signal followed by 50 s of acquisition of the ablation signal. For details of

the operating conditions for the laser ablation system and the MC–ICP–MS instrument, as well as the analytical method, see Hu et al. (2012). Present-day chondritic ratios of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282772$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0332$ (Blichert-Toft and Albarède, 1997) were used to calculate $\varepsilon\text{Hf}(t)$ values, and Hf model ages were calculated using the methods of Griffin et al. (2000).

4 Results

4.1 Zircon U–Pb geochronology

The results of zircon U–Pb LA–ICP–MS analyses are summarized in Supplementary Table 1. The five granitoid samples (DT14, DT15, DT17, DT18, and DT30) contain numerous inherited zircons that yield the youngest ages of 156–166, 156–156, 151–161, 157–172, and 164–174 Ma, respectively. Those Middle–Late Jurassic zircon grains are typically euhedral–subhedral, show clear oscillatory zoning, and have lengths of 50–200 μm and length-to-width ratios of 1:1 to 3:1 (Fig. 2). The zircons have Th contents of 72–248 ppm and U contents of 128–1232 ppm, with Th/U ratios of 0.10–0.76, which is consistent with a magmatic origin (Hoskin and Schaltegger, 2003). These results are consistent with the mean square weighted deviation (MSWD) ages of: 160.2 ± 1.5 Ma (sample DT14; $n = 3$; MSWD = 0.019; Fig. 2a), 159.5 ± 1.2 Ma (DT15; $n = 4$; MSWD = 0.002; Fig. 2b), 156.1 ± 1.2 Ma (DT17; $n = 11$; MSWD = 0.066; Fig. 2c), 164.6 ± 2.9 Ma (DT18; $n = 8$; MSWD = 0.53; Fig. 2d), and 168.9 ± 1.7 Ma (DT30; $n = 9$; MSWD = 0.065; Fig. 2e), respectively. These zircon age data indicate that the Labuco granitoids formed during the Middle–Late Jurassic.

The five samples of Middle–Late Jurassic intermediate–felsic intrusions contain inherited zircons that yield distinctly older ages than the magmatic zircons (Fig. 2f). This age range is roughly consistent with that of detrital zircons from the SQ (Pullen et al. 2011), indicating the intrusive rocks originated from the SQ crust.

4.2 Whole-rock geochemical data

The whole-rock geochemical data for the samples investigated in this paper are in Supplementary Table 2. On the basis of their petrology and geochemistry, the samples are classified into two types: low-Sr/Y granitoids (LSG) with Sr/Y ratios of 17–39, and high-Sr/Y granitoids (HSG) with Sr/Y ratios of 64–75.

4.2.1 LSG

The LSG ($n = 36$) have variable contents of SiO_2 (55.0–68.3 wt.%), TiO_2 (0.51–1.57 wt.%), and Al_2O_3 (15.4–19.0 wt.%), and have relatively high MgO contents of 1.20–4.09 wt.%, with Mg# varying from 43 to 64. On the total alkali–silica diagram (Fig. 3a), the samples plot in the fields of gabbroic diorite, diorite, and granodiorite. On the K_2O vs. SiO_2 diagram for subalkaline rocks (Fig. 3b), the LSG plot in the high-K calc-alkaline series and the shoshonite series fields, with $\text{K}_2\text{O}/\text{Na}_2\text{O}$ values of 0.91 to 1.45. According to Fig. 3c, the LSG samples are metaluminous to peraluminous, with an aluminium saturation index (A/CNK) of 0.94–1.26. The differentiation index (DI) of the LSG samples ranges from 57 to 79 (Fig. 3d).

Chondrite-normalized rare earth element (REE) patterns (Fig. 4a) slope towards

the right and show obvious fractionation between the light REEs (LREE) and heavy REEs (HREE), with $(\text{La/Yb})_N$ ratios ranging from 9.22 to 29.5. The samples show weak negative Eu anomalies ($\text{Eu/Eu}^* = 0.83\text{--}0.94$) (Fig. 3d). On primitive-mantle-normalized variation diagrams (Fig. 4b), the samples show a strong enrichment in large-ion lithophile elements (LILEs) (e.g., Rb, Th, U, and K), pronounced negative Nb, Ta, and Ti anomalies, and positive Pb anomalies.

4.2.2 HSG

HSG ($n = 6$) are characterized by high SiO_2 contents (72.4–73.6 wt.%) and relatively low TiO_2 (0.14–0.22 wt.%), Al_2O_3 (14.98–15.59 wt.%), MgO (0.23–0.44 wt.%), and low Mg# values (33–38). The HSG are high-K calc-alkaline series granites with a $\text{K}_2\text{O/Na}_2\text{O}$ ratio of 1.04–1.18 (Fig. 3a,b), and are peraluminous with A/CNK ratios of 1.04–1.18 (Fig. 3c). The HSG also have a high DI values of 85–88 (Fig. 3d).

Chondrite-normalised REE patterns (Fig. 4c) show obvious fractionation between LREE and HREE, with $(\text{La/Yb})_N$ ratios of 57–76 and a weak positive Eu anomaly ($\text{Eu/Eu}^* = 1.02\text{--}1.14$) (Fig. 3d). On primitive-mantle-normalized trace element diagrams (Fig. 4d) the samples also show a strong depletion in high field strength elements (HFSE) (e.g., Nb, Ta, and Ti) when compared with LILEs (e.g., Rb, Th, and U).

4.3 Zircon Hf isotope data

The zircon Hf-isotope data are presented in Supplementary Table 3 and shown in Fig.

5. The zircon $\epsilon\text{Hf}(t)$ values of the samples are as follows: -3.75 to -2.09 (DT14); -4.23 to -0.63 (DT15); -3.86 to -3.12 (DT17); -7.28 to -0.59 (DT18); and -3.52 to -1.71 (DT30). The Hf crustal model ages (TDMC) are 1.19–1.28, 1.11–1.31, 1.25–1.29, 1.11–1.48 and 1.18–1.28 Ga, respectively.

5 Discussion

5.1. Sample classification

There have been approximately 20 different classification schemes proposed for granites since the 1970s (e.g., Chappell, 1999; Chappell and White, 1974). Among these, a widely used classification scheme is that of Chappell and White (1974), which subdivides granites into I-type and S-type, although there are also A-type (alkaline, anhydrous, and anorogenic) and M-type (mantle-like) granites, which are essentially subcategories of the I-type.

