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REPLY

Reply to the comments on "Xenoliths in ultrapotassic volcanic rocks in the Lhasa block: direct evidence for crust–mantle mixing and metamorphism in the deep crust"

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Abstract Stepanov et al. (Contrib Mineral Petrol, 2017) question our conclusion that the UPVs in southern Tibet were derived by partial melting of an old, metasomatized subcontinental lithospheric mantle (SCLM) of the subducted Indian plate. Instead, they propose that these ultrapotassic volcanic rocks (UPVs) are shoshonitic and were generated in two steps: direct melting of crustal rocks first, and then the melts interacted with mantle peridotite. However, the trace element, isotopic, thermal, structural, and seismic evidence is consistent with the xenolith evidence (Wang et al in Contrib Mineral Petrol 172:62, 2016) for hybridisation of ascending Indian subcontinental lithospheric mantle-derived UPV magmas with the deep, isotopically unevolved, Tibetan crust. This necessitates a model whereby partial melting of subducting Indian SCLM generates the UPV suite of southern Tibet.

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Introduction

We welcome Stepanov et al.'s (2017) comment on our paper about the origin of xenoliths in ultrapotassic volcanic rocks (UPV) in the Lhasa block (Wang et al. 2016). Although our paper focused mainly on the origin of the xenoliths, we welcome the opportunity to reply to their questions about the origin of the host UPV. Stepanov et al. (2017) question our conclusion that the UPVs in southern Tibet were derived by partial melting of an old, metasomatized subcontinental lithospheric mantle (SCLM) of the subducted Indian plate. Instead, they propose that the rocks are shoshonitic and can be generated by the "direct melting of crustal rocks, followed by interaction with mantle peridotite", based on a model presented by Campbell et al. (2014) for the origin of shoshonites in the Red River Fault Zone of eastern Tibet. In this model, felsic shoshonitic partial melts derived from continental crust thrust into the mantle interact with the overlying mantle wedge during ascent to become mafic in composition (Stepanov et al. 2017). However, several lines of evidence from the UPVs in southern Tibet preclude this interpretation.

Stepanov et al. (2017) also propose that the UPV suite should be described as shoshonitic. However, while some of our samples do indeed classify as shoshonite according to the total alkali-silica nomenclature scheme (basaltic trachyandesitic compositions with $K_2O > Na_2O - 2.0$; Le Maitre et al. 2002), the majority plot in the field of ultrapotassic rocks according to the diagram used by Campbell et al. (2014) (Fig. 1). In southern Tibet, this suite of rocks

