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Key Points:

- Post-collisional ultrapotassic rocks in southern Tibet have extremely light Mo and B isotope compositions
- These light Mo-B isotope features are derived from subducted Indian continental crust
- Mo-B isotopes have the potential to discriminate between oceanic and continental subduction

Supporting Information:

Supporting Information may be found in the online version of this article.

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Light Mo Isotopes of Post-Collisional Ultrapotassic Rocks in Southern Tibet Derived From Subducted Indian Continental Crust

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Abstract Recycling of molybdenum isotopes in continental subduction zones remains debated. In this contribution, we re-visit the Mo isotope compositions of the Sailipu post-collisional ultrapotassic rocks in the Himalaya-southern Tibet orogen. These ultrapotassic rocks have very varying $\delta^{98/95}$Mo values of −0.66 to −0.07‰ and Mo/Ce ratios of 0.0008–0.005, which are lower than those of mid-ocean ridge basalts (MORB; $\delta^{98/95}$Mo = −0.20 ± 0.06‰, and Mo/Ce = 0.03) and oceanic subduction-related (i.e., mantle source involving fluids, residual slab, or oceanic sediments) magmatic rocks (e.g., modern arc lavas, Cenozoic OIB-type basalts in eastern China and the central Mariana Trough basalts in the back-arc basin, syn-collisional andesitic rocks in southern Tibet). Combined with the light Mo isotopes of the Himalayan schists and gneisses, we suggest that the light Mo isotopic signature of the Sailipu ultrapotassic rocks is derived from subducted Indian continental crust. This is consistent with the extremely low δ^{11}B (−17.4 to −9.7‰) and B/Nb (0.16–1) values and enriched Sr-Nd-Pb isotopes of the Sailipu ultrapotassic rocks. Thus, this study reveals the recycling of light Mo-B isotopes during continental subduction and demonstrates that Mo-B isotopes can effectively distinguish between continental and oceanic subduction.

Plain Language Summary Mo isotope systematics have been widely applied in the study of tracing recycled crustal materials, and abundant researches have proposed that heavy Mo isotopic compositions of arc-mafic magma can be ascribed to slab-dehydrated fluids. However, in continental subduction zones, the origin of the light Mo isotopes of post-collisional mafic rocks (oceanic sediments during prior oceanic subduction vs. subducted continental crust) remains controversial, hindering our understanding of the recycling of continental crustal materials. In this study, we report new Mo isotope data of post-collisional ultrapotassic rocks in the Lhasa block of the southern Tibetan plateau. We have used Mo isotope data along with B-Sr-Nd-Pb isotopes of these ultrapotassic rocks, in combination with Mo-B-Sr-Nd-Pb isotopes of the Himalayan crustal rocks (e.g., gneisses and schists) to trace the crustal components in the post-collisional mantle beneath southern Tibet. We concluded that the light Mo and B isotope compositions in southern Tibet were derived from subducted Indian continental crust rather than Neo-Tethyan oceanic sediments. Thus, this study not only reveals the recycling of light Mo-B isotopes in this typical collision orogen (i.e., Himalaya-Tibet orogen) but also shows the potential in discriminating between oceanic subduction metasomatism and continental subduction metasomatism.

1. Introduction

The processes of crustal material recycling in oceanic subduction zones have been extensively studied and are widely understood (e.g., Elliott, 2004; Stern, 2002). In contrast, our understanding of continental subduction that occurs when oceanic lithosphere is consumed and two continental plates collide to form orogenic belts (e.g., Ducea, 2016) is much less clear. It is generally accepted that the post-collisional mafic rocks, widespread in continental collision orogens, record the subduction and recycling of continental crustal materials (e.g., Chung et al., 2005; Conticelli et al., 2009). However, some studies suggest that post-collisional mafic rocks can also be derived from the partial melting of an enriched mantle metasomatized by prior oceanic subduction (e.g., Azizi et al., 2021; Dai et al., 2015). Determining the nature of recycled crustal components in the mantle source of

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post-collisional mafic rocks is of great significance in understanding the transition from oceanic to continental subduction and the evolution of orogenic belts.

However, in relation to mantle metasomatism, it is difficult to distinguish oceanic subduction from continental subduction. For example, both subducted oceanic sediments and subducted continental crust can exhibit high potassium contents and enriched Sr-Nd isotope signatures (Plank, 2014; Zhao et al., 2009). Recent studies show that molybdenum (Mo) isotopes are ideal tracers of material recycling in subduction zones and have the potential to discriminate between oceanic and continental subduction (e.g., Bezard et al., 2016; Fang et al., 2022; Freymuth et al., 2015, 2016; Villalobos-Orchard et al., 2020). Modern arc lavas erupted above oceanic subduction zones generally have heavy Mo isotopic compositions (e.g., Ahmad et al., 2021; Freymuth et al., 2015; König et al., 2016; H. Y. Li et al., 2021; X. H. Li et al., 2021), while post-collisional mafic rocks derived from continental subduction could have light Mo isotope signatures, as a result of an input from subducted and dehydrated continental crust, for example, the Liaodong Cretaceous arc-like basalts (Fang et al., 2022). The ∼110 Ma Liaodong basalts formed after the collision between the South China block and North China block. They exhibit arc-like trace element distribution patterns and highly enriched Sr-Nd isotope compositions, which were considered to inherit from the subducted continental crust (Zheng et al., 2019). Though the continental crust generally exhibits heavy Mo isotope compositions (e.g., S. Chen et al., 2022; Greber et al., 2014; Voegelin et al., 2014; Willbold & Elliott, 2017), it would undergo metamorphic dehydration during its deep subduction, leaving light Mo isotope compositions in the residual crust (e.g., Fang et al., 2022). However, Huang et al. (2023) argued that the light Mo isotope compositions of the post-collisional (Miocene) ultrapotassic rocks from the Sailipu area in the southern Tibetan plateau instead originated from subducted Neo-Tethyan pelagic sediments. Thus, the origin of the light Mo isotopic compositions of these post-collisional mafic rocks remains unclear. This uncertainty not only limits the use of Mo isotopes in distinguishing between oceanic and continental subduction but also hinders our understanding of the recycling of continental crustal materials in this typical collision orogen (i.e., Himalaya-Tibet orogen).

In this study, we report new Mo isotope data of the post-collisional ultrapotassic rocks in the Sailipu area of the Lhasa block, southern Tibet. We have used Mo isotope data along with B-Sr-Nd-Pb isotopes of these ultrapotassic rocks, in combination with Mo-B-Sr-Nd-Pb isotopes of the Himalayan crustal rocks (e.g., gneisses and schists) to trace the crustal components in the post-collisional mantle beneath southern Tibet.

2. Geological Setting and Sample Descriptions

The Himalaya-Tibet orogen is a tectonic collage of east-west trending microcontinent blocks that consist of (from north to south) the Songpan-Ganze, Qiangtang, Lhasa, and Himalaya blocks (Yin & Harrison, 2000). The Lhasa block of southern Tibet was the last of these blocks to be accreted onto Eurasia during the Early Cretaceous (Hao, Wang, Zhang, et al., 2019; Zhu et al., 2018) before Eurasia collided with the northward-drifting Indian plate in the early Cenozoic (60–55 Ma; Hu et al., 2015). The block is presently located between the Qiangtang and Himalayan blocks and is bounded by the Bangong-Nujiang suture zone to the north and the Indus-Yarlung Zangbo suture zone to the south (Yin & Harrison, 2000) (Figure 1a).

