Potassic volcanic rocks and adakitic intrusions in southern
Tibet: Insights into mantle-crust interaction and mass transfer
from Indian plate

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Abstract

Elucidating geodynamic processes at depth relies on a correct interpretation of petrological and geochemical features in magmatic records. In southern Tibet, both potassic volcanic rocks and adakitic intrusions exhibit high Sr/Y and La/Yb, and low Y and Yb concentrations. But these two rocks types have contrasting temporal-spatial distributions and isotopic variations. Here we present a systematic study on the postcollisional potassic and adakitic rocks in order to investigate their petrogenetic links with the coeval mantle-derived ultrapotassic rocks and shed light on the potential input from underthrust Indian continental crust. We found that adakitic intrusions with higher K_2O/Na_2O tend to display lower Y and higher SiO_2 , suggesting that the mantle-derived ultrapotassic melts, showing relatively high Y and Yb concentrations, only played a minor role in adakitic magmatism. Therefore, unradiogenic $^{143}Nd/^{144}Nd$ and the dramatic decrease of zircon $\epsilon_{Hf}(t)$ values since ~35 Ma shown by postcollisional adakites should be interpreted as reflecting the crust input from Indian continental crust. Unlike adakitic intrusions in southern Lhasa subterrane, potassic volcanic rocks share similar spatial distributions with ultrapotassic rocks, and their isotopic discrepancy is diminishing with volcanic activity becomes younger and migrates eastward. Evidence from whole-rock Pb and zircon Hf isotopes further indicates that potassic volcanic rocks are more likely to originate from partial melting of the overthickened and isotopically heterogeneous Lhasa terrane crust rather than the underthrust Indian crust. The elevated Rb/Sr and varying Sr/CaO in potassic volcanic rocks provide an argument for sanidine + plagioclase + clinopyroxene as the major fractionating phases during magmatic differentiation.

42 These findings not only highlight the significance of potassic and adakitic rocks in providing
43 constraints on the geodynamic processes beneath southern Tibet, but also imply that special
44 caution is needed if we attempt to probe into the nature of mantle lithosphere using isotopic
45 tracers from the Tibetan ultrapotassic rocks.

46 **Keywords:** Sr–Nd–Pb–Hf isotopes, potassic volcanic rocks, adakitic intrusions, Lhasa terrane,
47 Tibetan plateau

1. Introduction

Geological evolution of the Tibetan plateau is associated with generation and emplacement of various igneous rocks (Coulon et al., 1986; DeBon et al., 1986; Yin and Harrison, 2000; Chung et al., 2005; Zhu et al., 2013). During the past three decades, the studies about postcollisional magmatic rocks (< 40 Ma) in southern Tibet provides unique insights into a series of fundamental issues, such as the deep processes and their relations to plateau uplift (England and Houseman, 1989; Turner et al., 1996; Chung et al., 2005; Molnar and Stock, 2009), the Indian continental subduction and crustal thickening (Chung et al., 2009; Zhao et al., 2009; Chen et al., 2010, 2011; Chu et al., 2011; Liu et al., 2014a; Guo et al., 2015), and the formation of collision-related porphyry copper deposits (Hou et al., 2004, 2015a; Zheng et al., 2012; Wang et al., 2015; Yang et al., 2015).

However, the petrogenetic relationships among different rock types (e.g. mantle-derived ultrapotassic rocks, potassic volcanic rocks, and adakitic intrusions) remains controversial (Turner et al., 1996; Miller et al., 1999; Chung et al., 2005; Chen et al., 2012; Liu et al., 2014b; Hou et al., 2015a; Zhang et al., 2015), which constitutes a major limitation to comprehensively understand the geological evolution of Tibetan plateau. More contentious issue is whether the evolved isotopic signatures shown by postcollisional magmatic rocks can be directly linked to the mass transfer from underthrust Indian plate or, instead, reflect the nature of continental lithosphere beneath southern Tibet (Miller et al., 1999; Williams et al., 2004; Zhao et al., 2009; Chen et al., 2010; Chu et al., 2011; Liu et al., 2014b, 2015; Guo et al., 2015; Tian et al., 2015; Ma et al., 2016).

The Miocene potassic volcanic rocks have intermediate to felsic compositions ($\text{MgO} < 3$ wt.%) signatures and display “adakitic affinity” with the collision-type adakitic intrusions (Chen et al., 2010; Liu et al., 2014b). Meanwhile, the evolved Sr–Nd–Hf isotopes and relatively high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (> 1) make these potassium-rich rocks more comparable to the coeval mantle-derived ultrapotassic rocks (Miller et al., 1999; Zhao et al., 2009; Chen et al., 2012; Liu et al., 2014b; Tian et al., 2015). These observations indicate the potential of postcollisional potassic volcanic rocks to unravel petrogenetic links among different types of magmatic rocks, and thus to illuminate deep processes occurred in response to the continuous convergence between India and Asia.

In this paper, we revisited the petrogenesis of postcollisional potassic volcanic rocks and adakitic intrusions in southern Tibet. New zircon and whole-rock geochemical data allow us (i) to clarify the petrogenetic distinctions between potassic and adakitic rocks, (ii) to investigate crustal structure and composition of the Lhasa terrane, (iii) to provide reliable constraints on the mass transfer from underthrust Indian plate, and (iv) to better understand why crustal contamination had profound influence on the geochemical evolution of mantle-derived ultrapotassic magma.

2. Geological setting and sampling

The Lhasa terrane in southern Tibet is located to the south of and separated from the Qiangtang terrane by the Bangong-Nujiang suture zone (Yin and Harrison, 2000; Zhu et al., 2013). The Indus-Yarlung Zangbo suture zone, as the southern boundary, separates the Lhasa

terrane from the Indian continent (Fig. 1a). During the northward drift from eastern Gondwana, the Lhasa terrane underwent episodes of Tethyan seafloor subduction, which gives rise to a reworked ancient crust in the center and juvenile additions (i.e. newly extracted from mantle) to its northern and southern edges (Wen et al., 2008; Ji et al., 2009; Zhu et al., 2013; Jiang et al., 2014; Hou et al., 2015b). Accordingly, the Lhasa terrane can be subdivided into the northern, central, and southern Lhasa subterrane, which are separated by the Shiquanhe-Nam Tso mélangé zone and the Luobadui-Milashan fault from north to south (Fig. 1b).

As a consequence of the Tethyan seafloor subduction and the continental collision between India and Asia thereafter, the Mesozoic to early Cenozoic magmatic rocks are widely distributed in the Lhasa terrane (Fig. 1a). The Gangdese batholith can be subdivided into the north Gangdese batholith (194 – 110 Ma, Harris et al., 1990; Zhu et al., 2013) and the south Gangdese batholith (210 – 44 Ma, DeBon et al., 1986; Ji et al., 2009; Jiang et al., 2014). In the northern and central Lhasa subterrane, Gangdese batholith and its associated volcanic rocks are postulated to be products of the obliteration of Bangong-Nujiang Neo-Tethyan ocean and the continental collision between Qiangtang and Lhasa terrane (Zhu et al., 2013; Chen et al., 2014; Li et al., 2014; Wang et al., 2014). To the south, the emplacement of south Gangdese batholith is commonly attributed to the low-angle northward subduction of Indus-Yarlung Zangbo Neo-Tethyan seafloor (Coulon et al., 1986; Wen et al., 2008; Ji et al., 2009; Zhu et al., 2013; Jiang et al., 2014). The Linzizong volcanic succession (65 – 43 Ma), with geochemical compositions being very similar to the bulk continental crust (Niu et al., 2013), occurred in response to the India-Asia continental collision at early Eocene (cf. Zhu et al., 2015).

