Zircon xenocrysts in Tibetan ultrapotassic magmas: Imaging the deep crust through time

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Geology 2014;42;43-46
doi: 10.1130/G34902.1
Zircon xenocrysts in Tibetan ultrapotassic magmas: Imaging the deep crust through time

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ABSTRACT

Zircons entrained in mantle-derived magmas offer a unique opportunity to identify cryptic magmatic episodes in the deep crust and thus to image lithospheric thickening and crustal evolution. We investigated zircon xenocrysts from mantle-derived ultrapotassic rocks in southern Tibet to evaluate their potential as a probe of crustal evolution. Similar age (Proterozoic–Paleozoic) distributions of these zircons and those in the Lhasa terrane detrital spectra demonstrate the continental origin of xenocrysts with high U/Yb. Time-progressive variations in zircon εHf(t) reveal three major magmatic pulses ca. 90, 50, and 20 Ma, suggesting significant crustal growth in the Lhasa terrane at those times. This is consistent with major mantle inputs previously documented from surface rocks in the Lhasa terrane. Increasing Dy/Yb and U/Yb since ca. 55 Ma are interpreted to reflect progressive crustal thickening in response to the India-Asia convergence. Zircon xenocrysts with varying U-Pb ages and heterogeneous Hf isotopes indicate assimilation of Lhasa terrane crust in the genesis of ultrapotassic magmas.

INTRODUCTION

Since its separation from Gondwana (Zhu et al., 2011a), the Lhasa terrane has undergone a series of subduction events that have modified the crust through successive magmatic pulses (Yin and Harrison, 2000; Chung et al., 2005; Ji et al., 2009; Zhu et al., 2011b, 2013). However, plateau uplift associated with the continued India-Asia convergence has also led to extensive erosion in southern Tibet (Harrison et al., 1992; Yin and Harrison, 2000; Hetzel et al., 2011) that may have obscured once-exposed magmatic records, and thus hampers understanding of the evolution of the Lhasa terrane. As typical mantle-derived high-Mg rocks (MgO > 3 wt%), postcollisional ultrapotassic volcanics (UPV) in southern Tibet carry not only information on mantle sources, but also signals from crustal fragments entrained during magma ascent (Miller et al., 1999; Nomade et al., 2004; Zhao et al., 2009). These UPV rocks contain abundant zircon xenocrysts of pre-eruption age (cf. Liu et al., 2011), offering a prime opportunity to reveal signatures of magmatic pulses hidden in the deep crust of the Lhasa terrane. Using a combined in situ method of zircon chronology, trace element, and Hf isotope geochemistry, we present a systematic study of these xenocrystic zircons. Our zircon data show a more detailed pattern of mantle input, crustal reworking, and thickening in the central Lhasa subterrane than those revealed from surface rocks and, as a case study, our findings underscore the potential of zircon xenocrysts from mantle-derived magmas to image crustal evolution through time.

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TEC TONIC SETTING AND ULTRAPOTASSIC MAGMATISM

The Lhasa terrane, characterized by reworked ancient crust in the center and juvenile additions to both its northern and southern edges, can be subdivided into the northern, central, and southern subterranes (Zhu et al., 2011b). In the northern and central Lhasa subterranes, Early Cretaceous granitoid magmatism and coeval volcanic rocks (ca. 143–102 Ma) are widely exposed as a result of either southward subduction of the Bangong-Nuijiang Tethyan seafloor (Zhu et al., 2011b, 2013) or northward flat-slab subduction of the Neo-Tethyan oceanic lithosphere (cf. Kapp et al., 2007a). The Gangdese batholith (Triassic–Cenozoic) and Linzinzong volcanic rocks (ca. 63–40 Ma) distributed in the southern Lhasa subterrane are interpreted as resulting from the Neo-Tethyan oceanic seafloor subduction and subsequent India-Asia continental collision (cf. Chung et al., 2005). After the India-Asia collision in the early Paleogene, postcollisional magmatism in southern Tibet (including the Tethyan Himalaya) mainly consists of potassic-ultrapotassic volcanic rocks, adakitic intrusive rocks, and S-type granitoids (cf. Chung et al., 2005; Aikman et al., 2008; Zhao et al., 2009; Liu et al., 2011).

The majority of the Miocene UPV rocks are restricted to the central Lhasa subterrane, forming a magmatic belt roughly parallel to the east–west–trending direction of the Lhasa terrane (Fig. 1A). These UPV rocks commonly occur as bedded lava flows unconformably overlying the Cretaceous–Paleogene volcanoclastic–sedimentary strata (Miller et al., 1999; Nomade et al., 2004; Liu et al., 2011); some crop out as dikes crosscutting Cretaceous Xigaze marine forearc strata in the southern Lhasa subterrane. Crustal xenoliths are abundant in the UPV rocks (Figs. 1B–1D).