After the initial India-Lhasa collision in the early Cenozoic (60–55 Ma) (e.g., Hu et al., 2015) and the breakoff of the Neo-Tethyan oceanic slab at ca. 45 Ma (Ji et al., 2016; Zhu et al., 2015), the Himalaya-southern Tibet region evolved into a post-collisional setting. The post-collisional (ca. 26–8 Ma) magmatic rocks in the Lhasa block mainly include felsic adakitic intrusions and potassic-ultrapotassic lavas (e.g., Chung et al., 2005; Guo & Wilson, 2019) (Figure 1a). Generally, the ultrapotassic rocks were considered to be derived from an enriched mantle (Guo & Wilson, 2019; Guo et al., 2015; Huang et al., 2015; Liu et al., 2014), while the felsic adakitic rocks and potassic rocks were suggested to be ascribed to the reworking of the lower crust beneath the Lhasa block (e.g., Hao, Wang, Ma, et al., 2022; Hao, Wang, Wyman, et al., 2019; Hou et al., 2004).

This study focuses on the ultrapotassic volcanic rocks that were collected widely across the N-S trending Sailipu basin (Figure 1b) in the Lhasa block. Previous phlogopite K-Ar and zircon U-Pb dating indicate that they erupted during the early Miocene (19–16 Ma; Cheng & Guo, 2017; C. Sun et al., 2008). All samples in this study are fresh and free of significant alteration. These rocks classify as trachyandesites and contain phenocrysts of phlogopite (5–10 vol.%), clinopyroxene (5–10 vol.%), olivine (3–10 vol.%), and plagioclase (3–5 vol.%) set in a phlogopite, clinopyroxene, plagioclase, Fe-Ti oxide, and glass groundmass (Figure S1 in Supporting Information S1).

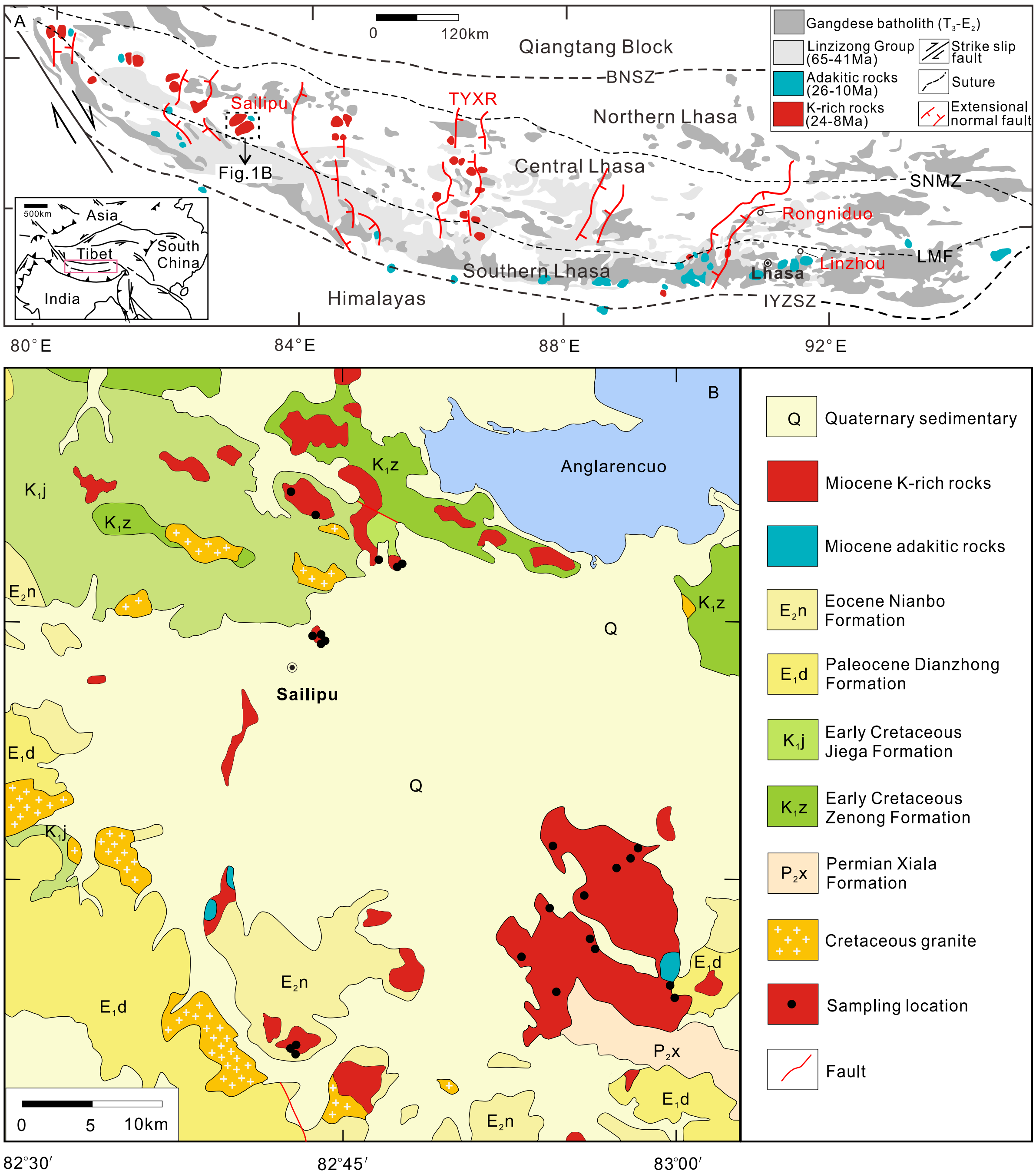

Figure 1. (a) Simplified geologic map of the Lhasa block showing the distribution of Cenozoic magmatic rocks, modified from Guo et al. (2015). BNSZ, Bangong-Nujiang suture zone; IYZSZ, Indus-Yarlung Zangbo suture zone; SNMZ, Shiquan River-Nam Tso Mélange Zone; LMF, Luobadui-Milashan Fault; TYXR, TangraYumco-Xuruco rift. The insert shows the locations of the Lhasa block in the India-Tibet collisional zone. (b) Regional geological map showing the distribution of post-collisional K-rich rocks in the Sailipu area.

3. Results

The analytical methods and data are provided in Supporting Information S1.

