

MAFIC LAVAS ON THE PUNA PLATEAU SAMPLE THE DIVERSE LITHOSPHERIC
ARCHITECTURE OF THE LONG-LIVED ANDEAN OROGEN

by

Kendra E. Murray

A Prepublication Manuscript Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

In the Graduate College
THE UNIVERSITY OF ARIZONA
2010

Abstract

Mafic lavas erupted on the Puna plateau are the best available geochemical window into the history of the upper mantle in the southern central Andes, where long-lived (>200 Myr) subduction, arc magmatism, retroarc thrusting, plateau formation, and rifting have both shaped and responded to changes in the composition and volume of the lithosphere. Here, we present whole-rock elemental and Nd-Sr-Pb isotopic analyses for a suite of late Cenozoic primitive lavas from this region. While our isotopic data suggest a mantle end-member ($\epsilon_{\text{Nd}} = 0$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$) isotopically primitive relative to the Neogene central Andean arc, there is no direct evidence of the involvement of MORB-like depleted mantle. Barring cryptic crustal contamination, the wide range of Nd and Sr isotopic values in the most primitive lavas in this suite ($\text{Mg}\# > 60$) define a Puna “mantle array” that is an isotopically heterogeneous source region. The dominance of an old, enriched lithospheric signature is consistent with mantle melt generation in the lower part of the lithosphere, perhaps driven by small lithospheric foundering events.

1. Introduction

Mafic lavas recently erupted on Puna plateau (Fig. 1) have advanced our understanding of magmatic processes and the nature of the upper mantle in the central Andes (18°S - 28°S), where the continental crust dominates the elemental and isotopic signatures observed in Neogene to Recent frontal arc volcanism [i.e. *Davidson, et al.*, 1991]. In the ongoing discussion of the central Andean lithospheric architecture and arc petrogenesis [*Beck, et al.*, 1996; *Davidson, et al.*, 1991; *de Silva*, 1989; *Francis and Hawkesworth*, 1994; *Haschke, et al.*, 2006; *Hildreth and Moorbath*, 1988; *Lucassen, et al.*, 2007; *Mamani, et al.*, 2008; *Rogers and Hawkesworth*, 1989; *Thorpe, et al.*, 1984], these primitive (Mg# >60) volcanics provide the best window into the geochemistry of the central Andean upper mantle and how it has changed in response to postulated lower lithospheric foundering [i.e. delamination *Kay and Kay*, 1993], retro-arc thrusting and crustal thickening [*DeCelles, et al.*, 2009; *Haschke, et al.*, 2006], and batholith production [*de Silva and Gosnold*, 2007; *Ducea*, 2001].

Puna mafic lavas are referred to in the literature as likely products of “delamination magmatism” [*Kay and Kay*, 1993], i.e. mantle melts generated during convective removal of lower cordilleran lithosphere. Foundering of dense lithosphere into less dense asthenosphere has been invoked to explain “missing” lower crustal residue in regions subject to significant crustal shortening and/or batholith-producing magmatism [*DeCelles, et al.*, 2009, and references therein]. Geochemical and geophysical observations in the central Andes since the early 1990s [*Beck and Zandt*, 2002; *Kay, et al.*, 1994; *Yuan, et al.*, 2002] have suggested that lithospheric removal is inevitable in Cordilleran arcs; indeed, in other Cordilleran arc systems such as the Sierra Nevada it is impossible to account for the current lithospheric column of felsic material

without invoking a loss of significant mass of residual material into the mantle [Ducea, 2001]. Despite these observations, if delamination is an important mechanism here little is understood about the style(s) and scales of lithospheric removal that could exert control over the observable signal of foundering events.

Here, we present elemental and Sr-Nd-Pb isotopic data for a new suite of mafic lavas from the Puna plateau, which allow us to (1) expand the spatial coverage of this dataset in the central Andes, (2) contribute to the effort to parse contributions from the subcontinental lithosphere, asthenosphere, subduction-related fluids and sediments, and upper crustal sources and (3) examine these lavas in the context of other volcanic products from the broad Neogene volcanic arc of the central Andes. In particular, we aim to examine the mantle material contributing to the source compositions of these lavas, in order to evaluate hypotheses concerning the scale(s) of proposed lower lithospheric removal in the region and the possible role of this process in Andean Cordilleran evolution.

2. Geologic Setting

2.1 The Central Andes

The central Andean Cordillera preserves a >150 Ma record of arc magmatism, during which variations in the location and geochemistry of the arc occurred at 10^5 to 10^8 Myr time scales [DeCelles, *et al.*, 2009; Haschke, *et al.*, 2006]. Since the Early Jurassic, the axis of the Andean arc has migrated east [Haschke, *et al.*, 2006; Lucassen, *et al.*, 2006]. Intriguing compilations of geochemical data from Jurassic to Recent arc magmatism [Haschke, *et al.*, 2006; Haschke, *et al.*, 2002] suggest a periodicity in heightened magmatic activity and increasing crustal thickness over 20-40 myr time intervals, terminated by 5-15 Myr periods of relative

magmatic quiescence. To explain these trends, Haschke and colleagues suggest a model of repeated episodes of slab shallowing and break-off [Haschke, *et al.*, 2006]. Recently, Ramos [2009] expanded this slab control model to include the dynamics of other processes in the cordillera, including the plateau formation, crustal thickening, and fold and thrust belt propagation. Alternatively, DeCelles *et al.* [2009] proposed that these trends reflect a larger, predictable cordilleran cyclicality controlled by the geometry of the overriding South American lithosphere, which changes as the feedback between retroarc thrusting, melt production, and delamination operate independently of and in response to secular changes in the subducting slab dip. The Neogene volcanic record provides the opportunity to study the most recent flare-up in magmatic activity, and in particular to examine the evolution of the cordilleran lithospheric column in context of these overarching hypotheses about convergent margin evolution.