Figure 1. A: Geologic map showing sample localities and spatial distribution of postcollisional ultrapotassic-potassic rocks in southern Tibet. BNS—Bangong-Nujiang suture zone; SNMZ—Shiquan River–Nam Tso mélangé zone; LMF—Luobadui-Milashan fault; KF—Karakorum fault; IYYS—Indus-Yarlung Zangbo suture zone; STDS—Southern Tibetan detachment system; MCT—Main Central thrust; MBT—Main Boundary thrust. B–D: Field photos of variety of crustal xenoliths (dashed lines) identified in Miocene ultrapotassic rocks.
ANALYTICAL METHODS

The UPV rocks sampled from the central Lhasa subterrane (Fig. 1A) were crushed to 80 mesh after excluding obvious crustal xenoliths by hand-picking. Zircons extracted from such UPV host rocks were mounted in epoxy and polished to expose grain interiors. Detailed descriptions of the UPV samples, zircon cathodoluminescence images, in situ analytical methods, analytical data, and data plots are given in the GSA Data Repository1.

RESULTS

Zircons in nine UPV samples yield U-Pb ages ranging from 3134 Ma to 10 Ma (657 analyses; Tables DR1–DR4) and Figures DR1–DR3, and are mostly of Mesozoic–Cenozoic (160–10 Ma). These zircons define three major age peaks ca. 90, 50, and 20 Ma (Fig. 2A). The youngest zircon groups in each sample vary from 24 Ma in the west to 10 Ma in the east (Fig. 1A), consistent with previously published Miocene erosive ages (Table DR1). Zircons with older U-Pb ages are xenocrystic. Except for some ca. 90 Ma zircons with homogeneous interiors, most Mesozoic–early Paleogene zircon xenocrysts show clear oscillatory zoning (Fig. DR1). In contrast, the youngest zircons (24–10 Ma) are unzoned or typically exhibit weak zoning (Fig. DR1).

The UPV zircons have a wide range of $\epsilon_H(t)$ values (the deviation of the initial Hf isotope ratio between the zircon sample and chondritic reservoir) that define three major perturbations at ca. 120–80 Ma, 60–45 Ma, and 25–10 Ma (Fig. 2B). In the Mesozoic population, zircon $\epsilon_H(t)$ values yield a rapidly increasing trend (from −15.4 to +5.5) in the Early Cretaceous (ca. 120 Ma), followed by a decreasing trend (from +6.9 to −11.6) in the Late Cretaceous (ca. 80 Ma). In the Cenozoic populations, zircons are characterized by highly variable $\epsilon_H(t)$ values (from −11.9 to +12.5) during the early Paleogene (ca. 60–45 Ma) and then by decreasing $\epsilon_H(t)$ at ca. 45 Ma (from +5.1 to −13.5; Fig. 2B). Compared with the Mesozoic and early Paleogene zircons, zircon $\epsilon_H(t)$ values are overall low throughout the Miocene (−21.2 to +1.2; Fig. 2B).

The Th/U of zircons in UPV rocks range from 5.1 to 0.1 (Table DR3; Fig. 3A), except for a few with Th/U < 0.07 (Fig. 3A). The UPV zircons have similar positive Ce and negative Eu anomalies (Fig. DR3). However, relative to middle rare earth elements (MREEs), their enrichments of heavy (H) REEs are different. Some zircons, with U-Pb ages younger than 55 Ma, have generally low HREE/MREE, whereas other zircons show elevated HREE abundances (Fig. DR3).

DISCUSSION

Origin of Zircon Xenocrysts in Ultrapotassic Rocks

Previous studies revealed that postcollisional UPV rocks in the Lhasa terrane have continental crust–like Sr-Nd-Pb isotopic signatures and high $\delta^{18}$O (cf. Miller et al., 1999; Nomade et al., 2004; Zhao et al., 2009), although major element compositions are consistent with their being of mantle origin. Such contrasting features of crust- and mantle-derived magmas imply that zircon xenocrysts in UPV rocks could have originated from a metasomatized mantle reservoir or been entrained during magma ascent through the crust.

