Potassic-ultrapotassic mafic rocks delineate two lithospheric mantle blocks beneath the southern Peruvian Altiplano

G. Carlier* IRD, UR X199, 213, rue la Fayette, 75480 Paris, France, and Centre National de la Recherche Scientifique, UMR 7160 (Minéralogie-Pétrologie) and MNHN, USM 201, 61, rue Buffon, 75005 Paris, France
J.P. Lorand Centre National de la Recherche Scientifique, UMR 7160 (Minéralogie-Pétrologie) and Muséum National d'Histoire Naturelle, USM 201, 61, rue Buffon, 75005 Paris, France
J.P. Liégeois Isotope Geology, Musée Royal de l'Afrique Centrale, B-3080 Tervuren, Belgium
M. Fornari l'Institut de Recherche pour le Développement, UMR 6526 Géosciences Azur, Université de Nice-Sophia Antipolis, Parc Valrose, 06108 Nice cedex 02, France
P. Soler Laboratoire d'Océanographie Dynamique et de Climatologie, UMR 7617 CNRS/IRD/UPMC/MNHN, Mision en el Peru, La Mariscala 115, San Isidro, Lima 18, Peru
V. Carlotto INGEMMET, Avenida Canada 1470, San Borja, Lima 41, Peru
J. Cárdenas Universidad Nacional San Antonio Abad del Cusco, Avenida de la Cultura, Cusco, Peru

ABSTRACT

The Altiplano of southern Peru displays a large spectrum of Cenozoic potassic (K) and ultrapotassic (UK) mafic rocks that delineate two deep lithospheric mantle blocks that have undergone different depletion and enrichment events. Phlogopite lamproites indicate that the eastern Altiplano block is underlain by a metasomatized harzburgitic mantle of Paleoproterozoic to Archean age (depleted mantle age, T_{DM} = 1130–2485 Ma; ε_{Nd} = −5.0 to −11.4; $^{87}Sr/^{86}Sr_i$ = 0.7100–0.7159). Beneath the western Altiplano block, the presence of a younger (T_{DM} = 837–1259 Ma; ε_{Nd} = +0.6 to −6.3; $^{87}Sr/^{86}Sr_i$ = 0.7048–0.7069) metasomatized lherzolitic mantle is deduced from multiple occurrences of diopside-rich K-UK lavas (leucitites, leucite-bearing tephrites, olivine, and diopside trachybasalts). A third suite of young (<2 Ma) K-UK rocks outlines the active Cusco Vilcanota fault system separating the western and eastern Altiplano blocks; this third suite, composed of diopside-phlogopite lamproites and augite kersantites, minettes, and trachybasalts, sampled a composite mantle source that probably included an asthenospheric component (T_{DM} = 612–864 Ma; ε_{Nd} = −1.1 to −3.5; $^{87}Sr/^{86}Sr_i$ = 0.7051–0.7062), in addition to lithospheric components inherited from the eastern and western Altiplano blocks. The spatial distribution of the south Peruvian K-UK magmatism suggests that K-UK melts reached the surface through reuse of older translithospheric weakness zones extending at least to the depth of magma generation. These latter were reactivated by a dextral transpressional regime imposed on the two rigid lithospheric blocks by the Andean orogen.

Keywords: Altiplano, Peru, potassic-ultrapotassic rocks, lithospheric mantle.

INTRODUCTION

Although mafic potassic (K) and ultrapotassic (UK) rocks are, by volume, a small group, they are of great interest because their very high concentrations of incompatible trace elements are products of enrichment processes that affect the subcontinental lithospheric mantle beneath cratonic and circum-cratonic areas (McKenzie and Bickle, 1988). Current petrogenetic models suggest that K-UK magmas are the earliest melts to be generated when the metasomatized lithospheric mantle beneath these areas undergoes heating and extension (Gibson et al., 1995; Peccerillo, 1999). Thus, K-UK magmas can provide information on the composition and geometry of discrete lithospheric mantle domains where surface exposures of mantle rocks or mantle xenoliths are lacking.

