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**Eocene rhyolites in the Shanglaxiu–Xialaxiu area of
north–eastern Qiangtang Block, Tibet: partial melting of
juvenile crust?**

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22 Abstract

23 Many granitoids and their eruptive equivalents are substantially derived from the
24 uppermost proportion of continental crust, and so their petrogenesis and source are
25 significant in understanding the evolution and characteristics of continental crust. The
26 Eocene felsic rocks in the Qiangtang block (central Tibet) commonly have enriched Nd
27 isotope compositions and have been considered to be related to the recycling of ancient
28 continental crustal material. In this paper we report new data on early Eocene felsic
29 rocks with positive $\epsilon_{\text{Nd}}(t)$ values in the northeastern Qiangtang block, which can be used
30 to help understand Cenozoic evolution and characteristics of continental crust in the
31 Qiangtang block. These rocks consist of rhyolites and occur in the Shanglaxiu and
32 Xialaxiu areas in the north-eastern Qiangtang block. Zircon U–Pb dating yields ages
33 of 47.8 ± 0.6 and 44.2 ± 0.7 Ma for the Shanglaxiu and Xialaxiu rhyolites, respectively,
34 and so they represent the earliest record of Eocene magmatism in the Qiangtang block.
35 The Shanglaxiu–Xialaxiu rhyolites have relatively low calculated zircon saturation
36 temperatures (719–819 °C), along with high SiO_2 (74.8–83.3 wt.%) and K_2O (5.1–7.8
37 wt.%) contents, and low MgO (0.2–0.3 wt.%), Cr and Ni contents. They are enriched
38 in light rare earth elements (LREEs), Rb, K, Th, Zr, and Hf, and are depleted in Nb, Ta,
39 Ti, Sr, and P, with moderately negative Eu anomalies. The Shanglaxiu rhyolites have

positive whole-rock $\epsilon_{\text{Nd}}(t)$ (0.3–0.4) and zircon $\epsilon_{\text{Hf}}(t)$ (1.8–10.4), and variable zircon $\delta^{18}\text{O}$ (6.3–7.3‰). The Xialaxiu rhyolites have slightly different whole-rock $\epsilon_{\text{Nd}}(t)$ (–1.5 to –1.6), but similar zircon $\epsilon_{\text{Hf}}(t)$ (2.2–7.7) and $\delta^{18}\text{O}$ (6.7–7.2‰). We propose that the Shanglaxiu–Xialaxiu rhyolites were most probably generated by partial melting of the pre-existing juvenile crust with the addition of minor sedimentary material. This partial melting was possibly triggered by the south-dipping continental subduction of the Songpan–Ganzi block. The pre-existing juvenile crust was probably formed during the subduction of Paleo–Tethyan oceanic slab in Paleozoic–Early Mesozoic.

Keywords:

Rhyolites; juvenile crust; continental subduction; Eocene; Qiangtang; Tibet

55 1. Introduction

56 The continental crust has long been a significant area of geological research (Niu
57 et al., 2013; Rudnick, 1995). Incompatible trace element signatures of mantle-derived
58 island-arc magmas (IAB) and the bulk continental crust are remarkably similar in that
59 both are relatively enriched in “water-soluble” elements (e.g., Ba, K and Pb) and
60 depleted in “water-insoluble” elements (e.g., Nb, Ta and Ti) (Niu et al., 2013; Rudnick
61 and Gao, 2014). Consequently, it is widely accepted that the continental crust was
62 principally generated through subduction zone magmatism (Rudnick, 1995).
63 Nevertheless, this standard “island-arc model” is not completely correct because bulk
64 arc crust is too mafic and has a dominantly basaltic composition (Holbrook et al., 1999)
65 which is significantly different from the andesitic bulk composition of continental crust
66 (Rudnick and Gao, 2014). Furthermore, it has been argued that arc crust does not
67 contribute to net continental growth owing to the mass balance of subduction erosion,
68 sediment recycling and arc crust production (Niu et al., 2013).

69 In order to resolve these issues, many recent studies have proposed the
70 “continental collision model” of crustal growth in continental collision zones, which
71 are significant sites for continental crust growth (Niu et al., 2013; Zhang et al., 2016;
72 Zhu et al., 2023). The continental collision model has been tested and validated in a

number of orogens, for instance, the Gangdese (Niu et al., 2013; Zhu et al., 2023), east and west Kunlun (Zhang et al., 2016), north Qaidam (Zhao et al., 2017) and west Qinling orogenic belts (Kong et al., 2018).

It is clear that felsic rocks (e.g., dacites and rhyolites) are largely derived from the uppermost proportion of continental crust, and therefore their petrogenesis and source characteristics are significant in our understanding of the growth and evolution of continental crust. Cenozoic magmatic rocks are widely distributed in the Qiangtang block, central Tibet (Fig. 1a) and range in age from ~64 Ma to 2.3 Ma (Chung et al., 2005; Jiang et al., 2006; Roger et al., 2000; Spurlin et al., 2005; Wang et al., 2001; Wang et al., 2008; Xu et al., 2016, 2019a; Zhang et al., 2015; Zhang et al., 2020).

Interestingly, the Nd isotopic characteristics of the Cenozoic crust-derived magmatic rocks in the western-central ($\epsilon_{\text{Nd}}(t) = -8.3$ to -2.1 ; Chen et al., 2013; Liu et al., 2008; Liu et al., 2022; Long et al., 2015; Ou et al., 2017; Wang et al., 2008) and southeastern ($\epsilon_{\text{Nd}}(t) = -4.6$ to -0.8 ; Jiang et al., 2006; Lin et al., 2018; Wang et al., 2001; Xu et al., 2019b; Zhang et al., 2005) Qiangtang blocks are more enriched than those in the Yushu–Nangqian area in the northeastern ($\epsilon_{\text{Nd}}(t) = -1.4$ to 2.5 ; Roger et al., 2000; Spurlin et al., 2005; Xu et al., 2016; Yang et al., 2008; Zhang et al., 2015) Qiangtang block, suggesting that the composition of continental crust in the Qiangtang block is

heterogeneous. This is supported by recent studies that report mafic and felsic granulite xenoliths from the lower continental crust in potassic volcanic rocks from the Qiangtang (Lai et al., 2011), and so the magma source of the Eocene adakitic rhyolites might be a mixture of metamorphosed mafic and sedimentary rocks (Long et al., 2015).

The petrogenesis and geodynamic setting of the Cenozoic magmatic rocks in the northern Qiangtang block remain controversial with various models being proposed. These include continental subduction (Roger et al., 2000; Spurlin et al., 2005; Wang et al., 2008; Xu et al., 2016; Zhang et al., 2020), delamination of the lower crust (Chen et al., 2013; Zeng et al., 2020), convective removal of lower lithosphere (Chung et al., 1998), and movement of Eocene regional-scale strike-slip fault system (Liang et al., 2006; Yang et al., 2008).

As the earliest record of Eocene magmatism within the Qiangtang block, the rhyolites in the Shanglaxiu–Xialaxiu area (Fig. 1b) can help understand the petrogenesis and geodynamic setting of the Eocene magmatic rocks and the relatively depleted Nd isotope compositions of continental crust in the northeastern Qiangtang block. Therefore, in this paper we report detailed geochronological and geochemical data of the less studied early Eocene rhyolites of the eastern Qiangtang block in the Shanglaxiu–Xialaxiu area. Our work shows that partial melting of juvenile crust in the

northeastern Qiangtang block was triggered by the south-dipping continental subduction of the Songpan-Ganzi block in a post-collisional contractional setting. Based on the spatial extension characteristics (from northwest to southeast) and the similar Nd isotopic signatures between the Permian basalts associated with the Emeishan mantle plume and the co-existing Cenozoic magmatic rocks, we propose that the juvenile crust in the northeastern Qiangtang block may have originated from the underplating of Permian basaltic magmas.

2. Geological background and samples

The Tibetan Plateau, the largest uplifted region on earth consists from north to south of the Songpan-Ganzi (SG), Qiangtang (QT), Lhasa and Himalaya blocks ([Chung et al., 2005](#); [Yin and Harrison, 2000](#)). These four approximately east-west trending blocks are separated by the Paleo-Tethyan Jinshajiang (JS), Meso-Tethyan Bangong-Nujiang (BS), Neo-Tethyan Indus (IS) suture zones from north to south, respectively ([Fig. 1a](#)). The Qiangtang block is subdivided into the northern and southern Qiangtang sub-blocks by the intervening Longmucuo-Shuanghu suture zone of the Paleo-Tethys Ocean ([Metcalf, 2013](#); [Ou et al., 2017](#); [Wang et al., 2021](#)). The Qiangtang block has

undergone a sequence of collisional events since the northern and southern Qiangtang sub-blocks collided in Early Permian (Zhang et al., 2016), such as the late Triassic collision of the northern Qiangtang sub-block and the Songpan–Ganzi block that generated the Jinsha suture zone, and the Cretaceous collision of the southern Qiangtang sub-block and Lhasa block that generated the Bangong–Nujiang suture zone (Ou et al., 2017; Wang et al., 2000a; Zhu et al., 2016). Consequently, it has been proposed that the lithosphere of the Qiangtang block was mainly modified by the Tethys oceanic or intra–continental subduction (Wang et al., 2008; Xu et al., 2016; Zhang et al., 2020; Zhu et al., 2016).

Since the Late Paleocene–Early Eocene, the convergence and collision between the Indian continent and the Eurasian continent has generated a significant amount of shortening and a series of large–scale left–lateral strike–slip faults in eastern Tibet, such as the Fenghuoshan–Nangqian thrust belt, the Jinshajiang fault system and the Batang–Lijiang fault system (Chung et al., 2005; Spurlin et al., 2005; Xu et al., 2016; Yin and Harrison, 2000). These strike–slip faults are essentially perpendicular to the northeastward orientation of convergence (Spurlin et al., 2005). In addition, many syn–contractional sedimentary basins (e.g., Fenghuoshan basin, Shanglaxiu–Xialaxiu basin, Nangqian basin and Gongjue basin) developed within these fault systems, and

the ages of the sedimentary rocks as well as the interbedded volcanic rocks of the basins indicate that the basins and fault systems formed during the Paleocene–Eocene (Horton et al., 2002; Spurlin et al., 2005).

Eocene–Early Oligocene (50–29 Ma) magmatic rocks are widespread in the Qiangtang block, including potassic or shoshonitic magmas and (high–K) calc–alkaline magmas (Chung et al., 1998, 2005; Hou et al., 2003; Jiang et al., 2006; Ou et al., 2017; Roger et al., 2000; Spurlin et al., 2005; Wang et al., 2001; Wang et al., 2008; Xu et al., 2016, 2019a; Zhang et al., 2020). Some workers have suggested that these magmatic rocks may be accompanied by the development of the sedimentary basins mentioned above (Chung et al., 2005; Horton et al., 2002; Spurlin et al., 2005; Wang et al., 2008).

The Shanglaxiu–Xialaxiu district is situated on the northern margin of the Eastern Qiangtang block, just north of the Nangqian basin (Fig. 1a). Major stratigraphic units exposed in this district are Triassic marine carbonates and minor clastic units overlain by Paleocene and Eocene red beds and carbonates. The Paleocene–Eocene stratigraphic units unconformably overlie the Triassic units. The uppermost fill of the Shanglaxiu basin is older than that of the Xialaxiu and Nangqian basins, as the Shanglaxiu basin lacks Eocene carbonates. The Shanglaxiu–Xialaxiu rhyolites unconformably overlie Triassic carbonates and sandstones, which are the basal parts of the

Shanglaxiu–Xialaxiu basin (Horton et al., 2002; Spurlin et al., 2005).

The igneous rocks in the Shanglaxiu–Xialaxiu basin predominately consist of rhyolites, which are the earliest Eocene magmatic rocks that have been reported from the Qiangtang block (Roger et al., 2000; Spurlin et al., 2005). The outcrop of rhyolite in Xialaxiu is ~13.5 km long and ~4 km wide and trends in a NW–SE direction. This is ~11 km southwest of a minor isolated rhyolitic flow at Shanglaxiu. All these rhyolites have an obvious fluxion structure (Fig. 2e). Six rhyolite samples were collected from the Shanglaxiu and two from Xialaxiu (Fig. 1b). The rhyolites from both areas are light grey and light violet respectively, and the Shanglaxiu samples are more altered than those from Xialaxiu. They display typical a porphyritic texture with phenocrysts that consist of quartz (5–10%), K-feldspar (10–15%), plagioclase (~5%) and biotite (< 2%) (Fig. 2b–c, e–f), with accessory zircon. The groundmass is dark grey, and predominantly consists of quartzofeldspathic minerals.

