Linking the Tengchong Terrane in SW Yunnan with the Lhasa Terrane in southern Tibet through magmatic correlation

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ABSTRACT

New zircon U–Pb data, along with the data reported in the literature, reveal five phases of magmatic activity in the Tengchong Terrane since the Early Paleozoic with spatial and temporal variations summarized as Cambrian–Ordovician (500–460 Ma) to the east, minor Triassic (245–206 Ma) in the east and west, abundant Early Cretaceous (131–114 Ma) in the east, extensive Late Cretaceous (77–65 Ma) in the central region, and Paleocene–Eocene (65–49 Ma) in the central and western Tengchong Terrane, in which the Cretaceous–Eocene magmatism migrated from east to west. The increased zircon $\epsilon_{\text{Hf}}(t)$ of the Early Cretaceous granitoids from -12.3 to -1.4 at ca. 131–122 Ma to -4.6 to $+7.1$ at ca. 122–114 Ma, identified for the first time in this study, and the magmatic flare-up at ca. 53 Ma in the central and western Tengchong Terrane indicate increased contributions from mantle- or juvenile crust-derived components. The spatial and temporal variations and changing magmatic compositions over time in the Tengchong Terrane closely resemble those of the Lhasa Terrane in southern Tibet. Such similarities, together with the data of stratigraphy and paleobiogeography, enable us to propose that the Tengchong Terrane in SW Yunnan is most likely linked with the Lhasa Terrane in southern Tibet, both of which experienced similar tectonomagmatic histories since the Early Paleozoic.

Keywords

Zircon U–Pb age and Hf isotope; Changing magmatic composition; Tengchong Terrane; Lhasa Terrane; Paleogeographical link

1. Introduction

Locating the paleogeographical positions of micro–continents or terranes is the starting point for reconstructing the tectonic evolution of ancient orogenic belts. Such positions can be explored through different approaches including paleontological and stratigraphical correlation, provenance of detrital zircons, and paleomagnetic data as exemplified by the paleogeographical studies on the micro–continents or terranes in northern Gondwanaland (Wopfner, 1996; Metcalfe, 1998; Wopfner and Jin, 2009; Veevers et al., 2005; McQuarrie et al., 2008; Shi et al., 2008; Guynn et al., 2012; Usuki et al., 2013; Zhu et al., 2011a, 2013; Zhang et al., 2013; Li et al., 2014a, b). Although much attention has been focused on the paleogeographical positions of the micro–continents or terranes in northern Gondwanaland, proposed reconstruction models remain diverse (cf. Ali et al., 2013; Metcalfe and Aung, 2014; for synthesis). For example, as part of northern Gondwanaland, the Tengchong Terrane in SW Yunnan has been considered a component of the Sibumasu Terrane that is linked with the Qiangtang Terrane to the west on the basis of similarities with the Late Carboniferous–Early Permian glacial–marine diamictites and faunas (Wopfner, 1996; Metcalfe, 2011, 2013; Metcalfe and Aung, 2014). However, others argue that the Tengchong Terrane is not the part of the Sibumasu Terrane and that this terrane should be linked with the Lhasa Terrane to the west due to the comparable magmatic histories and Permian stratigraphy and paleobiogeography between them, as well as the significant differences in the records between the Tengchong Terrane and the Sibumasu Terrane (Shi et al., 2008; Wopfner and Jin, 2009; Zhang et al., 2013; Liao et al., 2015).

As a direct consequence of mantle–crust interaction, widespread granitoids can be used as a proxy to unravel the nature and architecture of the continental crust with temporal and spatial resolutions. This is because the geochemical compositions and emplacement ages of granitoids can be precisely determined (cf. Zhu et al., 2011b; Ping et al., 2013), resulting in their effective applications in regional correlation and paleogeographical reconstruction of micro–continents or terranes (cf. Lin et al., 2013; Robinson et al., 2014). Here, we report new zircon U–Pb ages and Hf isotope data of the granitoids from the Tengchong Terrane in SW Yunnan. These new data, along with the data in the literature (Table 1), reveal the geochronological framework of magmatism in a regional context and changing magmatic compositions over time in

this terrane. Our work shows that the geochronological framework of magmatism and changing magmatic compositions in the Tengchong Terrane closely resemble those of the Lhasa Terrane in southern Tibet. Such resemblance implies a similar tectonic setting for the Tengchong and Lhasa terranes since the Early Paleozoic and thus enables us to propose that the Tengchong Terrane is most likely linked paleogeographically with the Lhasa Terrane in southern Tibet. Our results provide robust lines of evidence from magmatic petrology and geochemistry for the paleogeographical link between the Tengchong Terrane in SW Yunnan and the Lhasa Terrane in southern Tibet.

2. Geological background and samples

South Asia is mainly composed of several terranes or micro-continents, including South China, Indochina, Sibumasu, and East Malaya (Metcalf, 1991; Deng et al., 2014a), in which the Sibumasu and Indochina terranes are separated by the Changning–Menglian, Chiang Mai/Inthanon, and Bentong–Raub suture zones (Metcalf, 2011). The Tengchong Terrane investigated in this study is located in the northern Sibumasu and southeastern Lhasa Terranes (Fig. 1a). It is separated from the Baoshan Terrane to the east by the Bangong–Nujiang–Longling–Ruili suture zone and from the West Burma Terrane to the west by the Myitkyina suture (Fig. 1b) (Yang et al., 2012; Xu et al., 2012; Li et al., 2014a). The Santaishan peridotites within the Longling–Ruili suture zone (Fig. 1b) most likely represent the remnant of the Longling–Ruili Ocean that was connected to the west with the Bangong–Nujiang Ocean (Zhang et al., 1996; Liu et al., 2002; Mao et al., 2014). The oldest unit in the Tengchong Terrane is termed as the Neo–Paleoproterozoic Gaoligongshan Group, composed mainly of leptynite, schist, silicolite, marble, and slate and experienced greenschist–amphibolites facies metamorphism (cf. Li et al., 2012a; Eroğlu et al., 2013; Deng et al., 2014b; Zhao et al., 2015). The Carboniferous–Lower Permian sequence is extensive and consists mainly of glacial–marine diamictite, sandstone, and limestone (Fig. 1b). Some Silurian–Devonian and Lower Cretaceous sequences consisting of sandstone and mudstone are sporadically exposed in the central–eastern parts of the Tengchong Terrane. This terrane is intruded by abundant magmatic rocks of Mesozoic–early Cenozoic age (Fig. 1b) and covered by minor Quaternary volcanic rocks (Zhao and Liu, 2010).

A series of N–S and NE–SW trending faults are developed in the Tengchong Terrane (Fig. 1b). Existing studies indicate that the Nujiang–Longling–Ruili Fault (NLRF) separated the tectonic mélange to the west and the Cambrian–Ordovician granitoids to the east (Jiang et al., 1998; Huang et al., 2010; Xie et al., 2011; Mao et al., 2014) and that the Dayingjiang Fault (DYJF), Gudong–Tengchong Fault (GTF), and the Binlangjiang Fault (BLJF) have controlled the distributions of varying Carboniferous–Permian sequences (cf. YBGMR, 1982; Jiang et al., 1998; An et al., 2009) in which the GTF is interpreted to represent the north extension of the DYJF (Fig. 1b) (Jiang et al., 1998; Wang et al., 2006). Therefore, these faults are considered as boundary faults that divided the Tengchong Terrane into three magmatic belts.

