Exotic lithosphere mantle beneath the western Yangtze craton: Petrogenetic links to Tibet using highly magnesian ultrapotassic rocks

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ABSTRACT

Highly magnesian ultrapotassic rocks that erupted ca. 30–40 Ma on either side of the northern Ailao Shan–Red River fault (western Yunnan) have initial $^{87}Sr/^{86}Sr$ values of 0.7064–0.7094 and ϵ_{Nd} values of −3.8 to −4.6. Such isotopic compositions are distinct from asthenospheric signatures and most likely probe the lower lithosphere. Sm-Nd model age and trace element data for the Yunnan lavas indicate that at the time of eruption the mantle source was an old (>1 Ga) mica-bearing spinel harzburgite. However, such Proterozoic enriched lithospheric mantle could not have survived the thermo-tectonic processes associated with continental flood volcanism that affected the same part of the western Yangtze craton 250 Ma. Emeishan flood basalt volcanism would have purged the shallow mantle of all its fusible constituents and any enrichments would be younger than 250 Ma. We propose that the lithosphere mantle beneath the western Yangtze craton is exotic and probably represents part of the Tibetan lithosphere extruded to the east 40–50 Ma. The Indo-Asia collision provides a suitable mechanism and explains the link between the west Yangtze craton and northern Tibet in terms of provenance (Sr-Nd) and the similar two-dimensional seismic velocity structure.

Keywords: ultrapotassic rocks, lithosphere mantle, metasomatism, Tibet, west Yunnan.

INTRODUCTION

Cenozoic mafic potassic and ultrapotassic magmas in the Tibetan Plateau provide a post-collisional window into the thermal and compositional structure of the deep lithosphere (Arnaud et al., 1992; Turner et al., 1996; Miller et al., 1999). In addition, geochronological and geochemical investigations are also relevant to the study of mountain building, regional uplift, and Cenozoic climate change (Turner et al., 1993). Previous studies concentrated on post-collisional volcanism in northern and western Tibet (Coulon et al., 1986; Arnaud et al., 1992; Turner et al., 1993, 1996; Miller et al., 1999); studies of the volcanic rocks from the eastern Tibetan Plateau are limited. Chung et al. (1998a) reported that the main phase of magmatism in this area occurred 40–30 Ma, predating potassic magmatism in the interior of the Tibet Plateau. Following the convective removal model of Turner et al. (1993), Chung et al. (1998a) proposed diachronous uplift of the Tibetan Plateau, with significant implications for Cenozoic climate change.

This paper presents major, trace element, and Sr-Nd isotopic data for a set of potassic and ultrapotassic rocks from both sides of the northern Ailao Shan–Red River fault, west Yunnan (Fig. 1). These data are compared with those published for lavas from southwestern and northern Tibet, in an attempt to define melting mechanisms and to reveal the regional heterogeneity of the mantle lithosphere. It is demonstrated that the Yunnan lavas were generated at a shallower depth than the Tibetan lavas, but that they have a similar provenance. The geodynamic implications of these data are discussed.

SAMPLES AND ANALYTICAL RESULTS

The samples were collected from Midu, Haidong, Shigu, and Madeng in western Yunnan (Table 1[1]). These localities straddle the Ailao Shan–Red River fault, along which continental extrusion of Indochina relative to southern China occurred in the mid-Tertiary (Tapponnier et al., 1982). Madeng is west of the fault and the other three localities are east of the fault. Some of these lavas have been dated as between 40 and 30 Ma (Chung et al., 1998a). These lavas are phenocryst rich, containing phlogopite, olivine, and clinopyroxene.

Most of the Yunnan lavas are ultrapotassic in nature, in contrast to the shoshonitic affinity of the most mafic rocks from northern Tibet (Fig. 2A). They have high MgO (to 17%) and are uniformly low in TiO_2 and P_2O_5, which remain virtually constant except for samples with extremely low MgO (Fig. 2B). Compared to those from western Yunnan, potassic rocks from northern Tibet have low MgO and K_2O, and high TiO_2 and Fe_2O_3 contents. The ultrapotassic rocks from southwestern Tibet generally show a compositional affinity to the Yunnan samples, although some aspects, such as Ti and P, are intermediate between the two.