3.1. Geochemical and Sr-Nd-Pb Isotopic Data

The studied Sailipu samples ($SiO_2 = 52.8–59.2$ wt.%) mostly plot in the trachyandesite fields with a few in basaltic trachyandesite fields in the TAS diagram (Figure 2a), and all of them belong to the ultrapotassic series ($K_2O > 3$

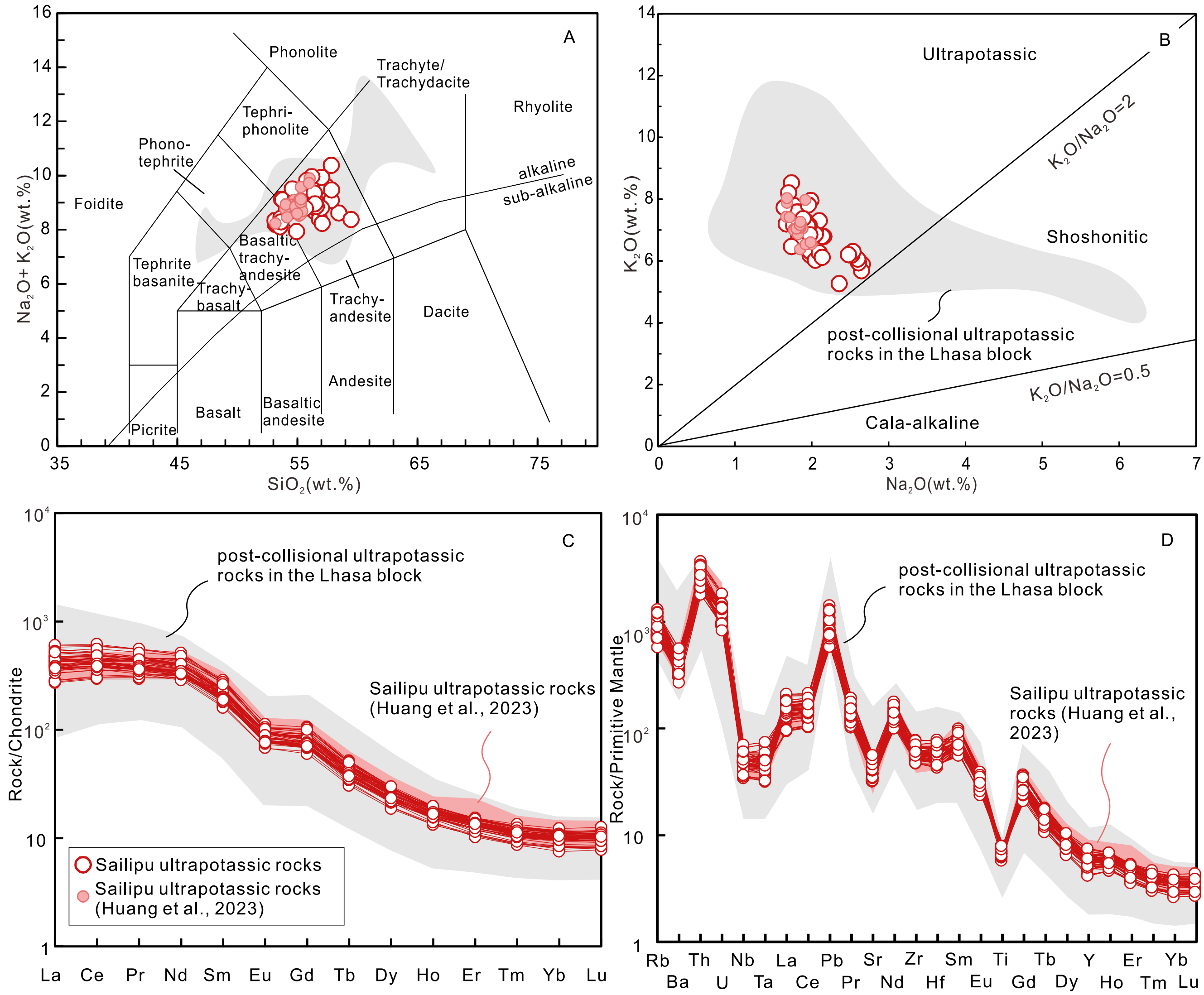

Figure 2. Major-, trace-elemental compositions for post-collisional ultrapotassic rocks in the Sailipu area. (a) Total alkalis versus SiO_2 diagram; (b) K_2O versus Na_2O. Literature ultrapotassic rocks in the Lhasa block are from Guo et al. (2015); Hao, Wang, Kerr, et al. (2022) and references therein. (c) Chondrite-normalized rare earth element diagram. (d) Primitive mantle-normalized trace-element spider diagram. The normalization values are from S. Sun and McDonough (1989).

wt.%, MgO > 3 wt.% and $K_2O/Na_2O > 2$, Foley et al., 1987) (Figure 2b). They are near-primary melts, as indicated by high $Mg^{\#}$ values (63–76), and Cr (234–886 ppm), Ni (112–440 ppm) contents. The Sailipu ultrapotassic rocks are enriched in light rare earth elements (LREEs) and have relatively flat heavy REE (HREEs) patterns (Figure 2c), with negative Eu anomalies (Eu/Eu* = 0.6–0.7). Their primitive mantle-normalized multi-element patterns show enrichment in large ion lithophile elements and depletion in high field strength elements (HFSEs, e.g., Nb, Ta, and Ti; Figure 2d).

The Sailipu ultrapotassic rocks have relatively high but variable initial $^{87}Sr/^{86}Sr$ isotopic ratios (0.7169–0.7314) and low $\varepsilon_{Nd}(t)$ values (−15.5 to −13.5), which are similar to post-collisional ultrapotassic rocks elsewhere in the Lhasa block (Guo et al., 2015; Hao, Wang, Kerr, et al., 2022 and references therein) (Figure 3a). They have enriched Pb isotopic compositions with $(^{207}Pb/^{204}Pb)_i = 15.74–15.76$, $(^{208}Pb/^{204}Pb)_i = 39.48–39.65$, and $(^{206}Pb/^{204}Pb)_i = 18.57–18.67$ and plot close to the field of Indian continental crust (represented by Higher Himalayan Crystalline Sequence, Tian et al., 2017) in Pb isotope diagrams (Figures 3b and 3c).

