Late-Triassic Biotite Monzogranite from the Western Litang Area, Yidun Terrane, SW China: Petrogenesis and Tectonic Implications

ZHU Yu, LAI Shaocong*, QIN Jiangfeng, ZHANG Zezhong and ZHANG Fangyi

State Key Laboratory of Continental Dynamic, Department of Geology, Northwest University, Xi’an 710069, China

Abstract: The Late Triassic igneous rocks in the Yidun terrane can provide vital insights into the evolution of Paleo-Tethys in western China. We present new zircon U–Pb, whole-rock geochemistry, and Sr–Nd–Pb–Hf isotopic data for the Litang biotite monzogranites, Yidun terrane. The biotite monzogranites have zircon U–Pb age of 206.1±1.0 Ma (MSWD=1.9, n=30), which indicates Late Triassic magmatism. The biotite monzogranites display I-type affinity, high Na2O (3.38–3.60 wt%) contents, medium SiO2 (67.12–69.13 wt%), and low P2O5 contents (0.10–0.12 wt%). They are enriched in Rb, Th, and Ba and depleted in Nb and Ta, with negative Eu anomalies (Eu/Eu*=0.74–0.81). They have evolved Sr–Nd–Pb–Hf isotopic composition, i.e., (87Sr/86Sr)=0.714225 to 0.714763, negative εNd(t) values of −2.0 to −2.6 with two-stage Nd model ages ranging from 1.01 to 1.05 Ga, negative εHf(t) values of −3.4 to −4.1 with two-stage Hf model ages of 1.85 to 1.88 Ga, suggest a matured crustal sources. Their low Al2O3/TiO2 ratios and medium CaO/Na2O ratios, medium MgO and SiO2 contents, low [molar Al2O3/(MgO+FeO)] values, and high [molar CaO/(MgO+FeO)] values indicate that the Litang biotite monzogranite was formed by partial melting of metabasaltic rocks. Based on the previous studies, we propose that the Litang biotite monzogranite was derived from the westward subduction and closure of the Ganzí-Litang ocean during the Late Triassic. The mantle wedge-derived mafic melts provided sufficient heat for partial melting of ancient metabasalt protolith within the middle–lower crust.

Key words: Late Triassic, biotite monzogranite, zircon U–Pb dating, Sr–Nd–Pb–Hf isotopes, Yidun terrane

Corresponding author: shaocong@nwu.edu.cn.

1 Introduction

The eastern Tibetan Plateau locates in the junction zone among Songpan–Ganzi, Yidun, Qiangtang and eastern Lhasa terranes (Peng et al., 2014). The Yidun terrane locates between the Qiangtang and the Songpan-Ganzi blocks (Fig. 1b), which attracted wide interest. Voluminous Triassic arc-related granitic igneous rocks in the eastern Yidun terrane were considered to be related to the closure of Paleo–Tethys in this region. (Roger et al., 2004; Zhang et al., 2006, 2007; Xiao et al., 2007; Zhao Yongjiu, 2007; Yuan et al., 2010). These NNW-trending granites distributed more than 300 km (Fig. 1c), most occur in the southern to middle segment of the belt (Qu et al., 2002).

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi:

This article is protected by copyright. All rights reserved.
Fig. 1. Geological sketch map of the Yidun terrane and strata distribution (after by Peng et al., 2014) (China basemap after China National Bureau of Surveying and Mapping Geographical Information).

CAOB: the central Asia orogenic belt; SGT: Songpan-Ganzi terrane; GLS: Ganzi–Litang suture; JS: Jinsha suture; BNS: Bangong-Nujiang suture; XGF: Xiangcheng–Geza fault; XHF Xianshui He fault.

The NNW-trending Yidun arc is composed of Triassic calc-alkaline volcanic rocks with intercalated flysch deposits, and overlie variably metamorphosed Paleozoic rocks (Reid et al., 2005). Two Triassic deformation events have been identified in this area (Reid et al., 2005). The Early Triassic deformation was associated with the closure of the Jinsha Paleo–Tethyan Ocean and the late-phase deformation likely was a consequence of closure of the Ganzi–Litang Palaeo–Tethyan ocean (Reid et al., 2005). The volcanic rocks in back-arc basins in the northern and the middle part of the eastern Yidun terrane provide a great deal of information to elucidate the interactions between the subduction slab and mantle wedge (Floyd et al., 1991; Todd et al., 2011). Voluminous Late Triassic porphyry- or skarn-type Cu-polymetallic ore deposits occur in the southern part of Yidun terrane (Hou Zengqian et al., 2001,
2003; Wang et al., 2011; Leng et al., 2012; He et al., 2013; Peng et al., 2014), such as the Zhongdian and Pulang porphyry Cu ore deposits (Leng et al., 2012). Late Triassic bimodal volcanic rocks host multiple sulfide deposits (Hou Zengqian et al., 2003), including the Gacun and luchun volcanogenic massive sulfide (VMS) ore deposits (Hou Zengqian et al., 2001, 2003), were also discovered.