In southern Peru, Cenozoic K-UK rocks are common within the Inner Arc domain of the Andean orogen (Sandeman et al., 1995, 1997; Carlier et al., 1997; Carlier and Lorand, 1997, 2003; Sandeman and Clark, 2004). These are small (≤50 km^2) monogenic stocks, plugs, necks, dikes, or volcanoes, all closely associated with calc-alkaline felsic and shoshonitic volcanic and intrusive rocks. K-UK rocks and associated calc-alkaline and shoshonitic intrusions occur in three tectonic settings (Fig. 1): along the still-active, NW-trending Cusco Vilcanota fault system, which separates the Peruvian Altiplano into two structural blocks, the western and eastern Altiplano; along NNW-trending magmatic lineaments within the eastern Altiplano; and along WNW-trending magmatic lineaments within the western Altiplano.

This paper presents major and trace element data for 33 south Peruvian K-UK rock samples (including 27 new analyses; Data Repository Table 1)[1] reported along with key mineralogical features, a compilation of radiometric ages (including seven new data; Table 2 [see footnote 1]), and new Sr-Nd isotopic compositions for 20 samples (Table 3; see footnote 1). Evolved rocks (MgO < 4 wt%) containing plagioclase or K-feldspar phenocrysts that indicate extensive fractional crystallization and minette samples that assimilated crustal materials and/or mixed with peraluminous granites were not included in the present database because these petrogenetic processes may have obscured mantle source characteristics (Carlier et al., 1997; Sandeman and Clark, 2004). Geochemical data, coupled with petrographic observations, suggest that at least two lithospheric blocks of different age and composition exist beneath the south Peruvian Altiplano; that K and UK magmas obey general tectonic controls on a regional scale; and that pre-Andean structures were reactivated during Cenozoic time.

PETROGRAPHY AND GEOCHEMICAL DATA

In the eastern Altiplano, K-UK rocks are early Miocene (25–23 Ma) sanidine- and orthopyroxene-phlogopite lamproites, and late Miocene (7.5 Ma) olivine minettes (Table 2; see footnote 1). Liquidus minerals are Ti- and Al-poor fluorophlogopite in sanidine-phlogopite lamproites and olivine minettes, and enstatite and augite in orthopyroxene-phlogopite lamproites (Carlier et al., 1997; Carlier and Lorand, 2003). Sanidine- and orthopyroxene-phlogopite lamproites are ultrapotassic (K_2O/Na_2O > 2), CaO poor (<4 wt%), and enriched in compatible transition elements (115–364 ppm Ni, 0.57 < Mg# < 0.73) (Fig. 2). Olivine minettes differ by having slightly higher CaO contents (5.5 wt%) and much lower K_2O/Na_2O (0.8), likely re-

*Present address: Laboratoire de Minéralogie, USM 201, MNHN, CP 52, 61, rue Buffon, 75005 Paris, France; e-mail: gabi@mnhn.fr.

[1]GSA Data Repository item 2005116, Tables 1–3, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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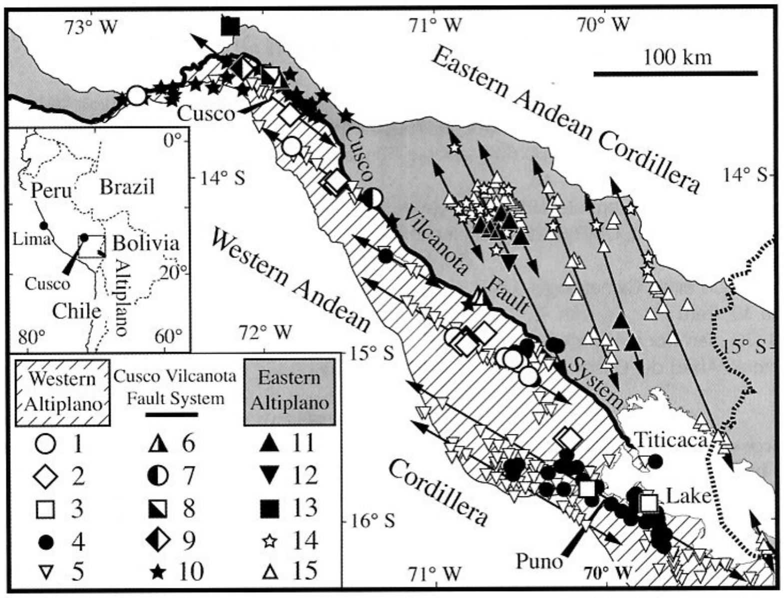