Previous studies that reported whole-rock geochemical data from SQ granitoids (Li et al., 2014a,b; Liu et al., 2014; Zhang et al., 2011) divided the Middle–Late Jurassic intermediate–felsic intrusive rocks into two types: normal calc-alkaline I-type granitoids (NIG), highly fractionated I-type granitoids (HFIG). Adakitic granitoids occur in the Renaco area of the SQ (Hao et al., 2016). According to these studies, the NIG are characterized by varying A/CNK, low $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$, high contents of HFSE. In contrast, the HFIG are characterized by high SiO_2 , DI, $(\text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$, TFeO/MgO, HFSE, and pronounced negative Eu anomalies (Li et al., 2014b; Liu et al., 2014). The adakitic granodiorites in the Renaco area are characterized by high Sr,

and low Y and Yb concentrations, and high Sr/Y ratios, suggesting a geochemical affinity to adakitic granites (Hao et al., 2016).

The LSG have varying SiO₂ content and A/CNK ratios, and high MgO and Mg#. The majority of the LSG have relatively low Zr + Nb + Y + Ce contents (282–406 ppm) and a low 10,000 × Ga/Al value (0.97–3.00) (Fig. 6a). With increasing SiO₂, P₂O₅ decreases and Pb increases (Fig. 6b,c), which is an important criterion for distinguishing I-type granites from S-type granites (Chappell and White, 1992). In addition, the LSG also show an increase in Th with increasing Rb, which is also typical of the I-type granite evolution trend (Fig. 6d). As the geochemical characteristics of the LSG are consistent with those of the NIG (Li et al., 2014a, b; Liu et al., 2014; Zhang et al., 2011), the LSG are classified as normal calc-alkaline I-type granitoids (Chappell, 1999; Whalen et al., 1987).

The HSG exhibit low A/CNK ratios, MgO contents, Mg# values, Zr + Nb + Y + Ce contents (122–205 ppm), and 10,000 × Ga/Al values (2.10–2.40) (Fig. 6a). In contrast to both the NIG and HFIG, however, the HSG do not have a negative Eu anomaly and have relatively low HREE abundance (Fig. 4c) and high Sr/Y (63.8–74.7) ratios, indicating an adakitic affinity. As the HSG plot in the adakite fields on trace element discrimination diagrams (e.g., Fig. 6e,f) and are geochemically consistent with the adakitic granodiorites in the Renaco area (Hao et al., 2016), we classify the HSG as adakitic I-type granitoids.

5.2 Constrains on magma sources

Recent studies have reported that the NIG were generated by partial melting of ancient mafic lower crust, with varying contributions from mantle-derived components, whereas the HFIG were generated from NIG magmas by low-pressure fractional crystallization of plagioclase and/or K-feldspar in shallow magma chambers (Li et al., 2014a,b; Liu et al., 2014; Zhang et al., 2011). It has also been suggested that the adakitic granodiorites were derived from thickened lower crust of the SQ (Hao et al., 2016).

5.2.1 LSG

Intermediate–felsic calc-alkaline, I-type granitoids are usually generated by either partial melting of mafic–intermediate meta-igneous lower crust (Chappell and White, 2001; Petford and Atherton, 1996), or by advanced assimilation-fractional crystallization of mantle-derived basaltic parental magmas (Grove et al., 1997). The latter process, however, is not proposed for the LSG, because: (1) the abundances of incompatible trace elements, such as LREE, in the melt should increase with progressive fractional crystallization of mafic magmas; and (2) if relatively recent mantle-derived components played an important role in the origin of the LSG, then the Hf crustal model ages should be younger and have a larger variation than the small range of Paleoproterozoic Hf crustal model ages measured in our samples. That being said, the LSG isotopic and geochemical data indicate that small amounts of relatively recent mantle components might have been assimilated by the granitic melts.

Experimental studies show that dehydration-melting of hydrous mafic or

intermediate meta-igneous lower crust can produce granitic melts (Wolf and Wyllie, 1994). Dehydration melting of tholeiitic amphibolites may also produce melts of intermediate–felsic composition and a granulitic restite at 8–12 kbar, and a garnet-granulite to eclogitic restite at 12–32 kbar (Rapp and Watson, 1995); the resultant melts are usually low in K_2O and have a high Na_2O/K_2O ratio of >1 . As the HREE contents of the LSG are not depleted, garnet could not have been stable in the melt region and so the LSG melts could not have formed at high pressure. Furthermore, as most of the LSG samples are enriched in K_2O and have K_2O/Na_2O ratios of >1 , their melts were probably not derived from a tholeiitic amphibolite source. Dehydration melting of medium-to-high K basaltic compositions can produce K-rich melts with $Na_2O/K_2O < 1$ at $SiO_2 > 65$ wt.% (Sisson et al., 2005). Furthermore, the negative zircon $\epsilon Hf(t)$ values (-7.28 to -0.59) and the Paleoproterozoic Hf crustal model age (TDMC) (1.11–1.48 Ga) indicate that these rocks were generated by the partial melting of ancient lower crust. Pronounced depletions in P, Nb, Ta, and Ti (Fig. 4b) indicate advanced fractional crystallization during the formation of the LSG, probably by the fractionation of apatite and Ti-bearing phases (e.g., ilmenite and/or rutile), respectively.

In summary, we propose that LSG magmas were generated by partial melting of ancient mafic lower SQ crust and that the magma subsequently underwent varying degrees of fractional crystallization of apatite, ilmenite, and/or rutile.

5.2.2 HSG

The high Sr/Y and $(La/Yb)_N$ ratios of the HSG indicate an adakitic affinity, similar to

the adakitic granodiorites in the Renaco area (Hao et al., 2016). The genesis of adakitic magmas remains in debate, but several hypotheses have been proposed, including: (1) partial melting of an oceanic slab with or without contributions from a mantle wedge (e.g., Defant and Drummond, 1990; Eyuboglu et al., 2011; Rapp et al., 1999; Martin et al., 2005; Zhang et al., 2010); (2) the mixing of felsic and basaltic magmas (e.g., Guo et al., 2007; Streck et al., 2007); (3) partial melting of thickened or delaminated lower crust (e.g., Atherton and Petford, 1993; Chung et al., 2003; Gao et al., 2004; Hou et al., 2004; Li et al., 2015; Wang et al., 2005; Xu et al., 2002); (4) fractional crystallization of parental basaltic magmas with or without crustal assimilation (e.g., Castillo et al., 1999; Macpherson et al., 2006); and (5) partial melting of subducted continental crust (Lai and Qin, 2013; Wang et al., 2008).

The HSG are characterized by high SiO₂, low MgO and Mg#, and similar amounts of K₂O and Na₂O (~3.5–4.0 wt.%), which is in contrast with typical slab-derived adakites (Martin et al., 2005). These geochemical features, in combination with their low Cr (2.81–5.10 ppm, except for one sample with 19.3 ppm) and Ni (1.59–4.01 ppm, except for one sample with 13.3 ppm) contents, indicate an evolved magma source and exclude melt-mantle interaction that commonly occurs when slab-derived melt encounters mantle peridotites in the wedge above a subducting slab (Rapp et al., 1999; Smithies, 2000). Chang (2012) described Late Jurassic adakitic dacites that were generated by partial melting of an oceanic slab, in Renaco, SQ. The adakitic dacites are characterized by low K₂O contents (2.05–2.44 wt. %) and positive $\epsilon_{\text{Hf}}(t)$ values (+1.9 to +7.6), and yield Hf crustal model ages of

643–968 Ma (Fig. 5). As the HSG have high K₂O contents (3.61–4.21 wt. %), negative $\epsilon_{\text{Hf}}(t)$ values (-4.23 to -0.63), and Hf crustal model ages of 1.11–1.31 Ga (Fig. 5), they could not have been derived from an oceanic slab.