With the continuous convergence between India and Asia, postcollisional magmatism is widespread in the central and southern Lhasa subterrane, and mainly consists of mantle-derived ultrapotassic volcanic rocks (UPVR), potassic volcanic rocks (PVR), and adakitic intrusions (see review by Chung et al., 2005). Mantle-derived ultrapotassic rocks, with zircon U–Pb ages varying from 24 Ma to 10 Ma (Liu et al., 2014a), usually occurred as lava flows outcropping throughout the central Lhasa subterrane (Turner et al., 1996; Miller et al., 1999; Williams et al., 2004; Zhao et al., 2009; Liu et al., 2014a, 2015; Guo et al., 2015) (Fig. 1b). Potassic volcanic rocks of intermediate to felsic compositions were mainly distributed in the central and southern Lhasa subterrane (Turner et al., 1996; Miller et al., 1999; Liu et al., 2014b). Ar–Ar dating and zircon U–Pb dating on these high-potassium intermediate to felsic rocks yield the Miocene eruptive ages (Miller et al., 1999; Nomade et al., 2004; Chen et al., 2010; Liu et al., 2014b), which confirms that they are coeval with the Tibetan ultrapotassic rocks (Chung et al., 2005; Liu et al., 2014a). Particularly, a remarkable feature for the early-Miocene potassic volcanic rocks in southwestern Tibet is their bimodal distribution with overlying mantle-derived ultrapotassic lava (Liu et al., 2014b). In contrast, adakitic magmatism, which commonly occurred as small-volume intrusions or dikes and intruded into the Gangdese batholith and associated syn-collisional volcanic rocks, were concentrated in the southern Lhasa subterrane (Fig. 1b). High-quality zircon U–Pb dating results indicate that most adakitic intrusions were emplaced during the late Oligocene-Miocene (31 – 9 Ma, Chung et al., 2009; Xu et al., 2010; Chu et al., 2011; Zheng et al., 2012; Liu et al., 2014b; Hou et al., 2015a; Wang

et al., 2015), with a few of them emplaced as early as the Eocene (51 – 38 Ma, Guan et al., 2012; Ji et al., 2012).

Based on the aforementioned spatial distribution features, we collected 14 adakitic samples and 34 PVR samples from the Lhasa terrane (Fig. 1b). Six UPVR samples from Chazi area were also included in this study. Adakite samples from Dajia Co area are trachytic and contain ~10 % phenocrysts of sanidine and plagioclase (Fig. 2). The studied PVR samples are typified by good exposures of silica-oversaturated lava flows from Yangying, Chazi, Zabuye, and Xungba-Yare area (Fig. 2). Except for some trachydacite and trachyandesite samples, most PVR samples are typical trachytes in composition and have porphyritic texture (Fig. 2) with phenocrysts mainly composed of sanidine, plagioclase, clinopyroxene, and minor biotite (Fig. 2). Compared with the Chazi PVR samples, the associated ultrapotassic rocks have more clinopyroxene phenocryst. Details of sample location, rock types, and mineral assemblages for phenocryst and groundmass are summarized in supplementary material Table S1.

3. Analytical methods

3.1. Zircon U–Pb dating and Hf isotopes

Zircon grains extracted from crushed rocks were mounted in epoxy resins, and then were polished to expose interiors before being imaged by cathodoluminescence (CL). Zircon U–Pb dating was carried out using a laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences (GPMR-CUG), Wuhan. Laser sampling was performed by an

excimer laser ablation system (GeoLas 2005) with ablation spot size of 32 μm , and ion-signal intensities were acquired by the ICP-MS instrument (Agilent 7700x). Zircon 91500 was used as an external standard for U–Pb dating analysis. Each measurement consists of ~20 s background acquisition and ~50 s data acquisition. Details of the instrumental operating conditions and measurement parameters, off-line selection and integration of background and sample signals, time-dependent drifts correction and quantitative calibration have been summarized in Liu et al. (2010). Common Pb correction procedure was based on Andersen (2002). Analytical results of zircon standards (91500 and GJ-1) are shown in Fig. S1. Zircon U–Pb dating results are given in Table S2.

Zircon in situ Hf isotope analysis was conducted using a Thermo-Finnigan Neptune MC-ICPMS equipped with a 193 nm Excimer ArF laser-ablation system (GeoLas Plus) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Zircon in situ Lu–Hf isotopic data was acquired with the spot size of 44 μm and 60 μm . The mean value of $^{173}\text{Yb}/^{171}\text{Yb}$ for each analytic spot was used to calculate the fractionation coefficient of Yb (β_{Yb}). The β_{Yb} value and the $^{176}\text{Yb}/^{172}\text{Yb}$ ratio of 0.5887 were applied for evaluating the interference of ^{176}Yb on ^{176}Hf (Wu et al., 2006). Zircon standards, Mud Tank and GJ-1, were analyzed as quality control standards. As shown in Fig. S1, average $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for the Mud Tank and GJ-1 were 0.282512 ± 0.000019 (2σ , $n = 54$) and 0.282019 ± 0.000025 (2σ , $n = 54$), respectively, which agree well with the recommended values (Woodhead and Hergt, 2005). Zircon Lu–Hf isotopic data are given in Table S3.

3.2. Whole-rock major and trace elements

Major element analyses were performed using a sequential X-ray fluorescence spectrometer (Shimadzu XRF-1800) at the GPMR-CUG. Rock powder (~0.5 g) was mixed with 5.0 g compound flux ($\text{Li}_2\text{B}_4\text{O}_7$: LiBO_2 = 12 : 22), and then was fused in Pt-Au crucibles by heating at ~1050 °C for 11 minutes. The mixture was swirled repeatedly to ensure complete dissolution and homogenization, and then was poured into a mold to form a flat-surfaced disc (34 mm in diameter) for further analysis. Sample-preparing procedures and operating conditions of the XRF instrument have been described by Ma et al. (2012). Analytical results of whole-rock major elements are given in Table S4.

Trace element compositions were measured using an ICP-MS (Agilent 7500a) at the GPMR-CUG. Rock powder (~50 mg) was dissolved in a Teflon bomb using a mixture of HF and HNO_3 . Then the sealed Teflon bomb was heated at 190 °C for 48 hours. After evaporating the solution to incipient dryness at 115 °C, the dried sample was refluxed with 30% HNO_3 . The final solution was diluted to ~100 g with 2% HNO_3 in a polyethylene bottle. Detailed operating conditions of the ICP-MS instrument and data reduction processes have been described by Liu et al. (2008). Trace element compositions of the studied samples are listed in Table S4. Analytical results of procedural blanks and international rock standards are given in Table S5.

3.3. Whole-rock Sr–Nd isotopes

The Sr and Nd isotopic compositions were measured using a Thermo-Finnigan TRITON thermal ionization mass spectrometer (TIMS) at the Institute of Geology and Mineral

Resources, Tianjin. Rock powders were dissolved in Teflon bombs using HF + HNO₃, and chemical separations were performed using conventional ion exchange procedures. Sr and Nd isotopic ratios were normalized against $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. The Sr standard BCR-2 and NBS987 yield average $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.704983 ± 0.000011 (2σ , $n = 7$) and 0.710221 ± 0.000011 (2σ , $n = 8$) (Fig. S2), respectively. The average $^{143}\text{Nd}/^{144}\text{Nd}$ of the BCR-2 and a laboratory internal standard solution (LRIG-Nd) are 0.512636 ± 0.000006 (2σ , $n = 7$) and 0.512201 ± 0.000007 (2σ , $n = 8$) (Fig. S2), respectively, which are in good agreement with the recommended values (Li et al., 2007). Whole-rock Sr and Nd isotopic compositions are given in Table S4.

4. Results

4.1. Zircon U–Pb ages and Hf isotopes

Zircons from studied samples are mostly euhedral, showing crystal length of 200 – 70 μm and length-to-width ratio up to 5:1 (Fig. 3). Unlike zircons with typical magmatic zoning (Fig. 3), zircon grains separated from the Yangying PVR samples are colorless and weakly zoned, and some of them exhibit sector zoning in CL images (Fig. 3). Despite the differences in internal structure, zircons in this study commonly display variable concentrations of Th (7096 – 154 ppm) and U (4724 – 105 ppm), with Th/U varying from 2.42 to 0.40 (Table S2).

Analyzed zircons cover a range of U–Pb ages from 17 Ma to 9 Ma (Fig. 3). Zircons separated from sample DJC1312 yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 17.23 ± 0.16 Ma (2σ , $n = 18$), which is the oldest age in this study. Zircons from the Yangying PVR samples have

the youngest ages, showing $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 9.88 ± 0.37 Ma (2σ , $n = 12$) to 9.15 ± 0.37 Ma (2σ , $n = 15$) (Fig. 3). After rejecting inherited zircon analytical spots, three samples from Chazi area yield U–Pb ages of 11.23 ± 0.14 Ma (2σ , $n = 16$), 11.14 ± 0.16 Ma (2σ , $n = 16$), and 11.28 ± 0.15 Ma (2σ , $n = 16$), respectively (Fig. 3). Two PVR samples from Xungba-Yare area are slightly older, yielding zircon $^{206}\text{Pb}/^{238}\text{U}$ ages of 16.61 ± 0.31 Ma (2σ , $n = 17$) and 16.76 ± 0.28 Ma (2σ , $n = 14$) (Fig. 3).