3. Analytical methods and results

SIMS zircon U–Pb dating and Hf–O isotopic analyses were carried out at the State Key Laboratory of Isotope Geochemistry (SKLaBIG), Guangzhou Institute of

Geochemistry, Chinese Academy of Sciences (GIGCAS). Whole-rock major and trace element analyses were carried out at Wuhan Sample Solution Analytical Technology and SKLaBIG, GIGCAS. Sr–Nd isotope analyses were carried out at Wuhan Sample Solution Analytical Technology. More details of the analytical methods are presented in [Appendix 1](#).

3.1 Zircon U–Pb ages

Zircon U–Pb data are presented in Table [S1](#) of [Appendix 1](#). Zircon CL images show that zircon crystals from samples SLX01-7 and XLX01-1 are narrow with a length–width ratio of 1.5–6, and are euhedral with clear oscillatory zoning, showing typical igneous zircon characteristics. These zircons also have high Th/U ratios of 0.63–2.20, supporting their igneous origin ([Hoskin and Schaltegger, 2003](#)).

For sample SLX01-7, 19 analyzed spots of these zircons were plotted on a Tera–Wasserburg (TW) concordia diagram and yielded a concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 47.8 ± 0.6 Ma (MSWD = 1.8) ([Fig. 3a](#)).

For sample XLX01-1, 19 analyzed spots of these zircons were plotted on a TW concordia diagram and yielded a concordant $^{206}\text{Pb}/^{238}\text{U}$ age of 44.2 ± 0.7 Ma (MSWD = 2.4) ([Fig. 3b](#)). Previous work reported that the Shanglaxiu rhyolite formed at $51.2 \pm$

0.2 Ma (biotite Ar–Ar, [Spurlin et al., 2005](#)) and the Xialaxiu rhyolite formed at 49.5 ± 0.2 Ma (biotite Ar–Ar, [Spurlin et al., 2005](#)) and 51.4 ± 0.6 Ma (whole rock, K–feldspar and biotite Rb–Sr isochron, [Roger et al., 2000](#)). These ages are all older than our SIMS zircon ages. However, given the significant alteration of the major rock-forming minerals in these samples, it is likely that the SIMS zircon ages (47.8 ± 0.6 and 44.2 ± 0.7 Ma) better represent the formation time for these rocks.

3.2 Major and trace element compositions

The results of major and trace element analyses are reported in Table [S2](#) of [Appendix 1](#) on a volatile-free basis. Samples from the Shanglaxiu area have higher loss on ignition (LOI) with values of 3.5–5.6 wt.% relative to those from the Xialaxiu area with values of 2.0–2.1 wt.%. Consequently, it is necessary to be cautious about the effects of alteration. Elements such as the HFSE and REE are generally regarded to be relatively immobile during moderate hydrothermal alteration. In contrast, other elements like the LILE, Na and Ca are much more mobile during sub-solidus alteration ([Wang et al., 2021](#)). With the exception of samples SLX01-2 and SLX01-5, the rhyolites show a lack of correlation between LOI and K_2O , Na_2O , Al_2O_3 , MgO , Fe_2O_3T , P_2O_5 , Y,

Th, and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values, suggesting that alteration has limited impact on these elements (Fig. S1 in Appendix 1). For samples SLX01-2 and SLX01-5 the elements above do not form part of the following discussion.

The Shanglaxiu–Xialaxiu rhyolites exhibit high SiO_2 (74.8–83.3 wt.%), K_2O (5.1–7.8 wt.%) and CaO (0.1–2.3 wt.%) contents, and intermediate Al_2O_3 (14.3–15.7 wt.%) values, and low Na_2O (0.4–1.2 wt.%), TiO_2 (0.17–0.19 wt.%), MnO (0–0.03 wt.%) and MgO (0.2–0.3 wt.%) concentrations. All the samples entirely fall in the subalkaline and rhyolite field in a total alkali–silica (TAS) diagram (Fig. 4a). Additionally, the Shanglaxiu rhyolites classify as high–K calc–alkaline rocks and the Xialaxiu rhyolites as shoshonites on a SiO_2 vs. K_2O diagram (Fig. 4b). The A/CNK (molecular $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) ratios are 1.24–2.38, indicating that these rhyolites are peraluminous (Fig. 4c). On major–element Harker diagrams, total Fe_2O_3 ($\text{Fe}_2\text{O}_3\text{T}$), MgO , P_2O_5 , Na_2O , and CaO are inversely interrelated with SiO_2 , however, the correlation between Al_2O_3 or TiO_2 and SiO_2 is much less distinct (Fig. 5). These rocks are marked by low contents of Cr, Ni and high field strength elements (HFSE, e.g., Nb, Ta, Ti, and P), and enrichment in large ion lithophile elements (LILE, e.g., K, Rb, Pb and Cs).

Their chondrite–normalized REE patterns are subparallel (Fig. 7), and show a

characteristic of enrichment in LREE and depletion in HREE with $(\text{La/Yb})_N$ ratios ranging from 24 to 34. The LREE of these granites have fractionated more significantly than HREE (Fig. 7a) and they have moderately negative Eu anomalies with δEu [$=\text{Eu}_N/(\text{Sm}_N*\text{Gd}_N)^{1/2}$] values of 0.56–0.76. The Xialaxiu rhyolites exhibit higher REE and Y contents, and higher Rb/Sr ratios, compared to the Shanglaxiu rhyolites. However, the Xialaxiu rhyolites have lower Sr/Y ratios (5.5–5.8) compared to the Shanglaxiu rhyolites (16.5–24.7).

3.3 Sr–Nd–Hf–O isotope compositions

The whole-rock Sr–Nd isotope and in situ zircon Hf–O isotope analyses are given in Table S3 and S4 in Appendix 1, respectively. The initial Sr and Nd isotopic ratios were calculated using the zircon U–Pb ages from this study. The Shanglaxiu rhyolites have homogeneous isotopic compositions, with $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.7063\text{--}0.7064$, $(^{143}\text{Nd}/^{144}\text{Nd})_i = 0.512591\text{--}0.512598$, $\epsilon_{\text{Nd}}(t) = 0.3\text{--}0.4$ and depleted mantle Nd model ages (T_{DM}) ranging from 0.64–0.68 Ga. The Xialaxiu samples have slightly lower $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values (0.7060–0.7063), $(^{143}\text{Nd}/^{144}\text{Nd})_i$ values (0.512500–0.512504), and $\epsilon_{\text{Nd}}(t)$ values (–1.6 to –1.5), and older Nd model ages (T_{DM}) of 0.79–0.80 Ga than the

Shanglaxiu rhyolites.

Zircon Hf–O isotope analyses were carried out on the same grains used for U–Pb dating. Nineteen and seventeen spot analyses were obtained for samples SLX01-7 and XLX01-1, respectively. The Shanglaxiu rhyolites show depleted Hf isotopic compositions, with $^{176}\text{Hf}/^{177}\text{Hf}$ ratios = 0.282796–0.283036, and $\epsilon_{\text{Hf}}(t) = 1.8\text{--}10.4$ (Fig. 9c). The Xialaxiu rhyolites have slightly lower $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282808 to 0.282964, with more enriched $\epsilon_{\text{Hf}}(t)$ values ranging from 2.2 to 7.7 (Fig. 9d). The ranges of zircon $\delta^{18}\text{O}$ values for Shanglaxiu and Xialaxiu rhyolites are narrow and comparatively homogeneous, from 6.26‰ to 7.32‰ (average of 6.85‰) and 6.73‰ to 7.20‰ (average of 6.99‰) respectively (Fig. 9a, b), which are higher than the upper limit (6.5‰) of mantle-derived magmas (Valley et al., 2005).

4. Discussion

4.1 Petrogenesis

4.1.1 Rhyolite types

A range of granitoid classification schemes have been proposed over the past 40 years (e.g., Chappell 1999; Wu et al., 2007) with one of the most enduring of

classification schemes being the MISA (M-, I-, S-, and A-types) granitoids categorization scheme. I- and S-type granites are principally defined based on their aluminum saturation index (ASI, i.e. $A/CNK = \text{molecular } Al_2O_3 / (CaO + Na_2O + K_2O)$) with an A/CNK of > 1.1 being defined as an S-type granite and < 1 being an I-type granite (Chappell 1999; Chappell and White, 1992).

The Shanglaxiu–Xialaxiu rhyolites are markedly peraluminous with A/CNK ratios of 1.24–1.42 (the excessive A/CNK ratio of 2.38 for sample 19SLX01-3 is excluded owing to alteration), which indicates that they are S-type rhyolites ($A/CNK \geq 1.1$; Chappell and White, 1992). However, previous research has argued that the I- and S-type A/CNK criterion is not always effective (Wu et al., 2007) and peraluminous granite and S-type granite are not one and the same (Chappell et al., 2012; Chappell and White, 1992; Gao et al., 2022). This is because the A/CNK values of highly fractionated I-type granites overlap with those of highly fractionated S-type granites (Chappell, 1999), and intermediate to felsic peraluminous melts can be generated by dehydration melting of metaluminous rocks (e.g., amphibolites and felsic orthogneisses) under water-poor and low-melt-fraction conditions (Gao et al., 2022). Therefore, it is problematic to use the A/CNK values of these rhyolites to classify them as S-type. The presence of cordierite can also be used as a diagnostic mineral for S-type granitoids

(Wu et al., 2007), however no cordierite has been found in these rhyolites.

Experimental studies have shown that the contents of P_2O_5 correlate positively SiO_2 in S-type granite magmas, and that this does not occur in I-type magmas (Chappell, 1999). The lack of a positive correlation between the P_2O_5 and SiO_2 contents of the Shanglaxiu–Xialaxiu rhyolites (Fig. 5c), indicates that these rocks are I-type rather than S-type. This is also supported by the lack of inherited zircons in these rhyolites (Chappell et al., 1998).

Yttrium and thorium abundances both increase in abundance in I-type melts but decrease in S-type melts (Chappell et al., 1998, 2012; Wang et al., 2021). The Y and Th contents of the rocks in this study resemble those of the I-type granites in the Southern Qiangtang block (He et al., 2019; Wang et al., 2021), and are higher than those of the S-type granites in Himalaya (Liu et al., 2014) (Fig. 8a–b). Additionally, I-type granites commonly have lower zircon $\delta^{18}O$ values than S-type granites (Wang et al., 2021). The rhyolites in this study all have relatively low $\delta^{18}O$ values of 6.26–7.32‰ (Fig. 9a, b), consistent with a source containing metagneous rocks and suggests that they are I-type (Wang et al., 2021).

Fig. 8d shows that all the rhyolites are magnesian with I-type granite affinity.

Previous studies have suggested that it is hard to discriminate between A-type granites and highly fractionated I-type granites owing to the similarity of their geochemical characteristics (Chappell et al., 1998; Wu et al., 2007). Generally, highly fractionated I-type granites have relatively low contents of FeOT (<1 wt.%, Wang et al., 2000b), which is in good concordance with the low contents of FeOT (0.14–1.22 wt.%) exhibited by these rhyolites. In addition, for highly fractionated I-type granites, the contents of both HREEs and Y increase and the negative Eu anomalies become more significant with fractional crystallization. These granites typically exhibit relatively flat or uniform chondrites-normalized REE patterns, or REE tetrad effects, which are similar to A-type granites (Chappell et al., 1998; King et al., 1997). However, the characteristics of REEs and Eu anomalies for these rhyolites are not consistent with those of A-type granites. More importantly, previous research (e.g., experimental petrology data, zircon saturation temperatures) has shown that A-type granites are characterized by high temperatures (King et al., 1997; Wang et al., 2018), which suggests that they cannot be generated by fractionation of I-type granites (Wu et al., 2007).

