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Notes

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ABSTRACT

The first in situ Hf and U-Pb isotope analyses of zircon separates from Mesozoic granites in southern Tibet identify a significant, previously unknown stage of magmatism. Igneous zircons (n = 34) from a granite within the Gangdese batholith show a weighted mean $^{206}Pb/^{238}U$ age of 188.1 ± 1.4 Ma and $\varepsilon_{Hf}(T)$ (the parts in 10^4 deviation of initial Hf isotope ratios between the zircon sample and the chondritic reservoir) values between +10.4 and +16.8, suggesting predominantly Early Jurassic intrusive activity with a juvenile mantle contribution. Of 40 inherited zircons from two Cretaceous S-type granites in the northern magmatic belt, 23 delineate a slightly older $^{206}Pb/^{238}U$ age cluster between 188 and 210 Ma. These zircons have $\varepsilon_{Hf}(T)$ values from −3.9 to −13.7, yielding crustal Hf model ages from ca. 1.4 to 2.1 Ga, suggesting a major episode of crustal growth in Proterozoic time and remelting of this crust in Early Jurassic time. Combining these with literature data, we interpret the Jurassic Gangdese magmatism as an early product of the Neo-Tethyan subduction that played a long-lasting role in the tectonic evolution of southern Tibet prior to the India-Asia collision.

Keywords: zircon, Hf isotope, U-Pb dating, Tibet, Neo-Tethyan subduction.

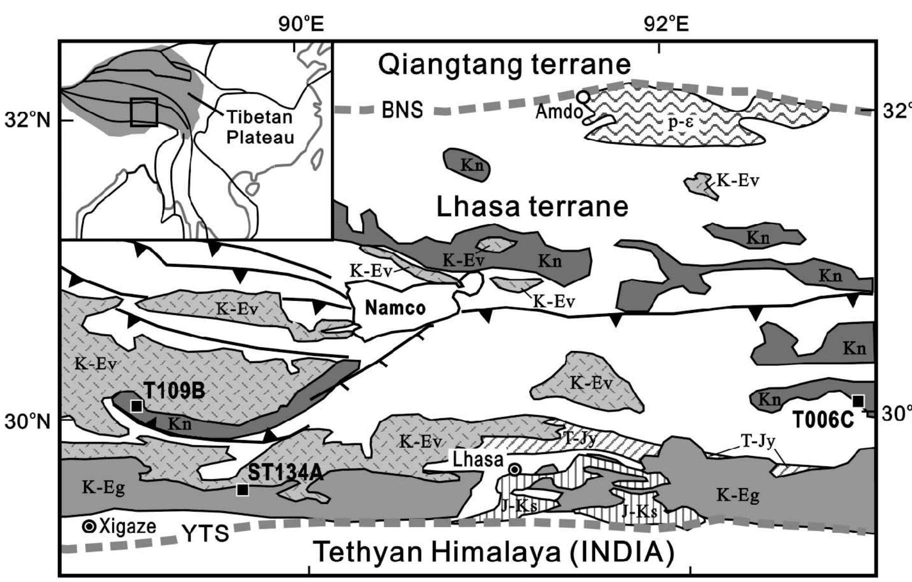

Figure 1. Simplified geologic map showing sample localities and distribution of major magmatic suites of Mesozoic ages in Lhasa terrane, southern Tibet (Pan et al., 2004). Inset denotes principal terrane boundaries in East Asia. BNS—Bangong-Nujiang suture; YTS—Yarlung-Tsangpo suture; T-Jy—Triassic–Jurassic Yeba Formation; J-Ks—Jurassic–Cretaceous Sangri Group; Kn—Cretaceous granitoids in northern magmatic belt; K-Eg—Cretaceous–Eocene Gangdese batholiths; K-Ev—Cretaceous–Eocene volcanic rocks; p-ε—Amdo gneiss.

INTRODUCTION

There is now general consensus that Tibet assembled by the accretion of a series of Gondwana-derived terranes to Asia in Mesozoic time (cf. Yin and Harrison, 2000). Numerous studies over the past few decades have helped develop an understanding of the India-Asia collision and related Cenozoic tectonic processes, which led to the formation of the Himalayas and the Tibetan Plateau. However, relatively little work has focused on the precollisional geology. This is particularly true for southern Tibet, which comprises essentially the Lhasa and Tethyan Himalaya terranes, north and south of the Yarlung-Tsangpo suture zone, respectively (Fig. 1); the precollisional configuration and crustal (and lithospheric) evolution of both terranes remain unclear. Thus, models proposed for Cenozoic Tibetan tectonic evolution have been based on assumptions of initial conditions with scarce data.