The Ganzi–Litang suture locates in the eastern Tibetan Plateau, it is still unclear that it is an in-situ suture zone marking relic of a subducted Paleo-Tethyan oceanic crust or a failed intracontinental rift (Li et al., 2017). Triassic granites recorded the information about the subduction of Paleo-Tethyan oceanic lithosphere (BGMRS, 1991; Hou, 1993; Hou Zengqian, 2004). Previous researches proposed that the arc volcanic rocks and granites formed during the westward subduction of Ganzi-Litang ocean in Late Triassic (Hou Zengqian and Mo Xuanxue, 1991; Hou, 1993). Available ages for the granites of the Yidun terrane show that there was more than one phase of granite intrusion (Hou Zengqian et al., 2001). However, it has always been a matter whether these granites were genetically related to Triassic westward or eastward subduction of the Yidun terrane (Hou Zengqian, 1993; Roger et al., 2010). The coetaneous I-type granites in the middle part of the Litang area could reveal significant geological significance. We aim to clarify the geochemical characteristics and relationships of these granites in different tectonic stages. This contribution presents new geochemical data, zircon U–Pb age data from laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), and Sr–Nd–Pb–Hf isotopic compositions of the biotite monzogranite from the western Litang area. The study may provide reasonable and serviceable information about the tectonic stage of the Yidun terrane.

2 Regional Geology

2.1 Geological background and field geology

The Yidun terrane is located between the Qiangtang and the Songpan–Ganzi terranes, separated by two Paleo-Tethyan oceanic subduction zones: The Jinsha suture to the west and the Ganzi–Litang suture to the east (Roger et al., 2008, 2010; Wang et al., 2011). It adjoins the Yangtze block, separated by the Longmenshan–Jinhe fault. The Songpan–Ganzi Triassic turbidite complex is one of the largest flysch turbiditic basins on Earth, which contains a succession with an average thickness of up to 10 km accumulated during Ladinian through Norian times (~230-203Ma) (Zhang et al., 2014). Traditionally, the Songpan–Ganzi terrane has been believed to be underlain by an oceanic basement (Roger et al., 2003), however, Zhang. (2001) proposed that it could be underlain by a South China-type Precambrian continental basement. The Ganzi–Litang suture in the eastern Tibetan Plateau, trending NNW–SSE, separates the Songpan–Ganzi terrane to the northeast and the Yidun terrane to the southwest (Li et al., 2017). Some of the mafic fragments in Ganzi–Litang suture were identified with affinity to the mid-ocean-ridge basalts (MORB) and thus the Ganzi–Litang suture was believed to be a Paleao-Tethyan suture zone (Yao Xueliang and Lan Yan, 2001; Li et al., 2017). In addition, the Ganzi–Litang suture merges into the Jinsha suture toward the northern end of the Yidun terrane, but the southern segment of the suture is poorly preserved (Yin and Harrison, 2000; Li et al., 2011; Wang et al., 2013a). The Jinsha suture represents the remnants of Palaeo-Tethyan branches that closed approximately during the Late Triassic to the earliest Jurassic (Zhang et al., 2014). The Jinsha and Ganzi–Litang oceans were consumed by Permian–Triassic subductions (Mo Xuanxue et al., 1994; Chang Chengfa, 1996). The collision between the Yidun terrane and the Qiangtang Block was occurred in the Early–Middle Triassic (Zhu et al., 2011).

The strata of the Yidun terrane vary across the north–south-trending Xiangcheng–Geza fault. The oldest rocks within the Yidun terrane are palaeozoic metasedimentary rocks in the Zhongza Massif (Leng et al., 2014; Li et al., 2017). The western part of the Yidun terrane, also known as the Zhongza Massif, is composed of weakly metamorphosed Paleozoic carbonate, clastic rocks and minor mafic volcanic rocks, with a Neoproterozoic basement composed of granitic gneisses and meta-volcanic rocks (BGMRS, 1991; Chang et al., 2000; Reid et al., 2005). The Zhongza Massif is stratigraphically similar to the Yangtze block (BGMRS, 1991) and was previously considered to be a microcontinent that rifted from the western Yangtze block during the opening of the Ganzi–Litang ocean in the Late Permian (Hou Zengqian, 1993). The eastern Yidun terrane consists mainly of Middle–Upper Triassic volcanic rocks intercalated with flysch deposits which were deformed and metamorphosed at a low
metamorphic grade (BGRMSP, 1991; Hou, 1993; Reid et al., 2005). In detail, the northern part of the Yidun terrane (the “Changtai” arc) is dominated by Upper Triassic volcanic rocks, which are bimodal and include both major rhyolites and minor interlayered basalts (Hou Zengqian et al., 2003). The southern part of the Yidun terrane (the “Zhongdian” arc) is composed on a small quantity of porphyries, felsic volcanics, bimodal volcanics, and granites (Ren Jiangbo et al., 2011) (Fig. 1c). Additionally, small volumes of Middle–Late Triassic intermediate–felsic porphyries intruded into the Upper Triassic Tumugou Group composed of volcanic and sedimentary rocks (Wang et al., 2011; Leng et al., 2012; Peng et al., 2014).