All the rhyolites in the Shanglaxiu–Xialaxiu area have relatively low calculated zircon saturation temperatures (719–819 °C, average of 774 °C, excluding the

abnormally high calculated temperature due to the effect of alteration; [Table S2](#)). Their temperatures are similar to those of I-type granites in southern Qiangtang (644–772°C; [Wang et al., 2021](#)), western Yangtze (723–852°C; [Zhao et al., 2008](#)) and Lachalan Fold Belt (764–781°C; [King et al., 1997](#)), and are lower than the A-type granites from western Yangtze (813–905 °C; [Zhao et al., 2008](#)), northern Qiangtang (average of ~941 °C; [Wang et al., 2018](#)) and Lachlan Fold Belt (839°C; [King et al., 1997](#)). In summary, on the basis of this wide range of evidence it is clear that the Shanglaxiu–Xialaxiu rhyolites are I-type felsic igneous rocks.

4.1.2 Assimilation and fractional crystallization

Although crustal assimilation during the ascent of magma is to a large extent inevitable, the effect of crustal assimilation on the Shanglaxiu–Xialaxiu rhyolites is likely to be limited because of (a) a scarcity of inherited zircons in these rhyolites; (b) a lack of wall-rock or crustal xenoliths; (c) all the rhyolites have relatively uniform $\epsilon_{\text{Nd}}(t)$ and $(^{87}\text{Sr}/^{86}\text{Sr})_i$ values and lack correlation between $\epsilon_{\text{Nd}}(t)$ and SiO_2 ([Fig. 5h–i](#)); (d) the SiO_2 vs. Mg# diagram ([Fig. 6a](#)) illustrates that the compositions of these rhyolites are inconsistent with the trend of crustal assimilation with fractional

crystallization (curve 3).

As the Shanglaxiu–Xialaxiu rhyolites have high silica compositions, the effects of fractional crystallization likely to be considerable. On multi–element normalized plots (Fig. 7b), these rhyolites are depleted in Ba, Nb, Ta, Ti, Sr, and P indicating that fractional crystallization could have played a significant role during magma evolution. The depletion in Sr and Ba and moderately negative Eu anomalies suggests plagioclase fractionation. Fractional crystallization of garnet could result in an increase in La/Yb and Dy/Yb values, whereas fractional crystallization involving amphibole would cause a slight increase in La/Yb values and a relatively significant decrease in Dy/Yb values (Davidson et al., 2007). However, these rocks display little evidence for garnet and amphibole fractional crystallization trends except that their La/Yb values are slightly positively correlated with SiO₂ contents in the Xialaxiu rhyolites (Fig. 5g), which suggests limited amphibole and plagioclase fractional crystallization. This is consistent with the fact that the Xialaxiu rhyolites are more peraluminous than Shanglaxiu rhyolites, as amphibole fractionation would result in more peraluminous melts (Chappell et al., 2012). In addition, as mentioned above, the P₂O₅ contents are negatively correlated with SiO₂ contents in these rocks (Fig. 5c), indicating the occurrence of apatite fractional crystallization during magma evolution.

353

354 4.1.3 Magma source

355 Generally speaking, the petrogenesis of magmatic rocks can be explained by the
356 processes of partial melting, crustal assimilation with fractional crystallization (AFC)
357 and magma mixing. Melts with compositions more felsic than andesite ($\text{SiO}_2 > 57 \text{ wt.}\%$)
358 cannot be generated by direct partial melting of the mantle ([Baker et al., 1995](#)).
359 Accordingly, the high-silica characteristics of Shanglaxiu–Xialaxiu rhyolites have not
360 been formed by direct partial melting of the mantle. Many petrogenetic models have
361 been proposed for the origins of felsic rocks including: (a) fractional crystallization of
362 mantle-derived mafic melts with or without crustal contamination ([Chen and Arakawa,](#)
363 [2005](#)); (b) partial melting of the mafic lower continental crust ([Hou et al., 2013](#); [Wang](#)
364 [et al., 2021](#)) and (c) binary mixing between felsic and mafic magmas ([Lu et al., 2013](#)).

365 Since no broadly coeval mafic magmatic rocks occur in the Shanglaxiu–Xialaxiu
366 district ([Fig. 1b](#)), it is unlikely that the rhyolites in this study are predominantly
367 generated by fractional crystallisation. The paleomagnetic, biostratigraphic and
368 sedimentological evidence suggests that the northern Qiangtang and south China blocks
369 were in close proximity during the Late Permian ([Huang et al., 1992](#); [Metcalf, 2013](#);

370 [Zhang et al., 2013](#)). Some Late Permian OIB-like mafic rocks related to Emeishan
371 plume activity have been reported along the northeastern margin of the northern
372 Qiangtang block ([Fig. 13](#); [Liu et al., 2016](#); [Wang et al., 2018](#)). In addition, the
373 Shanglaxiu–Xialaxiu rhyolites are situated between the Yanshiping bimodal volcanics
374 that are related to plume–subduction interaction in the central Qiangtang block and the
375 Late Permian mafic rocks in eastern Tibet ([Fig. 13](#)), suggesting that the subcontinental
376 lithospheric mantle beneath Shanglaxiu–Xialaxiu may be geochemically similar to that
377 beneath Yanshiping. The modeled fractionation trend of basalt from the Yanshiping
378 bimodal volcanics is consistent with the differentiation trend of the Emeishan high–Ti
379 basalts into the peralkaline A-type granitoids, indicating that the Yanshiping rhyolites
380 were not generated by direct fractional crystallization of the Yanshiping basalts ([Fig.](#)
381 [10a](#); [Wang et al., 2018](#)). The Th/Nb ratios of the Shanglaxiu–Xialaxiu rhyolites are
382 similar to those of the Late Permian Yanshiping rhyolites and are higher than the
383 modeled fractionation trend ([Fig. 10a](#)). This indicates that the Shanglaxiu–Xialaxiu
384 rhyolites comparable to Yanshiping rhyolites were not produced by direct fractional
385 crystallization (FC) of contemporaneous mafic magmas. As discussed above, the effect
386 of crustal contamination is negligible, thus the possibility that the studied rocks
387 produced by AFC or FC of mafic magmas can be ruled out. Although mixing between

felsic and mafic magmas is possible, the consistent zircon crystal morphology, the homogenous Sr–Nd–Hf–O isotopic contents and the scarcity of dark mafic xenoliths make an origin by mixing unlikely.

The characteristics of REE and some trace elements (e.g., Rb, Ba, Nb, Ta, Ti, P, Y) for these rhyolites are similar to the felsic rocks that were derived from juvenile crust, such as the Eocene Nangqian adakitic intrusions and Narigongma granitic porphyries in the northern Qiangtang block (Xu et al., 2016; Yang et al., 2008, 2014), and the Late Cretaceous Duoma–Namuqie granitic porphyries in the southern Qiangtang block (Wang et al., 2021). Furthermore, the relatively depleted isotopic compositions of the Shanglaxiu–Xialaxiu rhyolites are located between the end–member of depleted mantle (DM) and the field of Qiangtang lower crust composition (Fig. 11, 12). The composition of the rhyolites in the present study are similar to the Eocene mafic and felsic rocks in Nangqian (Deng et al., 2001; Spurlin et al., 2005; Xu et al., 2016, 2019a), the Paleocene–Eocene adakitic rocks in the eastern Qiangtang block (Yang et al., 2014; Zhang et al., 2015), the Late Permian Yanshiping bimodal volcanics (Wang et al., 2018), and the Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks (Xu et al., 2001; Song et al., 2004). This indicates that the Shanglaxiu–Xialaxiu rhyolites might have been derived from juvenile crust that was related to Emeishan

plume.

The Ce/Pb (3.4–11.1, average of 5.1), Th/U (3.1–5.9, average of 4.9), and Nb/U (2.6–4.1, average of 3.5) ratios of these rhyolites resemble those of lower continental crust (Fig. 10b–c). Additionally, felsic melts with SiO₂ compositions of > 65 wt.% and A/CNK values of ≥ 1.0 can be produced by dehydration partial melting of basaltic or andesitic rocks at pressures of 0.5–1.0 GPa and temperatures of 850–950 °C (Wang et al., 2021). Thus, it is plausible that these rhyolites were generated from juvenile crust similar to the Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks (Song et al., 2004; Xu et al., 2001). However, the Th/La ratios and Th contents of these rhyolites are significantly higher than those of the Late Permian basaltic rocks and are more similar to marine sediments, upper continental crust, and Eocene Duogecuoren adakitic rocks (Fig. 10d; Wang et al., 2008, and references therein). This suggests that the source of these rhyolites is not only related to the Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks, but also contains a component with high Th/La and Th. Previous experimental results have shown that the melting of sediments can result in an enrichment of Th in MORB (Johnson and Plank, 1999). Combined with the overlap of the ranges of (⁸⁷Sr/⁸⁶Sr)_i and ε_{Nd}(t) values between the studied rocks and the Paleozoic–Triassic sediments (She et al., 2006; Sigoyer et al.,

2014) (Fig. 11), it is likely that the source of these rhyolites contains sediments from the Songpan–Ganzi block.

This interpretation is further confirmed by the significant decoupling relationship between Nd and Hf isotopic compositions of our samples (Fig. 12a). Usually, the relationship between Nd and Hf would follow the mantle array ($\epsilon_{\text{Nd}}(t) = 1.59\epsilon_{\text{Hf}}(t) + 1.28$; Chauvel et al., 2008). However, for the Shanglaxiu–Xialaxiu rhyolites, the $\epsilon_{\text{Hf}}(t)$ values of zircon positively deviate from the whole–rock $\epsilon_{\text{Nd}}(t)$ values relative to the mantle array (Fig. 12a), which is likely to result from the incorporation of subducted sediments. This decoupling could be explained by two processes: (1) disequilibrium melting of zircon at the source results in the “zircon effect” — a term for the greater fractionation of Lu/Hf than Sm/Nd caused by zircon during chemical weathering or crustal melting (Tang et al., 2014); (2) the Nd–Hf isotopic compositions are inherited from the parental magma (Wang et al., 2021). Zircon is a stable, Hf–enriched mineral with an extremely low Lu/Hf ratio. During disequilibrium melting, the presence of residual zircons can cause an increase in the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the melts. This increase may result in the decoupling of the Hf isotope system from the Nd isotope system (Tang et al., 2014). However, due to the scarcity of inherited zircons and the slight depletion of Zr in these rhyolites (Fig. 7b), the contribution of disequilibrium

melting to the decoupling of the Nd–Hf isotope system is likely to be limited.

The positive deviation of Hf isotopic compositions from the mantle array can essentially be attributed to the abnormally high Lu/Hf ratios and/or the incorporation of material with relatively high Nd/Hf ratios in the magma source. The solubility of HFSEs (e.g., Hf) is lower than the solubility of LREEs (e.g., Nd) in sediment–derived aqueous fluids ([Polat and Münker, 2004](#)), hence sediments and fluids from the subducted slab would have relatively high Nd/Hf ratios ([Chauvel et al., 2008](#)). The studied rhyolites are likely to have been derived from juvenile crust similar to the Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks, which are closely related to Emeishan plume. Consequently, we use average sediments (GLOSS; [Chauvel et al., 2008](#)) and Permian basalt related to Emeishan plume source (high–MgO picrites with $\epsilon\text{Nd}(t = 47.8 \text{ Ma})$ values of 6.8; [Li et al., 2010](#)) to model the Nd–Hf mixing of the two end–members ([Fig. 12a](#)). The modelling results indicate that adding 20–40% sediments into the Permian basaltic rocks related to Emeishan mantle plume source can produce the Nd–Hf isotopic compositions of our samples. Additionally, the modelling suggests that the Xialaxiu rhyolites contain a higher proportion of sedimentary materials compared to the Shanglaxiu rhyolites, which is consistent with the Hf–O isotopic modeling results ([Fig. 12b](#)).

Garnet is a Lu-enriched mineral with a significantly high Lu/Hf ratio, and therefore a garnet-rich source could lead to an increase in the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the melts. Nevertheless, as discussed above, these rhyolites have relatively low calculated zircon saturation temperatures (719–819 °C, average of 774 °C) and are similar to adakitic rocks (Fig. 6b), indicating that garnet in their source is likely to be stable. The presence of residual garnets in the source may cause a reduction in $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of the melt, and it is likely to result in a negative deviation of the Hf isotopic system from the Nd isotopic system, similar to the Paleocene–Eocene adakitic rocks in the northeastern Qiangtang block (Fig. 12a; Yang et al., 2014; Zhang et al., 2015). In addition, the relatively flat HREEs pattern (Fig. 7a) do not support the presence of residual garnets in the source and so there is little evidence of the effect of residual garnet in the source on the decoupling of the Nd–Hf isotope system. Taking the above points into account, we infer that the primary factor contributing to the significant Nd–Hf decoupling in these rhyolites is the incorporation of subducted sediments. Due to the slight depletion of Zr in these rhyolites (Fig. 7b), disequilibrium melting of zircon in the source may also result in the decoupling of Nd–Hf isotopes.