Zircon Hf isotopic compositions are shown by plotting $\epsilon_{\text{Hf}}(t)$ value versus U–Pb age of individual analysis (Fig. 4). Varying zircon $\epsilon_{\text{Hf}}(t)$ values (-9.4 to $+1.4$, Fig. 4) can be observed in samples from Xungba-Yare area. Zircon Hf isotopic compositions of the Dajia Co and Yangying samples are much more homogeneous (Fig. 4), showing $\epsilon_{\text{Hf}}(t)$ variations lower than 5 units (-4.2 to $+0.2$, Table S3). In Chazi area, sample CZ1310 shares similar zircon $\epsilon_{\text{Hf}}(t)$ variation (-13.1 to -9.1 , Table S3) with the associated UPVR samples (-12.4 to -6.1 , Table S3), but both of which are significantly lower than those of other samples in this study (Fig. 4).

4.2. Whole-rock geochemistry

As illustrated in Fig. 5a, most of the studied samples are trachyte and trachydacite, and only a few of them are trachyandesite and rhyolite (Table S1). Samples from Dajia Co area have low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ($0.80 - 0.75$, Table S4) and high A/NK (i.e. molar $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$), which are comparable with postcollisional adakites in southern Tibet. By comparison, other samples are potassium-rich in nature ($\text{K}_2\text{O}/\text{Na}_2\text{O} > 1$, Fig. 5b) and exhibit relatively low A/NK ($\text{A/NK} < 1.56$, Fig. 5c). Compared with the mantle-derived UPVR samples ($\text{MgO} > 3$ wt.%,

$K_2O > 3$ wt.%, $K_2O/Na_2O > 2$; Foley et al., 1987), the PVR samples are much more silicic (Fig. 5a) and commonly display variably lower K_2O/Na_2O (1.09 – 3.31, Table S4). For instance, the Chazi PVR samples display lower MgO (0.97 – 2.98 wt.%) and K_2O/Na_2O (2.35 – 3.31) than the related UPVR samples (MgO = 3.01 – 3.45 wt.%, K_2O/Na_2O = 2.34 – 6.85) (Table S4). Another important observation is that the Miocene potassic volcanic rocks and the Eocene-Miocene adakitic intrusions defined separate trends of TiO_2 with decreasing SiO_2 (Fig. 5d).

In the primitive mantle-normalized incompatible trace element diagram (Fig. 6), the studied samples are relatively enriched in large ion lithophile elements (LILE, e.g. Rb, Th, and U) and light rare earth elements (LREEs). Negative anomalies of high field strength elements (HFSEs, e.g. Nb, Ta, and Ti) and relative depletions of heavy rare earth elements (HREEs) can be observed in these samples as well (Fig. 6). Compared with other samples, the Dajia Co samples show the lowest incompatible element concentrations (Fig. 6). The incompatible element distribution patterns for samples from Yangying, Chazi, Yare, and Zabuye are very similar and can be comparable with those of previously reported PVR samples. Particular, the Chazi PVR samples have slightly higher concentrations of incompatible element than the associated UPVR samples (Fig. 6).

With high Sr/Y (79 – 113) and La/Yb (37 – 46), low Y (8.78 – 11.0 ppm) and Yb (0.65 – 0.84 ppm) (Table S4), samples from Dajia Co area were plotted into the field of adakite (Figs. 7a and 7b). Samples collected from Xungba-Yare area also have low Y (11.2 – 19.0 ppm) and Yb (0.86 – 1.40 ppm), but their Sr/Y (10.1 – 73.2 ppm) are lower than those of the Dajia Co adakites (Fig. 7a). Other PVR samples, with higher Y and Yb concentrations, apparently

deviate from the data field of adakite (Figs. 7a and 7b). Moreover, although both adakite and potassic volcanic rocks exhibit high La/Yb, the PVR samples tend to display higher Sm/Yb at a given La/Yb (Fig. 7c). The UPVR samples from Chazi area have variably high Y (20.4 – 23.5 ppm) and Yb (1.34 – 1.61 ppm), and fall in the field of Tibetan ultrapotassic rocks (Figs. 7a and 7b).

Varying Sr and Nd isotopic compositions constitute another important feature of the studied samples (Fig. 8). Samples from Dajia Co, Yangying, and Zabuye are characterized by relatively low initial $^{87}\text{Sr}/^{86}\text{Sr}_i$ (0.7069 – 0.7124) and high $\epsilon_{\text{Nd}}(t)$ (-9.04 – -5.21) (Table S4). Particular, Sr and Nd isotopic compositions for the Dajia Co samples ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7069 - 0.7073$, $\epsilon_{\text{Nd}}(t) = -6.31 - -5.21$) are comparable with adakitic intrusions in southern Tibet (Fig. 8). But, with the exception of the sample YR1118 ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7079$, $\epsilon_{\text{Nd}}(t) = -4.7$), the majority of PVR samples from Xungba-Yare area has radiogenic Sr ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7223 - 0.7363$) and unradiogenic Nd isotopic compositions ($\epsilon_{\text{Nd}}(t) = -13.3 - -12.5$) (Table S4). It can be found that the Sr and Nd isotopic variations in the PVR samples partly overlap with the Tibetan UPVR samples (Fig. 8). In the Chazi area, the PVR samples exhibit lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ but nearly identical $\epsilon_{\text{Nd}}(t)$ with the UPVR samples (Fig. 8).

5. Discussion

5.1. Comparison between potassic volcanic rocks and adakitic intrusions

In southern Tibet, postcollisional magmatic rocks have been widely used to probe into the nature of deep crust and mantle lithosphere (Miller et al., 1999; Williams et al., 2004;

Chung et al., 2005; Ma et al., 2014; Hou et al., 2015a; Liu et al., 2015). Tibetan ultrapotassic rocks were thought to be products of low-degree melting of metasomatized lithospheric mantle due to the presence of mantle xenoliths, high concentrations of compatible element (e.g. Cr, Co, Ni), and enriched isotopic compositions (Turner et al., 1996; Miller et al., 1999; Williams et al., 2004; Chung et al., 2005; Liu et al., 2014b, 2015; Guo et al., 2015). Meanwhile, the generation of the Eocene-Miocene adakitic magmatism were usually attributed to high-pressure (≥ 50 Km) partial melting of the overthickened lower continental crust beneath southern Tibet (Hou et al., 2004, 2015a; Chung et al., 2009; Chen et al., 2011; Guan et al., 2012; Ji et al., 2012; Ma et al., 2014; Wang et al., 2015). Given that potassic volcanic rocks also exhibit variably high Sr/Y and La/Yb, relative depletions in HREEs, and low Y concentrations (Figs. 6 and 7), their adakitic geochemical signatures were regarded as an indicator for crustal thickening in response to the continental convergence between India and Asia (Miller et al., 1999; Chen et al., 2010, 2011; Liu et al., 2011, 2014b).

However, considerable petrogenetic and geochemical differences did exist between potassic volcanic rocks and adakitic intrusions. For instance, the PVR samples have extremely high K₂O (up to 10.6 wt.%) and K₂O/Na₂O (> 1) (Fig. 5), which does not match the original definition of adakite (Defant and Drummond, 1990; Petford and Atherton, 1996) and even differ from the “c-type” (i.e. potassic) adakites (Xiao and Clemens, 2007; Moyen, 2009). Moreover, radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$, unradiogenic $^{143}\text{Nd}/^{144}\text{Nd}$, and overall negative zircon $\varepsilon_{\text{Hf}}(\text{t})$ variations observed in the PVR samples make them comparable with mantle-derived ultrapotassic rocks rather than coeval adakites (Figs. 4 and 8) (Turner et al., 1996; Miller et al.,

1999; Gao et al., 2009; Chen et al., 2010, 2011; Liu et al., 2014b; Tian et al., 2015; Zhang et al., 2015). Aside from the geochemical distinctions between potassic and adakitic rocks, differences in spatial and temporal distributions may be more obvious. With formation ages ranging from 51 Ma to 9 Ma, adakitic magmatism is widespread in the southern Lhasa subterrane (Chung et al., 2009; Xu et al., 2010; Li et al., 2011; Guan et al., 2012; Ji et al., 2012; Zheng et al., 2012; Ma et al., 2014; Hou et al., 2015a; Wang et al., 2015). But the majority of potassic volcanism, as well as mantle-derived ultrapotassic magmatism, is concentrated in the central Lhasa subterrane and commonly has a Miocene eruptive age (Fig. 1b). Therefore, there are still many fundamental problems about the Tibetan potassic and adakitic rocks to be answered.