Previous studies have indicated that delamination-related adakitic melts generally contain significant proportions of mantle-derived compatible elements (e.g., MgO, CaO, Cr, and Ni) because of contamination by mantle peridotite (Rapp et al., 1999; Xu et al., 2002). As the HSG are not enriched in such compatible elements, their melts could not have been produced by the partial melting of delaminated lower crust. The high SiO₂ content, combined with the absence of mafic xenoliths in the HSG, suggest that mixing between felsic and basaltic magmas is also not a feasible mechanism for the formation of these magmas. This view is consistent with the lack of any significant volumes of coeval basalt, and the lack of intermediate or felsic lavas with high SiO₂ contents in the SQ, which would be expected if the HSG did form by magma mixing. Furthermore, as there is no crystallization differentiation trend between the LSG and HSG in Fig. 7, the HSG could not have formed by fractional crystallization of basaltic magmas. Recent studies have suggested that the SQ was located in an arc setting, related to oceanic subduction, in the Middle–Late Jurassic (Section 5.4). The absence of contemporaneous continental collision effectively rules out the possibility that melting of subducted continental crust led to the formation of the HSG.

Compared with the LSG, the HSG are more evolved, as shown on Harker diagrams of selected major and trace elements (Fig. 8). The HSG also have higher

Sr/Y, (La/Yb)_N and (Ga/Yb)_N ratios than do the LSG (Fig. 8j-l). Although high Sr/Y and (La/Yb)_N are considered to be indicative of adakites (Defant and Drummond, 1990), there are multiple ways to produce these two high ratios, including: melting or contamination of the source region with high Sr/Y and (La/Yb)_N magma; fractionation of mafic minerals during magmatic evolution; high-pressure fractionation of garnet from a mafic magma; and interaction between intermediate–acidic melts and mantle peridotite (Moyen, 2009). As discussed above, it is unlikely that the HSG were derived from a mixture of felsic and basaltic magmas. Furthermore, as the HSG and LSG have the same source but different Sr/Y and (La/Yb)_N ratios, it is unlikely that their source was contaminated with high-Sr/Y and high-(La/Yb)_N magmas.

Garnet can strongly fractionate the HREE from the middle REE (MREE) and LREE, and clinopyroxene and amphibole preferentially incorporate MREE over HREE. Fractionation of clinopyroxene, amphibole, and garnet will increase the (La/Yb)_N ratio of evolved melts, but fractionation of garnet alone will increase the Gd/Yb ratio (Huang and He, 2010 and references therein). The high (Gd/Yb)_N ratios of the HSG are therefore indicative of the partial melting of garnet-bearing lower crustal material (Fig. 8l).

Experimental results indicate that the negative Nb–Ta anomalies in adakitic rocks can only be explained by the presence of residual rutile (Nair and Chacko, 2008; Xiong, 2006; Xiong et al., 2005). The presence of residual rutile also explains the negative Ti anomalies (Prowatke and Klemme, 2005). Therefore, in addition to garnet, rutile is a key residual mineral in constraining magma sources (e.g., Nair and Chacko,

2008; Xiong, 2006; Xiong et al., 2005). Experimental studies indicate that garnet is stable at pressures above ~1.0 GPa (Green, 1982), and rutile at pressures above ~1.5 GPa (e.g., Xiong et al., 2005). In summary, we suggest that the HSG formed by partial melting of thickened, garnet-bearing lower crust, indicating that the source region was >50 km deep and at pressures of ~1.5 GPa (Nair and Chacko, 2008; Sen and Dunn, 1994; Xiong et al., 2005). This view is supported by the distribution of HSG data in the field of thickened-lower-crust-derived adakites in a discrimination diagram (Fig. 6b, 8c, d, k and m–o), with (La/Yb)_N ratios indicative of a source region in excess of 50 km deep (Fig. 8k).

5.3 Two types of crystal differentiation

Large amounts of geochronologic and geochemical data have been published for the coeval intermediate–felsic intrusions of the SQ (e.g., Hao et al., 2016; Li et al., 2014a,b; Liu et al., 2014; Zhang et al., 2010). We have compiled all of the existing data (except data for enclaves and dikes) for the Larelaxin, Caima, Qingcaoshan and Renaco intrusions. As described above, the NIG are characterized by low SiO₂ contents, and distinctive major and trace element (e.g., P₂O₅, Sr, Ba, Cr, and Ni) systematics. In contrast, the HFIG are characterized by high SiO₂ contents and DI, low Mg#, and marked depletions in Ba, Sr, P, and Eu. Our data show that the LSG have similar geochemical and Hf isotope characteristics to the NIG, which were generated by partial melting of ancient mafic lower crust. Our data also show that the HSG (include AG) and HFIG have similarly high SiO₂ and DI, low Mg#, low Cr and

Ni contents and Hf isotope composition; however, they differ in their Eu anomalies, and Sr/Y, (La/Yb)_N, and (Gd/Yb)_N ratios (Fig. 8j–l). Taken together, these results indicate that although the HSG and HFIG were derived from the same lower-crustal source region, their melts underwent different types of fractional crystallization, as outlined below.

5.3.1 Type 1: High-pressure differentiation

As discussed above, both the LSG and the HSG were generated by partial melting of ancient mafic lower crust, and the HSG are more evolved than the LSG. Previous studies have shown that high-pressure fractionation of garnet from a hydrous basaltic magma can form adakitic melts, resulting in a systematic decrease in Al₂O₃ and La, and an increase in Sr/Y with increasing SiO₂ content (Macpherson et al., 2006). As the major and trace element systematics of the LSG and the HSG exhibit negative trends in nearly all Harker diagrams (Fig. 8), high-pressure fractional crystallization must have played a role during their magmatic evolution. Similarly, the primitive-mantle-normalized and chondrite-normalized trace element and REE patterns of the rocks show a progressive depletion with increasing SiO₂ content, which is also indicative of high-pressure fractional crystallization (Fig. 4c).