The relatively high Mg# values of the late Eocene felsic rocks in Nangqian and the Paleocene–Eocene adakitic rocks in the eastern Qiangtang block contrast sharply with

the low Mg# values of the rhyolites in Shanglaxiu–Xialaxiu (Fig. 6a). A plausible explanation is that the parent magmas of the late Eocene felsic rocks in Nangqian were more closely related to the mantle than the rhyolites in this study as the Mg# values of the melts originating from partial melting of the lower crust are typically low (< 40 , Rapp and Watson, 1995). Therefore, these rhyolites are most likely generated by the partial melting of subduction–modified juvenile crust with the addition of 20%–40% sedimentary materials during the early Eocene south–dipping continental subduction along the Jinsha suture. The juvenile crust may originate from the underplating of older mantle melts during the Late Permian.

Additionally, the relatively more felsic Shanglaxiu rhyolites were unlikely to have been generated by the evolution of the Xialaxiu rhyolites because: (a) they occur in different locations (Fig. 1b); (b) our geochronology indicates that they are not contemporaneous, i.e., the Shanglaxiu rhyolites are older than the Xialaxiu rhyolites; (c) the Shanglaxiu rhyolites have slightly depleted isotopic compositions while the Xialaxiu rhyolites have slightly enriched isotopic compositions (Fig. 9, 11 and 12); (d) although their chondrite–normalized REE patterns are subparallel, the Xialaxiu rhyolites have higher REE than the Shanglaxiu rhyolites; (e) in contrast to the Xialaxiu rhyolites with normal arc affinities, the Shanglaxiu rhyolites have adakite–like

characteristics ([Fig. 6b](#)).

4.2 Geodynamic implications

Eocene magmatic rocks, are widely distributed in the Qiangtang block, and these have the potential to shed light on the processes of crustal evolution and the interaction between mantle and crust. A range of petrogenetic models have been proposed to interpret these igneous rocks and these include: (a) continental subduction ([Roger et al., 2000](#); [Spurlin et al., 2005](#); [Wang et al., 2001](#); [Wang et al., 2008](#); [Xu et al., 2016, 2019a](#); [Zhang et al., 2020](#)); (b) convective removal of the lower lithosphere ([Chung et al., 1998](#)); (c) movement of an Eocene regional-scale strike-slip fault system ([Liang et al., 2006](#); [Yang et al., 2008](#)); (d) delamination of the lower crust ([Chen et al., 2013](#); [Zeng et al., 2020](#)).

The Songpan–Ganzi–Qiangtang and Qiangtang–Lhasa blocks were accreted in the mid–Cretaceous and since then, the Qiangtang block is thought to have been in an intra–continental setting ([Yin and Harrison et al., 2000](#)). The Paleocene–Early Miocene thrust faults and associated contraction basins in Qiangtang indicate that the Qiangtang block was undergoing crustal shortening during the Paleocene–Early Miocene ([Spurlin](#)

et al., 2005; Tapponnier et al., 2001; Wang et al., 2008; Yin and Harrison et al., 2000).

In order to accommodate this crustal shortening, continental subduction is likely to have occurred beneath the Qiangtang block. The polarity of the continental subduction could have been either south-dipping along the Jinshajiang suture zone (Roger et al., 2000; Spurlin et al., 2005; Tapponnier et al., 2001; Wang et al., 2008; Xu et al., 2016; Yin and Harrison, 2000; Zhang et al., 2020) or north-dipping along the Bangong–Nujiang suture zone (Kapp et al., 2005; Spurlin et al., 2005). The latest geophysical studies indicate that the continental subduction polarity is more likely to be south-dipping along the Jinshajiang suture zone (Tapponnier et al., 2001; Zhao et al., 2010).

The subduction-related characteristics (depletion in HFSE and enrichment in LILE) of the Shanglaxiu–Xialaxiu rhyolites, and the isotopic compositions of ^{13}C – ^{18}O of the xenocryst aggregates from Eocene potassic rocks in eastern Qiangtang (Goussin et al., 2020) have subduction affinities. In addition, the high Th/La ratios and Th contents of these rhyolites are similar to marine sediments, upper continental crust, and Eocene adakitic rocks in Duogecuoren (Wang et al., 2008). The Sr–Nd isotopic compositions, variable $\epsilon\text{Hf}(t)$ values, and relatively high $\delta^{18}\text{O}$ contents show a fingerprint of Paleozoic–Triassic sediments from the Songpan–Ganzi block (She et al., 2006; Sigoyer et al., 2014). Furthermore, crustal xenolith studies reveal that the Qiangtang lower

continental crust mainly consists of Triassic Songpan–Ganzi sedimentary rocks (Long et al., 2015, and references therein). Thus, south-dipping continental subduction most likely contributed to the generation of Eocene volcanics in the eastern Qiangtang block.

Extension from northwest to southeast (Fig. 13) along with plume–subduction interaction proposed by Wang et al. (2018) can explain the formation of the Late Permian Yanshiping rhyolites (Wang et al., 2018), the Paleocene–Eocene adakitic rocks in the eastern Qiangtang block (Yang et al., 2014; Zhang et al., 2015), the Eocene mafic and felsic rocks in Nangqian (Deng et al., 2001; Spurlin et al., 2005; Xu et al., 2016), the Shanglaxiu–Xialaxiu rhyolites, and the Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks (Xu et al., 2001; Song et al., 2004). The experimental research of Kincaid et al. (2013) indicates that the buoyant plume material can be incorporated by the rollback–induced flow of subducted slab to transfer 1,500 km laterally toward the trench. Based on this conclusion and occurrence of the Late Permian OIB–like mafic rocks related to Emeishan plume activity in north–eastern Qiangtang (Liu et al., 2016), Wang et al. (2018) proposed that the rollback–induced flow of the Paleo–Tethyan oceanic slab resulted in the westward flow of Emeishan–plume material from the South China block to the adjacent northern Qiangtang block (Fig. 14a). The Permian basalts associated with the Emeishan mantle

plume in the northern Qiangtang block share similar Nd isotopic signatures with the co-existing Cenozoic magmatic rocks, suggesting that the juvenile crust in northern Qiangtang block may have originated from the underplating of Permian basaltic magmas. During the Paleocene–Eocene, partial melting of this pre-existing juvenile crust was triggered by south-dipping continental subduction, which generated the Shanglaxiu and Xialaxiu rhyolites successively (Fig. 14b). The generation of the slightly more isotope-enriched Xialaxiu rhyolites may require more sedimentary material involvement than Shanglaxiu rhyolites.

5. Conclusions

(1) The results of zircon SIMS U–Pb dating indicate that the Shanglaxiu and Xialaxiu rhyolites were generated at 47.8 ± 0.6 and 44.2 ± 0.7 Ma, respectively.

(2) The Shanglaxiu–Xialaxiu rhyolites were generated by partial melting of pre-existing juvenile crust with the addition of 20–40% sedimentary materials of the Songpan–Ganzi block. The generation of the Xialaxiu rhyolites may require more sedimentary material involvement than the Shanglaxiu rhyolites. The incorporation of subducted sediments is the primary factor contributing to

the significant Nd–Hf decoupling phenomenon observed in these rhyolites.

(3) The Shanglaxiu–Xialaxiu rhyolites were generated in a post–collisional contractional setting. South–dipping continental subduction of the Songpan–Ganzi block triggered partial melting of the pre–existing juvenile crust in north–eastern Qiangtang.

(4) The pre–existing juvenile crust may be formed by Emeishan–plume material that was incorporated by the rollback–induced westward flow of the Paleo–Tethyan oceanic slab.

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Figure captions

Fig. 1. (a) Map of Tibetan Plateau, showing major tectonic blocks and temporal–spatial distribution of Cenozoic magmas. Inset shows the location of the Tibetan Plateau in East Asia. (after [Chung et al., 2005](#); [Liu et al., 2022](#); [Wang et al., 2008](#)). The primary sutures between the blocks are: AKMS: Ayimaqin–Kunlun–Muztagh Suture; JS: Jinshajiang Suture; LCSS: Longmucuo–Shuanghu Suture; BS: Bangong Suture; IS: Indus Suture. Major faults: MBT: Main Boundary Thrust; ATF: Altyn Tagh Fault; KF: Kunlun Fault; RRF: Red River Fault; (b) Simplified geological map of Shanglaxiu–Xialaxiu district (after [Spurlin et al., 2005](#))

Fig. 2. Field photographs and photomicrographs of the Shanglaxiu rhyolites (a, b, c) and Xialaxiu rhyolites (d, e, f). (a, b, d, e) Field observations and photographs; (c) Porphyritic texture (plane–polarized light); (f) Quartz and feldspar phenocrysts (cross–polarized light). Bt: biotite; Qz: quartz; Sa: sanidine.

Fig. 3. SIMS zircon U–Pb age Tera–Wasserburg diagrams and representative zircon Cathodoluminescence (CL) images for the Shanglaxiu–Xialaxiu rhyolites. (a) The Shanglaxiu rhyolites; (b) The Xialaxiu rhyolites. The red, yellow and blue numbers represent the U–Pb age (red

circle), Hf isotope value (yellow circle) and O isotope value (blue circle), respectively.

Fig. 4. (a) SiO_2 versus ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) diagram; (b) SiO_2 versus K_2O diagram; (c) A/CNK versus A/NK diagram. The data for the XLX rhyolites (grey triangle) are from Roger et al. (2000) and Spurlin et al. (2005); the data for the Yanshiping Late Permian rhyolites (grey diagonal cross) are from Wang et al. (2018). The data used to construct the fields are as follows: Eocene metaluminous and peraluminous adakitic rocks in the Duogecuoren area (Wang et al., 2008); Neoproterozoic rocks and Late Permian mafic rocks in Songpan–Ganzi and west Yangtze (Li et al. 2003; Song et al. 2004; Xu et al. 2001); Nangqian Eocene metaluminous adakitic rocks (Xu et al., 2016). SLX: Shanglaxiu; XLX: Xialaxiu.

Fig. 5. (a) SiO_2 versus $\text{Fe}_2\text{O}_3\text{T}$; (b) SiO_2 versus MgO ; (c) SiO_2 versus P_2O_5 ; (d) SiO_2 versus Na_2O ; (e) SiO_2 versus CaO ; (f) SiO_2 versus Al_2O_3 ; (g) SiO_2 versus La/Yb ; (h) SiO_2 versus $\epsilon_{\text{Nd}}(\text{t})$; (i) SiO_2 versus $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{i}}$. I and S-type granite trends in c are from Chappell (1999). Crustal assimilation and factional crystallization/partial melting trends in h are from Wang et al. (2021). Fractional crystallization trends in j are from Xu et al. (2016) and references therein. The symbols are as in

Fig. 4.

Fig. 6. (a) SiO_2 versus Mg# (Mg number) diagram; (b) Yb_N versus $(\text{La}/\text{Yb})_N$ diagram (after Jiang et al., 2006). Mantle AFC curves after Stern and Kilian (1996) (curve 1) and Rapp et al. (1999) (curve 2). Crustal AFC is after Stern and Kilian (1996) (curve 3). The fields of adakites derived by partial melting of subducting oceanic crust, delaminated lower crust–derived adakitic rocks, thick lower crust–derived adakitic rocks, and metabasaltic and eclogite experimental melts (1–4.0 GPa) are after Wang et al. (2006). The field of the Eocene Nangqian felsic rocks is constructed using data of Xu et al. (2016), Zhang et al. (2020) and references therein. The data of the Paleocene–Eocene adakitic rocks in eastern Qiangtang (dark yellow rhombus) are from Yang et al. (2008) and Zhang et al. (2015). The values of Yb_N and $(\text{La}/\text{Yb})_N$ are normalized by the data of CI chondrite from Boynton (1984). The fields of the Eocene adakitic porphyry in Yulong and Eocene volcanic rocks in the Nangqian area are constructed using data of Jiang et al. (2006) and references therein. The field of the Eocene adakitic intrusions in the Nangqian area is constructed using data of Xu et al. (2016). The symbols are as in Fig. 4.