Collectively, clarifying petrogenesis of potassic volcanic rocks and adakitic intrusions requires answers to following questions. (i) How to reconcile “adakitic signatures” with high K_2O contents and evolved Sr–Nd–Pb isotopic signatures in the PVR samples? (ii) Did potassic volcanic rocks undergo similar potassium enrichment and isotopic enrichment processes with adakitic intrusions? (iii) Did mantle-derived ultrapotassic melts contribute to formation and evolution of potassic and adakitic magmatism? (iv) What is the relationship between the Indian continental subduction and postcollisional magmatism in southern Tibet? Note that “adakitic signatures” can be achieved through different processes (Moyen, 2009), including partial melting of overthickened or delaminated lower continental crust (cf. Xiao and Clemens, 2007; Chung et al., 2009), magma mixing (Guo et al., 2007a; Streck et al., 2007), and fractional crystallization of Y-enriched minerals (e.g. garnet, pyroxene, and amphibole; Richards and

Kerrick, 2007) or mineral assemblages (Chen et al., 2016). Following discussion will examine the possible influence of ultrapotassic magmatism and Indian continental subduction before emphasizing source heterogeneity and magmatic differentiation as controlling factors for producing potassic and adakitic rocks in southern Tibet.

5.2. Petrogenetic links with the Tibetan ultrapotassic rocks?

In previous studies, both adakitic intrusions and potassic volcanic rocks were suggested to have genetic links with mantle-derived ultrapotassic rocks (Guo et al., 2007b; Chen et al., 2012; Hou et al., 2015a; Yang et al., 2015; Zhang et al., 2015). Especially for some high $Mg^\#$ ore-bearing adakitic intrusions ($^{87}Sr/^{86}Sr = 0.707$, $\epsilon_{Nd}(t) = -5.1$ to -5.5), additional input of ultrapotassic melts has been invoked to explain their evolved Sr–Nd isotopic compositions, negative zircon $\epsilon_{Hf}(t)$ variations, and the formation of porphyry copper deposits (Yang et al., 2015). However, the decrease in zircon $\epsilon_{Hf}(t)$ values shown by adakitic intrusions starts earlier than the onset of mantle-derived ultrapotassic magmatism (Fig. 4), and postcollisional adakitic magmatism are concentrated in the southern Lhasa subterrane where only a few of ultrapotassic records have been identified (cf. Liu et al., 2013). Additionally, studies on the early-Miocene PVR samples from Xungba-Yare area, southwestern Tibet, demonstrate the isotopic discrepancy between potassic intermediate-felsic rocks and related ultrapotassic rocks (Fig. 9) (Miller et al., 1999; Liu et al., 2014b). These findings pose a fundamental question of whether ultrapotassic magma has contributed to coeval potassic and adakitic magmatism.

5.2.1. *The overestimated ultrapotassic input into adakitic magmatism*

Mantle-derived ultrapotassic rocks have much higher abundances of MgO, TiO₂, and compatible elements (e.g. Cr, Co, Ni) than magmatic rocks with crust origin (Fig. 5d). Also, except for extremely high K₂O/Na₂O (Fig. 5b), one of the most striking features of the Tibetan ultrapotassic rocks is their weak enrichment of LREEs relative to MREEs (i.e. low (La/Sm)_N) (Miller et al., 1999; Williams et al., 2004; Liu et al., 2015). It can be inferred that mixing with ultrapotassic melts will drive hybrid magma to be less silicic (i.e. lower SiO₂ and higher TiO₂) and more potassic (i.e. higher K₂O/Na₂O), and will shift its (La/Sm)_N toward a lower value. Based on these predictions, we found that ultrapotassic magmatism played a contrasting role in potassic and adakitic magmatism. For adakitic intrusions, the decreasing SiO₂ is coupled with a reduced K₂O/Na₂O and slowly increased TiO₂ (Figs. 5d and 10a), which are inconsistent with the substantial input from ultrapotassic magma. The positive co-variation trend between K₂O/Na₂O and SiO₂ (Fig. 10a) also casts doubt on the binary mixing with ultrapotassic melts as a possible way to account for generation of high K₂O adakite samples. Moreover, the variations of Sr/Y and Y in adakite samples have been attributed to the additional inputs from high-Y ultrapotassic melts (Yang et al., 2015). But this hypothesis is unable to explain why adakite samples with higher K₂O/Na₂O tend to have lower concentrations of Y (Fig. 10b). The third line of evidence for the negligible contribution from ultrapotassic magma comes from the correlation between K₂O/Na₂O and (La/Sm)_N, because both high-(La/Sm)_N and low-(La/Sm)_N adakite samples are characterized by relatively low K₂O/Na₂O (Fig. 10c). A possible explanation is that the Na-rich feature in adakitic intrusions may be inherited from magma

sources or reflect additional inputs of Na-rich mafic components (e.g. MORB-like or IAB-like melts) during magmatic evolution. We thus conclude that the direct contribution from mantle-derived ultrapotassic magma to postcollisional adakitic magmatism is overestimated in previous studies.

5.2.2. Contribution from ultrapotassic magma to potassic volcanism

In contrast with adakitic intrusions, a closer relationship between potassic and ultrapotassic rocks is suggested by similarities in spatial distributions (Fig. 1b), incompatible element distribution patterns (Fig. 6), and Sr–Nd–Pb–Hf isotopic compositions (Fig. 8). It can be found that the PVR samples display higher K_2O/Na_2O and TiO_2 than adakites at a given SiO_2 content (Figs. 5d and 10a). Besides, the correlations between La/Yb and Sm/Yb in adakites can be well reproduced by batch melting of amphibole- and eclogite-facies continental crust (Fig. 7c). But many PVR samples have higher Sm/Yb than adakites, which substantially deviate from the melting curves of amphibole-bearing eclogites (Fig. 7c). Combined with the variably low $(La/Sm)_N$ in those high- K_2O/Na_2O PVR samples (Fig. 10c), the La/Yb–Sm/Yb correlations defined by potassic volcanic rocks can be well explained by the involvement of ultrapotassic melts (Fig. 7c).

For the PVR samples from Yangying, Chazi, and Zabuye area, additional input from ultrapotassic melts can reconcile high Y and Yb concentrations with other adakitic geochemical signatures (e.g. high Sr/Y and La/Yb). Previous studies have shown that fractional crystallization of plagioclase would result in a rapid decrease of Sr/Y in melt fraction without

significantly change its Y concentration (Moyen, 2009; Liu et al., 2014b). The porphyritic texture and the phenocryst compositions of the PVR samples (Fig. 2) also preclude accumulation of Y-enriched minerals as a possible mechanism to produce high Y concentrations (Defant and Drummond, 1990; Petford and Atherton, 1996). Hence, the elevated Y concentrations in some PVR samples may result from magma mixing with high-Y ultrapotassic melts. As modeled in Fig. 7a, high Sr concentrations in ultrapotassic melts enable magma mixing processes to significantly raise Y concentrations with only limited variations of Sr/Y in the PVR samples. This modeling result is consistent with the positive K_2O/Na_2O and Y correlation defined by the PVR samples (Fig. 10b), and explains why some PVR samples, with Y concentrations up to 26.7 ppm, still have relatively high Sr/Y (> 50) (Fig. 7a).

However, both potassic and ultrapotassic rocks are age progressive (Chung et al., 2005; Zhao et al., 2009; Liu et al., 2014a), with ~23 Ma “bimodal” volcanic sequences at the west (Miller et al., 1999; Liu et al., 2014b) and ~9 Ma volcanic activities in the east end (Gao et al., 2007, 2009; Chen et al., 2010, 2012; Zhang et al., 2015). This phenomenon indicates that mantle-derived ultrapotassic melts may not always contribute to the associated potassic magmatism. As exemplified by the ~23 Ma PVR samples from Xungba-Yare area (Fig. 4), their poorly-varying and negative zircon $\epsilon_{Hf}(t)$ values provide clear evidence for derivation from ancient Lhasa terrane crust with little or no input from related ultrapotassic magma (Liu et al., 2014b). But our newly obtained data for the ~17 Ma Yare PVR samples indicate that their Sr–Nd and zircon Hf isotopic compositions are more comparable with coeval ultrapotassic rocks (Fig. 9). Similarly, the PVR samples from Zabuye, Tangra YumCo, and

Xuru Co also have younger eruptive ages, and their isotopic compositions are nearly identical with ultrapotassic rocks outcropping at the same place (Fig. 9). These observations lead to consideration that the isotopic discrepancy between potassic and ultrapotassic rocks is diminishing with postcollisional volcanic activity become younger and migrate eastward (Fig. 9). In other words, potassic volcanic rocks with the younger ages may have undergone more extensive hybridization with the associated ultrapotassic melts.

5.3. Contrasting role of the Indian crust material in generating adakitic and potassic rocks

If we accept the negligible role of ultrapotassic melts in generation and evolution of postcollisional adakites in southern Tibet, there should be another mechanism responsible for their high K₂O features, evolved Sr–Nd–Pb isotopes, and zircon Hf isotopic variations. Besides, considering that the Indian plate has subducted beneath the Lhasa terrane lithosphere (Kind et al., 2002; Nábělek et al., 2009; Wittlinger et al., 2009; Shi et al., 2015; Gao et al., 2016), another highly debated question is whether the underthrust Indian continental crust has contributed to postcollisional magmatism in southern Tibet (Chen et al., 2011; Chu et al., 2011; Ma et al., 2014; Tian et al., 2015; Zhang et al., 2015).