As part of our study of trans-Himalayan magmatism, we report the first in situ U-Pb dating and Hf isotope analyses of zircon separates from three granites in the Lahaska terrene using the sensitive high-resolution ion microprobe (SHRIMP) and laser ablation microprobe–multicollector–inductively coupled plasma mass spectrometry (LAM-MC-ICPMS), respectively. The results allow us to identify a significant stage of magmatic activity in southern Tibet during the Early Jurassic. This finding provides new constraints on the precollisional history and crustal evolution of the Lhasa terrane, and has implications for better delineating the Cenozoic or postcollisional tectonomagmatism in the region.

GEOLOGIC BACKGROUND AND SAMPLES

Tibet is composed of four east-west–trending continental fragments or terranes: from north to south, these are the Songpan-Ganze, Qiangtang, Lhasa, and Tethyan Himalaya, separated by the Jinsha, Bangong-

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Nujiang, and Yarlung-Tsangpo suture zones representing the Paleo-Tethyan, Meso-Tethyan, and Neo-Tethyan Ocean relicts, respectively (Yin and Harrison, 2000). The Lhasa terrane is believed to have dispersed from Gondwana during the Permian or Triassic (e.g., Allègre et al., 1984; Chang et al., 1986); it then drifted northward and finally collided with the Qiangtang terrane in the Early Cretaceous (Kapp et al., 2005b). The terrane is bounded to the south by the Yarlung-Tsangpo suture zone (Fig. 1), resulting from closure of the Neo-Tethyan Ocean due to the continental collision between India and Asia (Yin and Harrison, 2000).

The Lhasa terrane consists primarily of Paleozoic and Mesozoic sedimentary strata associated with igneous rocks (Pan et al., 2004). The latter include volcanics and widespread intrusive bodies that have been divided into two suites (Fig. 1): a southern Gangdese belt comprising Late Cretaceous and Paleogene batholiths dominated by dioritic and I-type compositions (Debon et al., 1986), and a northern magmatic belt that includes Early Cretaceous peraluminous, or S-type, granitoids (Xu et al., 1985; Harris et al., 1990). While the Gangdese magmatism is widely ascribed to the northward subduction of the Neo-Tethyan oceanic lithosphere under the Lhasa terrane, the petrogenesis of the northern magmatic belt is debated (Kapp et al., 2005b, for review).

As part of a more detailed, ongoing investigation of Gangdese batholiths (Wen et al., 2003, 2005), this paper reports a comparative study of the northern magmatic belt. Of ~30 granitic samples collected from this belt, 2 (T006C and T109B; Fig. 1) were chosen for zircon analysis. Zircons from sample T006C (biotite granite) are pink or light purple and ~100–250 μm long; crystal forms vary from long to short prismatic and the mean length/width ratio is ~2.7. Zircons from sample T109B (two-mica granite) are mostly transparent, pink to yellow, and ~50–300 μm long, marked by more variable forms, from long to short prismatic to rounded, and a smaller mean length/width ratio of ~1.9. A biotite granite (ST134A) from the central Gangdese belt (Fig. 1) unexpectedly yielded Jurassic zircon U-Pb ages: zircons from this sample are yellowish-pink and ~40–150 μm long, with crystal forms from short prismatic to rounded and a mean length/width ratio of ~2.1.

ANALYTICAL METHODS

Zircons were separated from ~5 kg granitic samples by heavy-liquid and magnetic methods. Cathodoluminescence images (taken at the Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences) were used to check the internal structures of individual zircon grains and to select positions for analyses (GSA Data Repository Fig. DR1[1]). In situ zircon U-Pb dating was carried out at the center using the SHRIMP II system, following the analytical procedures reported in Chung et al. (2003). In situ Hf isotope measurements were subsequently performed on the dated spots within the zircons using LAM–MC–ICPMS (Australian Research Council National Key Centre for Geochemical Evolution and Metallogeny of Continents, Macquarie University). The diameter of the laser-ablated craters is ~50 μm, about twice that of the spots made by SHRIMP dating. The analytical procedures were generally as reported in Griffin et al. (2002), with a New Wave UP193 Excimer laser being attached to a Nu Plasma MC-ICPMS.