Fig. 7. Chondrite-normalized REE patterns (a), Primitive mantle-normalized REE patterns (b) for the Shanglaxiu–Xialaxiu rhyolites, with the Yanshiping rhyolites (Wang et al., 2018), the Nangqian Eocene felsic rocks (Xu et al., 2016), the Nangqian shoshonitic mafic lavas (Deng et al., 2001; Spurlin et al., 2005), and the Yulong peraluminous adakitic porphyries (Jiang et al., 2006). Normalizing values are from Sun and McDonough (1989).

Fig. 8. (a) K₂O versus Y diagram; (b) K₂O versus Th diagram; (c) (10000*Ga/Al) versus Zr diagram (Whalen et al., 1987); (d) SiO₂ versus FeOT/(FeOT+MgO) diagram (after Wang et al., 2021). The data of the late Cretaceous I-type granites in southern Qiangtang are from He et al. (2019) and Wang et al. (2021). The field of the Himalayan leucogranites is constructed using data of Liu et al. (2014). The other literature data are the same to Fig. 4.

Fig. 9. Histograms of zircon $\delta^{18}\text{O}\text{‰}$ (a, b) and $\varepsilon_{\text{Hf}}(\text{t})$ (c, d) values for the Shanglaxiu–Xialaxiu rhyolites.

Fig. 10. (a) Th versus Th/Nb diagram (after Wang et al., 2018); (b) U versus Th/U diagram; (c) Nb/U versus Ce/Pb diagram (after Wang et al., 2021); (d) Th versus Th/La diagram (after Wang et al., 2008). The average Th/U value (~ 6) of lower CC (continental crust) is from Rudnick and Gao (2014). The data used to construct the fields are as follows: lower CC, bulk CC, and mantle (Rudnick and Gao, 2014); Eocene peraluminous and metaluminous adakitic rocks in Duogecuoren (Wang et al., 2008); Late-Permian mafic rocks in the Songpan–Ganzi and west Yangtze blocks (Song et al., 2004; Xu et al., 2001); Neoproterozoic rocks in the Songpan–Ganzi and west Yangtze blocks (Li et al., 2003); marine sediments, GLOSS, and upper CC (Wang et al., 2008, and references therein). The symbols and the other literature data are the same to Fig. 8.

Fig. 11. Whole-rock $(^{87}\text{Sr}/^{86}\text{Sr})_i$ versus $\epsilon_{\text{Nd}}(t)$ diagram. Data sources: MORB (Zindler and Hart, 1986); DM (Taylor and McLennan, 1985); Eocene felsic and mafic rocks in the Nangqian area (Deng et al., 2001; Spurlin et al., 2005; Xu et al., 2016); Late Permian bimodal volcanics in the Yanshiping area (Wang et al., 2018); Eocene adakitic rocks in the Duogecuoren area (Wang et al., 2008); Paleocene–Eocene adakitic rocks in the eastern Qiangtang block (Yang et al., 2014; Zhang et al., 2015); Late Permian basaltic rocks in the Songpan–Ganzi and west Yangtze blocks (Xu et al., 2001); Paleozoic–Triassic sediments in the Songpan–Ganzi block (She et al., 2006; Sigoyer et al.,

2014); granulite xenoliths in the northern Qiangtang block (Lai et al., 2011). The other literature data are the same to Fig. 8. The data of this study and Xialaxiu rhyolites from the literature are calculated at zircon ages of 47.8 Ma and 44.2 Ma respectively, other data are calculated at $t = 47.8$ Ma.

Fig. 12. (a) $\epsilon_{\text{Nd}}(t)$ versus $\epsilon_{\text{Hf}}(t)$ diagram; (b) $\epsilon_{\text{Hf}}(t)$ versus $\delta^{18}\text{O}$ diagram. In diagram (a), all the data for $\epsilon_{\text{Hf}}(t)$ are zircon $\epsilon_{\text{Hf}}(t)$, except for the data of the Late Cretaceous granites in southern Qiangtang and the Late Permian Yanshiping bimodal volcanics, which are whole-rock $\epsilon_{\text{Hf}}(t)$. In diagram (b), only the data for $\epsilon_{\text{Hf}}(t)$ of the Late Permian Yanshiping bimodal volcanics are whole-rock $\epsilon_{\text{Hf}}(t)$. $\text{Hf}_{\text{PM}}/\text{Hf}_{\text{C}}$ is the ratio of hafnium concentration in the parental mantle magma (PM) to the supracrustal sedimentary melt (C). The hollow circle on the dashed line represents the mixing ratio (in 10% intervals) between the two end members. $\delta^{18}\text{O} = 6.5\text{‰}$ is the conservative lower limit of the non-mantle supracrustal melt (Valley et al., 2005). Data sources: Average sediment ($\epsilon_{\text{Nd}}(t) = -8.9$, $\epsilon_{\text{Hf}}(t) = +2 \pm 3$), OIB, MORB, Island arc lavas, and mantle array (Chauvel et al., 2008; Wang et al., 2018); Late Cretaceous granites in southern Qiangtang (Wang et al., 2021); the $\epsilon_{\text{Nd}}(t)$ of Permian basalt related to Emeishan plume is the maximum value ($\epsilon_{\text{Nd}}(t) = +6.8$) calculated from high-MgO picrites (Li et al., 2010), and its $\epsilon_{\text{Hf}}(t)$ ($\epsilon_{\text{Hf}}(t) = +12.1$) is assumed to follow the mantle array. The

Hf and O isotopic compositions of supracrustal zircon (UCC, $\epsilon_{\text{Hf}}(t) = -12$, $\delta^{18}\text{O} = 10\text{‰}$) are from Wang et al. (2021). Permian basalts related to Emeishan plume are assumed to have whole-rock $\epsilon_{\text{Hf}}(t)$ and mantle zircon $\delta^{18}\text{O}$ values of +12.1, and 5.3‰, respectively. The other literature data are the same as Fig. 11.

Fig 13. Distribution of Cenozoic crust-derived magmatic rocks in the Qiangtang block. The blue field represents the westward extension of the Emeishan plume. Data sources: Cenozoic crust-derived magmatic rocks in the western-central Qiangtang block (Chen et al., 2013; Liu et al., 2008; Liu et al., 2022; Long et al., 2015; Ou et al., 2017; Wang et al., 2008); Cenozoic crust-derived magmatic rocks in the northeastern Qiangtang block (Roger et al., 2000; Spurlin et al., 2005; Xu et al., 2016; Yang et al., 2008; Zhang et al., 2015); Cenozoic crust-derived magmatic rocks in the southeastern Qiangtang block (Jiang et al., 2006; Lin et al., 2018; Wang et al., 2001; Xu et al., 2019b; Zhang et al., 2005); Late Permian OIB-like mafic rocks related to Emeishan plume activity (Liu et al., 2016); Late Permian Yanshiping bimodal volcanics and Late Permian basalts/gabbros in eastern Tibet (Wang et al., 2018, and references therein). The $\epsilon_{\text{Nd}}(t)$ values of these Cenozoic crust-derived magmatic rocks are calculated at $t = 47.8$ Ma.

Fig. 14. Schematic illustration of the generation of the juvenile crust in the Shanglaxiu–Xialaxiu district during the Late Permian (a) (modified from [Wang et al., 2018](#)) and the formation of the Shanglaxiu–Xialaxiu rhyolites triggered by the south–dipping continental subduction of the Songpan–Ganzi block during the early Eocene (b) (redrafted from [Spurlin et al., 2005](#); [Wang et al., 2008](#)). ELIP: Emeishan large igneous province; JS: Jinshajiang Suture.

Fig. S1 The whole–rock K_2O , Na_2O , Al_2O_3 , MgO , Fe_2O_3T , P_2O_5 , Y, Th, and $(^{87}Sr/^{86}Sr)_i$ versus LOI diagram.

granitoids (Wu et al., 2007), however no cordierite has been found in these rhyolites.

Experimental studies have shown that the contents of P_2O_5 correlate positively SiO_2 in S-type granite magmas, and that this does not occur in I-type magmas (Chappell, 1999). The characteristics of lack of a positive correlation between the P_2O_5 and SiO_2 contents of the rocks in our study are inconsistent with S-type granites on a SiO_2 -vs.- P_2O_5 diagram (Shanglaxiu-Xialaxiu rhyolites (Fig. 5c), which indicates that these rocks are I-type rather than S-type. This is also supported by the lack of inherited zircons from metasedimentary sources in these rhyolites (Chappell et al., 2008, 1998).

Yttrium and Thorium/thorium abundances can be used to distinguish between I- and S-type granites as both increase in abundance in I-type melts but decrease in S-type melts (Chappell et al., 2008, 1998, 2012; Wang et al., 2021). The Y and Th contents of the rocks in this study resemble those of the I-type granites in the Southern Qiangtang block (He et al., 2019; Wang et al., 2021), and are higher than those of the S-type granites in Himalaya (Liu et al., 2014) (Fig. 8a-b). Additionally, I- and S-type granites can be effectively distinguished by oxygen isotopes in zircon, as I-type granites commonly have lower zircon $\delta^{18}O$ values than S-type granites (Wang et al., 2021). The rhyolites in this study all have relatively low $\delta^{18}O$ values of 6.26-7.32‰ (Fig. 9a, b), consistent with a source containing metaigneous rocks and suggests that they are I-