Rare earth element (REE) patterns of the Yunnan lavas are characterized by a light REE enrichment ($[La/Yb]_n$ = 6.5–14.2) and a flat

[1]GSA Data Repository item 2001097, Major and trace element and Sr-Nd isotopic compositions of the ultrapotassic rocks from western Yunnan, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

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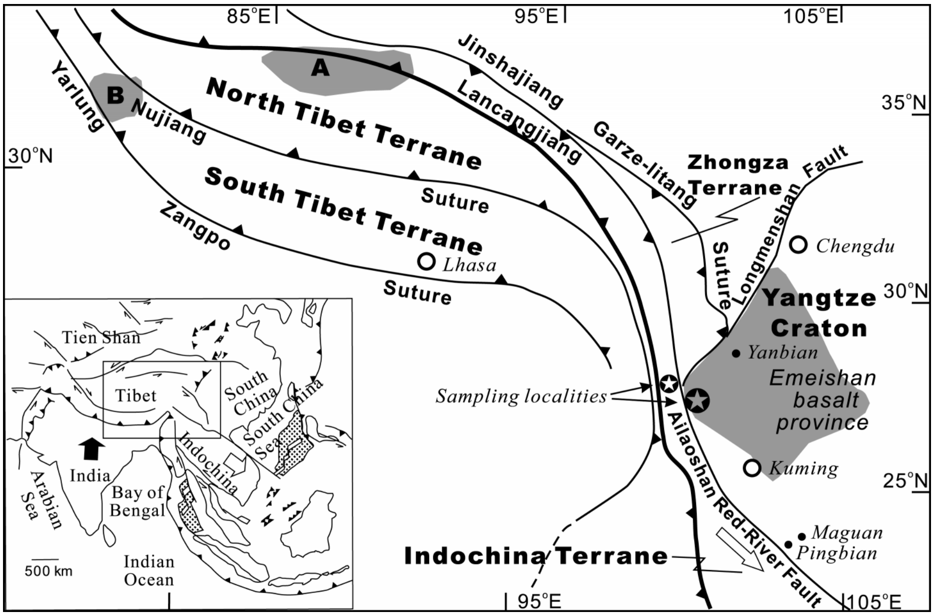

Figure 1. Sketch map showing major tectonic units of southern China and location of studied ultrapotassic rocks. Modified after Chung et al. (1998a). Shaded areas marked with A and B represent locations of shoshonitic lavas in northern Tibet (Turner et al., 1996) and ultrapotassic-potassic rocks from southwestern Tibet (Miller et al., 1999), respectively.

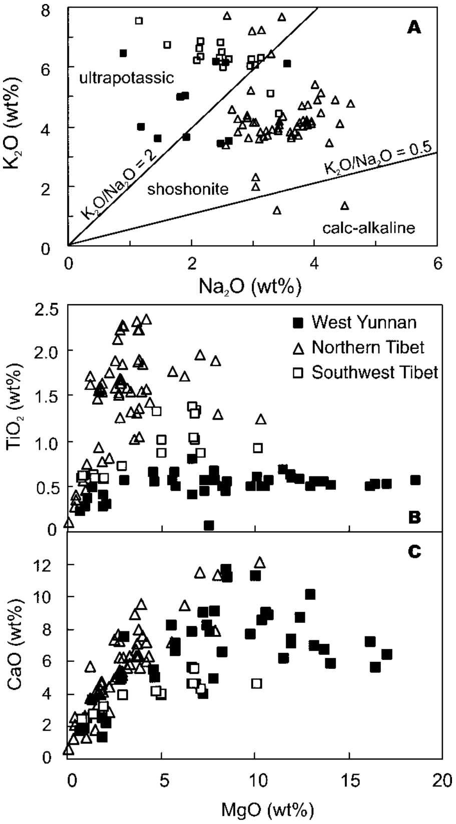

Figure 2. A: Plot of K_2O against Na_2O, showing ultrapotassic characteristics of most Yunnan samples. B, C: Variation of TiO_2 and CaO against MgO. Data sources: western Yunnan, Xie and Zhang (1995), this study; northern Tibet, Turner et al. (1996); southwestern Tibet, Miller et al. (1999).