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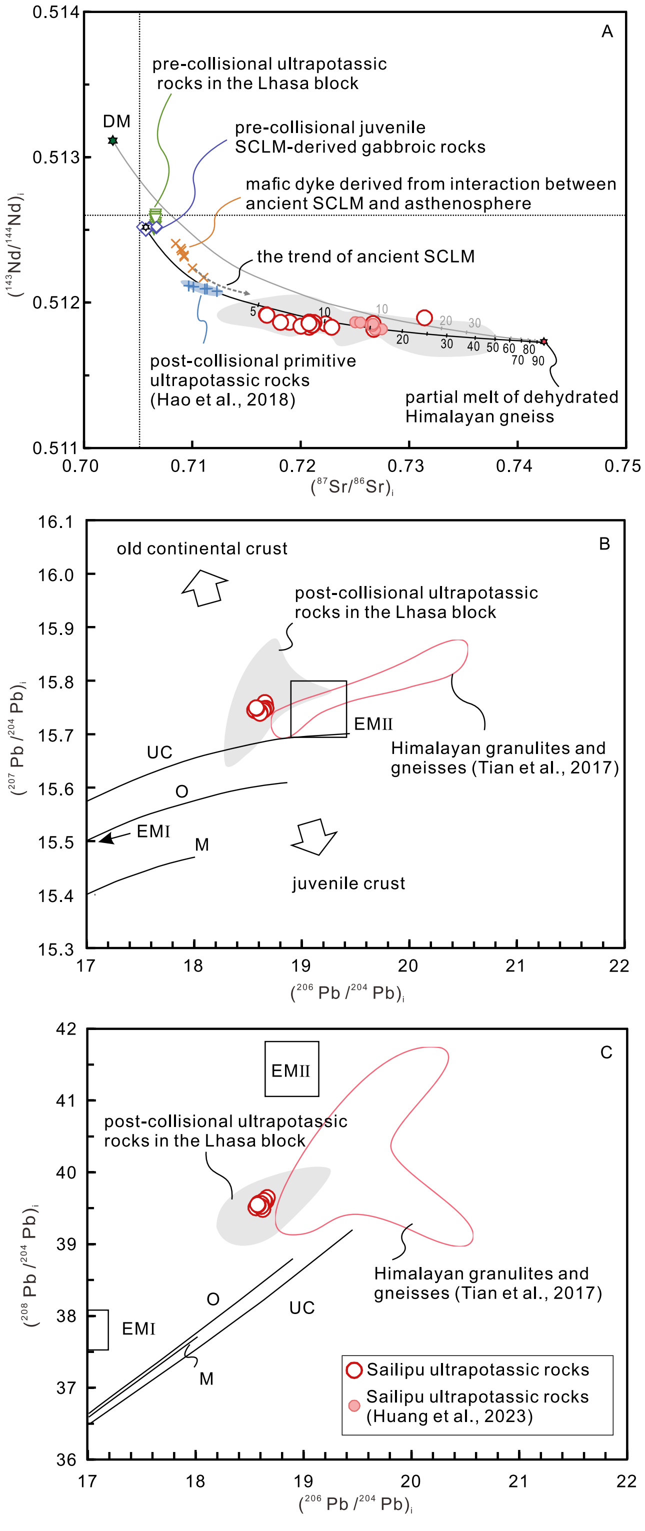

Figure 3.

3.2. Mo and B Isotopic Compositions

The Sailipu ultrapotassic rocks contain a relatively small range of Mo concentrations (0.25–1.50 ppm) and show variable Mo isotope compositions ($\delta^{98/95}$Mo = −0.66 to −0.07‰), which extend to be lower than those of MORBs

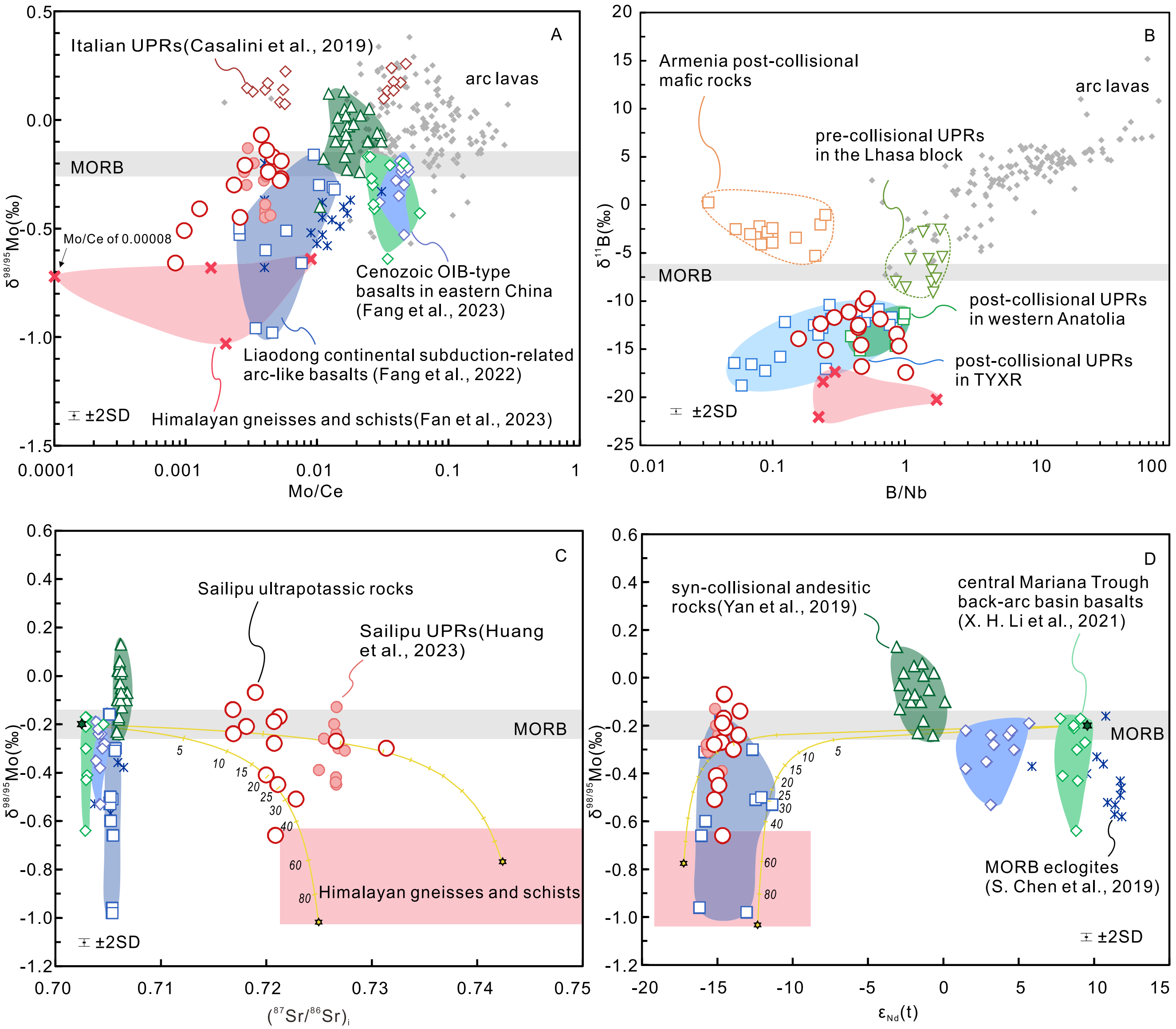

Figure 4. (a) $\delta^{98/95}$Mo versus Mo/Ce ratios, (b) δ^{11}B versus B/Nb ratios, (c) and (d) $\delta^{98/95}$Mo versus $(^{87}Sr/^{86}Sr)_i$ and $\varepsilon_{Nd}(t)$, respectively, for the Sailipu ultrapotassic rocks in the Lhasa block. The data for Mo isotopes of arc lavas are from Ahmad et al. (2021), H. Y. Li et al. (2021), and X. H. Li et al. (2021) and references therein. The literature data of B isotopes and B/Nb ratios in Figure 4b are from Hao, Wang, Kerr, et al., 2022 and references therein. The gray fields for δ^{11}B and $\delta^{98/95}$Mo of the MORBs are from Marschall et al. (2017) and Freymuth et al. (2015), respectively. The yellow lines represent the mixing curves between the mantle source and the different Indian continental crust endmembers. The numbers (%) show the proportions of Indian continental crust involved in the depleted mantle source.