Of note, the HSG have higher SiO₂ contents than the LSG. The results of melting experiments indicate that a slight increase in the SiO₂ content of the parent material does not produce melts with a higher SiO₂ content under moderate pressures (Huang and He, 2010 and references therein). High SiO₂ contents are generally controlled by the temperature and pressure of the source region because these parameters control

the mineralogy of melt residues. Under high pressure and low temperature, garnet, which has a low SiO₂ content of ~40%, is the dominant solid phase. With increasing temperature and decreasing pressure, plagioclase, which has a SiO₂ content of >50%, replaces garnet as the dominant phase (Huang and He, 2010 and references therein). These observations are consistent with our contention that garnet remained in the HSG source region (and that differentiation occurred under high-P, low-T conditions), because subduction of cold oceanic crust would have decreased the temperature of the paleo-subduction zone (thus maintaining conditions within the garnet stability field).

We suggest that the geochemical systematics of the LSG and HSG can be explained by a gradual deepening of the magma source region and high-pressure differentiation of garnet beneath a thickened lower crust (>50 km). This interpretation of magma origin and petrogenesis is supported by petrological and geochemical data from the adakitic granodiorites in the Renaco area of the SQ (Hao et al., 2016).

5.3.2 Type 2: Low-pressure fractional crystallization

The La contents of the NIG and HFIG increase whereas their Sr/Y ratios decrease with increasing SiO₂ content (Fig. 8i,j). This is in contrast to the expected effects of high-pressure garnet differentiation, and indicates low-pressure fractional crystallization (Castillo et al., 1999). In chondrite-normalized REE diagrams (Fig. 4a), the HFIG are enriched relative to the NIG, which suggests low-pressure fractional crystallization of plagioclase and/or K-feldspar, rather than garnet. The low Sr and Ba contents of the HFIG are also consistent with this inference, and these results, combined with previous findings (Li et al., 2014b; Liu et al., 2014), suggest that the

HFIG magmas underwent significant fractional crystallization of plagioclase and/or K-feldspar. Given the positive trend between K_2O and SiO_2 in Fig. 3b, we suggest that plagioclase was the principal fractionating phase and that the major and trace element systematics of the HFIG were the product of low-pressure fractional crystallization of plagioclase at shallow depths (Li et al., 2014a,b; Liu et al., 2014).

5.4 Tectonic setting

Recent studies have shown that Middle–Late Jurassic magmatic rocks in the SQ are compositionally diverse. Slab-derived adakites that yield zircon U–Pb ages of 154 Ma have been found in the Renaco area (Chang, 2012), and coeval high-Nb gabbroic enclaves, derived from partial melting of mantle wedge peridotite, have been found in the Larelaxin of the SQ (Li et al., 2014b). These rocks, together with the ancient lower-crust-derived I-type granitoids and adakitic granodiorites (e.g., Hao et al., 2016; Li et al., 2014a,b), indicate that the Middle–Late Jurassic magmatism involved interaction between the subducting oceanic slab, the mantle wedge, and the lower SQ crust. Furthermore, recent study of Lower and Middle Jurassic strata in the SQ suggests that the Lower Jurassic Sewa Formation was deposited during the opening of the Bangong–Nujiang Ocean, whereas the Middle Jurassic Shaqiaomu Formation was deposited during closure of the ocean (Chen, 2013). According to recent work, the Middle–Late Jurassic intrusive bodies provide the oldest evidence of subduction zone magmatism in the SQ. Furthermore, the paleo-continental arc was active until the Early Cretaceous, at which time much larger-scale magmatism was triggered by slab

breakoff or convective removal of the lithospheric mantle after collision between the Lhasa and Qiangtang terranes (e.g., Chen et al., 2014,2015; Wu et al., 2014,2015; Xu et al., 2016; Yan et al., 2016; Zhu et al., 2011,2013; Zhang et al., 2014). We therefore propose that the Middle–Late Jurassic magmatism along the southern margin of the SQ resulted from the northward subduction of the Bangong–Nuijiang Ocean lithosphere beneath the SQ.

5.5 Across-arc variations in magma chemistry: Implications for tectonic shortening and crustal thickening in subduction zones

In terms of an across-arc section of magma chemistry in the SQ from Labuco to Linqunshan (i.e., from south to north), most of the LSG are located in the south near Labuco and were emplaced in the BNSZ, whilst the HSG are located along the southern margin of the SQ, and the NIG and HFIG are located near Qingcaoshan and Linqunshan; i.e., towards the center of the SQ and far from the subduction zone (Fig 1b). This distribution, together with the subduction zone origin of the Middle–Late Jurassic magmatic rocks and the magmatic evolution between the LSG and the HSG, indicates that the geochemical systematics of the LSG and HSG reflect an abrupt thickening of crust at the active continental margin of a subduction zone. However, most of the intrusive rocks in this region experienced low-pressure fractional crystallization in shallow magma chambers, indicating the central SQ had a relatively thin crust. As discussed above, however, we suggest that the geochemical variations in the LSG, HSG, NIG and HFIG reflect a change in thickness of the continental crust

characterized by thickening at an active continental margin and crustal thinning towards the center of the SQ. Figure 9 summarises our petrogenetic model that explains the compositional diversity and geographic distribution of Middle–Late Jurassic magmatism in the SQ.

The Andes plateau is characterized by one of the thickest continental crusts on Earth, reaching in excess of 70 km (Giambiagi et al., 2012; Mcquarrie et al., 2005; Wigger et al., 1994; Zandt et al., 1994). Thickening of the Andean crust is believed to have resulted from tectonic shortening in the Neogene during subduction of the Nazca oceanic plate beneath the South American continental plate (Sempere et al., 1990; Sheffels, 1990). These observations lead us to propose that tectonic shortening is an important mechanism causing crustal thickening in subduction zones in general. As discussed above, the northward subduction of the Bangong–Nujiang Ocean lithosphere beneath the SQ occurred during the Middle–Late Jurassic. Paleo-magnetic and structural studies indicate that the Qiangtang terrane was shortened in the north–south direction by ~1000 km since the Middle Jurassic (Ren et al., 2013; Liu, 2014a,b). Taking these results together, we propose that the extrusion of SQ caused by the subduction of the Bangong–Nujiang Ocean lithosphere caused tectonic shortening and thickening of continental crust at the active continental margin during the Middle–Late Jurassic, as indicated by the occurrence of adakitic I-type granitoids (HSG) (Fig. 9; the blue line shows the relationship between crust thickness and distance from the subduction zone). According to the results of previous studies of the magmatic rocks of the SQ, we estimate pressure curves for the source magma in the

subduction zone. We suggest that the margin of the overlying continental crust is represented by a sharp crustal thickening, accompanied by a marked increase in pressure in the source magma, thereby resulting in the formation of the adakitic rocks. However, farther away from the subduction zone the continental crust is not significantly thickened within the intra-plate region, leading to a gradual decrease in pressure and the formation of highly fractionated rocks (Fig. 9).