Zircons with pre-eruptive ages have been identified from mantle xenoliths and mantle-derived rocks, as exemplified by the kimberlite and mantle xenoliths from the Kaapvaal craton and alkaline basalt from the Eger rift (cf. Konzett et al., 2000; Siebel et al., 2009), suggesting that pre-eruptive metasomatism in mantle sources can be recorded by mantle zircons. However, the majority of zircon xenocrystals in the Tibetan UPV rocks are not mantle derived, but instead have continental crust affinity, for the following reasons. Mantle zircons are characterized by lacking pronounced Eu anomalies, low Th and U contents (in mantle zircons from phlogopite-bearing peridotite and kimberlite), and anomalously high Th/U (>3 in zircons from veined harzburgite; Fig. 3A) (cf. Konzett et al., 2000; Hoskin and Schaltegger, 2003; Siebel et al., 2009). These are in contrast to most zircon xenocrystals in the UPV rocks that display negative Eu anomalies (Fig. DR3), high Th and U abundances, and varying but relatively low Th/U (2.5–0.07; Fig. 3A). Furthermore, the relatively high U/Yb values of UPV zircons are consistent with a continental crust origin rather than being inherited from recycled oceanic crust characterized by low U/Yb (Fig. 3B) (Grimes et al., 2007). These observations, together with the crustal xenoliths found in the UPV rocks (Figs. 1B–1D), make the Lhasa terrane and underthrust Indian continent as the two potential provenances for zircons in the UPV rocks. Given that the 160–55 Ma magmatism is very rare in the northern Indian crust (Yin and Harrison, 2000; Zhu et al., 2013) but is extensive in the Lhasa terrane (Chung et al., 2005; Wen et al., 2008; Ji et al., 2009; Zhu et

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Footnote 1: GSA Data Repository item 2014011, detailed analytical methods, sample description, in-situ analytical data (Tables DR1–DR4), and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
al., 2011b), we conclude that the Lhasa terrane crust is the dominant provenance for zircon xenocrysts in the UPV rocks, and assimilation of Lhasa crust plays a significant role in the petrogenesis of the Tibetan ultrapotassic rocks.

Zircon Records of Crustal Reworking During Mesozoic–Cenozoic Magmatism

Crustal formation and reworking processes are thought to be closely related to magmatism and its associated thermal perturbation during plate convergence (Hawkesworth and Kemp, 2006). Substantial mantle input into magma can be recorded by zircon Hf isotopic ratios because the emplacement of voluminous basaltic magmas will enable more primitive magmas to crystallize zircons with high $e_{\text{Hf}}(t)$ values. Zircons preserved in the UPV rocks reveal three magmatic pulses in the deep crust, all of which are marked by varying Hf isotopic compositions (Fig. 2). Based on the continental crust origin, we interpreted such magmatic pulses presented by UPV zircons as indicating significant mantle inputs that can be linked to the crustal formation and reworking in the central Lhasa subterrane at those times.

The interpretation here is further supported by the correspondence between UPV zircon records and surface rocks related to the crustal growth in the Lhasa terrane (Wen et al., 2008; Ji et al., 2009; Zhu et al., 2011b, 2013). The Mesozoic crustal growth recorded by UPV zircon Hf isotope commenced at ca. 115 Ma with an increasing trend in $e_{\text{Hf}}(t)$ that remains high until ca. 90 Ma (Fig. 2B), possibly corresponding to the 113 ± 5 Ma mafic-flare-up postulated to result from slab break-off of the southward-subducting Bangong-Nujiang Tethyan seafloor (Zhu et al., 2011b, 2013) and/or the rollback of the Neo-Tethyan subducting slab (ca. 100–80 Ma; cf. Wen et al., 2008). The relatively high $e_{\text{Hf}}(t)$ values of the early Paleogene (ca. 60–45 Ma) zircons (Fig. 2B) are similar to the syncollisional magmatic records in the southern Lhasa subterrane (cf. Ji et al., 2009; Zhu et al., 2013), which can be explained by rollback and subsequent break-off of the Neo-Tethyan oceanic slab (ca. 65–45 Ma; Chung et al., 2005; Ji et al., 2009) and/or by Asian plate lithospheric removal (ca. 60–50 Ma; Kapp et al., 2007b). The wide range of Miocene zircon $e_{\text{Hf}}(t)$ values (>10 ε units) suggests a continued mantle contribution to the postcollisional magmatism, which could have been triggered by convective thinning of overthickened lithospheric mantle (Chung et al., 2005; Zhao et al., 2009; Liu et al., 2011) or rollback of subducted Indian lithosphere (Nomade et al., 2004).