Whole-rock granite samples were powdered and measured for major and trace element and Sr-Nd isotope compositions; the analytical methods and results are in Table DR1 (see footnote 1). The zircon U-Pb dating and Hf isotope results are summarized in Tables DR2 and DR3 (see footnote 1), respectively. The $\varepsilon_{Hf}(T)$ values (the parts in 10^4 deviation of initial Hf isotope ratios between the zircon sample and the chondritic reservoir) and $T_{DM}{}^{C}$ (the zircon Hf isotope crustal model ages based on a depleted-mantle source and an assumption that the protolith of the zircon's host magma has the average continental crustal $^{176}Lu/^{177}Hf$ ratio of 0.015), were calculated following Griffin et al. (2002), using the ^{176}Lu decay constant adopted in Blichert-Toft and Albarède (1997). Our conclusions would not be significantly affected if alternative decay constants proposed by more recent studies were used.

ANALYTICAL RESULTS

Zircon U-Pb Ages

Zircons from both granites of the northern belt are largely inherited. In sample T006C, which has an SiO_2 content of 67 wt%, ASI of 1.07, and an Rb-Sr mineral isochron age of 141 ± 2 Ma (Table DR1; see footnote 1), none of the zircons dated (22 analyses for 22 grains, Table DR2; see footnote 1) yielded U-Pb ages in accord with the crystallization age of the rock. These U-Pb results, which plot along the concordia line except for three analyses (Fig. DR2; see footnote 1), show a large age range from ca. 188 to 1860 Ma.

Zircons from sample T109B show similar characteristics in U-Pb ages (21 analyses for 18 grains, Table DR2), which range from ca. 121 to 1750 Ma. Only the youngest analysis is coeval with the crystallization age (ca. 120 Ma, Table DR1). In this sample, most inherited zircons contain higher concentrations of U (>800 to ~4000 ppm) and Th (>400 to ~3000 ppm) relative to the previous sample T006C but similar Th/U ratios (~1.1–0.3). This sample also has a more evolved whole-rock composition, with SiO_2 of 73 wt% and ASI of 1.17, coupled with higher U abundance (6.2 ppm, Table DR1), than the previous sample.

[1]GSA Data Repository item 2006156, zircon U-Pb age and Hf isotope data, with geochemical compositions of the host rocks, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

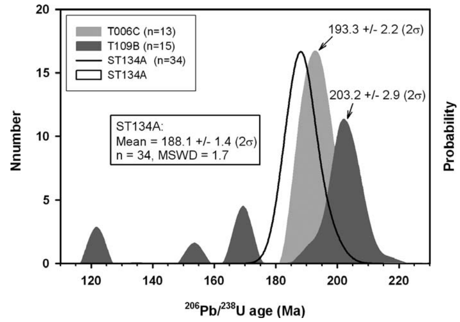

Figure 2. Relative probability plots of zircon $^{206}Pb/^{238}U$ ages for three samples studied, combined with histogram of analytical values for sample ST134A. MSWD—mean square of weighted deviates.

Zircons from both samples show clusters in $^{206}Pb/^{238}U$ ages between ca. 188 and 210 Ma (Table DR2). About half of the zircons in samples T006C (n = 13) and T109B (n = 10) define age clusters at 193.3 ± 2.2 Ma (95% confidence; mean square of weighted deviates [MSWD] = 1.5) and 203.2 ± 2.9 Ma (MSWD = 4.5), respectively.

In contrast, 34 zircons dated from sample ST134A are all magmatic and yielded a weighted mean of $^{206}Pb/^{238}U$ age of 188.1 ± 1.4 Ma (95% confidence; MSWD = 1.7), slightly younger than the two clusters but overlapping the total age range observed in the two granites from the northern belt (Fig. 2). These zircons have relatively low and uniform U and Th concentrations (~100–150 and 70–100 ppm, respectively, Table DR2; see footnote 1), yielding uniform Th/U ratios (~0.5–1.0) typical of an igneous origin (Hoskin and Black, 2000). This U-Pb date is therefore interpreted to represent the crystallization age of the sample that, together with Hf isotope data and whole-rock geochemistry (see following), suggests previously unrecognized plutonism in the Early Jurassic, significantly older than that in the surrounding Late Cretaceous to Paleogene Gangdese batholiths.