Our results show that the subduction of an oceanic plate changes the thickness of the continental crust and that variations in the geochemistry of arc magmatism, particularly adakitic magmas, can be used to infer changes in crustal thickness and the geometry of subduction zones. We consider that similar variations in magma geochemistry to that found in the SQ could be a common phenomenon in settings where tectonic shortening and crustal thickening have occurred as a result of subduction zone processes. In summary, across-arc variations in magma geochemistry provide important clues to the nature of tectonic shortening, crustal thickening, and the geometry of modern and ancient subduction zones.

6 Conclusions

1. The Labuco plutons of the southern margin of the SQ were emplaced during the Middle–Late Jurassic (169–156 Ma).
2. The samples from Labuco can be divided into LSG and HSG based on their major and trace elements. The geochemical differences between the LSG and the HSG resulted from their different magma-source depths within the ancient mafic lower crust of the SQ. The LSG were generated by partial melting of ancient mafic lower

crust, whereas the HSG were derived from thickened lower crust.

3. Our results, together with existing data, indicate that tectonic shortening and crustal thickening began when the Bangong–Nujiang Ocean lithosphere subducted northwards beneath the SQ during the Middle–Late Jurassic.

4. Across-arc variations in magma geochemistry in active and ancient continental arcs are important for reconstructing tectonic shortening, crustal thickening, and the geometry of subduction zones.

Acknowledgments

We thank Qiang Wang and an anonymous reviewer for constructive and helpful reviews, and Associate Editor Zeming Zhang for careful editorial handling. This research was funded by the National Science Foundation of China (Grant No. 41272240, 41402190), a China Geological Survey project (Grant No. 1212011221093, 12120113036700). Supporting data are included as three Supplementary Tables in a CSV file.

References

- Atherton, M.P., Petford, N., 1993. Generation of sodium-rich magmas from newly underplated basaltic crust. *Nature* 362, 144–146.
- Blichert-Toft, J., Albarède, F., 1997. The Lu–Hf geochemistry of chondrites and the evolution of the mantle–crust system. *Earth Planetary Science Letters* 148, 243–258.
- Castillo, P.R., Janney, P.E., Solidum, R.U., 1999. Petrology and geochemistry of

- Camiguin island, southern Philippines: insights to the source of adakites and other lavas in a complex arc setting. *Contributions to Mineralogy and Petrology* 134, 33–51.
- Cao, M.J., Qin, K.Z., Li, G.M., Li, J.X., Zhao, J.X., Evans, N.J., Hollings, P., 2016. Tectono-magmatic evolution of Late Jurassic to Early Cretaceous granitoids in the west central Lhasa subterrane, Tibet. *Gondwana Research*.
- Chang, Q. S., 2012. Petrology, Geochronology and Geochemistry of Rena–Co Volcanic Rocks along Southern Margin of Qiangtang Terrane, Tibetan Plateau. A Dissertation Submitted to China University of Geosciences for Master Degree (in Chinese with English abstract).
- Chappell, B.W., 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. *Lithos* 46, 535–551.
- Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. *Pacific Geology* 8:173–174
- Chappell, B.W., White, A.J.R., 1992. I- and S-type granites in the Lachlan Fold Belt. *Trans. R. Soc. Earth & Environmental Science Transactions of the Royal Society of Edinburgh* 83, 1 – 26.
- Chappell, B.W., White, A.J.R., 2001. Two contrasting granite types: 25 years later. *Australian Journal of Earth Sciences* 48, 489–499.
- Chen, S.S., Shi, R.D., Gong, X.H., Liu, D.L., Huang, Q.S., Yi, G.D., Wu, K., Zou, H.B., 2015. A syn-collisional model for Early Cretaceous magmatism in the northern and central Lhasa subterrane. *Gondwana Research*.

- Chen, Y., Zhu, D.C., Zhao, Z.D., Meng, F.Y., Wang, Q., Santosh, M., Wang, L.Q., Dong, G.C., Mo, X.X., 2014. Slab breakoff triggered ca. 113 Ma magmatism around Xainza area of the Lhasa Terrane, Tibet. *Gondwana Research* 26, 449–463.
- Chen, Y.F., 2013. Depositional sequences and tectonic deformation characteristics of Late Triassic-Middle Jurassic stratigraphy in Rena-Co regions, Gerze county, Tibet. A Dissertation Submitted to China University of Geosciences for Doctoral Degree (in Chinese with English abstract).
- Chung, S.L., Liu, D.Y., Ji, J.Q., Chu, M.F., Lee, H.Y., Wen, D.J., Lo, C.H., Lee, T.Y., Qian, Q., Zhang, Q., 2003. Adakites from continental collision zones: melting of thickened lower crust beneath southern Tibet. *Geology* 31, 1021–1024.
- Chung, S.L., Chu, M.F., Ji, J.Q., O'Reilly, S.Y., Pearson, N.J., Liu, D.Y., Lee, T.Y., Lo, C.H., 2009. The nature and timing of crustal thickening in Southern Tibet: geochemical and zircon Hf isotopic constraints from postcollisional adakites. *Tectonophysics* 477, 36–48.
- Defant, M.J., Drummond, M.S., 1990. Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* 347, 662–665.
- Eyuboglu, Y., Chung, S.L., Santosh, M., Dudas, F.O., Akaryali, E., 2011. Transition from shoshonitic to adakitic magmatism in the eastern Pontides, NE Turkey: Implications for slab window melting. *Gondwana Research* 19, 413–429.
- Gao, S., Rudnick, R.L., Yuan, H.L., Liu, X.M., Liu, Y.S., Xu, W.L., Ling, W.L., Ayers, J., Wang, X.C., Wang, Q.H., 2004. Recycling lower continental crust in the North

- China craton. *Nature* 432, 892–897.
- Giambiagi, L., Mescua, J., Bechis, F., Tassara, A., Hoke, G., 2012. Thrust belts of the southern central andes: along-strike variations in shortening, topography, crustal geometry, and denudation. *Geological Society of America Bulletin* 124(7-8), 1339–1351.
- Govindaraju, K., 1994. Compilation of working values and sample description for 383 geostandards. *Geostandards Newsletter* 18, 1–158.
- Green, T.H., 1982. Anatexis of mafic crust and high pressure crystallization of andesite. In: Thorpe, R.S. (Ed.), *Andesites: Orogenic Andesites and Related Rocks*. John Wiley and Sons, New York, pp. 465–487.
- Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., Achterbergh, E., Reilly, S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM-MC-ICPMS analysis of zircon megacrysts in kimberlites. *Geochimica et Cosmochimica Acta* 64, 133–147.
- Grove, T.L., Donnelly-Nolan, J.M., Housh, T., 1997. Magmatic processes that generated the rhyolite of Glass Mountain, Medicine Lake volcano, N. California. *Contributions to Mineralogy and Petrology* 127, 205–223.
- Guo, F., Nakamuru, E., Fan, W., Kobayoshi, K., Li, C., 2007. Generation of palaeocene adakitic andesites by magma mixing; yanji area, ne china. *Journal of Petrology* 48, 4, 661–692.
- Hao, L.L., Wang, Q., Wyman, D.A., Ou, Q., Dan, W., Jiang, Z.Q., Wu, F.Y., Yang, J.H., Long, X.p., Li, J., 2016. Underplating of basaltic magmas and crustal