Mingguang–Menglian–Bangwai Magmatic Belt (MMB): This belt is located in the eastern Tengchong Terrane and is bounded by the NLRF to the east and the GTF–DYJF to the west (Fig. 1b). The two batholiths investigated (i.e., Menglian and Xiaotang) intrude into the Gaoligongshan Group metamorphic rocks. The Menglian Batholith consists mainly of monzogranites and granodiorites with abundant dioritic enclaves. The host monzogranites are composed of quartz (20–30%), plagioclase (25–40%), alkali–feldspar (25–30%), biotite (2–3%), and minor hornblende (approx. 1%). The Xiaotang Batholith includes monzogranites with minor dioritic enclaves. The host monzogranites are composed of quartz (approx. 30%), plagioclase (25–35%), alkali–feldspar (30–35%), biotite (2–3%), and minor muscovite (approx. 1%). Accessory minerals include titanite, apatite, and Fe–Ti oxides.

Guyong–Cizhouba Magmatic Belt (GC): It lies in the central Tengchong Terrane and is bounded by the GTF–DYJF to the east and BLJF to the west (Fig. 1b). Four plutons (Guyong, Xinqi, Cizhouba, and Lapai) are investigated in this study. The Guyong and Xinqi plutons intrude into the Carboniferous Menghong Group and consist mainly of monzogranites and granodiorites with minor dioritic enclaves. The host rocks are composed of quartz (20–25%), plagioclase (30–35%), alkali–feldspar (30–35%), biotite (1–3%), and minor hornblende (1–5%). Accessory minerals include titanite, zircon, and Fe–Ti oxides. The Cizhouba and Lapai plutons intrude into the Gaoligongshan and Menghong groups and consist mainly of granodiorites. The host granodiorites are composed of quartz (approx. 25%), plagioclase (30–40%), alkali–feldspar (25–35%), and biotite (3–8%), as well as accessory minerals.

Sudian–Longpen Magmatic Belt (SL): It lies in the western Tengchong Terrane and is separated from the GC by the BLJF–DYJF to the east (Fig. 1b). The magmatic

rocks (including minor mafic enclaves) exclusively intrude into the Gaoligongshan Group. This study investigates four plutons: Muwen, Sudian, Bengdong, and Longpen. The Muwen and Sudian plutons consist mainly of granodiorites showing mineral assemblage of quartz (20–25%), plagioclase (35–45%), alkali–feldspar (25–30%), and biotite (3–10%). The Bengdong pluton consists of granodiorites and monzogranites including minerals of quartz (approx. 25%), plagioclase (25–35%), alkali–feldspar (30–35%), biotite (3–5%), and minor hornblende (1–2%). The Longpen pluton consists mainly of granodiorites that are composed of quartz (15–25%), plagioclase (35–45%), alkali–feldspar (30–35%), biotite (approx. 5%), and hornblende (3–5%). Accessory minerals include titanite, corindon, and Fe–Ti oxides.

3. Analytical methods and results

In this study, 12 granitoid samples from the different magmatic belts in the Tengchong Terrane were dated by the LA–ICPMS U–Pb method and measured by the *in situ* Hf isotope using a Neptune Plus MC–ICPMS system. The descriptions of the analytical methods used are given in Appendix A. The analytical data are provided in [Tables S1](#) and [S2](#). The zircon grains mostly show long prismatic forms and exhibit clear oscillatory zoning ([Fig. 2](#)), indicating a magmatic origin.

In the MMB belt, 24 analyses from one granodiorite sample (13TC04) north of Menglian ([Fig. 1b](#)) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 113 ± 0.6 – 118 ± 0.7 Ma with a weighted mean age of 114.3 ± 0.6 Ma (MSWD = 1.0) ([Fig. 3a](#)). The remaining one analysis provides an inherited $^{206}\text{Pb}/^{238}\text{U}$ age of 128 ± 0.7 Ma. The youngest age group of this sample shows a zircon $\varepsilon_{\text{Hf}}(t)$ of -0.1 to $+7.1$ and Hf–isotope crustal model ages (T_{DM}^{C}) of 0.6 – 1.0 Ga. To the south of Qinghe ([Fig. 1b](#)), 21 analyses from one monzogranite sample (13TC09) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 114 ± 0.8 to 122 ± 0.7 Ma with a weighted mean age of 117.6 ± 0.8 Ma (MSWD = 1.8) ([Fig. 3b](#)). These analyses display zircon $\varepsilon_{\text{Hf}}(t)$ varying from -3.5 to $+3.2$ and corresponding T_{DM}^{C} model ages of 0.9 – 1.2 Ga. Farther to the south near Xiaotang, 16 analyses from one granodiorite sample (13LH02) ([Fig. 1b](#)) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 47 ± 0.2 to 50 ± 0.3 Ma with a weighted mean age of 48.5 ± 0.4 Ma (MSWD = 0.9) ([Fig. 3c](#)). These analyses have zircon $\varepsilon_{\text{Hf}}(t)$ of -3.4 to -0.5 and T_{DM}^{C} model ages of 1.0 – 1.2 Ga.

In the GC belt, 23 analyses from one monzogranite sample (13TC19) south of Guyong ([Fig. 1b](#)) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 72 ± 0.4 to 76 ± 0.6 Ma with a weighted

mean $^{206}\text{Pb}/^{238}\text{U}$ age of 74.3 ± 0.5 Ma (MSWD = 0.8) (Fig. 3d). These analyses display exclusively negative zircon $\varepsilon_{\text{Hf}}(t)$ of -8.8 to -3.4 and T_{DM}^{C} model ages of 1.2 – 1.5 Ga. Approximately 10 km to the southwest near Jinjia (Fig. 1b), 14 analyses from one monzogranite sample (13MB06) yield $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 73 ± 0.6 to 77 ± 0.5 Ma with a weighted mean age of 73.8 ± 0.5 Ma (MSWD = 0.2) (Fig. 3e). These analyses are characterized by negative zircon $\varepsilon_{\text{Hf}}(t)$ of -8.3 to -4.6 and Mesoproterozoic T_{DM}^{C} model ages of 1.3 – 1.6 Ga. The remaining three analyses provide Late Cretaceous U–Pb ages ranging from 90 to 81 Ma. Farther to the south (Fig. 1b), 21 analyses from one monzogranite sample (13ZX06) south to Cizhouba yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 64 ± 0.4 to 68 ± 0.4 Ma with a weighted mean age of 65.6 ± 0.6 Ma (MSWD = 3.3) (Fig. 3f). These analyses have varying zircon $\varepsilon_{\text{Hf}}(t)$ from -6.9 to $+6.5$ and T_{DM}^{C} model ages of 0.6 – 1.4 Ga. Just approximately 5 km to the east of the above locality near Xinqi, however, 21 analyses from one granodiorite sample (13XQ02) (Fig. 1b) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 49 ± 0.5 to 52 ± 0.5 Ma with a weighted mean age of 50.4 ± 0.4 Ma (MSWD = 0.2) (Fig. 3g). This sample has zircon $\varepsilon_{\text{Hf}}(t)$ varying from -7.8 to -5.0 , yielding T_{DM}^{C} model ages of 1.3 – 1.4 Ga. Farther to the southwest in Lapai (Fig. 1b), 14 analyses from one monzogranite sample (13LLS04–1) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 49 ± 0.3 to 52 ± 0.4 Ma with a weighted mean age of 50.5 ± 0.4 Ma (MSWD = 0.5) (Fig. 3h), showing negative to small positive zircon $\varepsilon_{\text{Hf}}(t)$ (-8.6 to $+1.4$) and varying T_{DM}^{C} model ages (0.9 – 1.5 Ga).