Figure 1. Structural sketch map and location of potassic-ultra potassic (K-UK), calc-alkaline, and shoshonitic magmatic intrusions in southern Peruvian Altiplano (rock nomenclatures after Woolley et al., 1996). 1—leucitites, leucite-bearing tephrites, phonotephrites, tephriphonolites, trachytes, theralites; 2—diopside trachybasalts; 3—olivine trachybasalts; 4—shoshonite suites; 5—metaluminous felsic intrusions; 6—diopside-sanidine-phlogopite lamproites; 7—augite kersantites; 8—augite minettes; 9—augite trachybasalts; 10—high-K calc-alkaline and shoshonitic suites; 11—sanidine-phlogopite lamproites; 12—orthopyroxene-phlogopite lamproites; 13—olivine minettes; 14—orthopyroxene minettes and shoshonites; 15—peraluminous felsic intrusions. 14 and 15 are after Carlier et al. (1997), Sandeman et al. (1997), Carlier and Lorand (2003), Sandeman and Clark (2004), and unpublished data. Straight lines indicate main magmatic lineaments.

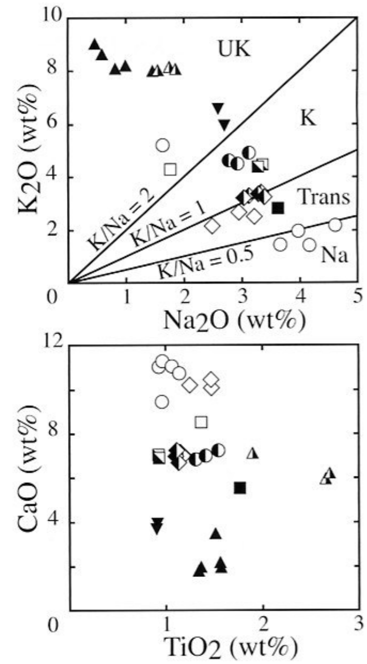

Figure 2. K_2O vs. Na_2O and CaO vs. TiO_2 plots discriminating different potassic (K) and ultrapotassic (UK) rocks of southern Peruvian Altiplano. (Symbols as in Figure 1.) Note that low K_2O/N_2O (<0.4) ratios of leucitites and leucite-bearing tephrites are ascribed to general analcitization affecting leucite and glass, feature commonly observed in this rock type (i.e., Gibson et al., 1995; Cvetkovic et al., 2004).

flecting the strong hydrothermal alteration of the rocks. Both lamproites and minettes display similar incompatible trace element patterns characterized by very high large ion lithophile element (LILE) contents ($Ba_{PM} \leq 1200$; $U_{PM} \leq 1000$; the subscript PM indicates primitive mantle normalized), a huge positive Pb anomaly (Pb_{PM}/Ce_{PM} = 2.3–10.9), strong light rare earth element (LREE) enrichment (La_{PM} = 107–153; La_{PM}/Yb_{PM} = 21–30), and a marked negative Nb-Ta anomaly ($Nb_{PM}/La_{PM} < 0.4$) without a corresponding negative Zr-Hf anomaly (Zr_{PM}/Sm_{PM} = 0.9–1.3; Fig. 3). Such ratios are diagnostic geochemical features of K-UK melts erupted in convergent margins with active subduction (i.e., Peccerillo, 1999; Conticelli et al., 2002; Cvetkovic et al., 2004) or of the remelting of such a source. Sr-Nd isotopic data define a trend toward an Rb-enriched reservoir (ε_{Nd} = −8.5 to −11.4; $^{87}Sr/^{86}Sr_i$ = 0.7103–0.7159) in an $^{87}Sr/^{86}Sr_i$ vs. ε_{Nd} diagram (Fig. 4A). All eastern Altiplano K-UK rocks yield old T_{DM} (depleted mantle) model ages, ranging from 1130 to 2485 Ma (Fig. 4B).