- growth in a continental arc: Evidence from Late Mesozoic intermediate-felsic intrusive rocks in southern Qiangtang, central Tibet. *Lithos* 245:223–242.
- Hu, Z.C., Gao, S., Liu, Y.S., Hu, S.H., Chen, H.H., Yuan, H.L., 2008b. Signal enhancement in laser ablation ICP-MS by addition of nitrogen in the central channel gas. *Journal of Analytical Atomic Spectrometry* 23, 1093–1101.
- Hu, Z.C., Liu, Y.S., Gao, S., Hu, S.H., Dietiker, R., Günther, D., 2008a. A local aerosol extraction strategy for the determination of the aerosol composition in laser ablation inductively coupled plasma mass spectrometry. *Journal of Analytical Atomic Spectrometry* 23, 1192–1203.
- Hu, Z.C., Liu, Y.S., Gao, S., Liu, W.G., Zhang, W., Tong, X.R., Lin, L., Zong, K.Q., Li, M., Chen, H.H., Zhou, L., Yang, L., 2012. Improved in situ Hf isotope ratio analysis of zircon using newly designed X skimmer cone and jet sample cone in combination with the addition of nitrogen by laser ablation multiple collector ICP-MS. *Journal of Analytical Atomic Spectrometry* 27, 1391–1399.
- Hoskin, P.W.O., Schaltegger, U., 2003. The composition of zircon and igneous and metamorphic petrogenesis. *Reviews in Mineralogy and Geochemistry* 53, 27–62.
- Hou, Z.Q., Gao, Y.F., Qu, X.M., Rui, Z.Y., Mo, X.X., 2004. Origin of adakitic intrusives generated during mid-Miocene east-west extension in southern Tibet. *Earth and Planetary Science Letters* 220, 139–155.
- Huang, F. and He, Y., 2010. Partial melting of the dry mafic continental crust: Implications for petrogenesis of C-type adakites. *Chinese Science Bulletin* 55, 22, 2428–2439.

- Kapp, P., Murphy, M.A., Yin, A., Harrison, T.M., Ding, L., Guo, J.H., 2003. Mesozoic and Cenozoic tectonic evolution of the Shiquanhe area of western Tibet. *Tectonics* 22, 1029.
- Kapp, P., Yin, A., Harrison, T.M., Ding, L., 2005. Cretaceous-Tertiary shortening, basin development, and volcanism in central Tibet. *Geological Society of America Bulletin* 117, 865–878.
- Lai, S.C., Qin, J.F., 2013. Adakitic rocks derived from the partial melting of subducted continental crust: evidence from the eocene volcanic rocks in the northern qiangtang block. *Gondwana Research*, 23(2), 812–824.
- Li, J.X., Qin, K.Z., Li, G.M., Richards, J.P., Zhao, J.X., Cao, M.J., 2014a. Geochronology, geochemistry, and zircon Hf isotopic compositions of Mesozoic intermediate–felsic intrusions in central Tibet: petrogenetic and tectonic implications. *Lithos* 198, 77–91.
- Li, S.M., Zhu, D.C., Wang, Q., Zhao, Z.D., Sui, Q.L., Liu, S.A., Liu, D., Mo, X.X., 2014b. Northward subduction of Bangong–Nujiang Tethys: Insight from Late Jurassic intrusive rocks from Bangong Tso in western Tibet. *Lithos* 205, 284–297.
- Li, Y.L., Li, X.H., Wang, C.S., Wei, Y.S., Chen, X., He, J., Xu, M., Hou, Y.L., 2015. Miocene adakitic intrusions in the Zhongba terrane: Implications for the origin and geochemical variations of post-collisional adakitic rocks in southern Tibet. *Gondwana Research*.
- Liu, D.L., Huang, Q.S., Fan, S.Q., Zhang, L.Y., Shi, R.D., Ding, L., 2014. Subduction

- of the Bangong–Nujiang Ocean: constraints from granites in the Bangong Co area, Tibet. *Geological Journal* 49, 188–206.
- Liu, J.Y., 2014a. Research of the characteristics of structural deformation of Early-Middle Jurassic in Renacuo area, Gaize, Tibet. A Dissertation Submitted to China University of Geosciences for Master Degree (in Chinese with English abstract).
- Liu, D.L., Shi, R.D., Ding, L., Huang, Q.S., Zhang, X.R., Yue, Y.H., Zhang, L.Y., 2015. Zircon U–Pb age and Hf isotopic compositions of Mesozoic granitoids in southern Qiangtang, Tibet: Implications for the subduction of the Bangong–Nujiang Tethyan Ocean. *Gondwana Research* <http://dx.doi.org/10.1016/j.gr.2015.04.007>
- Liu, Z.B., 2014b. Upper Palaeozoic –Mesozoic structural characteristics and tectonic evolution of the west part of South Qiangtang basin. A Dissertation Submitted to China University of Geosciences for Doctoral Degree (in Chinese with English abstract).
- Ludwig, K.R., 2003. Isoplot 3.00: a geochronological toolkit for Microsoft Excel. *Berkeley Geochronology Center Special, Publication* pp. 41–70.
- Macpherson, C.G., Dreher, S.T., Thirwall, M.F., 2006. Adakites without slab melting: high pressure differentiation of island arc magma, Mindanao, the Philippines. *Earth Planetary Science Letters* 243, 581–593.
- Martin, H., Smithies, R.H., Rapp, R., Moyen, J.F., Champion, D., 2005. An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid:

- relationships and some implications for crustal evolution. *Lithos* 79, 1–24.
- Mcquarrie, N., Horton, B. K., Zandt, G., Beck, S., Decelles, P. G. 2005. Lithospheric evolution of the andean fold–thrust belt, bolivia, and the origin of the central andean plateau. *Tectonophysics* 399(1), 15–37.
- Moyen J.F., 2009. High Sr/Y and La/Yb ratios: The meaning of the ‘adakitic signature’. *Lithos* 112: 556–574
- Nair, R., Chacko, T., 2008. Role of oceanic plateaus in the initiation of subduction and origin of continental crust. *Geology* 36, 583–586.
- Petford, N., Atherton, M., 1996. Na-rich partial melts from newly underplated basaltic crust: the Cordillera Blanca Batholith, Peru. *Journal of Petrology* 37, 1491–1521.
- Prowatke, S., Klemme, S., 2005. Effect of melt composition on the partitioning of trace elements between titanite and silicate melt. *Geochimica et Cosmochimica Acta* 69, 695–709.
- Pullen, A., Kapp, P., Gehrels, G.E., Ding, L., Zhang, Q.H., 2011. Metamorphic rocks in central Tibet: lateral variations and implications for crustal structure. *Geological Society of America Bulletin* 123 (3–4), 585–600.
- Rapp, R.P., Shimizu, N., Norman, M.D., Applegate, G.S., 1999. Reaction between slab–derived melts and peridotite in the mantle wedge: experimental constraints at 3.8 GPa. *Chemical Geology* 160, 335–356.
- Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust–mantle recycling. *Journal of Petrology* 36, 891–931.