5.3.1. The input of Indian continental crust into adakitic magmatism

Zircon Hf isotopic mapping and detrital zircon studies have revealed the formation of voluminous juvenile crust in the southern Lhasa subterranean (Wen et al., 2008; Ji et al., 2009;

Zhu et al., 2013; Jiang et al., 2014; Wu et al., 2014; Hou et al., 2015b). As a result, the majority of Gangdese batholith in southern Lhasa subterranean was dominated by recycling of juvenile crust materials (Wen et al., 2008; Ji et al., 2009; Zhu et al., 2013; Jiang et al., 2014; Hou et al., 2015b). The dominant role of juvenile crust in producing 52 – 35 Ma adakitic intrusions is supported by their positive zircon $\varepsilon_{\text{Hf}}(t)$ variations (Fig. 4). In this regard, the dramatic decrease of co-magmatic zircon $\varepsilon_{\text{Hf}}(t)$ values since ~35 Ma (Fig. 4) can be viewed as a strong evidence for the enhanced mass transfer from underthrust Indian continental crust into magma sources of adakites in southern Lhasa subterranean (Chu et al., 2011; Ji et al., 2012; Ma et al., 2016).

The Indian crust input into adakitic magmatism is further manifested by correlations between Nd isotopic ratio and major and trace element indicators (Fig. 11). As illustrated in Fig. 11a, adakite samples can be divided into two groups: (i) samples with dramatically increased $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and restricted $^{143}\text{Nd}/^{144}\text{Nd}$ (trend A), and (ii) samples showing relatively low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ but varying $^{143}\text{Nd}/^{144}\text{Nd}$ (trend B). A possible explanation is that there are different mechanisms responsible for potassium enrichment and Nd isotopic variations in adakites. For adakite samples with poorly-varying but relatively high $^{143}\text{Nd}/^{144}\text{Nd}$ (trend A), magmatic differentiation may be a possible way to shift $\text{K}_2\text{O}/\text{Na}_2\text{O}$ and SiO_2 toward higher values without modifying Nd isotopic composition (Figs. 11a and 11b). It can be found that the majority of adakitic intrusions, with plagioclase and sanidine as major phenocryst phases (Fig. 2b, Williams et al., 2004; Guo et al., 2007b; Wang et al., 2015; Yang et al., 2015), are dacite and rhyolite in composition (Fig. 5a). Fractional crystallization of plagioclase will remove Na from the remaining liquid, and leave $\text{K}_2\text{O}/\text{Na}_2\text{O}$ of residual magma to increase. As a late

crystallization phase in intermediate-felsic magmas, K-feldspar does not participate during crystal-melt segregation (Glazner and Johnson, 2013), which also give rise to high K₂O content in remaining magma. Combined with the fact that Rb does not decline with Sr during feldspar crystallization (cf. Chapman et al., 2015), the elevated K₂O/Na₂O and Rb/Sr in these high-¹⁴³Nd/¹⁴⁴Nd adakite samples (trend A in Fig. 11) thus indicate the effect of magmatic differentiation on potassium enrichment.

But additional inputs of unradiogenic components (i.e. ancient crust or sediments-like) may be a requisite for generating adakites showing variably low ¹⁴³Nd/¹⁴⁴Nd (trend B, Fig. 11). It is noteworthy that high SiO₂ and low Y in those low-¹⁴³Nd/¹⁴⁴Nd adakites (Fig. 11d) not only imply a limited contribution from mantle-derived ultrapotassic melts, but also provide information about the low-¹⁴³Nd/¹⁴⁴Nd end-member. Lower Y and HREEs concentrations in adakitic melts were commonly thought to reflect a higher abundance of garnet relative to amphibole/clinopyroxene in magma sources (Fig. 7b) (Defant and Drummond, 1990; Petford and Atherton, 1996). But this explanation fails to reproduce the negative K₂O/Na₂O-Y correlations defined by the Tibetan adakitic intrusions (Fig. 10b). An alternative scenario is that the underthrust Indian crust material was involved in postcollisional adakitic magmatism (Xu et al., 2010; Chen et al., 2011; Chu et al., 2011; Ma et al., 2014). In the Tethyan Himalaya, the Eocene-Miocene leucogranites with radiogenic Sr and unradiogenic Nd isotopic compositions are interpreted as the products of Indian crust anatexis (King et al., 2011; Zeng et al., 2011; Hou et al., 2012; Liu et al., 2016). Moreover, these Himalayan leucogranites are depleted in Y and HREEs, and have comparable or even higher K₂O/Na₂O than adakitic

intrusions (Fig. 11c), suggesting that high K_2O/Na_2O , low Y, and felsic compositions in the low- $^{143}Nd/^{144}Nd$ adakite samples can be well explained by incorporation of the Indian crust components (Figs. 11b and 11c). Together with the dramatic decrease in zircon $\epsilon_{Hf}(t)$ values since ~35 Ma (Fig. 4), it is tenable that the Indian continental crust materials were involved in postcollisional adakitic magmatism (Xu et al., 2010; Chen et al., 2011; Chu et al., 2011; Ma et al., 2014) and even in some high-Sr/Y potassic volcanism (Zhang et al., 2015) from southern Lhasa subterrane.

5.3.2. Negligible contribution from Indian continental crust to potassic volcanism

On the other hand, potassic volcanic rocks are mainly distributed in the central Lhasa subterrane, and display higher $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$, lower $^{143}Nd/^{144}Nd$, and more negative zircon $\epsilon_{Hf}(t)$ variations than adakitic intrusions (Figs. 4 and 8). If the evolved isotopic compositions in postcollisional magmatic rocks are wholly attributed to the input from Indian continental crust, it will be difficult to explain why smaller amounts of the Indian crust material was incorporated into adakitic magmatism that is outcropped closer to the IYSZ than the coeval potassic volcanism (Fig. 1). Moreover, both Lhasa terrane and Indian plate were rifted from Gondwana (see reviews by Yin and Harrison, 2000 and Zhu et al., 2013), and ancient Lhasa basement share similar Sr–Nd isotopic compositions with Himalayan basement (cf. Liu et al., 2014b). Therefore, it may be more likely that the enriched Sr–Nd isotopic compositions of the PVR samples were inherited from the heterogeneous Lhasa terrane crust rather than the underthrust Indian continental crust.

488 Several lines of evidence indicate that the potassic volcanism is dominated by recycling
489 of the Lhasa terrane crust. The first evidence comes from the negative and variable co-
490 magmatic zircon Hf isotopic variations (Fig. 4), which are comparable with detrital zircon
491 records and magmatic zircons from the Paleozoic-Mesozoic granitoids outcropping in the
492 central and northern Lhasa subterrane (cf. Wu et al., 2014). Second, the PVR samples have
493 similar the Pb isotopic compositions with S-type granite and gneiss from Lhasa terrane
494 (average $^{207}\text{Pb}/^{204}\text{Pb} = 15.727 \pm 0.011$), but both of which exhibit lower Pb isotopic ratios
495 relative to the Tethyan Himalaya gneiss (average $^{207}\text{Pb}/^{204}\text{Pb} = 15.824 \pm 0.020$) (Vidal et al.,
496 1982; Gariépy et al., 1985). Additionally, seismic reflection profiles have revealed that the
497 eclogite-facies Indian crust extends as far north as the center of the Lhasa terrane at present
498 (Nábělek et al., 2009; Wittlinger et al., 2009; Shi et al., 2015). Given the progressively reduced
499 continental convergence rate since 50 Ma, it is pretty difficult for the Indian continental crust
500 to underthrust beneath the central Lhasa subterrane at early Miocene (Nábělek et al., 2009). An
501 alternative scenario is that the subducted (older) Indian crust had been detached from
502 lithosphere and consequently sunk into the deep mantle (Kind et al., 2002; Nábělek et al.,
503 2009). But in this case, partial melts of the eclogitized Indian crust would interact with
504 surrounding mantle during ascent, and inevitably gave rise to high MgO and compatible
505 element concentrations (Streck et al., 2007). This is inconsistent with the felsic compositions
506 and low compatible element concentrations shown by the PVR samples (Miller et al., 1999;
507 Liu et al., 2014b). Collectively, potassic volcanic rocks are less likely to retain geochemical

fingerprints of the Indian continental subduction. Instead, their negative zircon $\epsilon_{\text{Hf}}(t)$ values and whole-rock Pb isotopic signatures may reflect the nature of the Lhasa terrane crust.