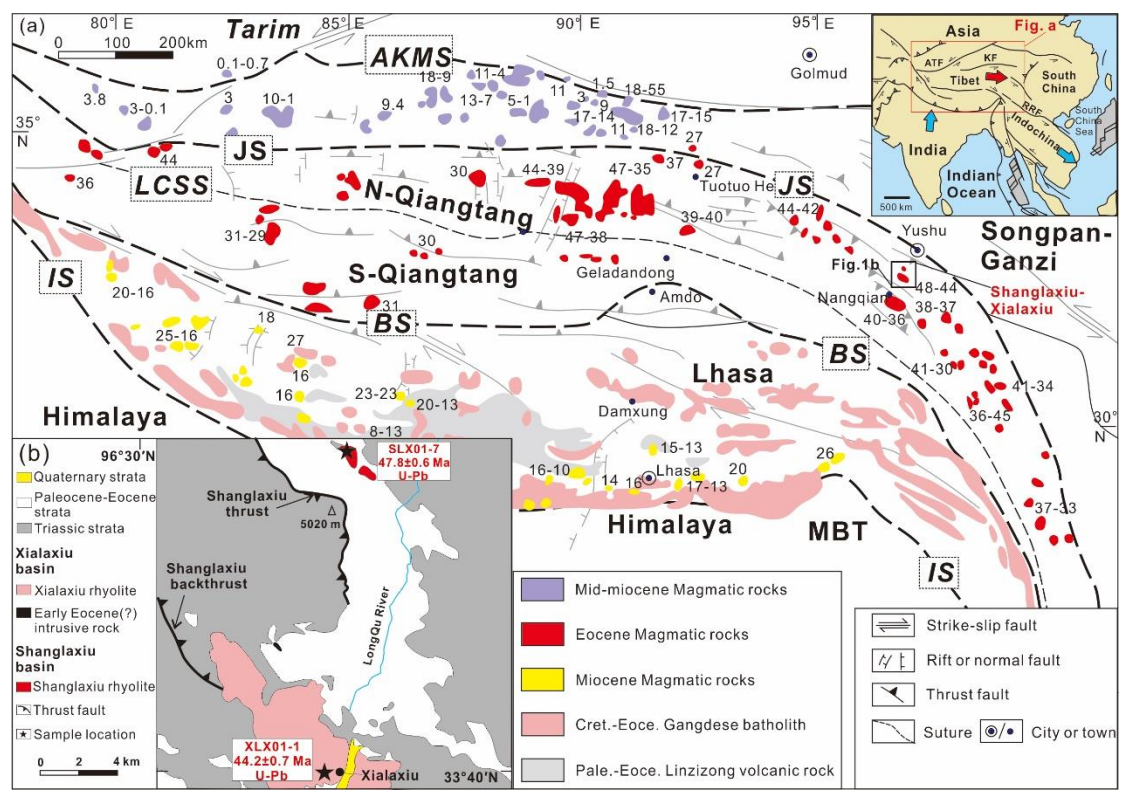


Figure 1

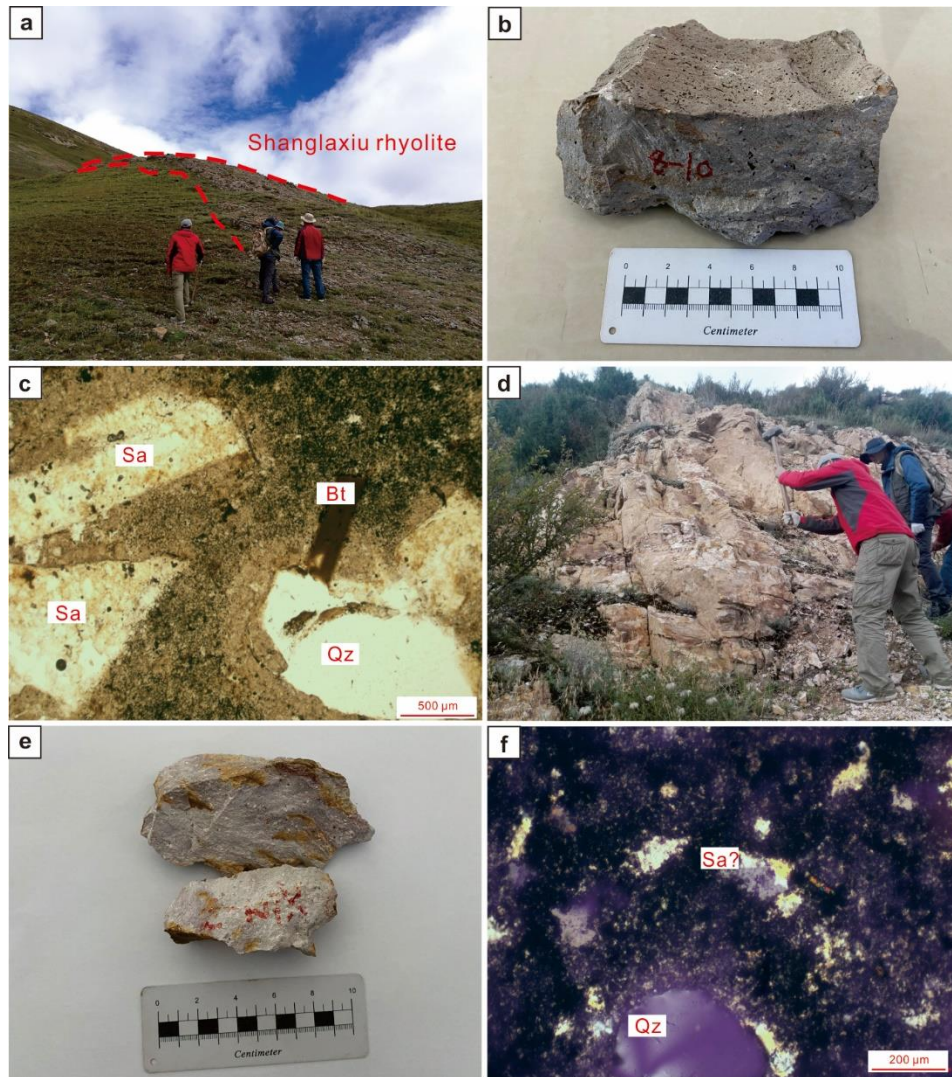


Figure 2

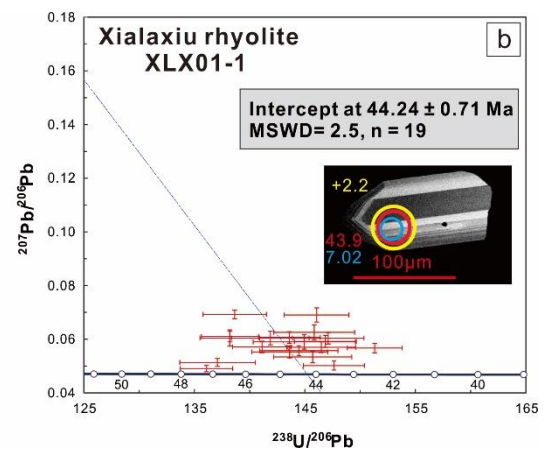
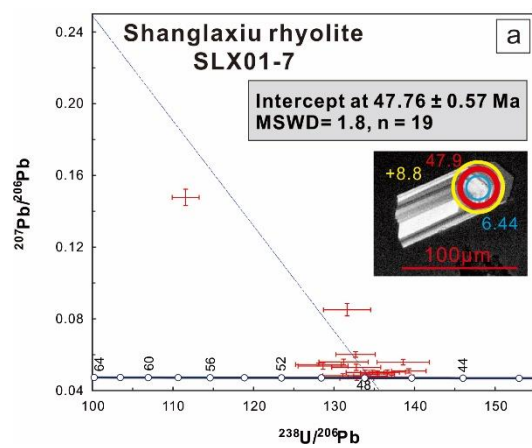