The Triassic successions were extensively deformed by a single generation of upright folding and thrust faulting (Reid et al., 2005). From the base upward, the Yidun Group is subdivided into the Lieyi, Qugasi, Tumugou and Lanashan Formations (BGRMSP, 1991; Wang et al., 2013a). The entire Lanashan Formation consists predominantly of black or gray slate and sandstone, whereas the Qugasi and Tumugou Formations have variable amounts of mafic to felsic volcanic rocks and tuffs accompanied by gray slate and sandstone (Wang et al., 2013b). Voluminous Late Triassic granitic and granodioritic plutons intruded deformed Paleozoic and Middle–Late Triassic volcano-sedimentary sequences across the Yidun terrane, such as the immense Dongcuo and Shengmu batholiths (Peng et al., 2014). Granitic plutons were emplaced into the sedimentary pile during and after Indosinian deformation across the Yidun terrane. Since the collision of India with Asia, the Yidun terrane has been incorporated into the eastern Tibetan Plateau (Reid et al., 2007).

2.2 Field geology and petrography

Six biotite monzogranite samples were collected in the western Litang area (Fig. 2). Field outcrops show that these rocks are medium- to fine-grained, and consist mainly of quartz (20–25 vol.%), plagioclase (25–35% vol.%), K-feldspar (20–30 vol.%), and biotite (5–10 vol.%), accessory minerals include zircon, apatite, and magnetite. The quartz crystals are xenomorphic to granular. The K-feldspar crystals are subhedral. The plagioclase crystals are subhedral platy (> 2 mm) and exhibit well-developed polysynthetic twinning. Some plagioclase (andesine) crystals show apparent zonal textures. The biotite consists of reddish brown euhedral to subhedral crystal (< 2 mm).

Fig. 2. Field photograph (a) and microscope photograph (b) of the biotite monzogranite from the western Litang area.
Kfs= potassium feldspar; Qtz-quartz; Bi-biotite; Pl-plagioclase.
3 Analytical Methods

In this study, major and trace elemental geochemistry, whole-rock Sr–Nd–Pb–Hf isotopic geochemistry, and zircon geochronology were analyzed at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China.

3.1 Zircon U–Pb dating

Zircon grains were separated from sample using conventional heavy liquid and magnetic techniques. Representative zircon grains were handpicked, mounted in epoxy resin disks, polished, and carbon-coated. Internal morphology was examined with cathodoluminescence (CL) microscopy prior to U–Pb isotopic dating. Zircon LA-ICP-MS U–Pb analyses were conducted with an Agilent 7500a ICP-MS equipped with a 193-nm laser following the method of Yuan et al. (2004). The \( ^{206}\text{Pb}/^{238}\text{U} \) and \( ^{207}\text{Pb}/^{206}\text{Pb} \) ratios were calculated using the GLITTER program and corrected using the Harvard zircon 91500 standard for external calibration. Common Pb contents were subsequently evaluated using the method described by Andersen (2002). Ages were calculated and concordia diagrams were plotted using ISOPLOT (version 3.0) (Ludwig, 2003).

3.2 Major and trace elements

The weathered surfaces of the samples were removed, and the fresh parts were then chipped and powdered to about a 200 mesh size using a tungsten carbide ball mill. Major and trace elements were analyzed using X-ray fluorescence (XRF; Rikagu RIX 2100) and inductively coupled plasma mass spectrometry (ICP-MS; Agilent 7500a), respectively. Analyses of United States Geological Survey and Chinese national rock standards (BCR-2, GSR-1, and GSR-3) showed that the analytical precision and accuracy for major elements were generally better than 5%. For trace element analyses, sample powders were digested using a HF+HNO\(_3\) mixture in high-pressure Teflon bombs at 190°C for 48 hours. For most trace elements, analytical error was less than 2% and the precision was greater than 10% (Liu Ye et al., 2007).