heavy REE distribution (Fig. 3A). Weak negative Eu anomalies are present in all samples. The large ion lithophile elements (LILE), in particular Rb and Ba, are significantly enriched relative to the high field strength elements (HFSE). The spidergrams show negative Nb, Ta, Ti, and positive K, Sr, Pb, and P anomalies. These patterns are similar to those for southwestern and northern Tibet. However, the enrichment of the LILE in the latter is much stronger than in the former. The lavas from northern Tibet also display relatively fractionated heavy REE patterns.

The Yunnan lavas have highly radiogenic $^{87}Sr/^{86}Sr$ (0.7064–0.7094) and unradiogenic $^{143}Nd/^{144}Nd$ ($\epsilon_{Nd} = -3.84$ to -4.64) ratios (Table 1; see footnote 1). Nd isotopic ratios are higher than those reported for the southwestern Tibetan lavas, but are similar to those for the northern Tibetan lavas. The Nd model ages relative to depleted mantle range from 1.1 to 1.4 Ga.

DISCUSSION

Constraints on Source Mineralogy

The Yunnan ultrapotassic lavas have undergone variable amounts of crystal fractionation. Plagioclase was not an important fractionated phase, given the negative correlation between MgO and Al_2O_3 (not shown) and the absence of plagioclase as phenocrysts in these lavas. Clinopyroxene and olivine were the main fractionated phases, as inferred from the correlations between MgO and CaO (Fig. 2C). Some olivine crystals in YBW-9 and YJX-29 have forsterite (Fo) contents as high as 0.927, and may be xenocrysts that were disaggregated from the mantle source. However, most Fo contents in the olivine phenocryst core vary between 0.87 and 0.89. The melts in equilibrium with these olivines would have MgO contents of ~14%. The high MgO characteristics of the parental magmas of the Yunnan lavas are also suggested by the samples (YH-5, 7, MgO = 12%–16%) that have no olivine phenocrysts. Therefore, many Yunnan lavas are near-primary melts.

The high K_2O content (>3%) in primitive rocks requires a potassic phase in the source region. Melts in equilibrium with phlogopite are expected to have significantly higher Rb/Sr and lower Ba/Rb values than those formed from amphibole-bearing sources (Furman and Graham, 1999). The Yunnan lavas show considerably higher Rb/Sr (>0.10) and lower Ba/Rb (<20) ratios, strongly suggesting that these lavas formed through melting of a phlogopite-bearing source (Fig. 3B). This is further supported by the positive correlation between La and La/K (Fig. 3C), which indicates that the bulk-rock partition coefficients for K (in the source) are higher than those for La (Feldstein and Lange, 1999). The rather uniform Ti and Fe contents in the Yunnan samples, regardless of their MgO contents, suggest buffering by Fe-Ti oxides in their source.

The flat heavy REE pattern in the Yunnan lavas is consistent with deviation from spinel facies mantle. This contrasts with a garnet facies source invoked for the lavas of northern Tibet (Turner et al., 1996). It follows that partial melting took place at a shallower level in Yunnan than in northern Tibet. Figure 3D shows that variable degrees (<1%) of partial melting of a hypothetical light REE–enriched mantle source ($[La/Yb]_n > 1$) in the spinel stability field can generate the La/Yb-Dy/Yb systematics of the ultrapotassic rocks from west Yunnan. The low Yb contents in the Yunnan lavas require a depleted mantle source. The calculation further shows that the Yb content in the source is ~10% of the primitive mantle value, which corresponds to the observed composition for harzburgites (McDonough and Frey, 1989). It is proposed that the Yunnan ultrapotassic rocks are melt products of metasomatized spinel facies harzburgites.