Figure 3

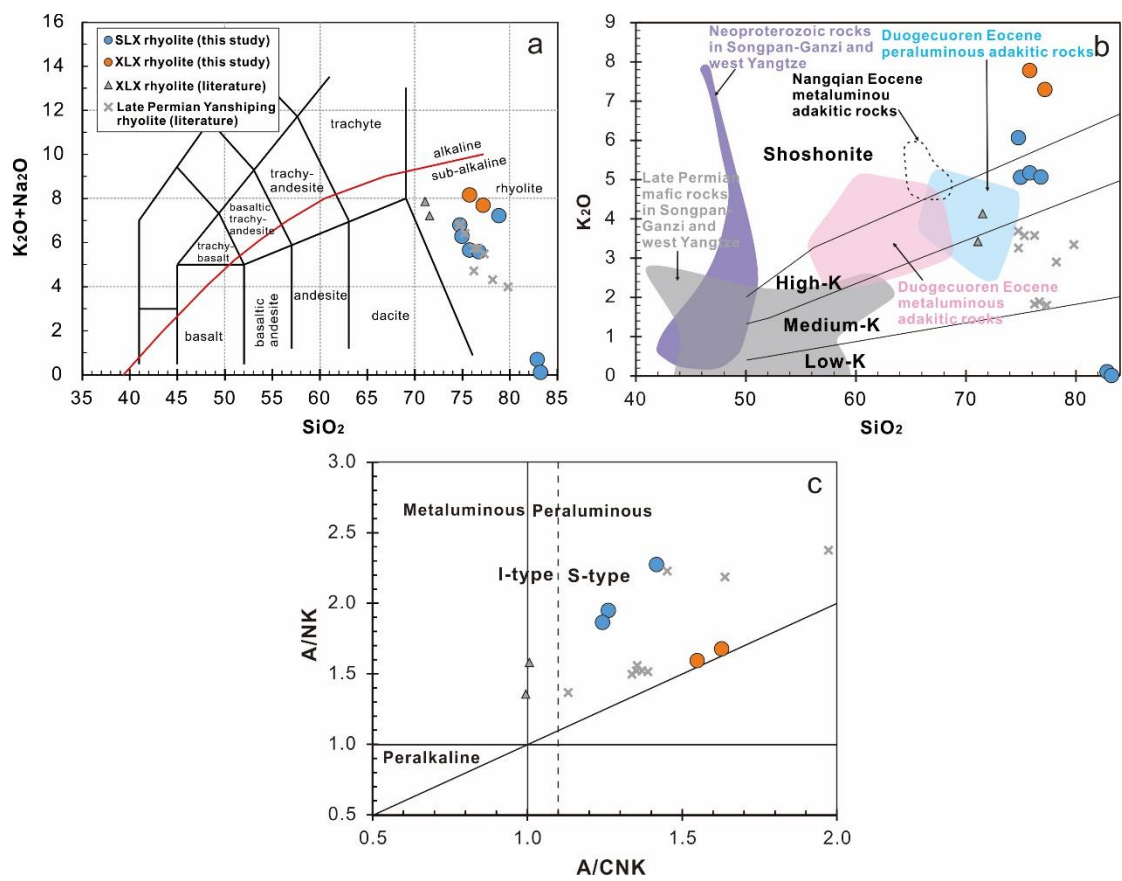


Figure 4

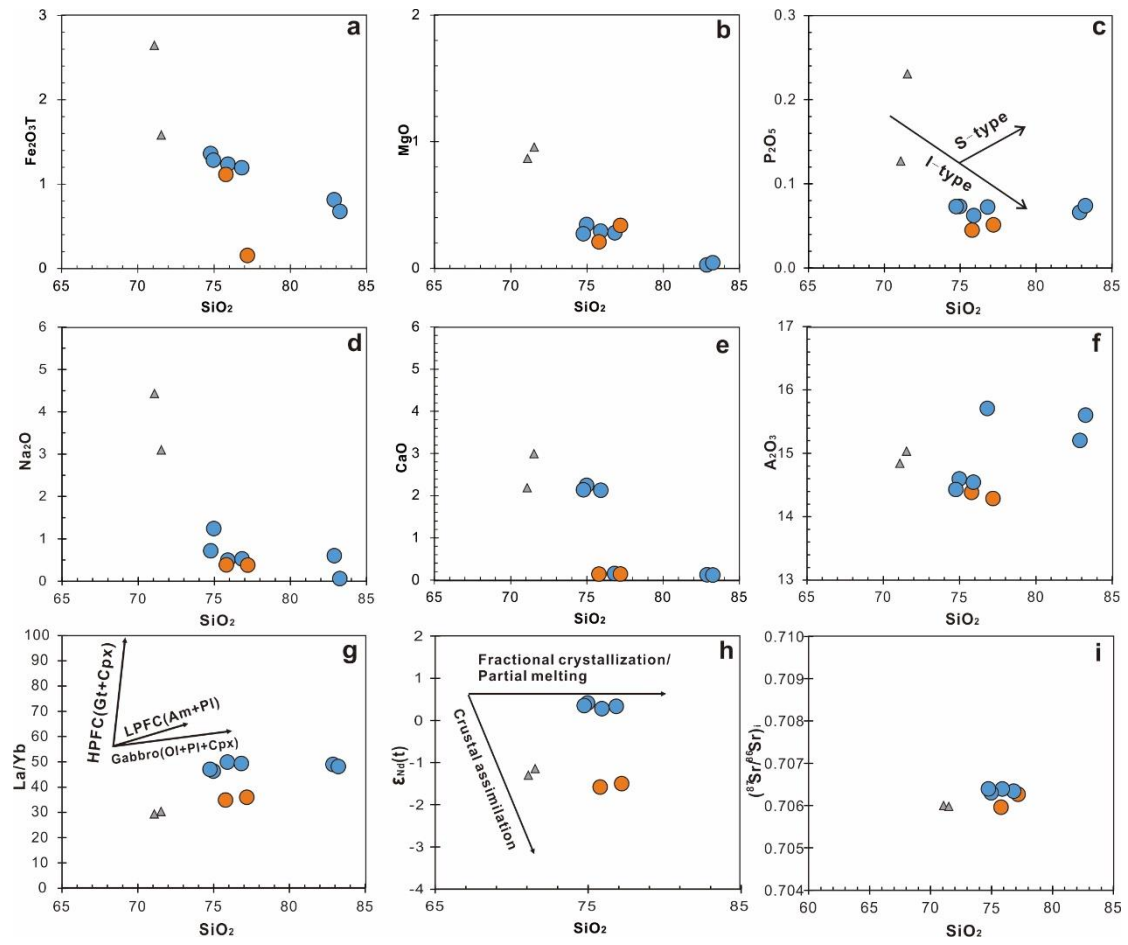


Figure 5

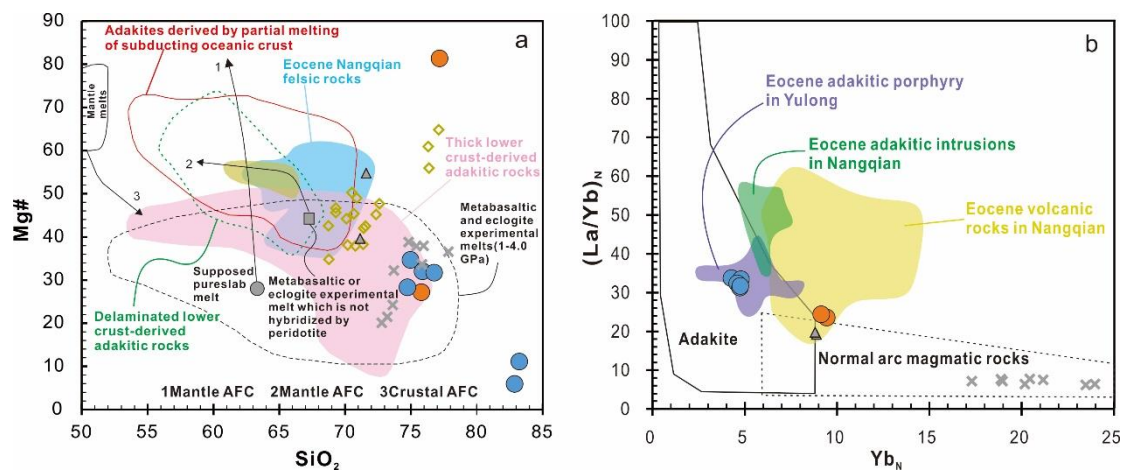


Figure 6

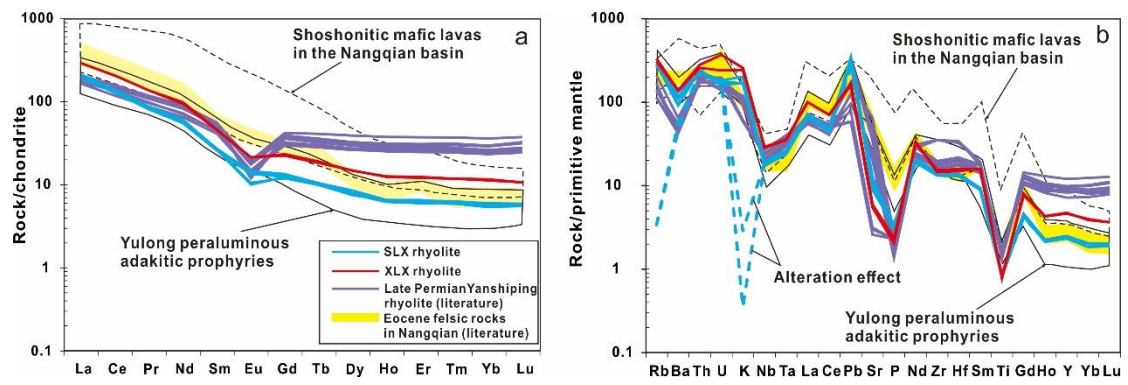


Figure 7

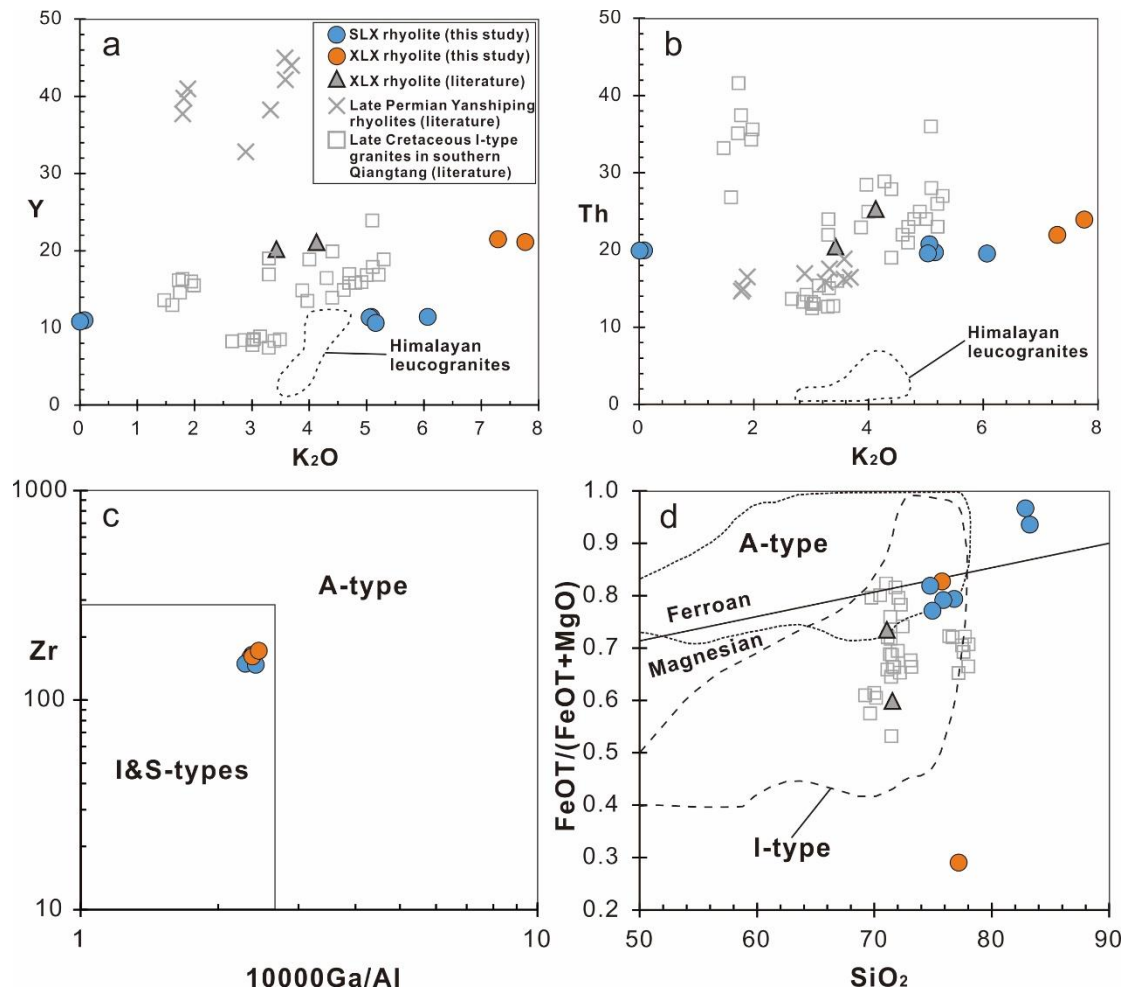


Figure 8

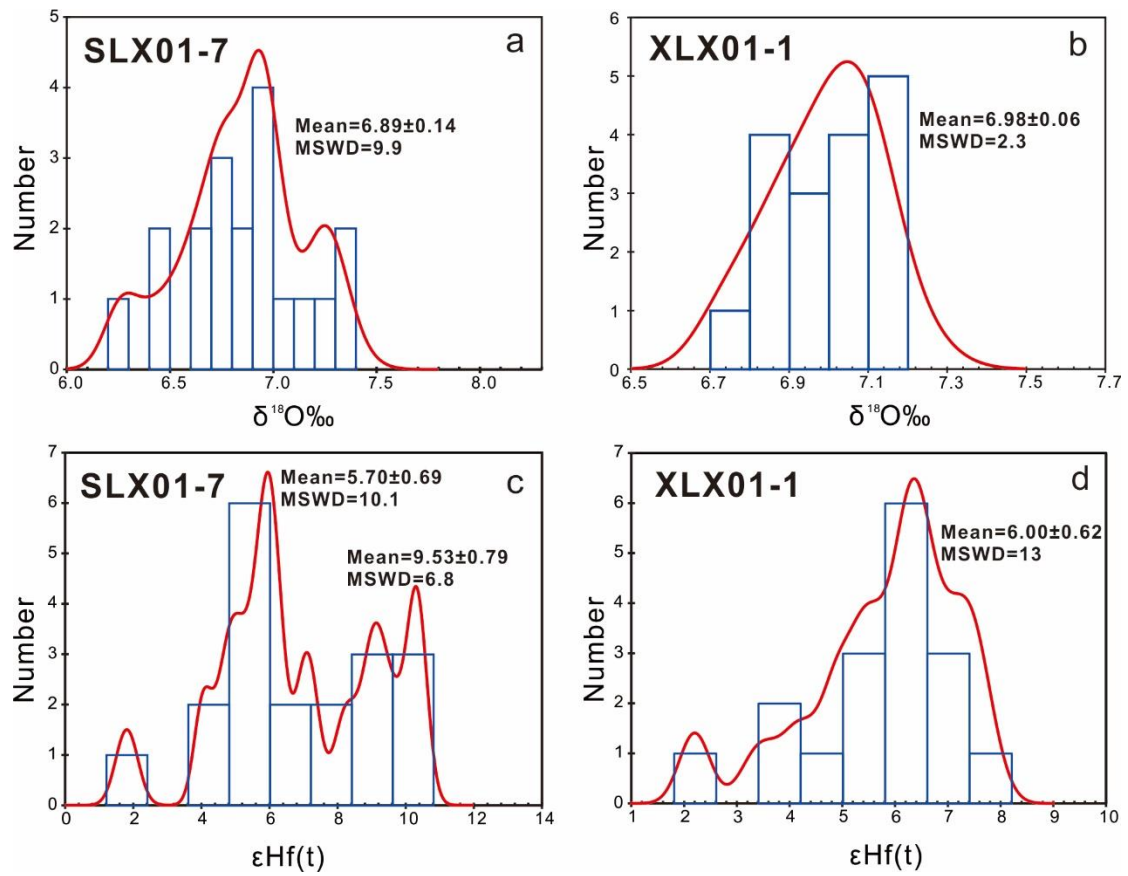


Figure 9

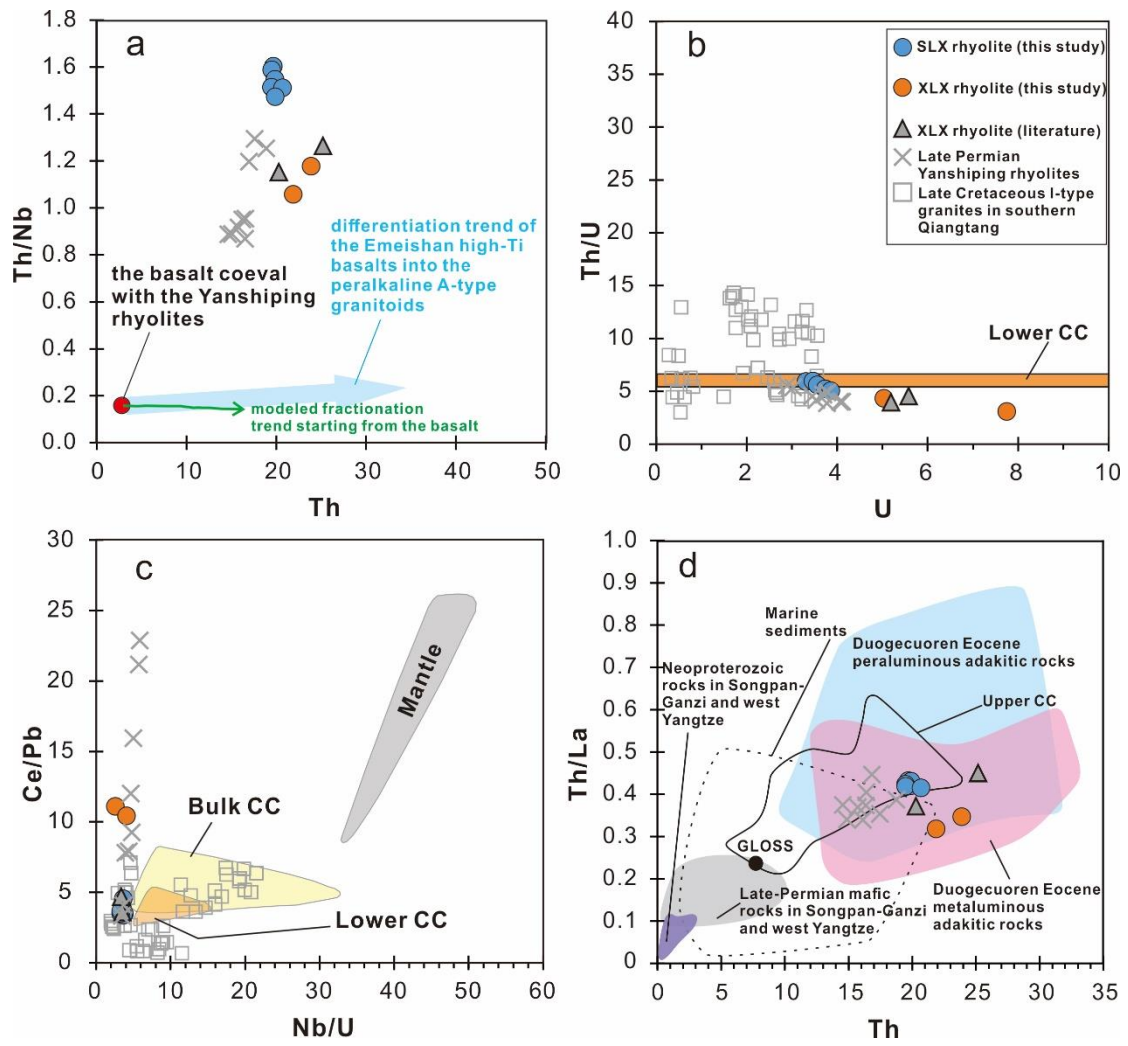