3.3 Whole-rock Sr–Nd–Pb–Hf isotopes

Whole-rock Sr–Nd–Pb isotopic data were obtained using a Nu Plasma HR multi-collector (MC) mass spectrometer. Sr and Nd isotopic fractionations were corrected to \( ^{87}\text{Sr}/^{86}\text{Sr} = 0.1194 \) and \( ^{146}\text{Nd}/^{144}\text{Nd} = 0.7219 \), respectively. During the analysis period, the NIST SRM 987 standard gave an average value of \( ^{87}\text{Sr}/^{86}\text{Sr} = 0.710250 \pm 2 \) (2σ, n=15) and the La Jolla standard gave an average value of \( ^{146}\text{Nd}/^{144}\text{Nd} = 0.511859 \pm 2 \) (2σ, n=20). Whole-rock Pb was separated through anion exchange in HCl–Br columns, and Pb isotopic fractionation was corrected to \( ^{207}\text{Pb}/^{206}\text{Pb} = 2.3875 \). Within the period of analysis, 30 measurements of NBS981 yielded average values of \( ^{206}\text{Pb}/^{204}\text{Pb} = 16.937 \pm 1 \) (2σ), \( ^{207}\text{Pb}/^{204}\text{Pb} = 15.491 \pm 1 \) (2σ), and \( ^{208}\text{Pb}/^{204}\text{Pb} = 36.696 \pm 1 \) (2σ). BCR-2 standard yielded average values of \( ^{206}\text{Pb}/^{204}\text{Pb} = 18.742 \pm 2 \) (2σ), \( ^{207}\text{Pb}/^{204}\text{Pb} = 15.620 \pm 1 \) (2σ), and \( ^{208}\text{Pb}/^{204}\text{Pb} = 38.705 \pm 1 \) (2σ) (Yuan et al., 2008). Total procedural Pb blanks were in the range 0.1–0.3 ng. Whole-rock Hf was also separated using single-anion exchange columns. In the course of the analysis, 22 measurements of JCM 475 yielded an average of \( ^{176}\text{Hf}/^{177}\text{Hf} = 0.2821613 \pm 0.0000013 \) (2σ) (Yuan Honglin et al., 2007).

4 Results

4.1 Zircon LA-ICP-MS U–Pb age

Zircon U–Pb concordia diagrams and CL images of the biotite monzogranite (LTW-05) from the western Litang area are presented in Fig. 3, and the results of the analyses are listed in Table 1.
Fig. 3. Representative zircons cathodoluminescence (CL) (a) images and zircon U-Pb concordia diagrams (b, c) of the biotite monzogranite from the western Litang area.

Zircons from the biotite monzogranite (LTW-05) are fawn to colorless, euhedral, long prismatic crystals (200–300 μm in length), with aspect ratios ranging from 2:1 to 3:1. Most of the grains are gray and display well-developed oscillatory zoning in CL images (Fig. 3a). Spots #7, #18, #22, #29 and #30 yielded relatively younger $^{206}\text{Pb} / ^{238}\text{U}$ ages (186±2 Ma to 198±2 Ma), which are attributed to Pb loss. The other 30 spots have U contents from 229 to 980 ppm, Th contents from 100 to 695 ppm, and Th/U ratios from 0.35 to 0.78. These 30 spots have concordant $^{206}\text{Pb} / ^{238}\text{U}$ ages from 202±2 Ma to 213±2 Ma (weighted mean age of 206.1±1.0 Ma, MSWD=1.9, n=30), which represent the crystallization age of the biotite monzogranite.

4.2 Major and trace element chemistry

Analytical data for major (wt%) and trace element (ppm) analyses of the biotite monzogranite samples are listed in Table 2.

The whole-rock geochemical results show SiO$_2$=67.12–69.13 wt%, K$_2$O=2.54–2.95 wt%,
Na₂O=3.38–3.60 wt%, and CaO=3.56–3.71 wt%. These rocks belong to the calc-alkaline series (Fig. 4a). The TiO₂, Al₂O₃, and MgO contents of these samples are 0.44–0.50 wt%, 14.94–15.96 wt%, and 1.02–1.17 wt%, respectively. These rocks are metaluminous with A/ CNK values of 0.99 to 1.01 (Fig. 4b). The samples have Fe₂O₃ᵀ contents from 3.82 to 4.81 wt%, low P₂O₅ contents from 0.10 to 0.12 wt%.

The total REE (ΣREE) values of the biotite monzogranite samples range from about 122.9 to 157.7 ppm. The LREE/HREE ratios are within the range of 8.1 to 11.0. These samples have relatively low Rb (102–107 ppm) and high Sr (185–197 ppm) contents, with low Rb/Sr ratios of 0.53–0.57. In the chondrite-normalized REE patterns (Fig. 5a), the biotite monzogranites enriched LREEs, and flat HREEs. They have variable (La/Yb)₅₇ and (Gd/Yb)₅₇ ratios of 9.73 to 14.00 and 1.59 to 1.74, respectively, with insignificant negative Eu anomalies (Eu/Eu*=0.74–0.81). The primitive mantle-normalized spider diagrams (Fig. 5b) show that the biotite monzogranite samples have the enrichment of Rb, Th, Pb, the depletion in Nb, Ta, Sr, and Ba.