($\delta^{98/95}$Mo = −0.20 ± 0.06‰, Freymuth et al., 2015) (Figure 4a). They have Mo/Ce ratios of 0.0008–0.005 (Figure 4a), which are also lower than those of MORB (~0.03). Their $\delta^{98/95}$Mo and Mo/Ce values are similar to the literature data ($\delta^{98/95}$Mo = −0.45 to −0.13‰; Huang et al., 2023), but significantly different from those of modern arc lavas (e.g., König et al., 2016; H. Y. Li et al., 2021).

Figure 3. (a) Sr-Nd isotopic compositions and (b and c) Pb isotopic compositions for the Sailipu post-collisional ultrapotassic rocks. The data for post-collisional ultrapotassic rocks elsewhere in the Lhasa block are the same as in Figure 2. The pre-collisional ultrapotassic rocks in the Lhasa block: Rongniduo Paleocene ultrapotassic rocks (Qi et al., 2018). The pre-collisional juvenile sub-continental lithospheric mantle (SCLM)-derived gabbroic rocks: the late Cretaceous gabbroic rocks (Lei et al., 2022). The mafic dyke derived from the interaction between ancient SCLM and asthenosphere: the late Cretaceous diabase-porphyrites (Hao et al., 2023). The endmembers of partial melts of the already dehydrated Higher Himalayan Crystalline Sequence (HHCS, as representative examples of Indian continental crust) and depleted mantle (DM) are from Guo et al. (2013). The numbers (%) on the mixing curve represent the proportions of Indian continental crust involved in mantle source (e.g., the DM, or a juvenile lithospheric mantle). Lead evolution curves for mantle (M), orogeny (O), and upper crust (UC) are from Soder and Romer (2018) and references therein.

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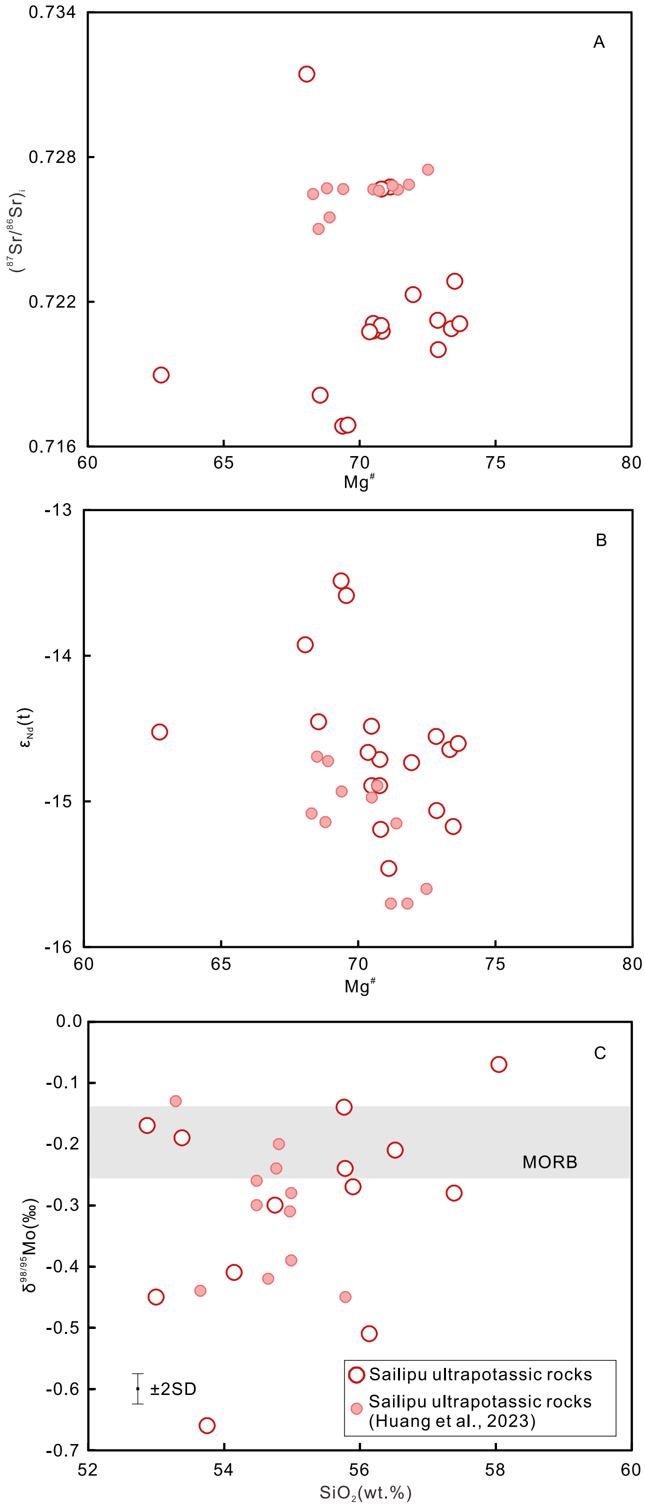

Figure 5. (a and b) Mg# versus $(^{87}Sr/^{86}Sr)_i$ and $\varepsilon_{Nd}(t)$, and (c) $\delta^{98/95}$Mo versus SiO_2, respectively, for the Sailipu post-collisional ultrapotassic rocks. The gray fields for $\delta^{98/95}$Mo of the MORBs are same as Figure 4.

The Sailipu ultrapotassic rocks display a wide range of B concentrations (5.3–35.8 ppm) and δ^{11}B values (−17.4 to −9.7‰), which are significantly lower than those of MORBs (δ^{11}B = −7.1 ± 0.9‰, Marschall et al., 2017), modern arc lavas (De Hoog & Savov, 2018), and the pre-collisional (Paleocene) ultrapotassic rocks from the Rongniduo area in the Lhasa block (Hao, Wang, Kerr, et al., 2022) (Figure 4b). Instead, their B isotopic compositions and B/Nb ratios (0.16–1) are similar to those of Miocene K-rich rocks from the western Anatolian region (down to −31‰, Palmer et al., 2019) and the TangraYumco-Xuruco rift (TYXR) in the Lhasa block (−20.5 to −10.3‰, Hao, Wang, Kerr, et al., 2022).

4. Discussion

4.1. Effects of Shallow-Level and Partial Melting Processes

It is important to consider the effects of shallow-level processes, such as alteration, crustal contamination, and fractional crystallization, before using Mo isotopes to trace the mantle source. All post-collisional ultrapotassic rocks studied here are generally free of secondary minerals, with low loss on ignition (LOI) values (mostly <2 wt.%), suggesting insignificant alteration after formation. In addition, the lack of correlation between their LOI values and the Mo concentrations and isotopic compositions of these samples (Figures S2a and S2b in Supporting Information S1) indicates that the Mo isotopic compositions of the Sailipu post-collisional ultrapotassic rocks have not been affected by alteration.