- Ren, H.D., Yan, M.D., Meng, Q.H., Song, P.H., Fang, X.M., 2013. “E/I” corrected paleomagnetic inclination indicates 1000 km N-S shortening of the Qiangtang terrane since the Middle Jurassic, *Chinese Journal of Geology* 48(2), 543-556.
- Sen, C., Dunn, T., 1994. Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: implications for the origin of adakites, *Contributions to Mineralogy & Petrology* 117 394–409.
- Sempere, T., Herail, G., Oller, J., and Bonhomme, M., 1990. Late Oligocene-early Miocene major tectonic crisis and related basins in Bolivia. *Geology* 18, 946–949.
- Sheffels, B.M., 1990. Lower bound on the amount of crustal shortening in the central Bolivian Andes. *Geology* 18, 812–815.
- Sisson, T.W., Ratajeski, K., Hankins, W.B., Glazner, A.F., 2005. Voluminous granitic magmas from common basaltic sources. *Contributions to Mineralogy & Petrology* 148(6), 635-661.
- Smithies, R.H., 2000. The Archaean tonalite–trondhjemite–granodiorite (TTG) series is not an analogue of Cenozoic adakite. *Earth and Planetary Science Letters* 182(1), 115–125
- Streck, M.J., Leeman, W.P., Chesley, J., 2007. High-magnesian andesite from Mount Shasta: a product of magma mixing and contamination, not a primitive mantle melt. *Geology* 35, 351–354.
- Sun, S.S., McDonough, W.F., 1989. In: Saunders, A.D. (Ed.), *Chemical and Isotope Systematics of Oceanic Basalts: Implications for Mantle Composition and*

- Processes. *Magmatism in ocean Basins*, 42. Geological Society Publication, pp. 313–345.
- Tatsumi, Y., 2005. The subduction factory: how it operates in the evolving Earth. *GSA Today* 15 (7), 4–10.
- Wang, Q., Wyman, D.A., Xu, J.F., Dong, Y.H., Vasconcelos, P.M., Pearson, N., Wan, Y.S., Dong, H., Li, C.F., Yu, Y.S., 2008a. Eocene melting of subducting continental crust and early uplifting of central Tibet: evidence from central-western Qiangtang high-K calcalkaline andesites, dacites and rhyolites. *Earth and Planetary Science Letters* 272, 158–171.
- Wang, Q., McDermott, F., Xu, J.F., Bellon, H., Zhu, Y.t., 2005. Cenozoic K-rich adakitic volcanic rocks in the Hohxil area, northern Tibet: lower-crustal melting in an intracontinental setting. *Geology* 33, 465–468.
- Wang, Q., Xu, J.F., Jian, P., Bao, Z.W., Zhao, Z.H., Li, C.F., Xiong, X.L., Ma, J.L., 2006. Petrogenesis of adakitic porphyries in an extensional tectonic setting, Dexing, South China: implications for the genesis of porphyry copper mineralization. *Journal of Petrology* 47, 119–144.
- Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology* 95, 407–419.
- Wigger, P.J., Schmitz, M., Araneda Manuel, Asch, G., Baldzuhn, S., Giese, P., Heinsohn, W.D., Martinez, E., Ricaldi, E., Rower, P., Viramonte, J., 1994. Variation in the crustal structure of the southern Central Andes deduced from

- seismic refraction investigations. In: Reutter, K.J., Scheuber, E., Wigger, P.J. (Eds.), *Tectonics of Southern Central Andes: Structure and Evolution of an Active Continental Margin*. Springer-Verlag, New York, pp. 23– 48.
- Wolf, M.B., Wyllie, P.J., 1994. Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time. *Contributions to Mineralogy and Petrology* 115, 369–383.
- Wu, H., Li, C., Hu, P.Y., Li, X.K., 2014. Early cretaceous (100-105 Ma) adakitic magmatism in the Dachagou area, northern Lhasa terrane, Tibet: implications for the Bangong-Nujiang Ocean subduction and slab break-off. *International Geology Review* 57(9-10), 1-17.
- Wu, H., Li, C., Xu, M.J., Li, X.K., 2015. Early cretaceous adakitic magmatism in the Dachagou area, northern Lhasa terrane, Tibet: implications for slab roll-back and subsequent slab break-off of the lithosphere of the Bangong–Nujiang Ocean. *Journal of Asian Earth Sciences* 97, 51–66.
- Xiong, X.L., 2006. Trace element evidence for the growth of early continental crust by melting of rutile-bearing hydrous eclogite. *Geology* 34, 945–948.
- Xiong, X.L., Adam, J., Green, T.H., 2005. Rutile stability and rutile/melt HFSE partitioning during partial melting of hydrous basalt: implications for TTG genesis. *Chemical Geology* 218, 339–359.
- Xu, J.F., Shinjio, R., Defant, M.J., Wang, Q., Rapp, R.P., 2002. Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: partial melting of delaminated lower continental crust? *Geology* 12, 1111–1114.

- Xu, W., Li, C., Wang, M., Fan, J.J., Wu, H., Li, X., 2015. Subduction of a spreading ridge within the Bangong Co–Nujiang Tethys Ocean: Evidence from Early Cretaceous mafic dykes in the Duolong porphyry Cu–Au deposit, western Tibet. *Gondwana Research*.
- Yan, M.D., Zhang, D.W., Fan, X.M., Ren, H.D., Zhang, W.L., Zan, J.B., Song, C.H., Zhang, T., 2016. Paleomagnetic data bearing on the Mesozoic deformation of the Qiangtang Block: Implications for the evolution of the Paleo- and Meso-Tethys. *Gondwana Research*.
- Yin, A., Harrison, T.M., 2000. Geologic evolution of the Himalayan–Tibetan orogen. *Annual Review of Earth and Planetary Sciences* 28, 211–280
- Yuan, H.L., Gao, S., Liu, X.M., Li, H.M., Günther, D., Wu, F.Y., 2004. Accurate U–Pb Age and Trace Element Determinations of Zircon by Laser Ablation–Inductively Coupled Plasma Mass Spectrometry. *Geostandards and Geoanalytical Research* 28, 353–370.
- Zandt, G., Velasco, A.A., Beck, S.L., 1994. Composition and thickness of the southern Altiplano crust, Bolivia. *Geology* 22, 1003–1006.
- Zhang, Y.X., 2007. Tectonic evolution of the middle-western Bangong–Nujiang suture, Tibet. A Dissertation Submitted to the Graduate School of The Chinese Academy of Science for Doctoral Degree (in Chinese with English abstract).
- Zhang, Z., Geng, Q.R., Peng, Z.M., Cong, F., Guan, J.L., 2011. Geochemistry and geochronology of the Caima granites in the western part of the Bangong Lake–Nujiang metallogenic zone, Xizang. *Sedimentary Geology and Tethyan*

Geology 31, 86–96 (in Chinese with English abstract).