4.3 Whole-rock Sr–Nd–Pb–Hf isotopes

This article is protected by copyright. All rights reserved.
Whole-rock Sr–Nd–Pb–Hf isotopic data for the biotite monzogranite from the western Litang area are listed in Tables 3, 4 and 5. All the initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios ($I_{\text{Sr}}$), $\varepsilon\text{Nd}(t)$, and $\varepsilon\text{Hf}(t)$ values were calculated for the time of 210 Ma based on the LA-ICP-MS U–Pb zircon ages for the Litang biotite monzogranite.

Three samples (LTW-03, LTW-04, and LTW-09) have high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.714225 to 0.714763, negative $\varepsilon\text{Nd}(t)$ values of $-2.0$ to $-2.6$, with two-stage model ages of 1.01–1.05 Ga. These samples are characterized by Sr = 186–192 ppm and Rb = 102–106 ppm. The $I_{\text{Sr}}$ vs. $\varepsilon\text{Nd}(t)$ diagram (Fig. 6a) shows similar features to matured continental crust source.

The biotite monzogranite samples have Pb contents of 13.8–15.4 ppm. In the diagram of the ($^{206}\text{Pb}/^{204}\text{Pb}$) vs ($^{208}\text{Pb}/^{204}\text{Pb}$) and ($^{206}\text{Pb}/^{204}\text{Pb}$) vs ($^{207}\text{Pb}/^{204}\text{Pb}$) (Fig. 7), the three samples plot in the range of MORB and lower continental crust, which indicate a depleted source region. The initial $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios of the biotite monzogranite samples from the western Litang area are 18.5694–18.6282, 15.7298–15.7326, and 38.9155–38.9642, respectively.

These samples (LTW-03, LTW-04, and LTW-09) have Lu contents of 0.28–0.31 ppm and Hf contents of 4.44–4.75 ppm. They have the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282560 to 0.282583 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios from 0.008513 to 0.009594. The $\varepsilon\text{Hf}(t)$ values are $-3.4$ to $-4.1$ with the two-stage model ages of 1.85–1.88 Ga. In the $\varepsilon\text{Nd}(t)$ vs. $\varepsilon\text{Hf}(t)$ diagram (Fig. 6b), the Litang biotite monzogranite samples indicate a lower crust source.

5 Discussion
5.1 Magmatic type of the Litang biotite monzogranite

The Late Triassic biotite monzogranite from the western Litang area has SiO$_2$ (67.12–69.13 wt%), medium K$_2$O (2.54–2.95 wt%), calc-alkalinity, A/CNK=0.99–1.01, relatively high Na$_2$O contents (3.38–3.60 wt%) and low P$_2$O$_5$ (0.10–0.12 wt%) contents. The A/CNK values are regarded as the criteria for I-type and S-type granites (Chappell and White, 1974, 2001; Wu Fuyuan et al., 2007; Wang Dezi et al., 1993). Wang Dezi et al. (1993) proposed that K and Rb are enriched in mature crust, whereas Sr is enriched in immature continental crust. The low Rb/Sr ratios (Rb/Sr=0.53 to 0.57 < 0.9) of the Litang biotite monzogranite suggest an I-type granite affinity. Moreover, in the (Na$_2$O+K$_2$O)/CaO vs. 10,000*Ga/Al and Y vs. 10,000*Ga/Al diagrams (Fig. 8a and b), all samples plot within the fields of I and S types. The Litang biotite monzogranite samples display a positive correlation between the Y and Rb (Fig. 8c), which indicates a typical I-type trend. Furthermore, in the K$_2$O–Na$_2$O diagram (Fig. 8d), the biotite monzogranite samples also plot in the I-type granite region.

Fig. 8. (Na$_2$O+K$_2$O)/CaO vs. 10000*Ga/Al (a) and Y vs. 10000*Ga/Al (after Whalen et al., 1987) (b), Y-Rb (c) (after Li et al., 2007) and Na$_2$O-K$_2$O (d) (after Collins et al., 1982) diagrams for the biotite monzogranite from the western Litang area.