Figure 10

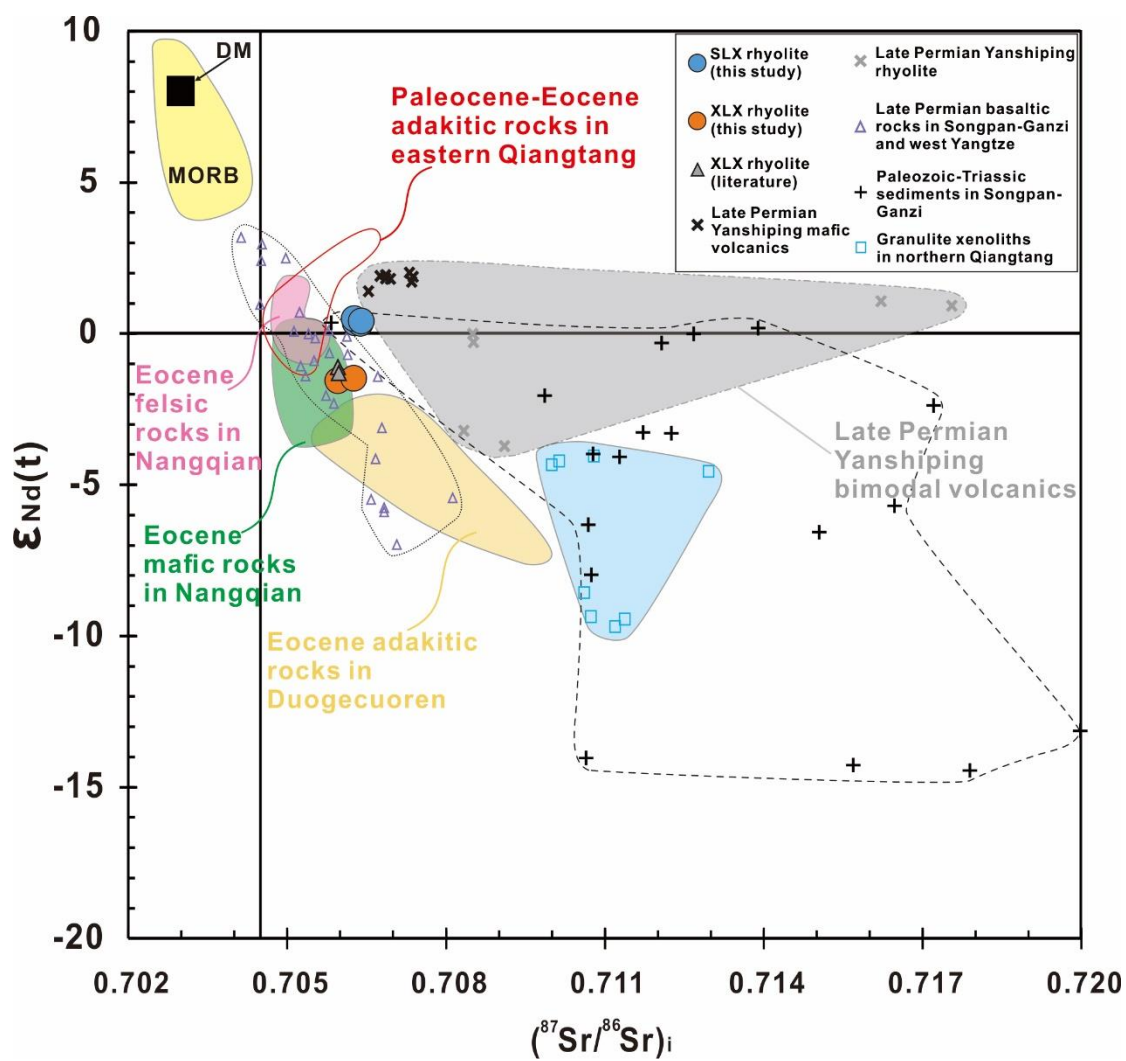


Figure 11

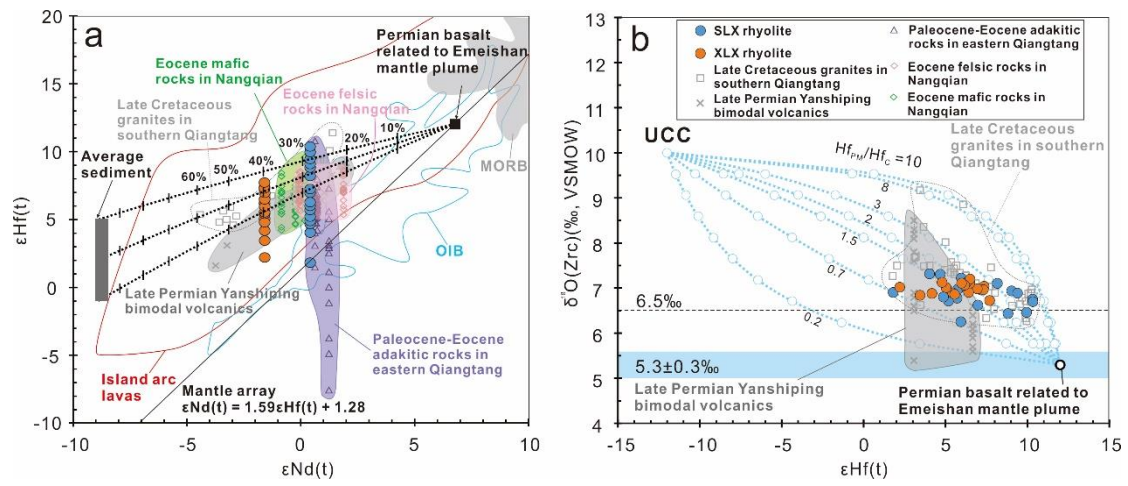


Figure 12

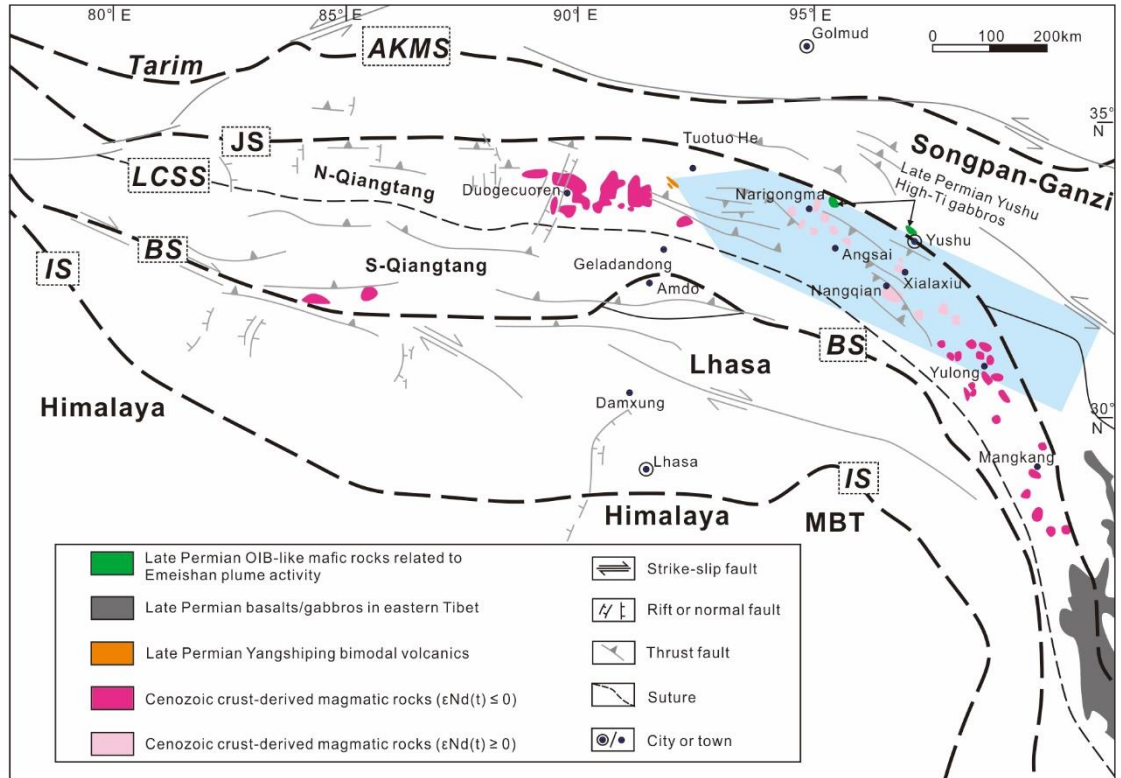


Figure 13

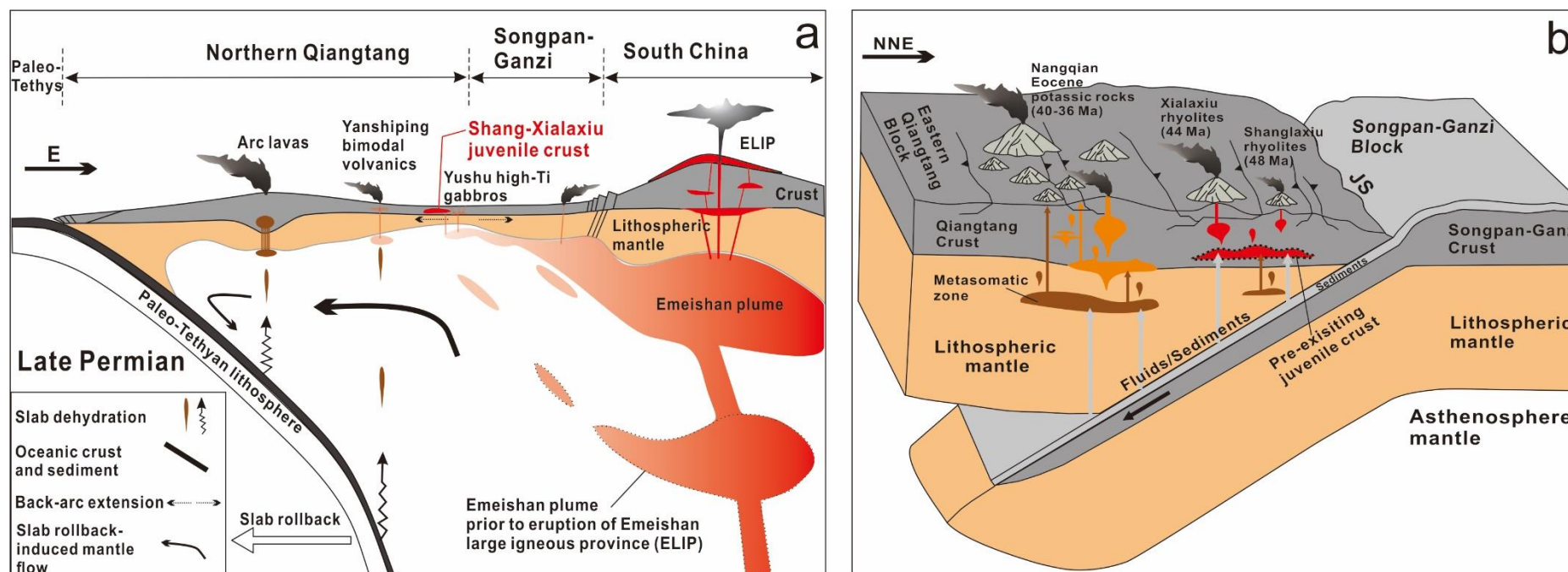


Figure 14



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**Supplementary material/Appendix (Files for online
publication only)**
Appendix 1.docx