In the western Altiplano, K-UK magmas erupted during the Oligocene (28–30 Ma), producing leucitites, leucite-bearing tephrites, theralites, and diopside trachybasalts, and, during the late Miocene (5–6 Ma), rare olivine trachybasalts (Table 2; see footnote 1). The liquidus (or near-liquidus) mineral is an Al (1–5 wt%) and Fe^{3+} (2–5.wt%) rich diopside that typically coexists with titanomagnetite. Compared with the eastern Altiplano K-UK rocks, their bulk-rock compositions are characterized by higher CaO contents (8.5–11.7 wt%) for similar TiO_2 (0.9–1.5 wt%) and Al_2O_3 contents (11.5–16 wt%) (Fig. 2). Other differences with eastern Altiplano K-UK bulk-rock analyses include lower compatible transition element contents (except one olivine trachybasalt with 247 ppm Ni and 610 ppm Cr) and, on average, lower incompatible trace element contents ($Ba_{PM} < 300$; Th_{PM} = 30–100; La_{PM} = 27–165; La_{PM}/Yb_{PM} = 6–40). Primitive mantle–normalized patterns display some features of subduction-related K-UK lavas (positive Ba, Sr, Pb anomalies coupled with strong Nb, Ta, and very slight Zr, Hf negative anomalies; Fig. 3). Isotopic compositions plot within the enriched domain of the mantle array; i.e., they are $^{87}Sr/^{86}Sr$ enriched relative to the bulk silicate earth, although much less so than those of the eastern Altiplano samples (Fig. 4A). Likewise, T_{DM} model ages (837–1241 Ma) for the western Altiplano samples are significantly younger than those of the eastern Altiplano (Fig. 4B).

The K-UK rocks that occur proximal to the Cusco-Vilcanota fault system are Quaternary (0–2 Ma) in age (Table 3; see footnote 1). These are diopside-sanidine-phlogopite lamproites (Carlier and Lorand, 1997), augite minettes, kersantites, and trachybasalts (Fig. 1). The liquidus mineral in diopside-sanidine-phlogopite lamproites is an Al- and Ti-poor diopside. Their whole-rock major element compositions are characterized by $K_2O/Na_2O > 5$, high TiO_2 (1.9–2.7 wt%), and low Al_2O_3 (<12.8 wt%) contents (Fig. 2). The other rocks (kersantites, minettes, trachybasalts) display Ti-poor and Al-rich augite as liquidus mineral. Their major element compositions are characterized by $K_2O/Na_2O < 2$ and intermediate CaO (6–8.5 wt%) contents for similar TiO_2 and Al_2O_3 concentration ranges compared with the potassic mafic rocks from the eastern Altiplano and western Altiplano (Fig. 2). Diopside-sanidine-phlogopite lamproites have low Ni (<100 ppm) and Mg# (<0.57), similar to western Altiplano K-UK rocks, whereas the other potassic mafic rocks

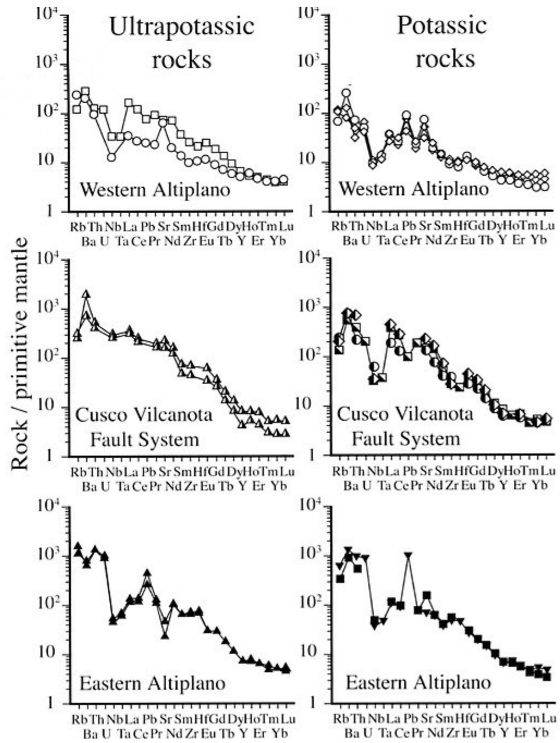

Figure 3. Incompatible element abundances normalized to primitive mantle values. Normalizing values after McDonough and Sun (1995). Symbols as in Figure 1.

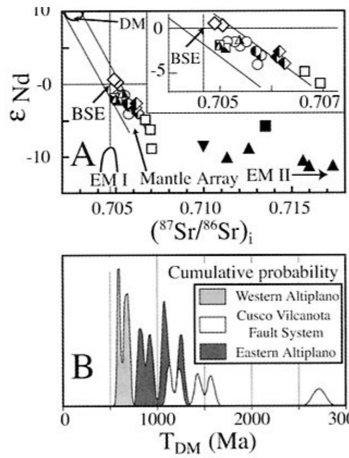

Figure 4. A: ε_{Nd} vs. $^{87}Sr/^{86}Sr_i$ plot for K (potassic) and UK (ultrapotassic) Peruvian rocks. DM—depleted mantle; BSE—bulk silicate earth; EM I and EM II—type I and type II enriched mantle. B: Cumulative probability of T_{DM} model ages of three domains. Curves were calculated by Isoplot software (Ludwig, 1999). Symbols as in Figure 1.