In the SL belt, 22 zircon analyses from one granodiorite sample (13ZN03) collected from Bengdong (Fig. 1b) provide $^{206}\text{Pb}/^{238}\text{U}$ ages of 53 ± 0.4 to 55 ± 0.4 Ma with a weighted mean age of 53.6 ± 0.2 Ma (MSWD = 0.6) (Fig. 3i). This sample displays negative zircon $\varepsilon_{\text{Hf}}(t)$ (-12.3 to -0.3) and Mesoproterozoic T_{DM}^{C} model ages (1.0 – 1.7 Ga). To the west, 20 analyses from one monzogranite sample (13SD08) from south of Sudian (Fig. 1b) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 66 ± 0.9 to 68 ± 1.0 Ma with a weighted mean age of 67.3 ± 0.2 Ma (MSWD = 1.1) (Fig. 3j). This sample is characterized by positive zircon $\varepsilon_{\text{Hf}}(t)$ of $+0.1$ to $+5.1$ and Neoproterozoic T_{DM}^{C} model ages of 0.7 – 1.0 Ga. Farther westward to Muwen (Fig. 1b), 14 analyses from one monzogranite sample (13SD10) yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 58 ± 0.5 to 61 ± 0.3 Ma with a weighted mean age of 58.9 ± 0.5 Ma (MSWD = 0.2) (Fig. 3k). These analyses have exclusively negative zircon $\varepsilon_{\text{Hf}}(t)$ of -11.3 to -6.1 and Mesoproterozoic T_{DM}^{C} model ages of 1.3 – 1.6 Ga. To the south, 22 analyses from one granodiorite sample (13TP08) collected from Longpen (Fig. 1b) provide $^{206}\text{Pb}/^{238}\text{U}$ ages of 54 ± 0.4 to 57 ± 0.4 Ma

with a weighted mean age of 55.0 ± 0.5 Ma (MSWD = 1.0) (Fig. 31) and yield negative zircon $\varepsilon_{\text{Hf}}(t)$ of -12.5 to -0.4 and T_{DM}^{C} model ages of 1.0–1.7 Ga.

4. Discussion

4.1. Geochronological framework of the magmatism in the Tengchong Terrane

The new zircon U–Pb data obtained in this study, along with the age data reported in the literature (Table 1), reveal the geochronological framework of the magmatism in the Tengchong Terrane as summarized below.

The new LA–ICPMS zircon U–Pb age data obtained in this study from the MMB belt show that the Menglian Batholith was emplaced at 117–114 Ma, close to or slightly younger than the emplacement ages of the Mingguang pluton in the north (130–120 Ma) (Xu et al., 2012; Cao et al., 2014; Zhu et al., 2015c), the Tieguoshan pluton in the center (121 Ma) (Chen et al., 2013), and the Lianghe–Xiaotang Batholith in the south within this belt (127–115 Ma) (Cong et al., 2011; Qi et al., 2011; Li et al., 2012b; Gao et al., 2014). In addition to these Early Cretaceous rocks that are dominant within this belt, intrusive rocks with varying zircon U–Pb ages of Triassic (234–213 Ma) (Li et al., 2010; Zou et al., 2011), Late Cretaceous (ca. 73 Ma) (Qi et al., 2015), and Eocene (53–49 Ma) (Xu et al., 2008; Wang et al., 2014a; this study) are also identified within this belt (Fig. 1b).

The new LA–ICPMS zircon U–Pb age data reported here indicate that the Guyong and Cizhouba plutons in the GC belt were emplaced at ca. 74.3 ± 0.5 Ma and 65.6 ± 0.6 Ma, respectively. Coeval magmatism was also identified by the LA–ICPMS and SHRIMP zircon U–Pb dating from the Sanchahe pluton in the west (75–65 Ma) (Xu et al., 2012; Qi et al., 2015) and the Cizhouba pluton in the center within this belt (72–65 Ma) (Xu et al., 2012; Qi et al., 2015) (Fig. 1b). These Late Cretaceous plutons (76–65 Ma) were emplaced earlier than the Xinqi pluton in the center and the Lapai pluton in the south within this belt (53–42 Ma) (Xu et al., 2008; Chen et al., 2015; this study) (Fig. 1b).

In the SL belt, four samples from the Muwen, Sudian, Longpen, and Bengdong plutons were dated in this study at 58.9 ± 0.5 Ma, 67.3 ± 0.2 Ma, 55 ± 0.5 Ma, and 53.6 ± 0.2 Ma, respectively, coeval with the abundant granitoids and gabbroic dykes

(stocks) that were dated at ca. 66–50 Ma in the literature (Fig. 1b) (Xu et al., 2012; Ma et al., 2014; Wang et al., 2014a, 2015; Qi et al., 2015). Minor granitoids and diorites intruding into the Gaoligongshan Group as stocks in the westernmost of this belt (west of the Nabang shear zone) (Fig. 1b) were dated at 245–206 Ma (Li et al., 2011; Huang et al., 2013).

In addition to the abundant Mesozoic–early Paleogene intrusive rocks within the Tengchong Terrane, minor Cambrian–Ordovician gneissic granitoids (495–460 Ma) (Eroğlu et al., 2013; Wang et al., 2013; Zhao et al., 2015), Early Cretaceous granodiorites (136–121 Ma), and Late Cretaceous–early Paleocene gneissic granitoids (89–63 Ma) (Li et al., 2012a; Eroğlu et al., 2013; Zhao et al., 2015) were also identified within the Gaoligong shear zone to the eastern margin of this terrane (Fig. 1b).

In summary, the age data currently available in the Tengchong Terrane (Fig. 1b) show that (1) approximately coeval minor Triassic intrusive rocks are distributed in the western (SL; 245–206 Ma) and eastern (MMB; 234–213 Ma) belts, (2) abundant Early Cretaceous granitoids (130–114 Ma) are mainly exposed in the eastern (MMB) belt, (3) extensive Late Cretaceous magmatism is mainly found in the central (GC) belt, and (4) abundant Paleocene–Eocene intrusive rocks are mainly distributed in the central (GC) and western (SL) belts, in which the Cretaceous–Eocene magmatism shows a spatial migration from east to west.

4.2. Magmatic comparison between the Tengchong and the Lhasa terranes

4.2.1. Cambrian–Ordovician magmatism

The Cambrian–Ordovician gneissic monzogranites and syenogranites (500–460 Ma) (Fig. 4a) (Li et al., 2012a; Eroğlu et al., 2013; Wang et al., 2013; Zhao et al., 2015) that were mainly distributed in the Gaoligong shear zone to the eastern margin of the Tengchong Terrane (Fig. 1b) are coeval with the Cambrian–Ordovician volcanic rocks (525–470 Ma) occurring in the north margin of the central Lhasa subterrane (Fig. 4b) (Ji et al., 2009a; Zhu et al., 2012; Hu et al., 2013; Ding et al., 2015). The zircon $\varepsilon_{\text{Hf}}(t)$ of the Cambrian–Ordovician gneissic granitoids (–11.4 to +4.6) in the Tengchong Terrane are identical to those of the coeval rhyolites in the

central Lhasa subterrane (−13.9 to +1.3) (Fig. 5a) (Zhu et al., 2012; Hu et al., 2013; Ding et al., 2015). These similarities indicate that the Cambrian–Ordovician magmatism both in the Tengchong and Lhasa terranes may have a similar origin, both of which represent part of the Early Paleozoic magmatic arc recovered from Turkey, Iran, Himalaya, Lhasa, Tengchong, and Baoshan as a result of the subduction of the proto–Tethyan Ocean lithosphere beneath the margin of Gondwanaland (cf. Cawood et al., 2007; Zhu et al., 2012; Wang et al., 2013).