5.4. Petrogenesis of potassic volcanic rocks in southern Tibet

As discussed above, potassic volcanic rocks are significantly affected by coeval mantle-derived ultrapotassic magmatism, but, unlike adakitic intrusions in southern Lhasa subterrane, the direct input from Indian continental crust appears to be very limited. However, there are still some questions to be answered, such as potassium enrichment mechanism and geochemical nature of crustal components in potassic volcanism. For example, high Sr/Y and low Y signatures in some PVR samples may be inherited from magma sources (Fig. 7a) rather than additional input from high-Y ultrapotassic melts. Moreover, mixing with ultrapotassic melts also fails to account for high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ shown by some PVR samples with high SiO_2 contents (e.g. ~23 Ma PVR samples from Xungba-Yare area, Fig. 10b). Hence, both magma sources and magmatic differentiation processes may serve as controlling factors in generating potassic volcanic rocks.

5.4.1. Identification of juvenile and ancient crust components from potassic volcanism

With the aid of zircon Hf isotopic mapping on the Mesozoic-Cenozoic granitoids, previous studies revealed the presence of ancient crust beneath central Lhasa subterrane (Zhu et al., 2013; Chen et al., 2014; Hou et al., 2015b). Meanwhile, the slab break-off during the Neo-Tethyan seafloor subduction triggered large-scale basaltic underplating and crustal

reworking (Coulon et al., 1986; Wen et al., 2008; Ji et al., 2009; Zhu et al., 2013; Chen et al., 2014; Jiang et al., 2014; Liu et al., 2014a), which consequently resulted in an isotopically heterogeneous lower crust beneath central Lhasa subterrane. In fact, the profound influence of ancient crust components on the Mesozoic-Cenozoic magmatic activities is manifested by high K_2O/N_2O and extremely evolved Sr–Nd isotopic compositions observed in the early-Cretaceous andesites (e.g. ~116 Ma andesites from Xainza area: $^{87}Sr/^{86}Sr_{(i)} = 0.7209 - 0.7218$, $\epsilon_{Nd}(t) = -13.0 - -13.6$, $K_2O/Na_2O = 1.31 - 1.63$, Chen et al., 2014) and some early-Miocene PVR samples (e.g. ~23 Ma PVR from Xungba-Yare area, $^{87}Sr/^{86}Sr_{(i)} = 0.7272 - 0.7397$, $\epsilon_{Nd}(t) = -11.8 - -14.5$, $K_2O/Na_2O = 1.29 - 5.86$, Miller et al., 1999; Liu et al., 2014b; Tian et al., 2015). Additionally, the involvement of juvenile crust components also explains why some PVR samples have lower initial $^{87}Sr/^{86}Sr$ and higher $\epsilon_{Nd}(t)$ than the associated ultrapotassic rocks (Fig. 9). In this regard, it is tenable that both juvenile and ancient crust components have contributed to postcollisional potassic volcanism in central Lhasa subterrane.

On the plot of $\epsilon_{Nd}(t)$ and $^{87}Sr/^{86}Sr$ (Fig. 8), the convex downward hyperbolic array for Sr and Nd isotopes in the PVR samples can be reproduced in terms of binary mixing between the juvenile and ancient crust components. With low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$, the juvenile crustal component is characterized by low K_2O/Na_2O (as low as 0.9), high Sr/Y, and very weak negative Eu anomaly, which indicates a geochemical affinity with adakitic intrusions in southern Lhasa subterrane (Figs. 12a and 12b). By contrast, the ancient crust component, showing radiogenic $^{87}Sr/^{86}Sr$ and unradiogenic $^{143}Nd/^{144}Nd$, appears to be more silicic (i.e. higher SiO_2) and potassic ($K_2O/Na_2O > 1.4$) (Figs. 12a and 12c). A common feature for

juvenile and ancient crust components are their enrichment of K_2O relative to Na_2O and depletions in Y and Yb (Fig. 12a and 12d). Ferreira et al. (2015) pointed out that potassium-rich felsic magma (e.g. the Guarany pluton in northeastern Brazil) might originate from melting within the amphibolitic lower crust. Wang et al. (2005) also revealed that K-rich adakites in the Qiangtang terrane were derived from partial melting of K-rich amphibole-bearing eclogites. As modeled in Fig. 7c, the positive correlations between Sm/Yb and La/Yb defined by adakite and PVR samples fit well with the predicted trends for partial melting of amphibole-bearing eclogite. We thus suggest that the Sr and Nd isotopic variations in the PVR samples document the contribution from two isotopically distinct crust end-members (Fig. 8). Whilst, except for the ultrapotassic input, high K_2O signatures in potassic volcanic rocks may be partly inherited from magma sources.

5.4.2. *Magmatic differentiation and potassium enrichment mechanism*

Apart from source heterogeneity and ultrapotassic input, the manner in which magma crystallizes also played a critical role in producing the compositional diversity of potassic volcanic rocks. With increasing SiO_2 , different variation trends of Sr/CaO can be observed in the PVR samples (Fig. 13a), and both high-Sr/CaO and low-Sr/CaO PVR samples are characterized by high Rb/Sr (Fig. 13b). Because higher Rb/Sr and SiO_2 indicate a greater extent of magmatic differentiation (Chapman et al., 2015), the contrasting trends of Sr/CaO with increasing Rb/Sr and SiO_2 may represent different fractionating phases during magmatic evolution.

Based on phenocryst compositions of the PVR samples (Fig. 2), we modeled compositional variations in remaining magma after fractionation of various mineral phases and mineral assemblages (Fig. 13b). Because Sr and Ca is preferentially concentrated in plagioclase during crystal-liquid segregation (Nagasawa and Schnetzler, 1971), fractional crystallization of plagioclase will lead to elevated Rb/Sr and poorly-varying Sr/CaO in remaining liquid (Fig. 13b). But for sanidine, the partition coefficient for Rb and Sr are significantly higher than Ca in crystal-liquid segregation (Stix and Gorton, 1990), suggesting that an elevated Rb/Sr and reduced Sr/CaO can be observed in remaining liquid (Fig. 13b). We found that the Yare PVR samples fit well with the modeling curve defined by plagioclase and sanidine as fractionating phases (Pl/Sa = 70: 30, Fig. 13b). This modeling result can be supported by the observation that plagioclase and sanidine are major phenocryst phases in the PVR samples from Xungba-Yare area (Fig. 2j). Besides, fractional crystallization of plagioclase can account for variably low Sr/Y and weak Eu negative anomalies in the ~23 Ma PVR samples from Xungba basin (Liu et al., 2014b). As for the Chazi and Yangying PVR samples, their extremely high Sr/CaO provide evidence for clinopyroxene as an important fractionating phase because Rb and Sr behave much more incompatible relative to Ca during liquid-crystal segregation (Rollinson, 1993; Huang et al., 2006). As shown in Fig. 13b, the best fit to positive correlations between Rb/Sr and Sr/CaO in these PVR samples involves fractional crystallization of clinopyroxene + sanidine + plagioclase (Cpx/Sa/Pl = 50: 30: 20, Fig. 13b), which is consistent with their phenocryst compositions as well (Figs. 2d and 2f) (Gao et al., 2009; Chen et al., 2010; Zhang et al., 2015).

It should be noted that fractional crystallization processes may also contribute to high K_2O/Na_2O in potassic volcanic rocks. We have shown that high K_2O contents in some adakites can be achieved through crystallization of feldspars (Fig. 11a). Similarly, high D_{Na}/D_K for clinopyroxene in crystal-liquid segregation ($D_{Na}/D_K = 7$, Huang et al., 2006) will shift K_2O/Na_2O of remaining liquid toward a higher value. As a consequence, high K_2O/Na_2O in the PVR samples may represent a combined influence of additional input from ultrapotassic magma, partial melting of amphibole-bearing eclogite-facies lower crust, and fractional crystallization dominated by feldspars and clinopyroxene.

5.5. Implications for petrogenesis of ultrapotassic rocks and mantle-crust interaction

5.5.1. Constraints on using ultrapotassic rocks to probe into deep mantle

Ultrapotassic rocks in the Alpine-Himalayan orogenic belts have long been viewed as a kind of primitive melt that originates from low-degree partial melting of metasomatized mantle (Foley et al., 1987; Conticelli, 1998; Williams et al., 2004; Zhao et al., 2009; Liu et al., 2014b, 2015; Guo et al., 2015). Based on this assumption, the enriched isotopic signatures shown by mantle-derived ultrapotassic rocks is widely utilized to trace the sedimentary subduction and deep carbon recycling at convergent plate margins (Conticelli, 1998; 2009; Liu et al., 2015; Ammannati et al., 2016). For instance, the evolved Sr–Nd isotopes in the Tibetan ultrapotassic rocks were commonly interpreted as representing mantle metasomatism driven by silicate melts or fluids released from the subducted Indian plate (Zhao et al., 2009; Guo et al., 2015).