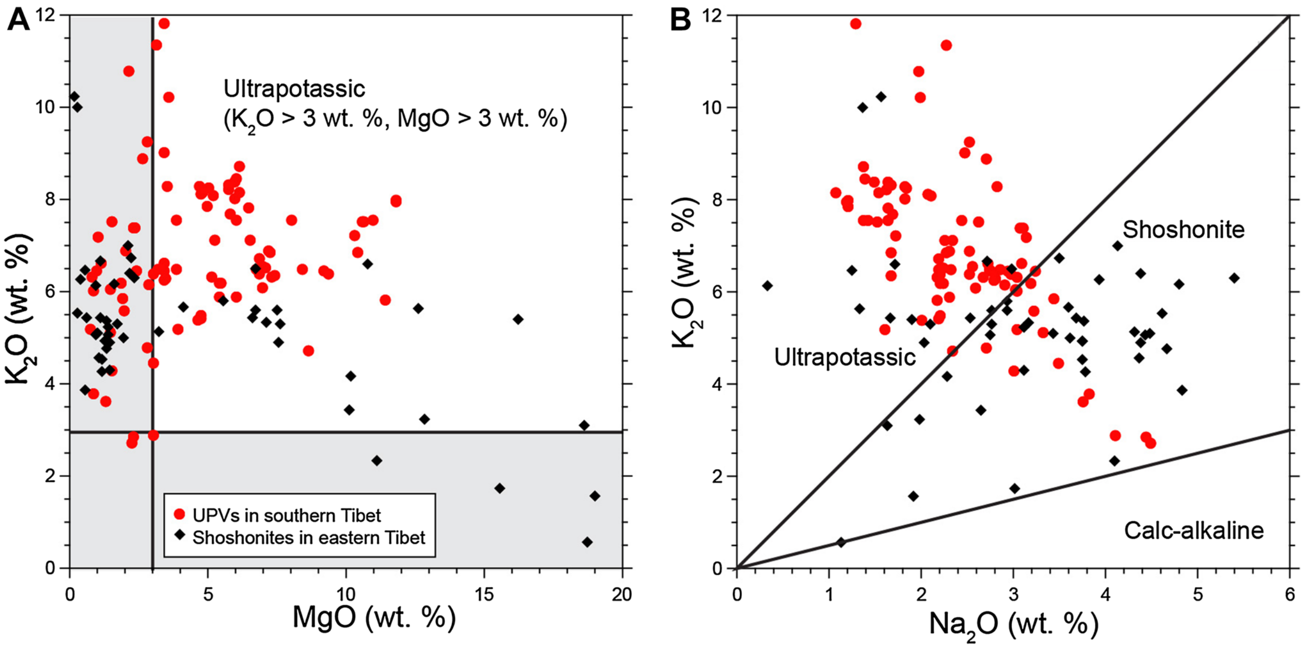

Fig. 1 **a** K_2O vs MgO plot and **b** K_2O vs Na_2O plot for UPVs in southern Tibet, and shoshonites in eastern Tibet. According to Foley et al. (1987, p 81) ultrapotassic rocks have "$K_2O > 3$ wt%, $MgO > 3$ wt% and $K_2O/Na_2O > 2$". Data for UPVs in southern Tibet are from Zhao et al. (2009) and Wang et al. (2014, 2015, and references therein), and data for shoshonites in eastern Tibet are from appendices of Campbell et al. (2014)

has widely been referred to as ultrapotassic, so we prefer to retain this terminology here.

Xenoliths in southern Tibet

Campbell et al. (2014) propose that the crustal xenoliths reported in our study represent fragments of the source of the UPV magmas, which then ascended through overlying depleted mantle (to acquire their variably more mafic compositions). This model implies that the crustal source was underthrust below the Tibetan lithosphere and intervening mantle wedge, and was presumably of Indian plate origin. However, as stated by Chan et al. (2009, p 45) "Ultramafic xenoliths, probably of crustal origin, attained peak metamorphic conditions of 920–1130 °C and 17–24 kbar, whereas felsic granulites equilibrated at 870–900 °C at an inferred pressure of 17 kbar". Given the established xenolith-derived geotherm of ~16 °C/km, this constrains the felsic granulite xenoliths of our study (Wang et al. 2016) to the Gangdese arc root (~55 km depth). Thus, these xenoliths were not derived from Indian plate crust thrust into the mantle, and cannot represent the deep source of shoshonitic magmas as suggested by Campbell et al. (2014).

Furthermore, deep seismic profiles (e.g., Nábělek et al. 2009) from the region provide no evidence for the presence of a mantle wedge in the western Gangdese belt (west of 89°E, where most UPVs occur). Thus, even if the UPV magmas were derived from partial melting of Indian plate crust, they would not have interacted with mantle during their ascent, as proposed by Campbell et al. (2014).

Geochemical evidence

Figure 2 shows that the εNd_i values for the southern Tibet UPVs increase with increasing SiO_2 and do not trend toward Indian metasedimentary crust, as represented isotopically by Himalayan leucogranites. In contrast, the most mafic shoshonitic samples from the Red River Fault Zone of eastern Tibet (Campbell et al. 2014) have the highest (most primitive) εNd_i compositions. The positive slope of UPVs in southern Tibet is more likely to be part of a mixing array between mafic magmas derived from an isotopically evolved source with felsic magmas derived from the isotopically unevolved southern Tibetan (Gangdese) crust, as suggested by the xenolith evidence. The Red River felsic shoshonites also seem to project to that Tibetan source (Fig. 2).

Another outcome of the εNd_i vs SiO_2 plot is that it also shows the isotopic similarity between the more mafic southern Tibet UPVs and the Himalayan leucogranites. This isotopic similarity suggests both were derived from ancient (Proterozoic) sources: Nd_{DM} model ages for the

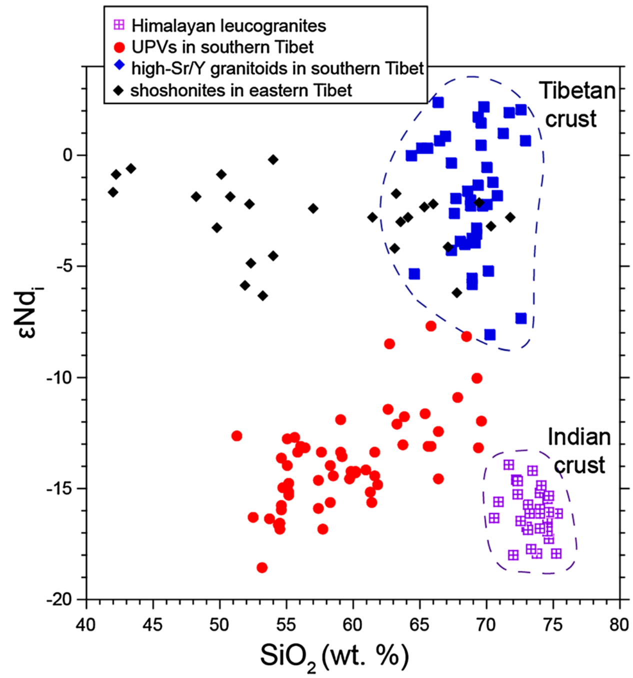

Fig. 2 εNd_i vs SiO_2 for the Himalayan leucogranites, UPVs in southern Tibet, and high-Sr/Y granitoids in southern Tibet (data for high-Sr/Y granitoids, and Himalayan leucogranites in southern Tibet are from Guo and Wilson (2012), and Wang et al. (2014, 2015, and references therein), sources of the rest of data are comparative to Fig. 1)