4.2.2. Triassic magmatism

The Triassic intrusive rocks exposed south of Nabang in the westernmost SL belt (245–206 Ma) (Li et al., 2011; Huang et al., 2013) and east of Lianghe in the MMB belt (234–213 Ma) (Li et al., 2010; Zou et al., 2011) (Fig. 1b) approximate the Triassic granitoids documented in the southern (205–201 Ma) (Ji et al., 2009b; Zhu et al., 2011b) and central Lhasa (228–205 Ma) subterrane (Zhu et al., 2011b; Song et al., 2014) (Fig. 4b). The zircon $\varepsilon_{\text{Hf}}(t)$ of the Triassic granitoids from Lianghe (−9.6 to +1.3) in the Tengchong Terrane are comparable to those of the coeval magmatism in the central (−14 to +2) Lhasa subterrane (Fig. 5a). The origin and geodynamical settings of the Triassic magmatism reported both from the Tengchong and Lhasa terranes remain poorly understood (cf. Zhu et al., 2011b; Song et al., 2014), and much more data are required to provide further effective constraints.

4.2.3. Early Cretaceous magmatism

The zonal Early Cretaceous magmatism (131–114 Ma) in the MMB belt of the Tengchong Terrane (Fig. 1b) closely resembles the Early Cretaceous magmatism in the central and northern Lhasa subterrane (Zhu et al., 2009b, 2011b). For example, based on the differences in zircon $\varepsilon_{\text{Hf}}(t)$, the Early Cretaceous felsic granitoids in the Tengchong Terrane can be divided into two phases, including the early phase (131–122 Ma) that is characterized by exclusively negative zircon $\varepsilon_{\text{Hf}}(t)$ of −12.3 to −1.4, and the late phase (122–114 Ma) that displays small negative to positive zircon $\varepsilon_{\text{Hf}}(t)$ of −4.6 to +7.1 (Fig. 5b). The enhanced zircon $\varepsilon_{\text{Hf}}(t)$ suggests an increase in contributions from mantle- or juvenile crust-derived melts over time. This temporal variation in zircon $\varepsilon_{\text{Hf}}(t)$ is very similar to the trend observed from the zonal Early

Cretaceous felsic granitoids that changed from -14 to -4 at 143–115 Ma to -1.1 to $+10.1$ at 110 ± 3 Ma in the central and northern Lhasa subterrane (Fig. 5b) (Zhu et al., 2009b, 2011b). In addition, the Early Cretaceous diorites (120 Ma) in the MMB belt of the Tengchong Terrane (-6.7 to -3.1) (Gao et al., 2014) have zircon $\varepsilon_{\text{Hf}}(t)$ similar to the coeval diorites (111–108 Ma) in the central Lhasa subterrane (-12.6 to -0.2) (Zhu et al., 2009b). Abundant geochronological and geochemical data indicate that the change in magmatic compositions from the early to late Early Cretaceous documented in the central and northern Lhasa subterrane is most likely associated with the slab breakoff and/or oceanic lithospheric detachment in response to the southward subduction of the Tethyan Bangong–Nujiang Ocean lithosphere (Zhu et al., 2009b, 2011b, 2013, 2015a; Sui et al., 2013; Chen et al., 2014).

4.2.4. Late Cretaceous magmatism

The Late Cretaceous granitoids (76–65 Ma) are widely exposed in the GC belt of the Tengchong Terrane (Fig. 1b). These rocks display exclusively negative zircon $\varepsilon_{\text{Hf}}(t)$ of -14 to -3 , comparable to those of the coeval Late Cretaceous granitoids (71–65 Ma) in the northern margin of the southern Lhasa subterrane (Zhu et al., 2015b) that are dominated by negative zircon $\varepsilon_{\text{Hf}}(t)$ (Fig. 5). It should be noted that the middle Cretaceous magmatism (110–80 Ma) is lacking in the Tengchong Terrane, while the coeval magmatism is widespread in the Lhasa Terrane (cf. Zhang et al., 2010a; Zhu et al., 2011b, 2013; Ma et al., 2013; Ji et al., 2014; Wang et al., 2014b; Zheng et al., 2014). Such a difference implies that the Lhasa Terrane may have experienced complex deep mantle processes during this time interval. For example, the Late Cretaceous magmatism in the southern Lhasa subterrane was proposed to be related to the northward subduction of the Neo–Tethyan ocean ridge (Zhang et al., 2010a) or slab rollback (Ma et al., 2013), and the coeval magmatism in the central and northern Lhasa subterrane was attributed to back–arc extension (Meng et al., 2014) and lithospheric delamination (Wang et al., 2014b), respectively.

4.2.5. Paleocene–Eocene magmatism

The Paleocene–Eocene intrusive rocks (65–49 Ma) are extensively exposed in the western Tengchong Terrane (including the SL belt and the southern segment of the

GC belt) (Fig. 1b). To the east of Tongbiguan, the intrusive rocks are predominantly granitic and are characterized by exclusively negative zircon $\varepsilon_{\text{Hf}}(t)$ of -15 to -1 (Fig. 5b). However, to the west of Tongbiguan, the intrusive rocks are composed of granitoids with abundant gabbroic dykes or stocks, and the granitoids are dominated by positive zircon $\varepsilon_{\text{Hf}}(t)$ (-5 to $+11$) (Fig. 5b) (Wang et al., 2014a, 2015; Qi et al., 2015). Such rock associations and zircon $\varepsilon_{\text{Hf}}(t)$ of the Paleocene–Eocene intrusive rocks exposed to the west of Tongbiguan are similar to those of the Gangdese Batholith in the southern Lhasa subterrane (Fig. 5a) (Ji et al., 2009b; Zhu et al., 2011b, 2013, 2015b). In addition, both the Tengchong and Lhasa terranes experienced magmatic flare-up events at ca. 53 Ma with increased contribution from mantle-derived melts. Such events were interpreted to have been a result of the slab breakoff of the Neo–Tethyan Ocean lithosphere beneath the southern Lhasa subterrane (cf. Zhu et al., 2015b).