5.2 Characteristics of sources

The biotite monzogranite samples in this study have SiO$_2$ (67.12–69.13 wt%), with Na$_2$O/K$_2$O ratios of 1.20–1.34, similar to granitic rocks generated by the dehydration partial melting of basaltic rocks (Rapp and Watson, 1995). The low Al$_2$O$_3$/TiO$_2$ and medium CaO/Na$_2$O ratios indicate that the samples approached the source of basalt-derived melt (Fig. 9a). In the Mg$^+$ vs. SiO$_2$ diagram (Fig. 9b), these rocks also show the features of melts from meta-igneous sources. Furthermore, in the [molar Al$_2$O$_3$/(MgO+FeO$_2$)] vs. [molar CaO/(MgO+FeO$_2$)] diagram (Fig. 9c), the biotite monzogranite samples plot with partial melts from metabasaltic sources. The studied biotite monzogranite samples...
have negative $\varepsilon$Nd(t) values of $-2.0$ to $-2.6$ with the two-stage model ages of $1.01$ to $1.05$ Ga, and corresponding negative $\varepsilon$Hf(t) values of $-3.4$ to $-4.1$ with two-stage model ages from $1.85$ to $1.88$ Ga, which indicate that the protolith was from the ancient continental crust. The Rb/Y–Nb/Y diagram of the biotite monzogranites also shows the feature of a crustal source (Fig. 9d). The Nb/Ta ratios ($10.37$–$12.86$) are considerably lower than those of mantle-derived rock ($17.5\pm2$) and closely approximate those of crustal rock ($\sim11$) (Taylor and McLennan, 1985). In summary, the biotite monzogranite was mainly derived from partial melting of the basalt in the ancient crustal sources.

5.3 Tectonic implications

Voluminous Late-Triassic granitoids and volcanics have been documented in the Yidun terrane. The chronology results for these igneous rocks are summarized in the Table 6 and Fig. 10.

The crystallization age of the biotite monzogranite from the western Litang area is $\sim206.1$ Ma. The geochemical characteristics indicate that these biotite monzogranites are derived from Paleoproterozoic to Mesoproterozoic mafic crustal sources. Indeed, the $\sim225$–$206$ Ma granitic rock of the Yidun terrane has I-type granite affinity (Hou Zengqian et al., 2001), which is explained as the products of partial melting of metaigneous rocks (Chappell and White, 2001). In the Rb vs. Y+Nb and Rb/Y-Nb/Y (9d) (after Jahn et al., 1999) diagrams for the biotite monzogranite from the western Litang area.

This article is protected by copyright. All rights reserved.
(1) Eastward-dipping subduction of the Jinsha oceanic lithosphere under the Zhongza Massif (Reid et al., 2005; Roger et al., 2008, 2010). They proposed that the east dipping subduction zone of Jinsha ocean generated the ~245–229 Ma granites in the western Yidun terrane (Roger et al., 2010). These ~245–229 Ma granitoids are inconsistent with the main age range of ~225–206 Ma (Hou zengqian et al., 2001; Roger et al., 2010). The Litang biotite monzogranite was formed at ~206 Ma and located at the eastern Yidun terrane (Fig. 1c). Although they have the typical subduction-related magmatism feature, the crystallization age is later than the main stage of Jinsha ocean eastward subduction which they proposed. Moreover, this assumption cannot account for the spatial distribution of the arc granitic plutons and the back-arc volcanic rocks in the northern part of Yidun terrane. Actually, the dominant granitic rocks are located at the eastern part of the Yidun terrane and the back-arc volcanic rocks in the Changtai region of the northern part of the Yidun terrane (Fig. 1c) (Wang et al., 2013a). In fact, there is no associated magmatic type ore deposits which were found to the east of the Ganzi-Litang suture (i.e., the Songpan-Ganzi fold belt) so far, but many plutons in the eastern Yidun terrane to the west of Ganzi-Litang suture (Peng et al., 2014). In addition, Wang et al. (2013b) pointed out that the eastward subduction of the Jinsha Ocean was implausible in terms of the source recycling feature. If the Jinsha oceanic slab subducted eastward, the Zhongza Massif would be an active continental margin and the Yidun Group would receive massive detritus in such an active continental margin. However, the Yidun Group displays the source features of a passive margin by the geochemical compositions of sedimentary materials (Wang et al., 2013b). We therefore conclude that the eastward subduction of the Jinsha ocean was implausible.