Subduction-Modified Mantle Beneath Western Yunnan

The presence of phlogopite in the absence of garnet constrains the source depth to <2.5 GPa (Edgar et al., 1976). Because the lithosphere thickness is ~100 km in this region (Yuan, 1989), this places the source of the Yunnan lavas within the lithospheric mantle. A lithospheric mantle source is also suggested by the high concentration of the LILEs and negative HFSE anomalies, chemical characteristics that appear to be lacking in the con-

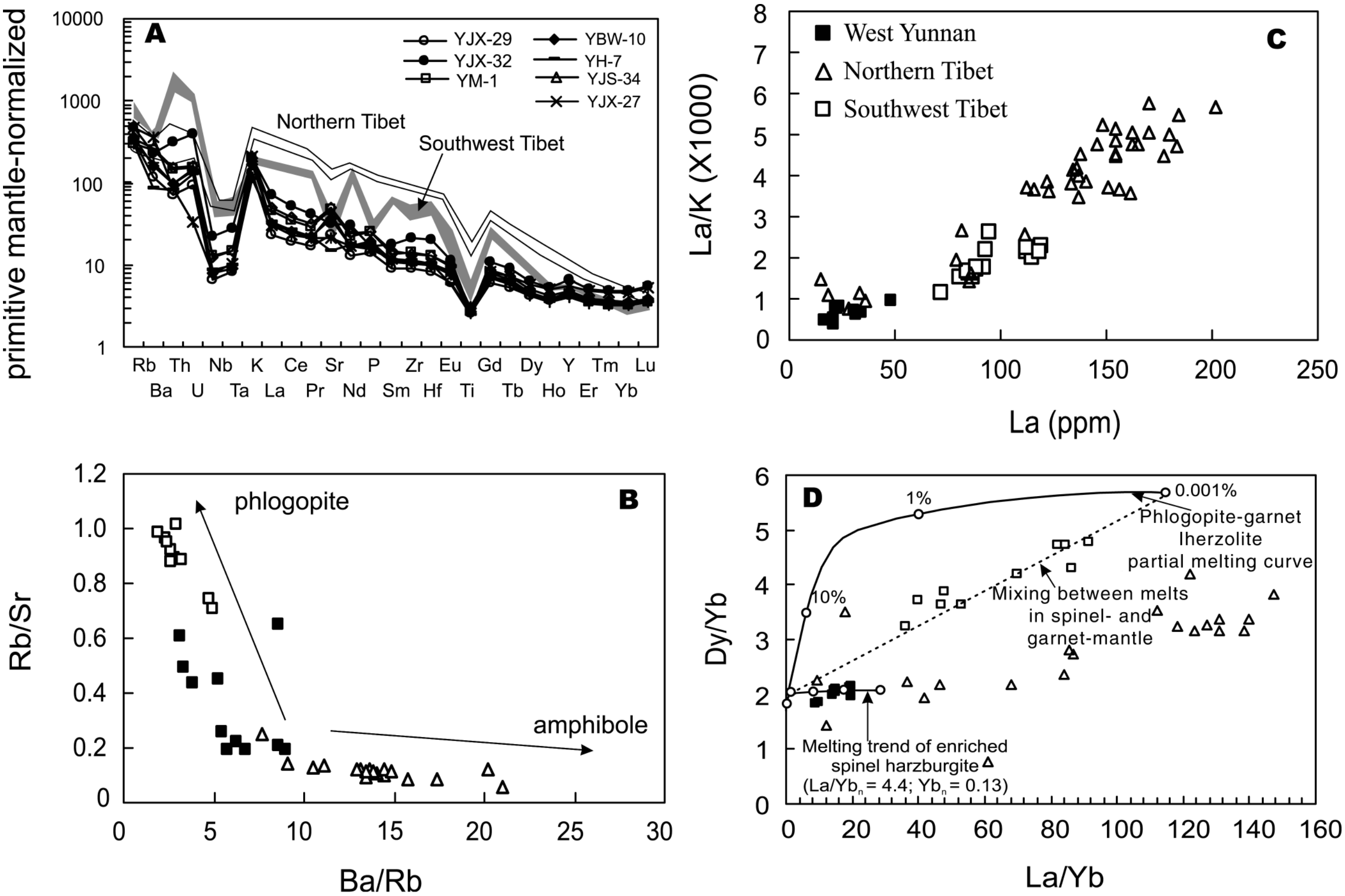

Figure 3. A: Primitive mantle-normalized trace element abundances for ultrapotassic rocks from west Yunnan. Normalizing values are from Sun and McDonough (1989). B: Rb/Sr vs. Ba/Rb. C: La/K vs. La. D: Variation of La/Yb and Dy/Yb for Yunnan ultrapotassic rocks. Melting model, mode, and partition coefficients are after Kinzler (1997). Source is phlogopite-bearing harzburgite with $(La/Yb)_n = 4.4$ and $Yb_n = 0.13$. Source mineralogy is 70% olivine, 23% orthopyroxene, 5% clinopyroxene, 2% spinel.

vective asthenosphere. However, the possibility remains that these chemical signatures resulted from crustal contamination during transport through the thick lithosphere. However, this is unlikely because the Yunnan samples do not adhere to mixing trends between asthenosphere and crust, and the high concentration of incompatible elements in these magmas makes their chemistry insensitive to crustal contamination.

The Nb/U (1.8–8.3) and Ce/Pb (0.6–4.7) ratios for the Yunnan samples are significantly lower than in mid-ocean ridge basalt and ocean island basalt (47 and 27, respectively, Hofmann et al., 1986), indicating the involvement of crustal components in their source region. The depletion of HFSEs relative to neighboring elements is considered to be indicative of subduction processes. We thus propose that the source region has been affected by slab-released fluids, a suggestion supported by a weak negative Eu anomaly unrelated to plagioclase fractionation.