4.3. Paleogeographical position and evolution of the Tengchong Terrane

South Asia is composed of a series of micro–continents or terranes (cf. Metcalfe, 2013). The paleogeographical positions of these micro–continents or terranes have been a matter of much debate for decades (cf. Wopfner, 1996; Ali et al., 2013; Metcalfe, 2013; Metcalfe and Aung, 2014; Usuki et al., 2013; Zhang et al., 2013; Li et al., 2014a). On the basis of the paleomagnetic re–investigation of Early Permian basalts from the Baoshan Terrane, Ali et al. (2013) placed the Baoshan Terrane in a transitional position between northeast Great India and northwest Australia. In their model, the Tengchong Terrane is directly adjacent to northwest Australia, but no lines of evidence are provided. Metcalfe (2011, 2013) compared the Late Carboniferous–Early Permian faunas in different micro–continents and terranes in South Asia and considered the Tengchong Terrane as a part of Sibumasu Terrane, which is interpreted to represent the eastern extension of the Qiangtang Terrane. In contrast, Shi et al. (2008) and Zhang et al. (2013) proposed that the Tengchong Terrane is paleogeographically linked with the Lhasa Terrane on the basis of the similarity of Permian stratigraphy (clastic rocks and carbonates; Fig. 6) and paleobiogeography and that both terranes are directly adjacent to north Australia. This paleogeographical link between the Tengchong and Lhasa terranes was recently supported by Liao et al. (2015) on the basis of the absence of Permian plume–derived

basalts in the Tengchong Terrane, which was similar to the Lhasa Terrane (Fig. 6). As presented and discussed earlier, both the Tengchong and Lhasa terranes experienced similar Cambrian–Ordovician, Triassic, Early Cretaceous, Late Cretaceous, and Paleocene–Eocene magmatic activity (Fig. 4b and 6), significantly differing from those in the Baoshan (Fig. 4c) and Western Qiangtang subterrane (Fig. 4d). More importantly, the spatial and temporal distributions, rock associations, and changing magmatic compositions over time of such magmatic activity closely resemble those of the Lhasa Terrane. This resemblance implies that the Tengchong and Lhasa terranes should have similar tectonomagmatic histories since the Early Paleozoic era, providing petrological and geochemical evidence for the paleogeographical link between the Tengchong and Lhasa terranes.

The question remains regarding the precise position of the Tengchong Terrane. Li *et al.* (2014a) placed the Tengchong Terrane directly adjacent to north India on the basis of the presence of an Indian Gondwana–derived detrital zircon signature (ca. 950 Ma) (Zhu *et al.*, 2011a) identified from two Carboniferous sandstone samples in the Tengchong Terrane. However, we consider that this link should be further verified due to the limited detrital zircon data and the occurrence of an Australian Gondwana–derived detrital zircon signature (ca. 1200 Ma) (Zhu *et al.*, 2011a) within the two sandstone samples. Furthermore, if this link is plausible, it is difficult to interpret the geodynamic processes responsible for its long journey across the Tethyan Ocean basins to reach its current position (i.e., located east of the Lhasa Terrane). This is because the current size of the Tengchong Terrane is too small ($70 \times 120 \text{ km}^2$) and is dominated by Meso–Neoproterozoic Hf isotope crustal model ages (Fig. 5c, Table S2), making it compositionally less depleted, physically less buoyant (Jordan, 1988; Niu *et al.*, 2003) and consequently less likely to have survived during its journey of drift across the Tethyan Ocean basins.

Therefore, from a petrological perspective, we argue that the Tengchong Terrane represents the eastern extension of the Lhasa Terrane (cf. Zhang *et al.*, 2013; Liao *et al.*, 2015) and thus experiences similar tectonomagmatic histories that can be briefly described below.

(1) As part of the northern margin of the Australian Gondwana, similar to the Lhasa Terrane during the Cambrian–Ordovician, the subduction of the proto–Tethyan Ocean lithosphere beneath the margin of the Gondwanaland triggered the Early Paleozoic magmatism in the Tengchong Terrane and central Lhasa subterrane (Fig. 7a)

(Zhu et al., 2012, 2013; Wang et al., 2013; Dong et al., 2013a).

(2) The Triassic magmatism in the Tengchong Terrane that is comparable to the Lhasa Terrane in terms of emplacement ages and lithologies is tentatively attributed to the southward subduction of the Bangong–Nujiang Tethyan Ocean lithosphere (Fig. 7b).

(3) After the initial collision between the Lhasa–Tengchong Terrane and Qiangtang–Baoshan Terrane (cf. Zhu et al., 2009a, b; Yang et al., 2009; Cao et al., 2014; and references therein) that is assumed to have occurred during the Early Cretaceous (cf. Zhu et al., 2015a and references therein), the slab breakoff and/or oceanic lithospheric detachment of the Bangong–Nujiang Tethyan Ocean lithosphere (Fig. 7c) may have triggered the extensive magmatism at ca. 120–110 Ma with enhanced contributions from mantle– or juvenile crust–derived melts documented both in the Tengchong (Fig. 5b) and Lhasa terranes (Zhu et al., 2009b, 2011b, 2013, 2015a; Sui et al., 2013; Chen et al., 2014).

(4) The ca. 110–90 Ma magmatic quiescence observed in the MMB belt of the eastern Tengchong Terrane may indicate the occurrence of crustal shortening and thickening along the Tengchong–Baoshan collision zone, analogous to the observations (Fig. 4a) and interpretations in the northern Lhasa–Qiangtang collision zone during this time interval (cf. Kapp et al., 2003, 2007; Wang et al., 2014b; and references therein).

(5) The late Cretaceous–Eocene magmatism (76–50 Ma) that is characterized by magmatic flare–up at ca. 53 Ma with significant contributions from mantle– and/or juvenile crust–derived components documented both in the GC and SL belts of the Tengchong Terrane and the southern Lhasa subterrane can well be explained by the northward subduction, slab rollback, and finally slab breakoff of the Neo–Tethyan Ocean lithosphere (Fig. 7d) (Ji et al., 2009b; Chu et al., 2011; Zhu et al., 2011b, 2013, 2015b).

5. Conclusions

(1) The Tengchong Terrane experienced Cambrian–Ordovician (500–460 Ma), Triassic (245–206 Ma), Early Cretaceous (131–114 Ma), Late Cretaceous (77–65 Ma), and Paleocene–Eocene (65–49 Ma) magmatic activity, significantly resembling the Lhasa Terrane but differing from the Baoshan and Western Qiangtang subterrane.

(2) Minor Triassic intrusive rocks are exposed in the western and eastern Tengchong Terrane. Cretaceous–Eocene magmatism is extensive and shows a spatial migration from east to west, including the Early Cretaceous granitoids in the east, Late Cretaceous granitoids in the center, and Paleocene–Eocene gabbroic rocks and granitoids in the center and west.

(3) The zircon $\varepsilon_{\text{Hf}}(t)$ of the Early Cretaceous granitoids in the eastern Tengchong Terrane increase from -12.3 to -1.4 at ca. 131–122 Ma to -4.6 to $+7.1$ at ca. 122–114 Ma, indicating an increased contribution of a mantle component. A magmatic flare-up at ca. 53 Ma with significant mantle input at ca. 53 Ma is documented in the western Tengchong Terrane.

(4) The spatial and temporal distribution, rock associations, and changing magmatic compositions with time observed in the Tengchong Terrane closely resemble the Lhasa Terrane, implying that the Tengchong and Lhasa terranes most likely experienced similar tectonomagmatic histories since the Early Paleozoic.

(5) Our observations and interpretations provide robust evidence from magmatic petrology and geochemistry perspectives for the paleogeographical link between the Tengchong Terrane in SW Yunnan and the Lhasa Terrane in southern Tibet.