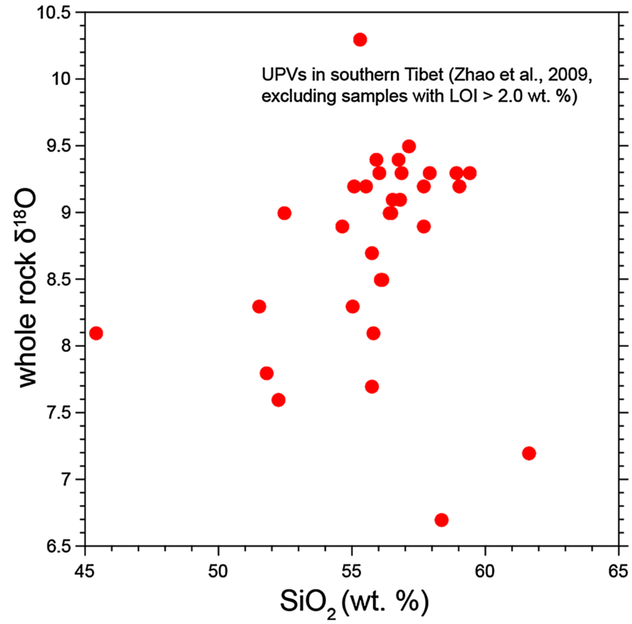

Fig. 3 $\delta^{18}O$ vs SiO_2 for the UPVs in southern Tibet (data from Zhao et al. 2009)

UPVs range from 1.4 to 2.3 Ga, and for the leucogranites between 1.9 and 2.7 Ga (Zhao et al. 2009; Guo and Wilson 2012). Remnants of a Paleoproterozoic arc exist on the northern margin of the Indian craton (Miller et al. 2000), which was the ultimate source of the Himalayan sediments. The chemical contrast between the Himalayan leucogranites and the southern Tibet UPVs (high vs low SiO_2 respectively) illustrates that the leucogranites were derived from offscraped Himalayan metasediments from the Indian craton, as shown by seismic arrays (e.g., Nábělek et al. 2009), whereas the UPVs were sourced from the subducting Indian SCLM, which was metasomatized during Paleoproterozoic arc magmatism.

Stepanov et al. (2017) also proposed that the O isotopic compositions of many Tibetan UPVs (+6.2 to +8.8‰; Wang et al. 2015) are well above the mantle value (+5.3 ± 0.3‰; Valley et al. 1998) and are inconsistent with a mantle melting origin. We argue that such O isotopic compositions are compatible with their extremely negative εNdi values (−19.0 to −8.0), similar to the compositions of High Himalayan Crystalline basement considered to be a proxy for the Indian plate lithosphere: $\delta^{18}O$ = +10 to +14‰, εNd = −18 to −10 (France-Lanord et al. 1988; Zhao et al. 2009). These isotopic values are in line with our conclusions in that the UPVs reflect derivation from an ancient (Proterozoic) source that was metasomatized during Paleoproterozoic arc magmatism.

Although the Earth's upper mantle has been well constrained to a limited range of $\delta^{18}O$ values (5.18 ± 0.28%; Mattey et al. 1994), portions of lithospheric mantle that have $\delta^{18}O$ values higher than the upper mantle also exist (Dorendorf et al. 2000; Auer et al. 2009; Liu et al. 2014). $\delta^{18}O$ values of 5.8–7.1‰ for olivine and 6.2–7.5‰ for clinopyroxene from the Kamchatka volcano are significantly heavier than typical mantle values, suggesting the mantle source was hydrated and metasomatized by $\delta^{18}O$-rich fluids (Dorendorf et al. 2000). This hydrated mantle material was subsequently involved in arc magmatism. $\delta^{18}O$-rich mantle also exists in southern Tibet. Peridotite xenoliths in a UPV dyke from Salipu in southern Tibet have olivine with Fo (Fo = 100 × Mg/(Mg + Fe)) of 88–91 that has significantly elevated $\delta^{18}O$ values of 8.03 ± 0.28‰ (Liu et al. 2014). These values are the highest so far reported for mantle peridotite. The existence of such $\delta^{18}O$-rich olivine suggests the lithospheric mantle in southern Tibet has been hydrated and metasomatized by $\delta^{18}O$-rich fluids or melts. We think ^{18}O was enriched in the mantle source during metasomatism by Paleoproterozoic arc magmas. This conclusion is supported by radiogenic isotopes (Sr-Nd-Pb; Zhao et al. 2009; Wang et al. 2015). In addition, the mantle–crust mixing revealed by Fig. 2 can also increase the O isotopic values of UPVs, because supracrustal rocks generally have higher $\delta^{18}O$ values (mostly > 8‰; Valley et al. 2005). $\delta^{18}O$ values of UPVs in southern Tibet show a rough positive correlation with SiO_2 (Fig. 3), suggesting