Exotic Origin of the Lithosphere Mantle Beneath the Western Yangtze Craton

The mantle source of the ultrapotassic lavas from west Yunnan shows isotopic affinity with that beneath Tibet. However, for most of their geological history, the Yangtze craton and Tibetan terrane were separate entities, and were brought together during the Mesozoic (Yin and Nie, 1996). It is important to understand the temporal evolution of the lithosphere prior to their tectonic juxtaposition. This is not possible for Tibet, and we must infer the characteristics of the lower lithosphere from the potassic rocks. However, in the western Yangtze craton there is evidence that the lower lithosphere may be very different from that inferred from the ultrapotassic rocks. Continental flood volcanism occurred during the Permian-Triassic (Fig. 1; Chung et al., 1998b), and the thermo-tectonic processes associated with the generation and transfer of huge volumes of tholeiitic melt over a few million years would have affected the lithospheric mantle beneath the Yangtze craton. The processes that produced the Emeishan basalt province would have purged the lithospheric mantle of all its fusible constituents (Gallagher and Hawkesworth, 1992), so that evidence of older processes would have been largely obliterated. One can infer that since that time the lithospheric mantle may have been affected by melt-enrichment processes, so that model Sm-Nd ages would be younger than 250 Ma. However, Nd model ages suggest a Proterozoic source for the Oligocene ultrapotassic lavas (Table 1; see footnote 1). The lithosphere beneath the western Yangtze craton is therefore not what one would expect. This requires emplacement of the Proterozoic enriched mantle sources in post-Triassic time. Such tectonic forces were most likely associated with the Indo-Eurasia collision ca. 55 Ma, when exotic Tibetan lithosphere could have been extruded eastward under the Yangtze craton.