(2) Orogenic collapse (Peng et al., 2014). They argued that the coeval occurrence of the Late Triassic intrusive rocks in the two sides of the Ganzi-Litang suture formed after Triassic crustal thickening of the Yidun and Songpan–Ganzi terranes caused by convergence between the Yangtze, North China and Qiangtang blocks (Xiao et al., 2007; Zhang et al., 2007; Peng et al., 2014). They explained that the enriched lithospheric mantle and lower crust are metamorphosed up to the eclogite facies and delaminated downwards into asthenosphere after Triassic crustal thickening (Peng et al., 2014). Subsequently, the delamination would cause the rise of hot asthenosphere to reach the lower crust and crustal extension (Sacks and Secor, 1990). These basaltic magmas which were formed by the partial melting of the upwelling asthenosphere led to large-scale partial fusion of middle-lower crust to form felsic magma (Stiel et al., 1993). Although this scenario can give a reasonable interpretation of the formation of Late Triassic granitic batholith in the Yidun terrane, this model neglects the discovery of crustal thickening and cannot explain the existence of the Ganzi–Litang and Jinsha ophiolite suture which were considered as the remnants of the subduction slab in the Zhongza Massif and eastern Yidun Terrane. In fact, no basement rocks have been reported in the eastern Yidun terrane because of thick coverage by Upper Triassic strata. It has been suggested that the Yidun arc was built on thinned continental crust, which may have consisted of Proterozoic basement derived from the Yangtze block.

Fig. 10. The summary of chronology results for Triassic igneous rocks in the Yidun terrane.
(Hou, 1993; Chang Chengfa, 1996; Reid et al., 2007).

Fig. 11. The Rb vs. Y+Nb (a) (after Pearce, 1984) and Rb/30-Hf-3Ta (b) (after Harris et al., 1986) diagrams of the biotite monzogranite from the western Litang area. Syn-COLG: syn-collisional granite; WPG: within-plate granite; VAG: volcanic arc granites; ORG: oceanic ridge granite; Post-COLG: post-collisional granite.

(3) Westward subduction of the Ganzi–Litang oceanic lithosphere. (Hou Zengqian et al., 2001, 2003, 2007, Leng et al., 2012; Wang et al., 2013a). Hou Zengqian et al. (2001, 2003, 2007) pointed out that the differences of magmatic type are due to different subduction dip angles based on the differences of magmatic type, rock assemblages and their host deposits in the northern and southern parts of eastern Yidun Terrane. Wang et al. (2013a) further proposed that the high silica adakites of the southern Yidun terrane (Xiangcheng and Shangri-La regions) were formed by early-stage subduction (~230 Ma-224 Ma) of Ganzi–Litang ocean. The transition from HSA (high silica adakitic rocks) to LSA (low silica adakitic rocks) at ~218–215 Ma in the Shangri-La region suggests partial melting of the metasomatized mantle wedge (Wang et al., 2011). Those authors also proposed that the back-arc volcanic rocks in the northern part of Yidun terrane (Changtai region) were caused by later-stage westward subduction (~224 Ma to the end of the Triassic) of Ganzi–Litang oceanic lithosphere, leading to the formation of arc granitic plutons. The ~216 Ma Daocheng granites in the south of Litang area, which are high-K, calc-alkaline and I-type granites, were derived from the partial melting of mafic–intermediate lower crust with a variably minor addition (< 20%) of depleted mantle–derived magma (He et al., 2013). Combined with the results of previous studies on mafic to intermediate volcanic rocks (Leng Chengbiao, 2009), the assemblage of fossils from the Tumugou formation (Huang Jianguo and Zhang Liuqing, 2005), and the diorites and granites in the eastern Yidun terrane (Hou Zengqian et al., 2001, 2004; Reid et al., 2007; Leng et al., 2012; Leng Chengbiao, 2009), He et al. (2013) further proposed that the Daocheng granites was generated in a syn-collisional tectonic setting during the westward subduction and closure of Ganzi–Litang paleo-ocean. In fact, subduction orogeny is the basic cause of the Yidun arc (Mabi awei et al., 2015). The arc-related granitoids or volcanics have been dated to have formed mostly between ~225 Ma and 206 Ma (Hou Zengqian et al., 2001, 2003; Lin Qingcha et al., 2006; Lai et al., 2007; Reid et al., 2007; Weislogel, 2008). Even the Cu (-Mo) mineralization in the southern Yidun arc was likely related to the westward subduction of the Ganzi–Litang oceanic plate during the Late Triassic (Dong et al., 2014). The Litang biotite monzogranites were formed at ~206 Ma which were accompanied by the voluminous arc-related magmatism in the eastern Yidun terrane during the ~225–206 Ma. The trace elements feature displays the obvious enrichment of LILE (e.g. Rb, Ba) and LREE and depletion of the HREE which are typical arc-like geochemical compositions (Fig. 5). The isotopic signatures show the lower crust source (Fig. 6, Fig. 7). The geochemical discriminant diagrams show the similar sources with the experimental melts of the meta-igneous (Fig. 9). The Litang biotite granites were located at the same tectonic region with those typical subduction-related magmatism (e.g. Shangri-La adakitic rocks and Daocheng I-type granites) and were the magmatism respond in the middle-lower crust under the tectonic setting of the westward subduction of
Ganzi-Litang ocean in the eastern Yidun terrane. Thus, we could deduce that the formation of Yidun arc–basin system also occurred within this time span.