Crustal Thickening History Recorded in Zircon Xenocrysts

Some UPV zircon xenocrysts have extremely high U/Yb ratios and low HREE/MREE ratios (Fig. DR3), similar to those in zircons of eclogite and granulite origin (Fig. 3B). Given the increasing enrichment of HREEs displayed by zircons from adakitic rocks ($\text{Dy}_N/\text{Yb}_N < 0.3$; Guan et al., 2012), the nearly flat HREE patterns in UPV zircons are not observed in any well-documented crustal suite and cannot have crystallized from the highly HREE-depleted adakitic magmas because of zircons’ strong preference for HREEs (Rubatto, 2002; Hoskin and Schaltegger, 2003). We interpret such HREE-depleted zircons with relatively high Th/U ratios (94% of analyses > 0.2) and concordant U-Pb ages as having crystallized under a very limited HREE supply.

One possible source supplying very limited HREEs is the melting residues after adakite melt extraction deep in the lower crust under eclogite facies conditions. With the presence of abundant garnet in such melting residues, the incompletely extracted interstitial residual melt would be expected to be highly depleted in HREEs. Zircons crystallized from such residual melt would therefore have low HREEs. This scenario suggests that the adakitic magmatism would occur earlier than ultrapotassic magmatism, and can be supported from the field observation that postcollisional volcanism in the Xungba area consists of ultrapotassic rocks and underlying coeval potassic rocks with adakitic geochemical signatures (Liu et al., 2011). Thus, we suggest that zircons with high $\text{Dy}_N/\text{Yb}_N$ and $\text{U}/\text{Yb}$ are indicative of thickened crust with eclogite and garnet-bearing granulitic lower crust. In this regard, the systematic changes in UPV zircon trace elements, i.e., the $\text{Dy}_N/\text{Yb}_N$ and $\text{U}/\text{Yb}$ ratios remain low until ca. 55 Ma and then rise dramatically (Fig. 4), can be interpreted as the consequence of significant crustal thickening of the central Lhasa subterrane at that time. Such interpretation in terms of zircon geochemical data is corroborated by Eocene adakitic rocks in the Gangdese batholith (51±3 Ma; Guan et al., 2012; Ji et al., 2012), high Sr/Y granitoids in the Tethyan Himalaya (ca. 44 Ma; Aikman et al., 2008), and the results of thermochronological studies (cf. Hetzel et al., 2011), all of which suggest a complicated crustal shortening history initiated before or in the early stage of the India-Asia continental collision (Kapp et al., 2007b; Hetzel et al., 2011).

A notable feature of Figure 4 is that no distinct excursions of $\text{Dy}_N/\text{Yb}_N$ and U/Yb ratios are seen in the Mesozoic zircon xenocrysts; this is different from Cenozoic zircons. This implies that crustal thickening in the central Lhasa subterrane did not reach the threshold beyond which HREE depletion in zircons was triggered.

Implications for Postcollisional Ultrapotassic Magmatism

The Tibetan Miocene ultrapotassic magmas are generally thought to represent melts of enriched mantle sources, and to be capable of tracing subduction events (cf. Miller et al., 1999; Zhao et al., 2009). However, the presence of abundant zircon xenocrysts and a wide range of zircon $e_{\text{Hf}}(t)$ values observed in the Miocene UPV zircons (25–10 Ma) indicate that materials across the full range of the lithosphere may have contributed to the UPV magmas. At least two kinds of crustal component may have been involved: juvenile lower crust and ancient Lhasa basement (middle-upper crust). Input from juvenile lower crust that might have been overthickened during India-Asia convergence can be supported by the entrained gabbroic xenoliths (Fig. 1D) and the positive $e_{\text{Hf}}(t)$ values of ca. 90 and 50 Ma zircon xenocrysts in the UPV rocks (Fig. 2B). Contribution from ancient Lhasa basement is supported by the presence of Proterozoic and Paleozoic zircon xenocrysts, the age distributions (two age peaks ca. 450 Ma and ca. 1050 Ma) and Hf isotopic compositions of which are comparable to the detrital zircon spectra in Permian–Carboniferous metasedimentary strata (Zhu et al., 2011a) and inherited zircons in S-type granite (ca. 206 Ma; Zhu et al., 2011a, 2013) from the Lhasa terrane (Fig. 5).

CONCLUSIONS

Continental-like signatures in the UPV zircons indicate a xenocrystic origin during magmatic ascent through the deep crust, corroborating the role of crustal contaminants in the petrogenesis of the UPV host rocks. These zircon xenocrysts yield $e_{\text{Hf}}(t)$ values and U-Pb ages indicative of several major magmatic pulses ca. 90, 50, and 20 Ma that correlate well with both crustal reworking and thickening histories of southern Tibet and match well with the known magmatic


Manuscript received 3 July 2013
Revised manuscript received 11 September 2013
Manuscript accepted 2 October 2013
Printed in USA