have Ni contents and Mg# comparable to eastern Altiplano phlogopite lamproites. However, all are strongly enriched in LILE, with similar concentrations of Ba_{PM} (1000–2000), higher LREE (La_{PM} = 165–449; La_{PM}/Yb_{PM} = 37–110), and lower Rb, Th, and U contents than the eastern Altiplano K-UK rocks (Table 1; see footnote 1). The primitive mantle–normalized patterns for diopside-sanidine-phlogopite lamproites display strong positive Ba anomalies, but lack negative high field strength element (HFSE) anomalies ($Nb_{PM}/La_{PM} > 0.8$; $Zr_{PM}/Sm_{PM} > 0.9$). In contrast, the patterns for kersantites, minettes, and trachybasalts display such anomalies (Fig. 3). Isotopic ratios, although more homogeneous (ε_{Nd} = −1.1 to −3.2, $^{87}Sr/^{86}Sr_i$ = 0.7052–0.7062), are similar to those of the Western Altiplano samples and plot within the $^{87}Sr/^{86}Sr$-enriched domain of the mantle array (Fig. 4A). The K-UK rocks that occur proximal to the Cusco-Vilcanota fault system yield even younger T_{DM} model ages (612–864 Ma) compared with both eastern Altiplano and western Altiplano samples (Fig. 4B).

DISCUSSION

High ($^{87}Sr/^{86}Sr)_i$ and low ε_{Nd}, coupled with high to extreme enrichment in incompatible trace elements and high La/Yb ratios relative to primitive mantle, are characteristic features of magmas dominated by melts from the enriched subcontinental lithospheric mantle (e.g., Gibson et al., 1995). The regional compositional variability of the Altiplano K-UK rocks cannot be accounted for by different degrees of contamination of these melts by the continental crust because contaminated samples were not included herein, and because the low silica and very enriched incompatible element contents would have been erased by a crustal input. Likewise, the lack of consistent covariation trends between major elements (e.g., Ca), highly incompatible trace elements (e.g., Th, La/Yb), and radiogenic isotopes exclude any model that would explain the regional space and time variability of the Altiplano K-UK rocks in terms of differing degrees of partial melting of a unique and homogeneous mantle source.

Modern petrogenetic models involve two-stage processes in the mantle source of mafic K-UK melts: first, long-term major element depletion by melt removal, and second, younger metasomatic enrichments in LILE and other incompatible trace elements (McKenzie and Bickle, 1988; Peccerillo, 1999). Because they display the same characteristic petrogenetic features through time within each domain of the Altiplano, the south Peruvian K-UK rocks are likely to have originated in two compositionally distinct lithospheric mantle domains that have different metasomatic histories. Moreover, significant differences in $^{87}Sr/^{86}Sr_i$ and ε_{Nd} between K-UK rocks of the eastern Altiplano and western Altiplano indicate that the two mantle sources evolved separately for a long time.

In the eastern Altiplano, phlogopite lamproites crystallized from silica-saturated Ca- and Al-poor reduced melts derived from carbon-bearing phlogopite-rich harzburgitic mantle (Carlier et al., 1997; Carlier and Lorand, 2003, and references therein). An important contribution of orthopyroxene in the melting assemblage is necessary to explain their high Si content; the presence of olivine accounts for their high Mg#s and high compatible transition element contents. Harzburgitic lithologies characterize cratonic to pericratonic mantle (Poudjom Djomani et al., 2001), an observation supported by the old T_{DM} model ages of eastern Altiplano K-UK rocks (1130–2485 Ma, Fig. 4B). Their Nd-Sr isotopic signature requires an old ^{143}Nd depletion, followed by Rb enrichment (Proterozoic or older in age). This enrichment can be related to metasomatism having precipitated Ti-rich oxides in the lithospheric mantle source of eastern Altiplano K-UK rocks, as indicated by their trace element signatures. In addition, variable contributions from a volumetrically minor asthenospheric component having a depleted mantle signature are needed to account for the wide spectrum of eastern Altiplano K-UK rocks in Figure 4A.