Hf Isotope Data

Of the 34 dated zircons from sample ST134A, 20 were analyzed for Hf isotope ratios. They yielded $\varepsilon_{Hf}(T)$ values from +10.4 to +16.8 that straddle the mean value of the depleted mantle at 188 Ma (Fig. 3A). This differs remarkably from the crustal-type Hf isotope composition of the Jurassic inherited zircons from the two granites in the northern

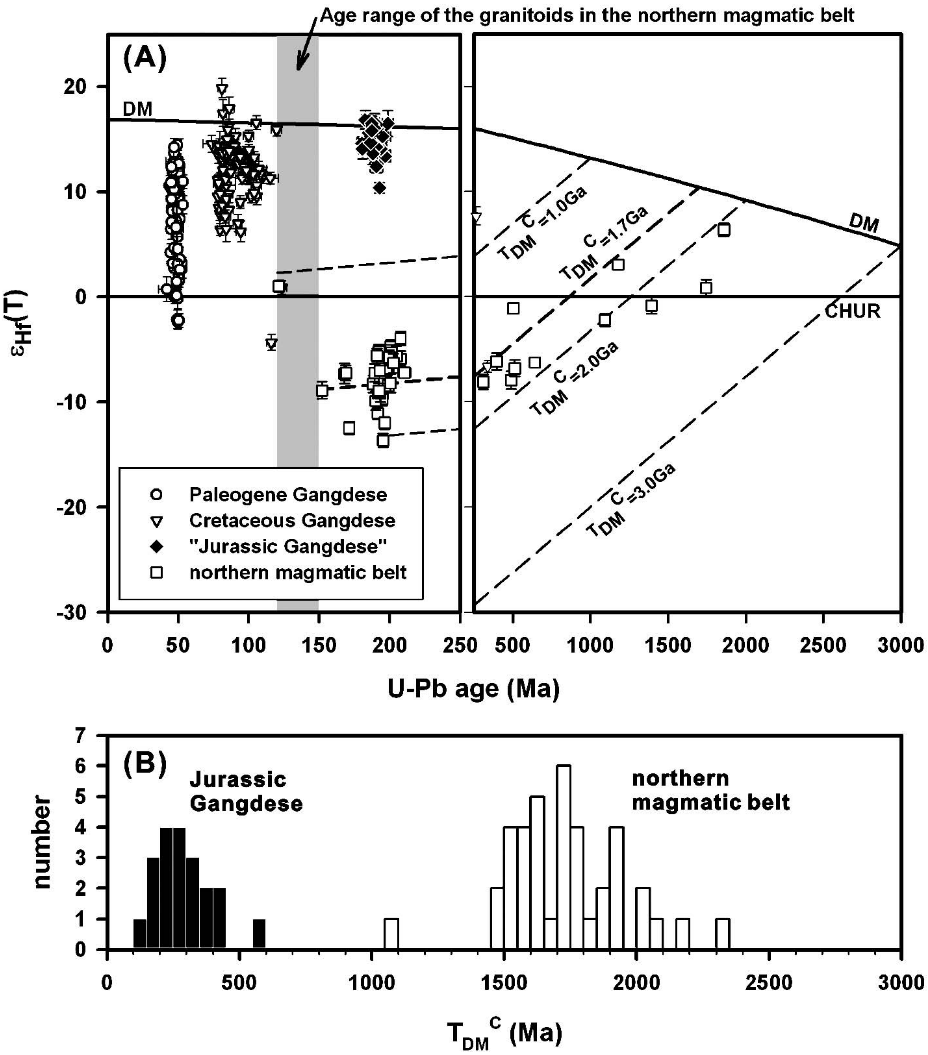

Figure 3. A: Plots of $\varepsilon_{Hf}(T)$ (the parts in 10^4 deviation of initial Hf isotope ratios between the zircon sample and the chondritic reservoir) vs. U-Pb ages. B: Histogram of T_{DM}^{C} (zircon Hf isotope crustal model age) for zircons of Jurassic Gangdese (sample ST134A) and northern magmatic belt (samples T006C and T109B). For comparison, our unpublished data for Cretaceous and Paleogene Gangdese zircons are also plotted in A. Calculation details regarding T_{DM}^{C} ages and notations of chondritic uniform reservoir (CHUR) and depleted-mantle (DM) curves are in Table DR3 (see footnote 1).