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Appendix

Descriptions of analytical methods

LA-ICPMS zircon U-Pb dating

Zircons were separated from granitoids with little alteration, using heavy-liquid and magnetic methods in the Laboratory of the Geological Team of Hebei Province, China and then purified by hand-picking under a binocular microscope. Cathodoluminescence (CL) images (Fig. 2) were taken at the Beijing GeoAnalysis Co., Ltd. to check internal structures of the individual zircons and to select the appropriate spots for the zircon isotope analyses. The zircon U-Pb dating was performed by LA-ICPMS at the Laboratory of Geoanalysis and Geochronology in Tianjin, Institute of Geology and Mineral Resources, China Geological Survey. The detailed operating conditions for the laser ablation system, the ICPMS instrument, and data reduction are identical to those described by Li et al. (2009). ICPMSDataCal (Liu et al., 2010) was used for off-line selection and the integration of background and analyse signals, time-drift correction, and U-Pb dating. Age calculations and plotting of concordia diagrams were made using ISOPLOT 3.0 (Ludwig, 2003). The zircon U-Pb isotopic data are given in Supplementary Table S1.

Zircon Hf isotopic analysis

In-situ zircon Hf isotopic analyses were conducted using a Neptune Plus MC-ICPMS (Thermo Fisher Scientific, Germany), coupled to a GeoLas 2005 excimer ArF laser-ablation system at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (Wuhan) with a beam size of 44 μ m and laser pulse frequency of 1Hz. Details of instrumental conditions and data acquisition were given in Hu et al. (2012). The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\varepsilon_{\text{Hf}}(t)$ values were calculated with the reference to the chondritic reservoir (CHUR) at the time of zircon growth from the magmas. The decay constant for ^{176}Lu of $1.867 \times 10^{-11} \text{ year}^{-1}$ (Söderlund et al., 2004), the chondritic $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282785 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0336 (Bouvier et al., 2008) were adopted. The Hf isotope crustal model age (T_{DM}^{C}) was calculated by assuming that its parental magma was derived from an average continental crust, with $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$, that originated from the depleted mantle source (Griffin et al., 2002). Our conclusions

would not be affected even if other decay constants were used. The zircon Lu–Hf isotopic data are given in Supplementary [Table S2](#).

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Figure captions:

Fig. 1. Tectonic framework of the Tengchong Terrane, Lhasa Terrane, and adjacent terranes. (a) Showing the Tengchong Terrane as part of the southeastern extension of the Lhasa Terrane (Mitchell, 1993 and Chung et al., 2005). (b) The spatial and temporal distributions of the magmatic rocks are clearly shown from the data collected and tested in this study (YBGMR, 1982 and Qi et al., 2015). Abbreviations: TCT = Tengchong Terrane; BST = Baoshan Terrane; NLRF = Nujiang–Longling–Ruili Fault; GTF = Gudong–Tengchong Fault; DYJF = Dayingjiang Fault; BLJF = Binlangjiang Fault.

Fig. 2. Cathodoluminescence (CL) images of representative zircon grains. The solid and dashed circles indicate the locations of LA–ICPMS U–Pb dating and Hf analyses, respectively.

Fig. 3. LA–ICPMS zircon U–Pb concordia diagrams of the granitoids.

Fig. 4. Histogram of the zircon U–Pb ages from magmatic rocks in the Tengchong Terrane (a), Lhasa Terrane (b), Baoshan Terrane (c), and Western Qiangtang subterrane (d).

Literature data of the Tengchong Terrane are from Yang et al. (2009), Li et al. (2010), Li et al. (2011), Zou et al. (2011), Xu et al. (2012), Wang et al. (2013, 2014a, 2015), Eroğlu et al. (2013), Huang et al. (2013), Ma et al. (2014), Cao et al. (2014), and Qi et al. (2015). Data of the Lhasa Terrane are from Zhu et al. (2009a, b, 2011b, 2012), Ji et al. (2009a), Dong et al. (2014), Hou et al. (2015), and references therein. Data of the Baoshan Terrane are from Liu et al. (2009), Dong et al. (2012, 2013a, b), Wang et al. (2013), Liao et al. (2013), and Yu et al. (2014). Data of the Western Qiangtang subterrane are from Hu et al. (2010), Zhang et al. (2011), Liu et al. (2012), Zhai et al. (2013), Li et al. (2014c), Zhang et al. (2014a, b), Wu et al. (2014), and Peng et al. (2014).

Fig. 5. (a) Plots of $\varepsilon_{\text{Hf}}(t)$ vs. U–Pb ages of the granitoids in the Tengchong and Lhasa terranes. (b) Amplified plots of $\varepsilon_{\text{Hf}}(t)$ vs. U–Pb ages from 140 to 40 Ma of the granitoids in the Tengchong and Lhasa terranes. (c) Histogram of Hf isotope

model age for zircons of the granitoids in the Tengchong Terrane.

Literature data of the Tengchong Terrane are from [Yang et al. \(2009\)](#), [Li et al. \(2010\)](#), [Zou et al. \(2011\)](#), [Li et al. \(2011\)](#), [Xu et al. \(2012\)](#), [Eroğlu et al. \(2013\)](#), [Huang et al. \(2013\)](#), [Wang et al. \(2013, 2014a\)](#), [Cao et al. \(2014\)](#), [Ma et al. \(2014\)](#), and [Qi et al. \(2015\)](#). Literature data of the Lhasa terrane are from [Zhu et al. \(2009a, b, 2011b, 2012\)](#), [Ji et al. \(2009b\)](#), [Dong et al. \(2014\)](#), [Hou et al. \(2015\)](#); and references therein.

Fig. 6. Generalized space–time diagrams showing the basement rocks, sedimentary covers, tectonic, and magmatic history of the Tengchong Terrane ([YBGMR, 1982](#); [Zhang et al., 1996](#)), Baoshan Terrane, and different subterranees in the Tibetan Plateau ([Jia, 2006](#); [Zhang et al., 2010b](#); [Zhu et al., 2013](#)).

Fig. 7. Schematic illustrations of the evolution of the Tengchong and Lhasa terranes from the Early Paleozoic to Cenozoic eras. The paleogeographical positions of Indochina, South China, and SW Borneo during the Early Paleozoic era are adapted from [Cocks and Torsvik \(2013\)](#), [Burrett et al. \(2014\)](#), [Li et al. \(2014b\)](#), [Zhang et al. \(2015\)](#), and [Metcalf \(2011\)](#). The paleogeographical positions of Western Qiangtang, Baoshan, and SW Borneo during the early Triassic are adapted from [Metcalf \(2013\)](#). The paleogeographical positions of West Burma and SW Borneo during the early Cretaceous are also adapted from [Metcalf \(2013\)](#). Abbreviations: T = Tengchong, L = Lhasa, B = Baoshan, S = Sibumasu, WB = West Burma, IC = Indochina, SC = South China, NC = North China, SWB = SW Borneo, G = Great India, H = Himalaya, EQ = East Qiangtang, WQ = West Qiangtang.