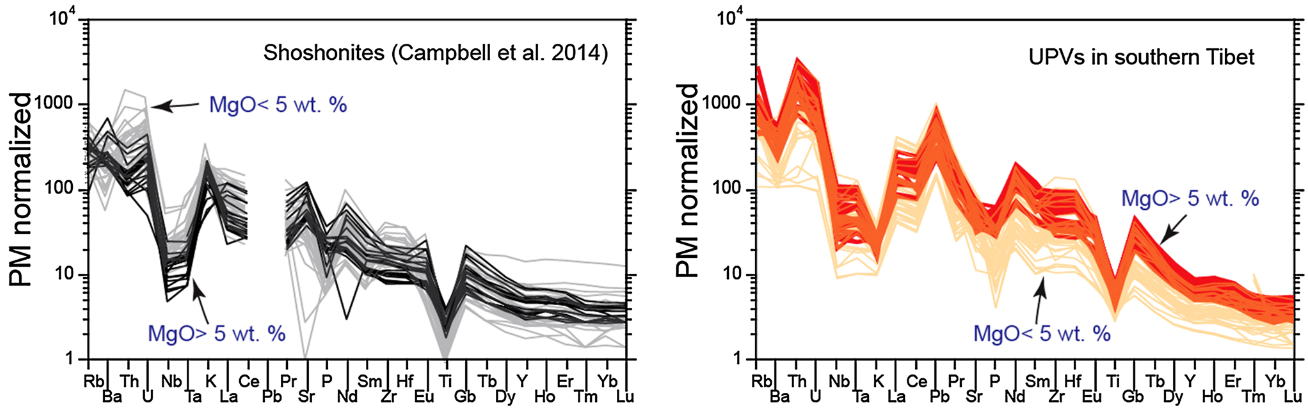

Fig. 4 **a, b** Primitive mantle (PM)-normalized trace element diagrams for shoshonites in eastern Tibet, and UPVs in southern Tibet (comparative data from sources given in Fig. 1). Normalization values are from Sun and McDonough (1989)

crustal mixing may also have contributed to an increase in $\delta^{18}O$.

We also contrast the chemical characteristics of the Red River shoshonites with the southern Tibet UPVs. Given that Fig. 2 shows that compositional variation of both suites was caused by mixing, Fig. 4 shows the contrasting nature of the mixing components. Figure 4a shows that the mafic members of the Red River suite (>5 wt% MgO) have lower incompatible element concentrations than the felsic members (<5 wt% MgO), suggesting that the trace element characteristics of the suite were controlled by the felsic (crustal) end-member. This is consistent with the Campbell et al. (2014) model. However, the southern Tibet UPV suite contrasts in that the highest concentrations of incompatible trace elements are in the mafic rocks (>5 wt% MgO, Fig. 4b), showing that an enriched mantle source, not continental crust, controlled the primary trace element geochemistry of that suite. Given that subcontinental mantle appears to be absent from the southern Tibetan lithosphere (e.g., Nábělek et al. 2009), the only other potential source for the UPV is the Indian plate SCLM, as concluded by Wang et al. (2016).

Indian lithospheric mantle melting, followed by variable interaction with the Tibetan crust can explain the trace element and isotopic characteristics of mafic and felsic ultrapotassic melts. However, "crustal melting, followed by variable interaction with the mantle model" proposed by Stepanov et al. (2017) would not be able to explain the mixing trend in εNd_i vs SiO_2 (Fig. 2) and the high trace element abundances in mafic UPV melts in southern Tibet.

Conclusion

The trace element, isotopic, thermal, structural, and seismic evidence is consistent with the xenolith evidence for hybridisation of ascending Indian subcontinental lithospheric mantle-derived UPV magmas with the deep, isotopically unevolved, Tibetan crust (Wang et al. 2016). This necessitates a model whereby partial melting of subducting Indian SCLM generates the UPV suite of southern Tibet, rather than a model whereby partial melting of subducted continental crust drives melting of the overlying mantle wedge to produce a shoshonitic suite, as proposed by Campbell et al. (2014) for the Red River Fault Zone in eastern Tibet.

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