magmatic belt that exhibit $\varepsilon_{Hf}(T)$ values from −11.1 to −4.7 (T006C) and from −13.7 to −3.9 (T109B), respectively. The only comagmatic grain (ca. 121 Ma) in sample T109B shows $\varepsilon_{Hf}(T)$ of +1, suggesting a magma source that has an isotope composition between the mantle and crustal values. The remaining inherited zircons, i.e., those with U-Pb ages between ca. 300 and 1860 Ma, show heterogeneous $\varepsilon_{Hf}(T)$ values from +6.4 to −12.5 (Fig. 3A), recording the isotopic variations in the multiple magmatic events that took place in the Lhasa terrane.

DISCUSSION

Crustal Evolution of the Lhasa Terrane

Zircons can effectively preserve the initial Hf isotope ratios of their host magmas, thus allowing their Hf isotope compositions to be utilized in much the same way as whole-rock Nd isotopes have been utilized as a powerful geochemical tracer for petrogenesis. For example, assuming that the protolith of a zircon's host magma had the $^{176}Lu/^{177}Hf$ ratio of the average continental crust (0.015; cf. Griffin et al., 2002), its Hf crustal model ages, or T_{DM}^{C}, may give a reasonable estimate of the elapsed time since the host magma was derived from a presumed depleted mantle source. The igneous zircons from sample ST134A that show juvenile mantle Hf isotope characteristics yield Phanerozoic T_{DM}^{C} ages (Fig. 3B) close to or even younger than the rock's crystallization age (Table DR3; see footnote 1). All zircons from the northern belt, in contrast, have much older T_{DM}^{C} ages, from ca. 1.0 to 2.3 Ga, peaking ca. 1.7 Ga (average = 1722 ± 240 Ma [1σ], n = 46; Fig. 3). This, together with the higher $\varepsilon_{Hf}(T)$ values observed in the older zircons (Fig. 3A), suggests significant growth of the continental crust within the Lhasa terrane between the late Paleoproterozoic and early Mesoproterozoic.

The zircon Hf isotope evidence of an important Proterozoic period of crustal growth in the Lhasa terrane is consistent with the whole-rock Nd model ages of the two granites from the northern belt (ca. 1470–1710 Ma, Table DR1) and available literature data. The latter include (1) whole-rock Nd model ages (ca. 1560–2100 Ma) reported for Carboniferous–Neogene sedimentary rocks (Harris et al., 1990), (2) Nd model ages (ca. 1240–1650 Ma) for the Amdo gneiss (Harris et al., 1990), the only basement complex exposed in the northern margin of the Lhasa terrane (Fig. 1), (3) Nd model ages (ca. 900–2190 Ma) for the Nyainqentanglha Range granitoids (Kapp et al., 2005a), and (4) substantial amounts of Proterozoic detrital zircons from a Carboniferous sandstone and sediments along the bank of the Yarlung-Tsangpo River (Liang et al., 2004). These allow us to conclude that the Lhasa terrane underwent a major stage of crustal formation in the Proterozoic, and this crust was remelted in the Early Jurassic, producing abundant igneous zircons that were later captured by the Cretaceous S-type plutonism in the northern magmatic belt.

Jurassic Gangdese and Related Magmatism

The zircon U-Pb ages and Hf isotopes of sample ST134A strongly suggest Early Jurassic intrusive activity that was marked by a dominant contribution from a juvenile mantle source. Although the data are insufficient for a detailed petrogenetic analysis, a comparison of the geochemical systematics of sample ST134A with those of nearby Cretaceous–Paleogene Gangdese granitoids (e.g., sample ST104A, Table DR1; see footnote 1) may help us explore the tectonic setting associated with the Jurassic magmatism. These two samples show relative enrichments in large ion lithophile and light rare earth elements, depletions in high field strength elements, and juvenile mantle–type Sr and Nd isotope ratios (Table DR1). Isotopic similarity is also revealed by the $\varepsilon_{Hf}(T)$ values of the igneous zircons from sample ST134A and the Cretaceous Gangdese granitoids (Fig. 3A). A common tectonic setting, i.e., an active convergent margin associated with northward subduction of Neo-Tethyan oceanic lithosphere under the Lhasa terrane, is therefore inferred for the Early Jurassic magmatism.