The post-collisional crustal thickness of the Lhasa block is about 70 km (W. P. Chen & Yang, 2004) and therefore, the effects of crustal contamination during magma ascent must be carefully evaluated. The Sailipu post-collisional ultrapotassic rocks show no correlation between Mg# values and $\varepsilon_{Nd}(t)$ values and $(^{87}Sr/^{86}Sr)_i$ ratios, indicating that they were not affected by crustal assimilation with concomitant fractional crystallization (Figures 5a and 5b). Their $\delta^{98/95}$Mo values are also not correlated with SiO_2 contents (Figure 5c), consistent with negligible crustal assimilation.

La/Yb and La/Sm ratios are sensitive to the degree of partial melting because La is more incompatible than Sm and Yb during mantle partial melting. The Sailipu post-collisional ultrapotassic rocks show positive correlations between La/Yb, La/Sm, and La (Figures 6a and 6b), which indicate that partial melting rather than fractional crystallization was a major factor in their formations. Moreover, fractional crystallization cannot fully account for the light and variable $\delta^{98/95}$Mo values because Mo is extremely incompatible in olivine and pyroxene (Wang & Becker, 2018). Besides, previous studies suggested that fractional crystallization of hydrated Mo-bearing minerals, such as hornblende and biotite, may result in residual melts with heavy Mo isotopes (Voegelin et al., 2014; Willbold & Elliott, 2017).

Recent studies have shown that Mo isotope fractionation during low degrees of partial melting is quite limited (McCoy-West et al., 2019). However, the significant Nb-Ta-Ti negative anomalies of the Sailipu ultrapotassic rocks likely indicate the presence of residual mineral phases, such as rutile or titanite, in the mantle source. Significantly, some residual mineral phases (e.g., rutile and sulfide) are important hosts of Mo (S. Chen et al., 2019; Skora et al., 2017; Zack, 2002). Thus, it is important to consider the effects of residual rutile and sulfide. The $\delta^{98/95}$Mo values of these rocks do not define any systematic trends with their TiO_2, Cu content, or Nb/Ta ratios (Figures 6c–6e), showing that residual mineral phases did not significantly influence the

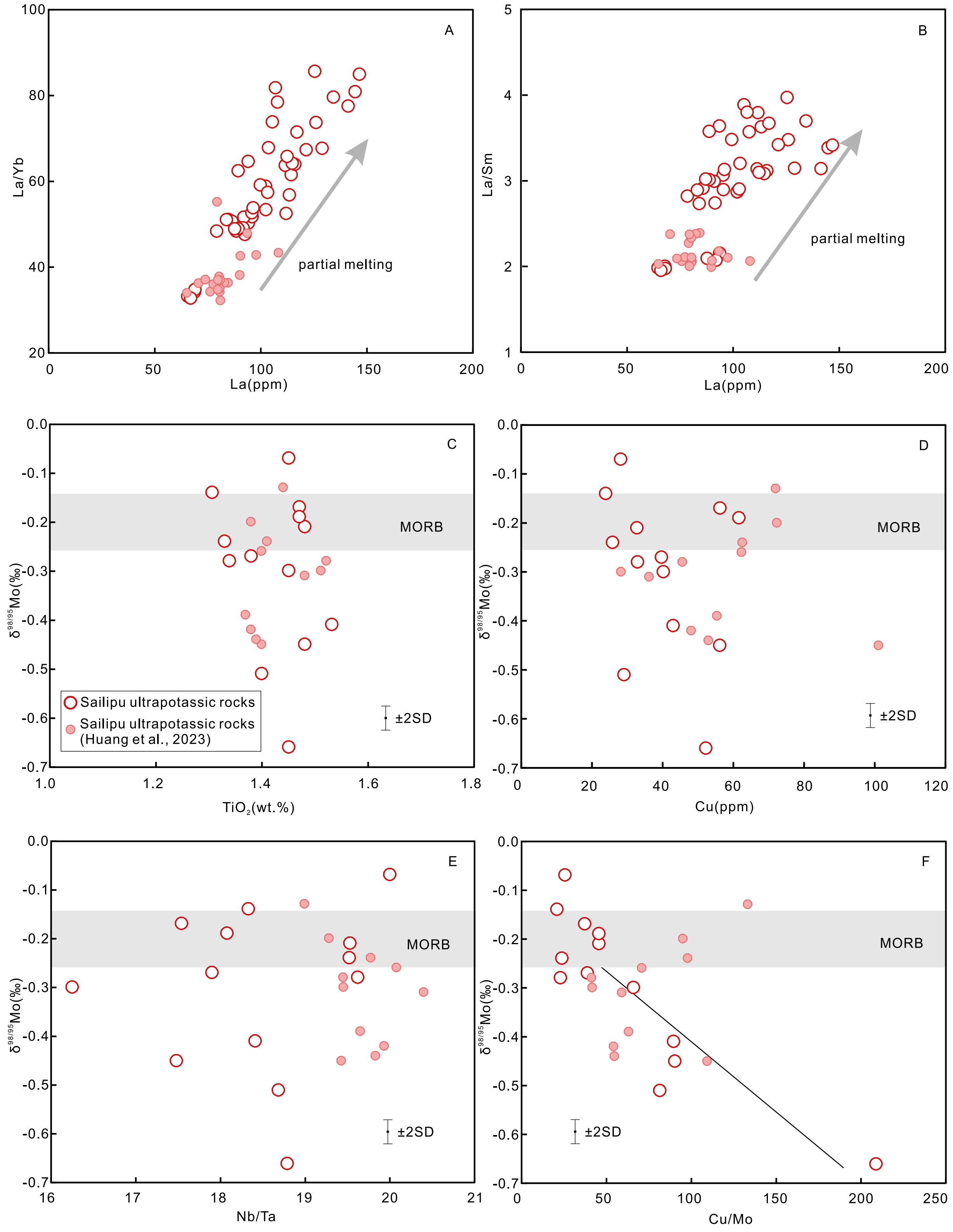

Figure 6. (a and b) La versus La/Yb and La/Sm, and (c–f) $\delta^{98/95}$Mo versus TiO_2, Cu, Nb/Ta, and Cu/Mo, respectively, for the Sailipu post-collisional ultrapotassic rocks. The gray fields for $\delta^{98/95}$Mo of the MORBs are same as Figure 4.

Mo isotope signature of these rocks. Moreover, the melts equilibrated with residual rutile would have a heavier Mo isotope signature, because rutile has an isotopically light Mo signature (S. Chen et al., 2019). Sulfide phases can selectively retain isotopically heavy Mo within the mantle (Liang et al., 2017; Voegelin et al., 2012) and may contribute to the generation of the lighter Mo isotopic compositions. However, Cu partitions into sulfides more easily than Mo (Y. Li & Audétat, 2012), and so low degree partial melting will produce melts with a positive correlation between $\delta^{98/95}$Mo values and Cu/Mo ratios. The fact that the studied samples with the lowest Cu/Mo have higher $\delta^{98/95}$Mo values (Figure 6f) precludes low degree partial melting as the cause of the light Mo isotopes of these samples. Thus, we conclude that the variable and low $\delta^{98/95}$Mo values of the ultrapotassic rocks are not due to residual rutile and/or sulfide.