These petrogenetic models, which try to emphasize refertilized mantle sources as the only factor for generating extremely enriched isotopic signatures in ultrapotassic rocks, have the problem of underestimating the influence of crustal contamination. Indeed, isotopic variations induced by crustal contamination may be buffered by much higher incompatible element concentrations (e.g. Sr and Nd) in mantle-derived ultrapotassic melts than most crustal contaminants (Conticelli, 1998). But in southern Tibet, crustal xenoliths and zircon xenocrysts with pre-eruptive ages were identified from ultrapotassic volcanic rocks (Liu et al., 2011, 2013, 2014a). The radiogenic Os isotopic compositions shown by the Tibetan ultrapotassic rocks further provide strong arguments for the occurrence of crustal contamination during magmatic evolution (Liu et al., 2015). These findings indicate that high MgO and $Mg^\#$ in ultrapotassic rocks do not necessarily imply they are primitive melts without assimilating any crustal materials. Furthermore, partially molten layers are very common in areas with very thick crust (e.g. Tibetan plateau, Nelson et al., 1996). As discussed above, the postcollisional potassic volcanic rocks, which may originate from partial melting of the Lhasa terrane crust, exhibit similar incompatible element concentrations and distribution patterns with ultrapotassic rocks (Fig. 6). This association with potassic volcanic rocks thus indicates the potential of crustal contamination to effectively modify isotopic compositions of mantle-derived ultrapotassic rocks in southern Tibet. Therefore, caution is needed if we try to probe into the nature of deep mantle using isotopic indicators from the Tibetan ultrapotassic rocks.

5.5.2. Elucidating mantle-crust interactions beneath southern Tibet

In previous sections, we have shown the geochemical and petrogenetic differences between adakitic intrusions and potassic volcanic rocks. New observations, together with the seismic reflection data (Nábělek et al., 2009; Wittlinger et al., 2009; Shi et al., 2015; Gao et al., 2016), lead us to propose following model to clarify petrogenetic links among different rock types (Fig. 14). Because geophysical studies have revealed the thinning of Indian continental crust during its northward subduction (Nábělek et al., 2009; Gao et al., 2016), it is likely that the upper part of the Indian crust may have been gradually scraped off and shortened to form the Himalayan orogenic belt, and the Indian lower crust and mantle lithosphere are consequently underplated beneath Lhasa terrane (Fig. 14). Accordingly, the underplating of Indian crust results in the dramatic decrease of zircon $\varepsilon_{\text{Hf}}(t)$ in the postcollisional adakitic intrusions (Fig. 4), and may account for the presence of ~500 Ma and ~800 Ma zircon xenocrysts in ultrapotassic veins from southern Lhasa subterrane (Liu et al., 2013).

Decoupling between upper crust and mantle lithosphere not only enable the buoyant Indian lithosphere to move further downward (Nábělek et al., 2009; Gao et al., 2016), but also imply that the Indian crustal input was restricted to postcollisional magmatism in southern Lhasa subterrane. Considering that potassic and ultrapotassic volcanism are concentrated in the central Lhasa subterrane (Liu et al., 2014a, 2015), the evolved Sr–Nd–Pb isotopic signatures and overall negative zircon $\varepsilon_{\text{Hf}}(t)$ values (Fig. 9) in the PVR samples are more likely to represent the geochemical nature of the overthickened Lhasa terrane crust and the hybridization processes with associated ultrapotassic melts during magmatic evolution (Fig. 14). This model highlights the potential of adakitic and potassic rocks to provide reliable

constraints on the mass transfer of from underthrust Indian continental crust, and sheds light on the profound influence of coeval mantle-derived ultrapotassic magma on formation and evolution of potassic volcanic rocks.

6. Conclusions

A systematic comparison between adakitic intrusions and potassic volcanic rocks revealed their petrogenetic distinction and clarified the relative roles played by mantle-derived ultrapotassic magma and underthrust Indian continental crust. In southern Lhasa subterranean, adakite samples with higher K_2O/Na_2O tend to display lower Y and higher SiO_2 contents, which argue against a direct contribution from high-Y ultrapotassic melts. Instead, the input from subducted Indian continental crust ought to be the main cause for the rapid decrease of zircon $\epsilon_{Hf}(t)$ values since ~35 Ma and the unradiogenic Nd isotopic signatures shown by adakitic intrusions. On the other hand, similarities in isotopic variations and temporal-spatial distributions indicate the close relationship between mantle-derived ultrapotassic rocks and potassic volcanic rocks. Whole-rock Pb isotopic signatures and zircon $\epsilon_{Hf}(t)$ variations in potassic volcanic rocks favor for an affinity with the Lhasa terrane, and the Sr–Nd isotopic correlations defined by the PVR samples can be fully reproduced in terms of binary mixing between juvenile and ancient Lhasa terrane crusts. The contrasting variation trends of Sr/CaO with increasing Rb/Sr and SiO_2 indicates that potassic magma may have undergone fractional crystallization of feldspars and clinopyroxene. With respect to the petrogenetic links with

674 potassic volcanic rocks, the influence of crustal contamination on isotopic compositions of the

675 Tibetan ultrapotassic rocks should not be ignored.

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Figure caption

Figure 1. (a) Topographic map showing tectonic boundaries and units of Tibetan plateau. (b) Geological map showing sampling locations and spatial distributions of the Mesozoic-Cenozoic magmatism. JSS = Jinsha Suture zone; BNS = Bangong-Nujiang suture zone; SNMZ = Shiquan river-Nam Tso Mélange zone; IYZS = Indus-Yarlung Zangbo suture zone; ATF = Altyn Tagh fault; KF = Karakorum fault; LMF = Luobadui-Milashan fault.

Figure 2. (a-j) Field occurrence and photomicrographs for postcollisional magmatic rocks in southern Tibet. Bi = biotite, Cpx = clinopyroxene, Opx = orthopyroxene, Phl = phlogopite, Pl = plagioclase, Sa = sanidine.

Figure 3. Tera-Wasserburg plots and cathodoluminescence images for representative zircon grains. Solid and dashed circles indicate the locations of U–Pb dating and Hf analysis, respectively, and U–Pb ages and $\epsilon_{\text{Hf}}(t)$ values are given for each analytic spot. Except for sample YR1117 (44 μm), zircon Hf isotopic data were obtained using spot size of 60 μm .

Figure 4. Time-correlated variation of initial Hf isotopic compositions for co-magmatic zircons separated from postcollisional magmatic rocks in southern Tibet. Error bars for individual zircon analysis represent two times of standard deviation (2σ). Calculation details of the chondritic uniform reservoir (CHUR) line and the dashed parallel lines with Hf isotope “crustal” model age (T_{DM}^{C}) are given in Table S3. Zircon U–Pb age and Hf isotopic data for

potassic volcanic rocks (Liu et al., 2014b; Hou et al., 2015a; Tian et al., 2015; Zhang et al., 2015), the Eocene-Miocene adakitic intrusions (Chung et al., 2009; Xu et al., 2010; Li et al., 2011; Guan et al., 2012; Ji et al., 2012; Zheng et al., 2012; Ma et al., 2014; Hou et al., 2015a; Wang et al., 2015), mantle-derived ultrapotassic rocks (Sun et al., 2008; Liu et al., 2014a; Tian et al., 2015), and the high Himalayan gneiss (Chu et al., 2011) are plotted for comparison. Data of the inherited zircons in previous studies have been rejected. Note that the beginning of zircon $\epsilon_{\text{Hf}}(t)$ decrease in adakites (~35 Ma) and the onset of ultrapotassic magmatism (~25 Ma) are asynchronous.

Figure 5. (a) Classification of total alkalis versus SiO_2 , with the alkaline/sub-alkaline divide line (Le Maitre, 2002). Previously reported Eocene-Miocene adakitic rocks (Zhao et al., 2001; Hou et al., 2004, 2015a; Chung et al., 2005; Guo et al., 2007b; Xu et al., 2010; Li et al., 2011; Guan et al., 2012; Ji et al., 2012; Ma et al., 2014; Wang et al., 2015; Yang et al., 2015; Zeng et al., 2016) and potassic volcanic rocks (Turner et al., 1996; Miller et al., 1999; Zhao et al., 2001; Williams et al., 2004; Gao et al., 2007, 2009; Wang et al., 2008; Chen et al., 2010, 2011, 2012; Liu et al., 2014b; Hou et al., 2015a; Tian et al., 2015; Zhang et al., 2015) are plotted for comparison. The shaded field represents the variation range of Tibetan ultrapotassic rocks (after Liu et al., 2015).