However, one could argue that the Nd model ages may simply reflect the antiquity of the subducted component and imply nothing about the timing of metasomatism, especially when sediments were added to source region. For example, enriched isotopic compositions of the potassic lavas could be explained by a Mesozoic (sediment) subduction that metasomatized the harzburgite mantle source. Such a refractory mantle protolith could have resulted from large degrees of melting caused by the Emeishan flood-basalt magmatism. However, this model fails to explain the common mantle source across the Ailao Shan–Red River fault. Distribution of Emeishan basalts is limited to the Yangtze craton (Fig. 1), thus the refractory mantle outside of the craton (i.e., Madeng) cannot adequately be accounted for by plume activity. Neogene basalts in the southwestern Yangtze craton (Maguan, Pingbian; Fig. 1) show a depleted mantle signature (Sun, 2000). This cannot easily be reconciled with a Mesozoic subduction of the Tethyan plate beneath the craton. Moreover, the positive correlation between ϵ_{Nd} and Sm/Nd, expected for a recent mixing event, is not observed for the Yunnan samples. We thus suggest that the enriched Sr-Nd isotopic compositions of the Yunnan lavas reflect the time-integrated effect of enrichment in the light REE and Rb relative to Sr.

The exotic lithosphere model is supported by the similar seismic velocity structure of the lithosphere in both Tibet and the western Yangtze craton (Yuan, 1989), which is very different from that farther east in the Yangtze craton. Geophysical data suggest that the exotic lithosphere may compose the lower crust and the upper mantle. The detachment of the Tibetan lithosphere from its upper counterpart may have occurred along the low-velocity zone in the lower crust. To the east, this exotic lithosphere may be beneath Yanbian (Fig. 1), because ultrapotassic rocks of similar composition and age have been documented in that area (Zhang, 1988). The southward extrusion of the Tibetan lithosphere is limited, given the depleted mantle beneath the southwestern Yangtze craton. Thus, the exotic lithosphere model conveniently explains the spatial heterogeneity of mantle sources beneath the western Yangtze craton and the Sr-Nd isotope provenance link between the Yunnan and northern Tibetan lavas.

What Triggered the Melting of the Lithosphere Mantle Beneath Western Yunnan?

The eruption of potassic magmas in the Tibetan Plateau was considered to be a response to convective thinning of the lithosphere (Turner et al., 1996), which triggered a temperature increase in the lithosphere and surface uplift. This model was adopted by Chung et al. (1998b) in an interpretation of the generation of potassic lavas from western Yunnan. However, it is still unclear why convective removal should be a two-stage process. In addition, the need for early removal, particularly in west Yunnan, is not clear, given the fact that it is distal to the collision zone and does not have the same altitude at the Tibetan Plateau. The exotic lithosphere model offers an efficient way to thin the lithosphere. Seismic data show that the depth to the low-velocity zone in the mantle is greater in Tibet than in west Yunnan (Yuan, 1989). It is proposed that during eastward extrusion the Tibetan lithosphere was mechanically thinned along low-velocity zones, where the presence of melt may have preferentially weakened the lithosphere. Moreover, in western Yunnan, the potassic lavas are spatially associated with picrite dikes for which geologic relationships suggest an early Tertiary intrusion age. Picrites are generally considered as melting products of mantle plumes (Campbell and Griffiths, 1990). Melting of the enriched lithosphere mantle in western Yunnan was probably induced by the combined effect of mechanical lithospheric thinning and thermal perturbation associated with anomalously hot mantle.

ACKNOWLEDGMENTS

We thank S.L. Sha for help in the field, R. Coyne, L. Whitaker, and Y. Liu for technical assistance with analyses, and S. Turner and S.-L. Chung for constructive reviews. This study is jointly supported by the Natural Science Foundation of China (grant 49925308), the Chinese Academy of Sciences (KZCX2-101, KZCX2-209), and the Royal Society of London.

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Manuscript received December 11, 2000
Revised manuscript received May 7, 2001
Manuscript accepted May 21, 2001

Printed in USA