In summary, the light Mo isotopic compositions of the Sailipu ultrapotassic rocks largely inherited from their mantle source rather than due to shallow-level and partial melting processes. Similarly, their B isotopic compositions also inherited from their source (Figure S3 in Supporting Information S1).

4.2. Light Mo Isotopic Compositions Sourced From Subducted Indian Continental Crust

Due to the infiltration of oceanic slab-derived fluids, modern mafic arc lavas generally have higher Mo isotopic compositions ($\delta^{98/95}$Mo = −0.2 to +0.4‰) and Mo/Ce ratios (Ahmad et al., 2021 and references therein; König et al., 2016; H. Y. Li et al., 2021; X. H. Li et al., 2021; Villalobos-Orchard et al., 2020) than those of MORBs (Freymuth et al., 2015). This is because ^{98}Mo is preferentially transported by fluids during slab subduction and dehydration (Freymuth et al., 2015). In contrast with these modern arc lavas, the Sailipu ultrapotassic rocks have overall relatively lighter Mo isotopes ($\delta^{98/95}$Mo = −0.66 to −0.07‰) and significantly lower Mo/Ce ratios (0.0008–0.005) (Figure 4a), indicating that their mantle source was not significantly affected by oceanic slab-derived fluids.

In contrast to modern arc lavas, low Mo/Ce ratios and light Mo isotopes have been recorded in residual oceanic crust. For example, the depleted MORB eclogites have low Mo/Ce ratios of 0.004–0.031 and $\delta^{98/95}$Mo values of −0.68 to −0.16‰ (Ahmad et al., 2021; S. Chen et al., 2019) (Figure 4a). Melts from residual oceanic crust can be injected into deep mantle and thus transfer the light Mo isotopes into the mantle. However, the igneous rocks derived from such a mantle source are characterized by depleted Sr-Nd isotopic compositions, for example, Cenozoic OIB-type basalts in eastern China (Fang et al., 2023) and the central Mariana Trough basalts in the back-arc basin (X. H. Li et al., 2021), which are different from the Sailipu ultrapotassic rocks (Figures 4c and 4d).

Recently, Huang et al. (2023) proposed that a light Mo isotope reservoir formed by subduction of Tethyan oceanic sediment should exist in the sub-continental lithospheric mantle (SCLM) beneath southern Tibet, and may contribute to the light Mo isotope compositions and low Mo/Ce ratios of the post-collisional Sailipu ultrapotassic rocks. Indeed, the oceanic sediments show variable Mo isotope compositions (Ahmad et al., 2021; Casalini et al., 2019; Freymuth et al., 2015, 2016; Gaschnig et al., 2017) with an average value of −0.29‰, which is slightly lower than that of MORBs (Freymuth et al., 2015). However, the Italian post-collisional (Miocene-early Pleistocene) ultrapotassic rocks were considered to be derived from a mantle source containing recycled oceanic sediments and show relatively high $\delta^{98/95}$Mo values (+0.07 to +0.26‰) (Casalini et al., 2019) (Figure 4a). In southern Tibet, the syn-collisional (~62 Ma) andesitic rocks from the Linzhou basin of the Lhasa block were demonstrated to have involved the subducted Neo-Tethyan oceanic sediments in their mantle source (Yan et al., 2019), yet, they mostly have heavy Mo isotopic compositions ($\delta^{98/95}$Mo = −0.24 to +0.13‰) and high Mo/Ce ratios (0.017–0.036) (Figure 4a). Moreover, these ~62 Ma andesitic rocks have Eu/Eu* values of 0.8–0.9 and Th contents of 4.6–9.0 ppm, which were also distinct from the Sailipu post-collisional ultrapotassic rocks with Eu/Eu* values of 0.6–0.7 and Th contents of 154–317 ppm.

Furthermore, the Sr-Nd isotope compositions of the post-collisional ultrapotassic rocks in southern Tibet are inconsistent with their derivation from the sediment-metasomatized SCLM beneath the Lhasa block formed during the Neo-Tethyan oceanic subduction: (a) The pre-collisional juvenile SCLM can be formed by the metasomatism of the Neo-Tethyan oceanic sediment. However, such a SCLM generally shows slightly depleted-less enriched Sr-Nd isotopes, which are distinct from the post-collisional ultrapotassic rocks. For instance, the late Cretaceous (~90 Ma) gabbroic rocks in southern Tibet were considered to be derived from the juvenile SCLM and showed depleted $(^{87}Sr/^{86}Sr)_i$ of 0.7054–0.7067 and $\varepsilon_{Nd}(t)$ of −2.2 to −1.7 (Lei et al., 2022). Moreover, the Rongniduo Paleocene (~64 Ma) ultrapotassic rocks in the Lhasa block were suggested to originate from this juvenile

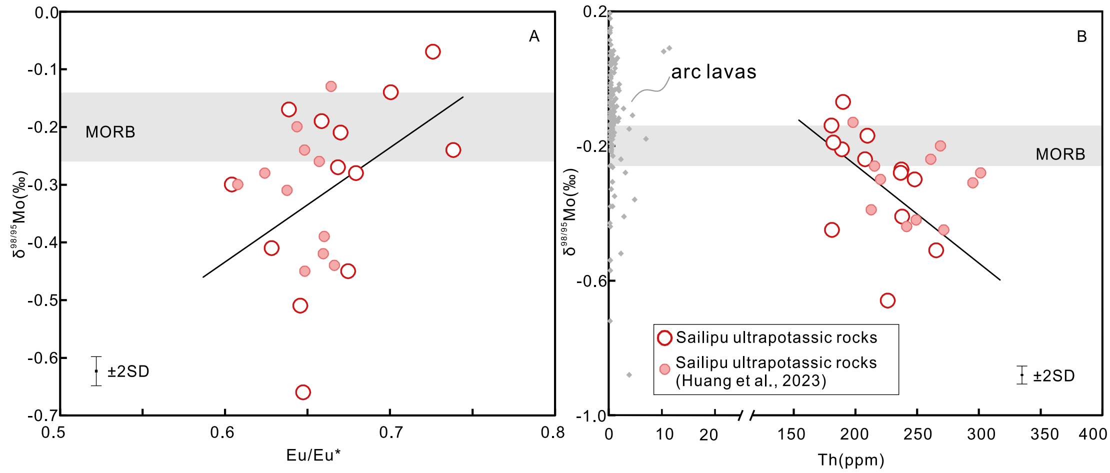

Figure 7. (a and b) $\delta^{98/95}$Mo versus Eu/Eu* and Th contents, respectively, for the Sailipu ultrapotassic rocks. The data for Mo isotope compositions of arc lavas are the same as in Figure 4.