Figure 1 Tectonic framework of the Tengchong Terrane

Xie et al.'s **Figure1**: W 160mm - H 145mm

Figure 2 Cathodoluminescence (CL) images

Xie et al.'s **Figure 2**: W 150mm - H 94mm

Xie et al.'s **Figure 3**: W 156mm - H 188mm

Figure 4 Histogram of the zircon U-Pb ages

Xie et al.'s **Figure 4: W 80mm - H 85mm**

Figure 5 Plots of $\epsilon_{\text{Hf}}(t)$ vs. U-Pb ages of the granitoids

Xie et al.'s **Figure 5: W 160mm - H 76mm**

Figure 6 Generalized space-time diagrams

Xie et al.'s **Figure 6**: W 160mm - H 132mm

Xie et al.'s **Figure 7**: W 160mm - H 198mm

Table 1 Summary of whole-rock geochemical data

Table 1 Summary of whole-rock geochemical data, zircon U–Pb ages, and Hf isotopic compositions of the intrusive samples from the Tengchong Terrane, SW Yunnan

No.	Sample	GPS Position	Rock type	SiO ₂ (wt.%)	A/CNK	C (%)	Age (Ma)	ε _{Hf} (t)	T _{DM} (Ga)	T _{DM} ^C (Ga)	Reference
Gaoligong shear zone											
1	Gao2a	24°48'12"N, 98°47'43"E	Gneissic granite	73.76	1.12	1.87	486	-1.6 to +4.6	0.9–1.2	1.1–1.6	Eroğlu et al., 2013
2	10DX43a	24°58'35"N, 98°43'44"E	Leucogranite	75.20	1.14	1.81	492 ± 5	-11.4 to -0.8		1.5–2.2	Wang et al., 2013
3	10DX43b	24°58'35"N, 98°43'44"E	Mylonitic granite	74.66	1.15	1.94	488 ± 6	-9.9 to -0.6		1.5–2.1	Wang et al., 2013
4	10DX44	25°00'08"N, 98°43'13"E	Gneissic granite	76.95	1.17	1.95	484 ± 6	-5.5 to -0.4		1.5–1.8	Wang et al., 2013
5	10DX45a	25°00'08"N, 98°43'13"E	Gneissic granite	74.51	1.10	1.35	488 ± 5	-11.4 to -1.5		1.6–2.2	Wang et al., 2013
6	10DX45b	25°00'08"N, 98°43'13"E	Leucogranite	69.30	1.23	2.96	485 ± 7	-7.5 to -0.6		1.5–1.9	Wang et al., 2013
7	10DX45d	25°00'08"N, 98°43'13"E	Leucogranite	74.59	1.13	1.74	491 ± 9	-7.5 to -0.6		1.5–1.8	Wang et al., 2013
8	11ML73	24°41'14"N, 98°47'33"E	Leucogranite	76.58	1.15	2.13	463 ± 3	-6.8 to -1.1		1.5–1.9	Wang et al., 2013
9	11ML74a	24°42'30"N, 98°46'20"E	Gneissic granite	76.36	1.20	2.80	460 ± 6	-5.8 to -1.9		1.6–1.9	Wang et al., 2013
10	11ML77	24°43'06"N, 98°45'29"E	Leucogranite	76.62	1.39	4.06	462 ± 5	-5.6		1.5–1.8	Wang et al., 2013
11	LL244a-1	25°00'41"N, 98°42'04"E	Gneissic granite	81.18	1.21	1.74	493 ± 4	+2.1		1.5	Zhao et al., 2015
12	LL250b-1	25°09'32"N, 98°42'22"E	Gneissic granite	76.39	1.10	1.33	495 ± 3	-1.7		1.6	Zhao et al., 2015
13	LL260c-1	24°58'25"N, 98°43'47"E	Gneissic granite	71.27	1.18	2.45	487 ± 5	-7.2		1.6	Zhao et al., 2015
14	Pm10-7	24°30'22"N, 98°32'50"E	Gneissic granite	76.14	1.14	1.62	498 ± 7				Li et al., 2012a
15	Pm10-2	24°30'22"N, 98°32'50"E	Gneissic granite	77.26	1.06	0.79	500 ± 14				Li et al., 2012a
Mingguang-Menglian-Bangwai Magmatic Belt (MMB)											
16	D0030	22°47'46"N, 98°20'21"E	Granite	74.06	1.19	2.70	234.2 ± 3.1	-8.5 to +1.3	0.9–1.3	1.2–1.8	Li et al., 2010
17		24°47'29"N, 98°24'39"E	Granite	70.11	1.27		213.1 ± 1.7	-9.6 to -6.7	1.2	1.7–1.9	Cong et al., 2010
18	DT12	25°46'19"N, 98°29'31"E	Syenogranite	77.40	1.07	0.48	130.6 ± 2.5				Zhu et al., 2015c
19	ZD1	24°38'28"N, 98°36'38"E	Rhyolite	74.73	2.30	1.09	130.0 ± 1.7				Bai et al., 2012
20	D9021	24°49'51"N, 98°23'39"E	Monzogranite	73.84	1.15	1.87	128.9 ± 2.4				Luo et al., 2012
21		24°35'50"N, 98°15'00"E	Granite	74.75	1.13	1.64	127.4 ± 1.0	-9.1 to -5.4	1.0–1.3	1.5–1.8	Cong et al., 2011
22	D1166	24°37'42"N, 98°17'00"E	Monzogranite	74.17	1.17		127.1 ± 1.0	-7.6 to -3.8	0.9–1.1	1.4–1.7	Li et al., 2012b

23	09QT20	25°05'41"N, 98°30'39"E	Quartz monzonite	65.28	0.96		125.0 ± 1.3	-7.8 to -4.9		1.0–1.1	Qi et al., 2011
24	GD14	25°49'08"N, 98°32'04"E	Monzogranite	76.00	1.03	0.44	124.1 ± 1.6				Zhu et al., 2015c
25	D2346	24°37'40"N, 98°16'00"E	Quartz diorite	62.39	0.94	2.18	123.8 ± 2.5				Li et al., 2012b
26		24°34'20"N, 98°17'50"E	Enclave	51.40	0.67		122.6 ± 0.8	+3.6 to +6.2	0.5–0.7	0.8–1.0	Cong et al., 2011
27	09QT33	24°57'31"N, 98°42'44"E	Granodiorite	67.99	0.98	0.08	122.3 ± 1.2	-9.6 to -4.8		1.0–1.2	Qi et al., 2011
28	GLS8	25°49'52"N, 98°47'19"E	Granite				122.0 ± 1.0	-18.9 to -4.3		1.0–1.5	Xu et al., 2012
29	ITCXC4	25°13'20"N, 98°41'26"E	Granite	75.70	1.10	1.30	121.6 ± 0.7				Chen et al., 2013
30	PM25-3	24°45'51"N, 98°23'39"E	Dacite	70.21	1.09	1.49	121.4 ± 1.4				Gao et al., 2012
31	ITCXC3	25°13'20"N, 98°41'26"E	Granite	75.00	1.09	1.26	121.2 ± 0.9				Chen et al., 2013
32	JJGLZ	25°51'00"N, 98°33'00"E	Monzogranite	72.96	1.06	0.90	120.0 ± 0.6	-4.9 to -1.4	0.9–1.0	1.3–1.5	Cao et al., 2014
33		24°36'34"N, 98°20'26"E	Diorite	58.79	0.93		119.8 ± 1.0	-6.7 to -3.1		1.0–1.1	Gao et al., 2014
34	GD02	25°39'50"N, 98°31'27"E	Monzogranite	72.70	1.06	0.98	119.6 ± 0.9				Zhu et al., 2015c
35		24°36'53"N, 98°20'48"E	Granodiorite	64.70	1.00	0.43	118.7 ± 1.5	-5.6 to -3.3		0.9–1.0	Gao et al., 2014
36	13TC09	24°46'09"N, 98°32'35"E	Monzogranite	74.26	1.14	1.81	117.6 ± 0.8	-3.5 to +3.2	0.7–0.9	0.8–1.2	This study
37		24°30'00"N, 98°17'10"E	Granodiorite	62.60	0.99	0.42	115.2 ± 1.1	-4.5 to 0.0	0.8–1.0	1.2–1.5	Cong et al., 2011
38	13TC04	24°59'26"N, 98°36'01"E	Monzogranite	67.58	1.06	1.20	114.3 ± 0.6	-0.1 to +7.1	0.5–0.8	0.6–1.0	This study
39	09QG36	25°58'21"N, 98°28'19"E	Granite	71.93	1.13	1.96	73.2 ± 0.7	-11.2 to -8.1	1.1–1.2	1.7–1.9	Qi et al., 2015
40	DX78C	24°42'30"N, 97°34'45"E	Metagabbro	53.53	0.82		53.1 ± 0.4	-5.1 to -2.2	0.8–0.9		Wang et al., 2014a
41	DX80C	24°42'30"N, 97°34'45"E	Metagabbro	51.88	0.89		50.1 ± 0.5	-7.1 to -4.1	0.9–1.0		Wang et al., 2014a
42	13LH02	24°43'32"N, 98°23'52"E	Granodiorite	75.77	1.07	0.87	48.5 ± 0.4	-3.2 to -0.5	0.8–0.9	1.1–1.2	This study
Guyong-Cizhouba Magmatic Belt (GC)											
43	09QG45	24°57'41"N, 98°19'13"E	Granite	72.28	1.02	0.43	76.6 ± 2.0	-8.8 to -5.7	1.0–1.1	1.5–1.7	Qi et al., 2015
44	TCXL2	25°25'22"N, 98°23'04"E	Granite				76.0 ± 1.0	-10.1 to -5.8		1.0–1.2	Xu et al., 2012
45	TCGY11	25°20'56"N, 98°17'43"E	Monzonite				74.9 ± 1.8	-9.2 to -4.6		1.0–1.1	Xu et al., 2012
46	13MB06	25°00'05"N, 98°19'56"E	Monzogranite	74.12	1.13	1.64	73.8 ± 0.5	-8.2 to -4.6	0.9–1.1	1.4–1.5	This study
47	13TC19	25°21'58"N, 98°18'53"E	Monzogranite	73.53	1.05	0.88	74.3 ± 0.5	-8.8 to -3.4	0.9–1.0	1.3–1.5	This study
48	XLH-6	25°26'49"N, 98°25'46"E	Granite	77.37	1.00	0.03	73.3 ± 0.2	-11.4 to -8.9		1.7–1.8	Chen et al., 2015