Zhang, Z.M., Zhao, G.C., Santosh, M., Wang, J.L., Dong, X., Shen, K., 2010. Late Cretaceous charnockite with adakitic affinities from the Gangdese batholith, southeastern Tibet: Evidence for Neo-Tethyan mid-ocean ridge subduction?. Gondwana Research 17(4), 615–631.

Zhang, Z.M., Dong, X., Santosh, M., Zhao, G.C., 2014. Metamorphism and tectonic evolution of the Lhasa terrane, Central Tibet. Gondwana Research 25, 170–189.

Zhu, D.C., Zhao, Z.D., Niu, Y., Mo, X.X., Chung, S.L., Hou, Z.Q., 2011. The Lhasa Terrane: record of a microcontinent and its histories of drift and growth. Earth and Planetary Science Letters 301, 241–255.

Zhu, D.C., Zhao, Z.D., Niu, Y.L., Dilek, Y., Hou, Z.Q., Mo, X.X., 2013. The origin and pre-Cenozoic evolution of the Tibetan Plateau. Gondwana Research 23(4), 1429–1454.

Fig.1. (a) Simplified geological map of the Tibetan Plateau showing the major blocks and the localities of rocks dated by previous work (ovals with numerals). (b) Map of the central Tibetan Plateau showing the distribution of Middle–Late Jurassic magmatism in the Southern Qiangtang; (c) Geological map of the Labuco area. (d–g) Photographs of intrusive rocks of the Labuco plutons. (h–j) Photomicrographs (cross-polarized light) showing the textures of diorites, granodiorites, and granites. Abbreviations: JSSZ = Jinsha Suture Zone; BNSZ = Bangong–Nujiang Suture Zone; IYZSZ = Indus–Yarlung Zangbo Suture Zone. SL = southern Lhasa subterrane, CL = central Lhasa subterrane, NL = northern Lhasa subterrane. Literature data are from Hao et al. (2016), Kapp et al. (2005), Li et al. (2014a,b), Liu et al. (2014), Zhang (2007), and Zhang et al. (2011). Bi = biotite, Pl = plagioclase, Qtz = quartz.

Fig. 2. (a–e) Zircon U–Pb concordia diagrams showing data of intrusive rocks from the Labuco plutons, and representative CL images. Yellow-solid and dashed circles show the locations of samples used for LA–ICP–MS U–Pb dating and Hf analyses, respectively; (f) Age spectrum of inherited zircons from the Labuco plutons. The age spectrum curve of detrital zircon is from Pullen et al. (2011).

Fig. 3. Geochemical classification diagrams for the Labuco intrusive rocks: (a) total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus SiO_2 ; (b) K_2O versus SiO_2 ; (c) ANK versus ACNK; (d) Eu/Eu^* versus Differentiation Index (DI), where $\text{DI} = \text{Quartz (Qtz)} + \text{Orthoclase (Or)}$

+ Albite (Ab) + Nepheline (Ne) + Leucite (Lc) + K-feldspar (Kfs), from CIPW values.

Data sources are as follows: normal calc-alkaline I-type and highly fractionated granitoids of the SQ (Liu et al., 2014; Li et al., 2014a,b; Zhang et al., 2011), diorite and granodiorite in the Renaco area of the SQ (Hao et al., 2016), and slab-derived adakites in Renaco, SQ (Chang, 2012).

Fig. 4. Chondrite-normalized REE and primitive-mantle-normalized multi-element diagrams for the Labuco intrusive rocks. Normalizing values are from Sun and McDonough (1989). The chondrite-normalized rare earth element patterns of liquid that evolved from the lowest-SiO₂ adakite are from Macpherson et al. (2006) and references therein. Data sources for other igneous rocks are as in Fig. 3.

Fig. 5. (a, b) Zircon $\epsilon\text{Hf}(t)$ values versus age, and (c, d) histograms of $\epsilon\text{Hf}(t)$ and Hf crustal model ages (TDMC) of zircons for the Labuco intrusive rocks. Data sources for other igneous rocks are as in Fig. 3.

Fig. 6. Geochemical classification diagrams for the Labuco intrusive rocks: (a) $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$ versus $(\text{Zr}+\text{Nb}+\text{Ce}+\text{Y})$; (b) P_2O_5 versus SiO_2 ; (c) Pb versus SiO_2 ; (d) Th versus Rb; (e) Sr/Y versus Y; and (f) $(\text{La}/\text{Yb})_{\text{N}}$ versus $(\text{Yb})_{\text{N}}$. The subducted oceanic-crust-derived, delaminated lower-crust-derived, and thickened lower-crust-derived adakite fields are after Wang et al. (2006). Abbreviations: FG = fractionated felsic granites, OGT = unfractionated I-, S- and M-type granites. Data

source for other igneous rocks are as in Fig. 3.

Fig. 7. Geochemical classification diagrams for the Labuco intrusive rocks: (a) La/Yb versus La; and (b) Zr versus Zr/Sm. Data source for other igneous rocks are as in Fig. 3.

Fig. 8. Selected major, trace element, and major element ratios plotted against SiO₂ for the Labuco intrusive rocks. The crustal thickness correlation is inferred after Chung et al. (2009). High-pressure fractional crystallization assumes the involvement of garnet (Macpherson et al., 2006), and low-pressure fractional crystallization involves olivine + clinopyroxene + plagioclase + hornblende + titanomagnetite (Castillo et al., 1999). The subducted oceanic-crust-derived, delaminated lower-crust-derived, and thickened lower-crust-derived adakite fields are after Wang et al. (2006). Data source for other igneous rocks are as in Fig. 3.

Fig. 9. Schematic illustration showing the development of Middle–Late Jurassic magmatism in the Southern Qiangtang above the paleo-subduction zone.

Abbreviations: LSG = low-Sr/Y granitoids; HSG = high-Sr/Y granitoids; NIG = normal calc-alkaline I-type granitoids; HFIG = highly fractionated I-type granitoids.

Figure 1

Figure 1

Figure 2

Figure 2

Figure 3

Figure 3

Figure 4

Figure 4

Figure 5

Figure 6

Figure 6 **Figure 6**

Figure 7

Figure 8

Figure 8

Figure 8

Figure 9

Fig. 9