Volcanic rocks intercalated with Jurassic sedimentary strata have been reported in the southern Lhasa terrane. These are andesitic to rhyolitic rocks from the uppermost Triassic–Middle Jurassic Yeba Formation (Yin and Grant-Mackie, 2005) and the Upper Jurassic–Lower Cretaceous Sangri Group (Pan et al., 2004); both are exposed in the eastern Gangdese region (Fig. 1) and are conventionally regarded as products of convergent margin magmatism, although few detailed petrologic and geochemical investigations exist. Additional information that supports the widespread occurrence of Jurassic magmatism in the southern Lhasa terrane includes (1) abundant Jurassic detrital zircons ($^{206}Pb/^{238}U$ ages = 194–169 Ma; 24 of 60 analyses) in a Cretaceous tuffaceous sandstone from the Gangdese belt (Liang et al., 2004), (2) the common presence of Jurassic zircons in the Yarlung-Tsangpo River sediments that show $^{206}Pb/^{238}U$ ages of ca. 182–175 Ma and $\varepsilon_{Hf}(T)$ values to +15 (Liang et al., 2004), and (3) the Jurassic inherited zircons (ca. 204–181 Ma) in the Nyainqentanglha Range granitoids (Kapp et al., 2005a).

We therefore propose that within the southern Lhasa terrane, there were three discrete stages of Gangdese arc magmatism in the Jurassic, Cretaceous, and Paleogene. Within this framework, the Neo-Tethyan subduction system must have played a crucial and long-lasting role in the tectonic evolution of the Lhasa terrane, from when the terrane was drifting northward from Gondwana until its final assembly with India. Whereas the latter two stages of the Gangdese magmatism appear to be separated by a magmatic gap from ca. 80 to 65 Ma (Chung et al., 2005; Wen et al., 2005), the temporal and spatial relationships between the former two stages remain relatively unknown and require more investigation.

Further Tectonic Implications

By the Early Jurassic, extensive and dominantly crustally derived magmatism may have already been active in the northern part of the Lhasa terrane, as evidenced by our results from the two S-type granites and a study by Kapp et al. (2005a) on the Nyainqentanglha Range granitoids. The latter work, albeit focused on the late Cenozoic exhumation and thermal history of the Nyainqentanglha massif, reported a total of 459 U-Pb analyses for zircons from more than 40 granitoid samples that identify an age peak ca. 210 Ma (Kapp et al., 2005a). Our sample T109B, which yields the zircon age cluster of ca. 203 Ma, was collected near the southern extension of the Nyainqentanglha Range (Fig. 1). The Jurassic and Cretaceous Gangdese magmatic activities, predating and postdating the final assembly of the Lhasa and Qiangtang terranes in Early Cretaceous time (Kapp et al., 2005b), respectively, are both associated with S-type magmatism in the northern Lhasa terrane that may reflect substantial crustal remelting there. Such an association not only reinforces the suggestion of a common tectonic setting for the two Gangdese magmatic stages, but also provides clues about the long-term debate on the petrogenesis of the northern magmatic belt, which has been attributed to (1) anatexis of thickened crust during the continental collision of the Lhasa and Qiangtang terranes (Xu et al., 1985; Pearce and Mei, 1988), (2) crustal melting caused by asthenospheric upwelling after the Lhasa-Qiangtang collision (Harris et al., 1990), or (3) low-angle northward subduction of the Neo-Tethyan oceanic slab (Coulon et al., 1986; Zhang et al., 2004; Kapp et al., 2005b). Kapp et al. (2005b) suggested that this low-angle subduction provided the driving force for a large-scale northward continental underthrusting during the Lhasa-Qiangtang collision. Our observations do not support the former two scenarios, but are not at odds with the third interpretation. If this is the case, the low-angle or flat-slab subduction should have taken place before and after the Lhasa-Qiangtang collision. How such a long-lasting subduction system evolved in the Neo-Tethys and how it interacted with the Lhasa-Qiangtang and then with the India-Asia continental collisions requires further detailed studies, which will elucidate the complex accretionary and collisional orogenic processes that operated in what is now the southern Tibetan Plateau.

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