Figure 6. (a-e) Primitive mantle normalized (after Sun and McDonough, 1989) incompatible element variation diagrams. Grey-shaded area indicates the incompatible element distribution

patterns for ultrapotassic rocks (cf. Liu et al., 2015). Average compositions for potassic volcanic rocks and adakitic intrusions are also plotted for comparison.

Figure 7. Adakite discrimination diagram (a) Sr/Y vs. Y and (b) (La/Yb)_N vs. Yb_N for postcollisional magmatic rocks in southern Tibet. The data fields of adakite and arc calc-alkaline rocks are based on Defant and Drummond (1990) and Petford and Atherton (1996). The variations of Sr/Y and Y in potassic volcanic rocks are modeled in terms of binary mixing with mantle-derived ultrapotassic melt (Fig. 7a). The labeled percentages along mixing curves donate the increments of input from ultrapotassic magma. In Fig.7b, batch partial melting trends are based on Petford and Atherton (1996). Himalayan low-Y leucogranites are plotted for comparison (Zeng et al., 2011; Hou et al., 2012; Liu et al., 2014c). (c) Plot of La/Yb vs. Sm/Yb for potassic and adakitic rocks in southern Tibet. Melting curves are drawn using batch melting equation: $C_{\text{liquid}} = C_{\text{initial}} / (D_R + f \times (1 - D_R))$, where f refers to melting degree and D_R refers to bulk partition coefficients for adakitic and potassic melts in equilibrium with eclogite and amphibolite residues (Table S6). Trace element concentrations of magma source (C_{initial}) are estimated from the average composition of the Jurassic arc-related magmatic rocks in southern Tibet (La = 17.1 ppm, Sm = 3.33 ppm, Yb = 2.04 ppm) (cf. Hou et al., 2015a). Modeling results indicate that both adakites and potassic volcanic rocks were derived from partial melting of overthickened continental crust with an amphibole-bearing eclogite in the residue. The elevated Sm/Yb in some PVR samples (e.g. samples from Chazi and Zabuye) are consistent with the additional input from ultrapotassic magma.

1059

1060 **Figure 8.** Sr and Nd isotopic correlations for potassic volcanic rocks and adakitic intrusions in
1061 southern Tibet. In order to clarify the dominant role of central Lhasa subterranean crust in
1062 producing radiogenic Sr and unradiogenic Nd isotopic signatures of the PVR samples, we
1063 modeled their Sr–Nd correlations in terms of binary mixing between juvenile and ancient crust
1064 components. The juvenile crust component (A) was assumed to have similar isotopic and
1065 element compositions with the PVR sample 07BB-04 (Chen et al., 2011). Sample GJ0601 and
1066 10XB03 (Liu et al., 2014b) were chosen to represent the ancient crust component (B and B').
1067 The data field of ultrapotassic rocks is shown for comparison (see references in Table S7).
1068 Note that the ultrapotassic input may not significantly change the Sr–Nd isotopic array for the
1069 PVR samples with respect to the overlap in Sr–Nd isotopic compositions.

1070

1071 **Figure 9.** Variations in $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$, $\epsilon_{\text{Nd}}(t)$, $^{206}\text{Pb}/^{204}\text{Pb}$, and co-magmatic zircon $\epsilon_{\text{Hf}}(t)$ for the
1072 potassic volcanic rocks in southern Tibet, which are listed from west (top) to east (bottom).
1073 Average values for whole-rock Sr–Nd–Pb and zircon Hf isotopes of the coexisting mantle-
1074 derived ultrapotassic rocks from different places are given in Table S7. Error bars represent
1075 two times of standard deviation.

1076

1077 **Figure 10.** (a–c) Plots of $\text{K}_2\text{O}/\text{Na}_2\text{O}$ vs. SiO_2 , Y, and $(\text{La}/\text{Sm})_{\text{N}}$, in order to show the
1078 mechanism responsible for the high-K feature in potassic and adakitic rocks. Major and trace
1079 element data of the Himalayan low-Y leucogranites are plotted for comparison (Zeng et al.,

2011; Hou et al., 2012; Liu et al., 2014c), which represents the input from underthrust Indian continental crust into adakitic magmatism.

Figure 11. (a-d) Plots of $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $\text{K}_2\text{O}/\text{Na}_2\text{O}$, SiO_2 , and Rb/Sr for the Eocene-Miocene adakitic intrusions in southern Lhasa subterrane. The adakite samples with variably low $^{143}\text{Nd}/^{144}\text{Nd}$ have mediate $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios, high SiO_2 contents, and relatively low Y concentration, which indicate the injection of melts from underthrust Indian crust (as represented by low-Y leucogranites) into adakitic magmatism. The increasing $\text{K}_2\text{O}/\text{Na}_2\text{O}$ in adakites is coupled with elevated SiO_2 and Rb/Sr , suggesting that high-K feature in adakites may not result from input of ultrapotassic melts but reflect the crystallization and differentiation of feldspars.

Figure 12. (a-d) Plots of $^{87}\text{Sr}/^{86}\text{Sr}$ vs. ratios and concentrations of selected elements ($\text{K}_2\text{O}/\text{Na}_2\text{O}$, Sr/Y , SiO_2 , and Y) for potassic volcanic rocks. Red arrows denote the additional input from mantle-derived ultrapotassic magma. Being characterized by low $^{87}\text{Sr}/^{86}\text{Sr}$, the juvenile crust component shares some geochemical similarities with adakitic intrusions in southern Lhasa subterrane, whereas the ancient crust component has more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ and higher $\text{K}_2\text{O}/\text{Na}_2\text{O}$.

Figure 13. Diagrams of (a) Sr/CaO vs. SiO_2 and (b) Rb/Sr vs. Sr/CaO showing the occurrence of fractional crystallization during the magmatic evolution of potassic volcanic rocks.

Geochemical modeling of fractional crystallization is based on the Rayleigh fractionation equation and given by $C_{\text{liquid}} = C_{\text{initial}} \times F^{(D-1)}$, where F is the fraction of remaining melt and D refers to partition coefficient. The initial concentrations of Rb, Sr, and CaO are set to be 400 ppm, 1500 ppm, and 5 wt.%, respectively. D values for plagioclase ($D_{\text{Rb}} = 0.041$, $D_{\text{Sr}} = 4.4$, $D_{\text{Ca}} = 4.25$) and sanidine ($D_{\text{Rb}} = 1.8$, $D_{\text{Sr}} = 7.3$, $D_{\text{Ca}} = 0.25$) are taken from Nagasawa and Schnetzler (1971) and Stix and Gorton (1990), respectively. For clinopyroxene, D_{Ca} (8.57) and D_{Sr} (0.297) are based on Huang et al. (2006), and D_{Rb} (0.032) is taken from Rollinson (1993). For biotite, D_{Ca} (0.615) is based on Higuchi and Nagasawa (1969), and D_{Rb} (3.26) and D_{Sr} (0.12) are from Rollinson (1993). Modeling curves are marked in 10% increments and labeled with corresponding mineral phases and assemblages.

Figure 14. Schematic illustration for the formation and evolution of postcollisional magma in southern Tibet. CC = continental crust; SCLM = sub-continent lithospheric mantle; MBT = main boundary thrust; MCT = main central thrust; STDS = southern Tibetan detachment system.

Liu et al. **Fig. 1** W165 mm - H87 mm (2-column fitting image)

Liu et al. **Fig. 2** W88 mm - H163 mm (1-column fitting image)

Liu et al. **Fig. 3** W133 mm - H220 mm (2-column fitting image)

Liu et al. **Fig. 4** W158 mm - H73 mm (2-column fitting image)

Liu et al. **Fig. 5** W170 mm - H113 mm (2-column fitting image)

Liu et al. **Fig. 6** W162 mm - H148 mm (2-column fitting image)

Liu et al. **Fig. 7** W83 mm - H168 mm (1-column fitting image)

Liu et al. **Fig. 8** W113 mm - H70 mm (2-column fitting image)

Liu et al. **Fig. 9** W168 mm - H72 mm (2-column fitting image)

Liu et al. **Fig. 10** W82 mm - H180 mm (1-column fitting image)

Liu et al. **Fig. 11** W171 mm - H113 mm (2-column fitting image)

Liu et al. **Fig. 12** W167 mm - H113 mm (2-column fitting image)

Liu et al. **Fig. 13** W167 mm - H113 mm (2-column fitting image)

Liu et al. **Fig. 14** W89 mm - H61 mm (1-column fitting image)

Graphical abstract

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