A more oxidized, clinopyroxene-rich mantle source is necessary to account for the Ca-rich western Altiplano K-UK rocks that systematically precipitated Fe^{3+}-rich clinopyroxene and Ti-magnetite. Derivation from wherlitic sources with contribution of clinopyroxene in the melting assemblage would account for the low

Mg#, low compatible transition element contents, and moderate LREE enrichment (La/Yb_{PM} = 6–40) of these rocks. Their strong Nb-Ta and slight Zr-Hf troughs also argue for residual Ti-rich oxides and clinopyroxene in the mantle source, as well as a significant contribution of phlogopite in the melting assemblage to account for the positive Ba anomalies. Collectively, these features suggest a more fertile mantle lithosphere beneath the western Altiplano, probably Late Proterozoic in age, as indicated by the less-enriched Sr and depleted Nd isotopic compositions and T_{DM} model ages of western Altiplano K-UK rocks (837–1259 Ma, Fig. 4B). As for the eastern Altiplano, the contribution of an asthenospheric component having a depleted mantle signature can explain the western Altiplano K-UK rock spectrum shown in Figure 4A (inset).

Pliocene–Quaternary K-UK rocks exposed along the Cusco Vilcanota fault system clearly show features intermediate between eastern Altiplano and western Altiplano K-UK rocks, such as clinopyroxene as liquidus phase and Fe^{3+}-rich mineral assemblages; intermediate CaO contents and CaO/Al_2O_3 ratios; and very high incompatible trace element contents. Such intermediate features are interpreted as a consequence of melts generated at the boundary between two blocks of different lithospheric mantle. Melting of mica + clinopyroxene ± apatite ± K-richterite veins seems to be the most appropriate interpretation for the origin of diopside-sanidine-phlogopite lamproites, combining low Mg#, low compatible transition element contents, and very high LILE contents (Carlier and Lorand, 1997). Conversely, a more significant contribution of olivine or orthopyroxene to the melting assemblage would explain the potassic rocks. The large variations of HFSE contents between K and UK rocks can be ascribed to the behavior of Ti-rich oxides + clinopyroxene during melting coupled with mantle source anomalies caused by pervasive infiltration metasomatism of volatile-rich, small-volume melts. Such noneutectic melts solidify over a large depth interval (McKenzie and Bickle, 1988), and can fractionate LILE from HFSE by means of chromatographic processes (Bedini et al., 1997). The homogeneous Sr-Nd isotopic compositions of Cusco-Vilcanota fault system K-UK rocks support the hypothesis of pervasive infiltration metasomatism of their mantle sources by low-viscosity melts. Younger T_{DM} model ages and the absence of Nb-Ta negative anomaly in these rocks are attributed to a greater participation of the asthenospheric mantle, which is probably shallower under the Cusco Vilcanota fault system.

CONCLUSIONS

The identification of two distinct lithospheric blocks beneath the southern Peruvian Altiplano lends further support to the hypothesis that a collage of terranes of various origins amalgamated beneath the eastern Andean Cordillera before the ongoing Andean orogeny. The craton-like stratigraphy beneath the eastern Altiplano is likely to be related to a thick and cold mantle structure, identified by geophysical data down to 140 km (Dorbath et al., 1993). The widespread K-UK magmatism indicates reactivation of both lithospheric blocks during Cenozoic time. The low-velocity zone beneath the ~70-km-thick crust of the Altiplano is currently interpreted as a relatively hot asthenospheric mantle upwelling (Dorbath et al., 1993; Sandeman et al., 1995; James and Sacks, 1999). In addition to obvious relationships with the abundance of K-UK melts, such a regional thermal anomaly likely reactivated the middle crust between 26 Ma and 5 Ma, thus producing the voluminous peraluminous granites and shoshonitic suites of the Altiplano (see also Sandeman et al., 1995, 1997; Sandeman and Clark, 2004).

K-UK melts discussed herein, including the eastern Altiplano lamproitic melts, formed at shallow depths (<100 km; Carlier et al., 1997; Carlier and Lorand, 1997, 2003). The spatial distribution of these melts in well-defined magmatic lineaments suggests that older lithospheric weakness zones controlled mantle melting by focusing thermal inputs and fluid ingress in both Altiplano lithospheric blocks. Parental melts then periodically reached the surface through reusing these older lithospheric weakness zones, which acted as transtensional areas in the dextral transpressional regime imposed on the two rigid lithospheric blocks by the Andean convergence.

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