49	DSP-1	25°25'36"N, 98°22'50"E	Granite	76.09	1.00	0.05	73.3 ± 0.3				Chen et al., 2015
50	TCBH6	25°05'52"N, 98°15'21"E	Granite				72.0 ± 0.8	-11.9 to -10.1		1.2	Xu et al., 2012
51	TCGY3	25°18'34"N, 98°15'24"E	Granite				67.8 ± 1.4	-13.1 to -8.7		1.1–1.3	Xu et al., 2012
52	09QG60	25°18'30"N, 98°12'45"E	Granite	75.26	0.98		64.8 ± 0.7	-10.5 to -4.6	0.9–1.2	1.4–1.8	Qi et al., 2015
53	09QG55	25°13'50"N, 98°12'02"E	Granite	72.73	0.99	0.33	64.9 ± 0.9	-13.4 to 0.0	0.7–1.3	1.1–2.0	Qi et al., 2015
54	09QG50	25°13'50"N, 98°11'42"E	Granite	70.84	0.96		65.3 ± 1.0	-13.9 to -5.3	1.0–1.3	1.5–2.0	Qi et al., 2015
55	13ZX06	25°05'40"N, 98°14'53"E	Monzogranite	77.40	1.14	1.58	65.6 ± 0.6	-6.9 to +6.5	0.6–1.1	0.6–1.4	This study
56	TCLL9	24°55'33"N, 98°15'00"E	Granite				53.2 ± 0.6	-12.3 to -5.4		1.0–1.2	Xu et al., 2012
57	LLS-2	24°55'14"N, 98°15'33"E	Granite	75.83	1.01	0.25	53.0 ± 0.2	-11.3 to -8.3		1.7–1.8	Chen et al., 2015
58	LLS-6	24°56'49"N, 98°16'45"E	Granite	74.1	1.02	0.29	52.7 ± 0.2	-11.6 to -8.6		1.6–1.7	Chen et al., 2015
59	13LLS04-1	24°55'31"N, 98°15'33"E	Monzogranite	76.30	1.02	0.32	50.5 ± 0.4	-8.6 to +1.4	0.7–1.1	0.9–1.5	This study
60	13XQ02	25°03'44"N, 98°17'38"E	Granodiorite	70.61	1.18	2.56	50.4 ± 0.4	-7.8 to -5.0	0.9–1.0	1.3–1.4	This study
Sudian-Longpen Magmatic Belt (SL)											
61	10QTN15	24°40'48"N, 97°35'15"E	Diorite	61.74	0.92		245.0 ± 2.9	+7.8 to +14.9	0.3–0.6	0.6–0.8	Huang et al., 2013
62	TCX7-4-5	24°43'00"N, 98°30'00"E	Granodiorite	63.5	0.95		219.0 ± 1.3				Li et al., 2011
63	TCX7-9-5	24°43'00"N, 98°30'00"E	Diorite	52.5	0.9		206.2 ± 4.5				Li et al., 2011
64	13SD08	25°07'33"N, 97°54'02"E	Monzogranite	70.20	1.02	0.66	67.3 ± 0.2	+0.5 to +3.1	0.6–0.7	0.7–1.0	This study
65	CBZ6	25°01'10"N, 97°45'12"E	Granite				65.8 ± 2.3	-5.9 to +4.7		0.6–1.0	Xu et al., 2012
66	CBZ4	25°01'10"N, 97°45'12"E	Granite				66.1 ± 1.3	0.0 to +4.1		0.6–0.8	Xu et al., 2012
67	10QTN39	24°36'43"N, 97°44'17"E	Granite	74.70	1.02	0.40	65.0 ± 1.1	-15.5 to -2.7	0.9–1.3	1.3–2.1	Qi et al., 2015
68	13SD10	25°06'51"N, 97°57'05"E	Monzogranite	72.15	1.02	0.44	58.9 ± 0.5	-11.3 to +1.6	0.7–1.2	0.9–1.6	This study
69	LD1	24°58'14"N, 97°51'45"E	Granite				56.3 ± 1.1	-9.0 to -3.4		0.9–1.1	Xu et al., 2012
70	13TP08	24°39'42"N, 97°46'03"E	Granodiorite	58.13	0.97		55.0 ± 0.5	-12.5 to -0.4	0.8–1.2	1.0–1.7	This study
71	NB07-18	24°36'42"N, 97°34'59"E	Granite				54.5 ± 1.6	-0.5 to +3.4		0.6–0.8	Xu et al., 2012
72	13ZN03	25°14'49"N, 98°06'02"E	Granodiorite	75.97	1.03	0.40	53.6 ± 0.2	-12.0 to -5.4	1.0–1.4	1.3–1.7	This study
73	10DX54B	24°42'30"N, 97°34'45"E	Metagabbro	51.85	0.78		53.2 ± 0.4	-3.1 to +4.9	0.5–0.8		Wang et al., 2015a
74	10DX55E	24°37'31"N, 97°37'46"E	Metagabbro	47.64	0.64		53.6 ± 0.7				Wang et al., 2015a
75	DX66D	24°42'30"N, 97°34'46"E	Leucogranite	75.71	1.06	0.79	52.8 ± 0.3	-4.0 to +11.1		0.4–1.4	Ma et al., 2014