Based on the evidence presented in this study and previous studies, we propose that the mechanism of the Litang biotite monzogranite may be as follows (Fig. 12).

Fig. 12. Geodynamic model for the biotite monzogranite from the western Litang area (after Wang et al., 2011)

In the Late Permian, the Ganzi–Litang ocean opened because of upwelling of the mantle plume, which formed the Emeishan large igneous province on the western margin of the Yangtze block at ~260 Ma (Tan, 1987; Song et al., 2004). During the Early–Middle Triassic, the westward subduction of the Jinsha oceanic lithosphere ceased and the Yidun terrane collided with the Qiangtang block (Hou Zengqian and Mo Xuanxue, 1991; Pullen et al., 2008; Zhu et al., 2011). At the beginning of the Late Triassic, the closure and westward subduction of Ganzi–Litang oceanic lithosphere started (Wang et al., 2011; He et al., 2013; Leng et al., 2014). The subduction triggered asthenosphere upwelling, which resulted in the upwelling of hot mantle-derived melt into the base of the crust and provided a large amount of heat required for partial melting of the crustal rocks (He et al., 2013; Wang et al., 2013a). The mantle-derived basaltic magma in the Litang area, similar with the presence of coeval mafic to intermediate volcanic rocks in the Zhongdian area (Leng Chengbiao, 2009) and the Daocheng I-type granites in the south of the Litang area (He et al., 2013), could have provided the heat source for the partial melting of Paleoproterozoic to Mesoproterozoic middle–lower crust (Leng Chengbiao, 2009; He et al., 2013). Actually, such massive granites (~5200 km$^3$) along the Ganzi–Litang suture zone in eastern Yidun terrane (Fig. 1c) required the upwelling of much more voluminous mantle-derived magmas, which supplied sufficient heat to melt the middle–lower crust (He et al., 2013). As subduction proceeded, these basaltic melts provided the heat source for the partial melting of the basalt protolith within the middle–lower crust and formed the biotite monzogranite magma in the western of Litang area.

6 Conclusions

Zircon U–Pb geochronology indicates that the biotite monzogranite from the western Litang area was emplaced at ~206.1 Ma, and thus belongs to the Late Triassic granitic rocks. The Litang biotite monzogranite has the similar features, with medium SiO$_2$ (67.12–69.13 wt%), medium K (K$_2$O=2.54–2.95 wt%), and relatively high sodium (Na$_2$O=3.38–3.60 wt%) contents. These rocks are metaluminous, calc-alkaline series, and I-type granites. The initial $^{87}$Sr/$^{86}$Sr isotopic ratios ($I_{Sr}$) were high (0.714225–0.714763), and $\varepsilon$Nd(t) values were negative (~0.2 to ~2.6), with $T_{DM}$ from 1.01 to 1.05 Ga; $\varepsilon$Hf(t) values were negative (~3.4 to ~4.1), with $T_{DM}$ ranging from 1.85 to 1.88 Ga. Moreover, the initial $^{206}$Pb/$^{204}$Pb, $^{207}$Pb/$^{204}$Pb, and $^{208}$Pb/$^{204}$Pb ratios of 18.5694–18.6282, 15.7298–15.7326, and 38.9155–38.9642, respectively, suggest that the parent magma was derived from matured continental
crust sources.

Based on previous researches, geochemical characteristics, and tectonic evolution, the Litang biotite monzogranite was derived from the partial melting of the metabasaltic rocks within the middle-lower crust under the tectonic background of the closure and westward subduction of the Ganzi-Litang oceanic lithosphere during the Late Triassic, where mantle-derived basaltic melts provided sufficient heat for the partial melting of basalt protolith within the ancient crustal.

Acknowledgements

We gratefully acknowledge the editor Prof. Hongfu Zhang for his work about this study. We thank the anonymous reviewers for through revision of the manuscript. This work was supported by the National Natural Science Foundation of China (41421002, 41772052, 41372067), and independent innovation project of graduate students of Northwest University (YZZ17192).

Manuscript received Dec. 5, 2017
Accepted Apr. 18, 2018
Associate EIC in charge: Zhang Hongfu
Edited by Fei Hongcai

References


and petrogenesis. Contributions to Mineralogy and Petrology, 95: 407–419.


About the first author
Zhu Yu, male; born in 1993 in Shannxi, doctor; mainly engaged in lithogeochemistry, in Northwest University.

E-mail: yuzhunwu@163.com.

About Corresponding author
Lai Shao-Cong, male; born in 1963 in Sichuan, Professor, mainly engaged in igneous petrology; E-mail: shaocong@nwu.edu.cn.