SCLM, yet, they show $(^{87}Sr/^{86}Sr)_i$ of 0.7065–0.7067 and $\varepsilon_{Nd}(t)$ of −1.9 to +0.1 (Qi et al., 2018) (Figure 3a). (b) The pre-collisional ancient SCLM beneath the Lhasa block cannot be the source of the post-collisional ultrapotassic rocks. Recently, Hao et al. (2023) suggested that the late Cretaceous (~90 Ma) mafic dykes (diabase-porphyrites) were generated by the interaction between the ancient SCLM and asthenosphere, which can thus be used to constrain the nature of the ancient SCLM (Figure 3a). A comparison of Sr-Nd isotopes between the post-collisional ultrapotassic rocks (Hao et al., 2018) in the Lhasa block and the ~90 Ma ancient SCLM (Figure 3a) suggested that the post-collisional ultrapotassic rocks cannot be derived from the ancient SCLM, let alone an ancient SCLM metasomatized by the subducted oceanic sediments. Therefore, the light Mo isotope compositions of post-collisional ultrapotassic rocks unlikely inherited from oceanic sediments.

Although no direct Mo isotope data has been documented for the exhumed ultrahigh-pressure rocks formed in continental subduction, Mo isotopic fractionation between fluids and residual slab during dehydration can result in light Mo isotopes in the subducted continental crust (Fang et al., 2022). The early Cretaceous arc-like basalts from the Liaodong Peninsula (Fang et al., 2022) related to continental subduction show low $\delta^{98/95}$Mo values (−0.98 to −0.16‰), low Mo/Ce ratios (Figure 4a) and enriched Nd isotopes (Figure 4d), which are similar to those of the Sailipu ultrapotassic rocks. In the case of southern Tibet, the schists and gneisses of the Tethyan Himalaya, as representative examples of Indian continental crust, have extremely low $\delta^{98/95}$Mo values (−1.03 to −0.64‰) and Mo/Ce ratios (0.0001–0.009, Fan et al., 2023) (Figure 4a). Moreover, the Sailipu post-collisional ultrapotassic rocks have $\delta^{98/95}$Mo values and Mo/Ce ratios that are intermediate between those of MORBs and the Indian continental crust (Figure 4a). Consequently, the involvement of the subducted Indian continental crust could be most likely responsible for the light Mo isotopes and low Mo/Ce ratios of the Sailipu ultrapotassic rocks. A simple mixing model shows that adding 10%–40% Indian continental crustal components to the depleted mantle (DM) can produce the light Mo isotope signatures of most Sailipu ultrapotassic samples (Figures 4c and 4d).

Importantly, we have observed that all Sailipu ultrapotassic rocks display negative Eu anomalies (Eu/Eu* = 0.6–0.7) and extreme enrichment of Th. These features were not reported in pre-collisional mafic rocks in the Lhasa block (e.g., Qi et al., 2018; Zhu et al., 2010). It is also noteworthy that the $\delta^{98/95}$Mo values of the Sailipu ultrapotassic rocks are positively correlated with Eu/Eu* values, and negatively correlated with Th contents (Figures 7a and 7b). Since the continental crust is characterized by a negative Eu anomaly and extreme enrichment of Th (Prelević et al., 2013; Tang et al., 2015), we propose that the light Mo isotope compositions of the Sailipu ultrapotassic rocks are more likely to originate from subducted continental crust rather than oceanic sediments.

Our explanation has been further verified by the very light B isotope compositions and low B/Nb ratios of the Sailipu ultrapotassic rocks, which are markedly similar to those of the post-collisional ultrapotassic rocks from the TYXR in the Lhasa block (Hao, Wang, Kerr, et al., 2022). The very low B/Nb ratios of these post-collisional ultrapotassic rocks indicate a fluid-starved source and their low δ^{11}B values cannot be derived from oceanic sediments or a stalled dehydrated oceanic slab. Combined with the light B isotope compositions of the schists and gneisses of the Tethyan Himalaya (Fan et al., 2023), Hao, Wang, Kerr, et al. (2022) proposed that the very light B isotope compositions of these post-collisional ultrapotassic rocks in southern Tibet are most likely derived from the subducted Indian continental crust.

In summary, the extremely light Mo-B isotopic compositions and negative Eu anomalies in combination with the extreme enrichment of Th, low Mo/Ce, and B/Nb ratios of the post-collisional ultrapotassic rocks in the Sailipu area of southern Tibet are due to the recycling of subducted Indian continental crust. Specifically, the post-collisional ultrapotassic rocks in southern Tibet were derived from a relatively DM (e.g., juvenile lithospheric mantle) metasomatized by subducted Indian continental crust.

4.3. Implications for Mo-B Recycling in Continental Subduction

Mo and B isotope systems are widely utilized in tracing material recycling in oceanic subduction zones (e.g., Bezard et al., 2016; Casalini et al., 2019; De Hoog & Savov, 2018; König et al., 2016; H. Y. Li et al., 2021; X. H. Li et al., 2021; Villalobos-Orchard et al., 2020). More recently, they have been increasingly used in continental subduction zones (Fang et al., 2022; Huang et al., 2023; Palmer et al., 2019). For instance, Hao, Wang, Kerr, et al. (2022) suggested that the extremely light B isotope compositions of the post-collisional ultrapotassic rocks in southern Tibet should be ascribed to the recycling of the subducted Indian continental crust. Fang et al. (2022) suggested that the continental subduction could contribute light Mo isotope compositions to the post-collisional mafic rocks, for example, the Liaodong Cretaceous arc-like basalts. However, given that continental subduction is generally induced by gravitational traction of the oceanic lithosphere, both oceanic and continental crustal materials can be recycled into the mantle in continental subduction zones and contribute to post-collisional mafic magmatism. Thus, the origin of light Mo isotope compositions for the post-collisional mafic rocks remains highly debated. For example, Huang et al. (2023) suggested that the light Mo isotope compositions of the post-collision ultrapotassic rocks likely originated from the subducted oceanic sediments. That is to say, the recycling of Mo isotopes in continental subduction zones remains unclear.

In this contribution, we re-visited the Mo isotopes of the Sailipu post-collisional ultrapotassic rocks in southern Tibet and have fully discussed that the light Mo isotope compositions of these rocks should be sourced from subducted Indian continental crust rather than the Neo-Tethyan oceanic sediment. This is also consistent with their very light B isotope compositions. Thus, combining this study with literature data (e.g., Fang et al., 2022), we argue for the point that the light Mo isotope compositions of the post-collisional mafic rocks have recorded the recycling of subducted continental crust. Collectively, the Mo-B isotopes have significant potential in discriminating between oceanic and continental subduction.

5. Summary

1. The Sailipu post-collisional (Miocene) ultrapotassic rocks in southern Tibet have extremely light Mo and B isotope compositions, with $\delta^{98/95}$Mo and δ^{11}B values ranging from −0.66 to −0.07‰ and −17.4 to −9.7‰, respectively.
2. The light Mo-B isotope compositions of these post-collisional ultrapotassic rocks should be derived from subducted Indian continental crust rather than the Neo-Tethyan oceanic sediments.
3. This study provides a perspective on the light Mo and B isotope recycling in continental subduction zones and shows the considerable potential of Mo-B isotopes in tracing crustal material recycling.

Data Availability Statement

The research data associated with the manuscript are listed in Supporting Information S1 and can be found on figshare Zhang et al. (2023).

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