2.2 Volcanism on the Puna Plateau

The Puna plateau (Fig. 1b) consists of a series of internally drained basins bounded by Paleozoic plutonic and metasedimentary rocks [Allmendinger, *et al.*, 1997], through which Neogene volcanics erupted. The Puna plateau is higher in mean elevation and more structurally dissected than its northern continuation in Bolivia and Peru, the Altiplano [Whitman, *et al.*, 1996]. Recent central Andean volcanics can be divided into three main categories: (1) andesitic-dacitic stratovolcanoes along the modern arc front in the Western Cordillera (Fig. 1a), of which 44 are active today [Francis and Hawkesworth, 1994], (2) intermediate to silicic ignimbrite flows erupted from large-volume ($>1000 \text{ km}^3$) caldera-forming eruptions, including the Altiplano-Puna Volcanic Complex [APVC, de Silva, 1989, Fig. 1a], and (3) low volume, relatively primitive lavas erupted east of the modern stratovolcanoes on both the Altiplano and

Puna plateaus (Fig. 1b). In addition to the small volume primitive flows on the Puna, which are the focus of this study, a variety of mid- to late Neogene volcanic centers are located in this region of the south central Andes, including volcanism developed along NW-SE trending lineaments [Matteini, *et al.*, 2002], the volcanic center at Cerro Tuzgle in the northern Puna [Coira and Kay, 1993], the Cerro Galan caldera complex (Fig. 1b) [Francis, *et al.*, 1989], and other silicic ignimbrites [Schnurr, *et al.*, 2007b]. Hypothesized Andean lithospheric foundering events are a possible mechanism for driving much of the large-scale crustal melting in the region [de Silva, *et al.*, 2006; Schnurr, *et al.*, 2007b].

Puna mafic flows [Déruelle, 1991; Knox, *et al.*, 1989; Thorpe, *et al.*, 1984, and references therein] are valuable targets for understanding the composition [Francis, *et al.*, 1989] and evolution [Kay, *et al.*, 1994] of the upper mantle beneath the region. Where dated, small-volume fissure flows and cinder cones on the Puna plateau are late Miocene to Pleistocene or younger in age (7.3 to <0.3 Ma), and appear to have peaked in activity in the early Pliocene [Risse, *et al.*, 2008]. The low volume flows and cones are associated with strike-slip and extensional faults [Kay, *et al.*, 1994]. Kay *et al.* (1994) used regional variability in major, trace element, and isotopic data from a suite of Puna mafic lavas to suggest that they are the products of a late Pliocene delamination of the lower lithosphere centered at the latitude of Cerro Galan. Like the stratovolcanoes in the region, the Puna primitive lavas have enriched isotopic compositions. A recent geochemical study of primitive lavas on the Puna [Drew, *et al.*, 2009] reports that even the most primitive basaltic lavas (47.53% SiO₂, 10.3% MgO) on the Puna have isotopic signatures (⁸⁷Sr/⁸⁶Sr = 0.705534, ε_{Nd} = -0.8) requiring long-term enrichment in incompatible elements relative to bulk Earth. These observations suggest that the enriched isotopic signature is a feature of the sub-continental lithospheric mantle [Drew, *et al.*, 2009].

3. Samples and Methods

Most lavas in this study are from the central and southern Puna, and were targeted for sampling to supplement and expand upon the dataset presented by Drew et al. [2009]. Of 26 whole-rock lava samples analyzed (Fig. 1b) five were collected in May 2008, while the remaining 21 were collected during October 2008 (Table 1.). Two lava flows sampled (MC-11 and MC-12) were previously studied by Coira and Kay [1993]. Sample Ns1 was dated by Risse et al. (sample RAN2, 2008) and has a Quaternary whole-rock Ar-Ar age of <0.1 Ma. Sample locations, elemental and isotopic data for this suite are presented in Table 1.

Fresh samples with no visible weathered surfaces and/or secondary minerals were powdered in an Al₂O₃-lined crusher. Powder aliquots were sent to the GeoAnalytical Laboratory in the School of Earth and Environmental Sciences at Washington State University for major and trace element analysis by X-ray fluorescence (XRF) [Johnson, 1999] and inductively coupled plasma mass spectrometry (ICP-MS). At the University of Arizona, 30-40 mg of whole rock powder for each sample dissolved in a hot mixture of concentrated HF and HNO₃ and was spiked with Rb, Sr, and mixed Sm-Nd isotope spike solutions [Otamendi, et al., 2009]. Rubidium, Sr and the bulk of the REEs were separated in conventional cation columns filled with AG50W-X4 resin with 1 N to 4 N HCl. Cation column wash was subsequently used for Pb separation in Sr-Spec resin columns (Eichron, Darien, Illinois). Lead washes were loaded into the Sr-Spec columns in 8 N HNO₃, and the Pb was eluted using 8N HCl [Drew, et al., 2009]. Nd and Sm separation from other REE was achieved in anion columns filled with LN Spec resin using 0.1 N to 0.5 N HCl; half of the separations were performed in single use 2 ml resin columns and the other half in 6 ml resin columns.

Isotopic analyses were conducted at the University of Arizona, using thermal ionization mass spectrometry (TIMS) for Sr and Nd analysis, and multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) in solution mode for Pb analysis. TIMS analyses were conducted on both an automated VG Sector multicollector instrument with adjustable 10^{11} Ω Faraday collectors and a Daly photomultiplier [Otamendi, *et al.*, 2009] and a VG Sector 54 instrument [Ducea, *et al.*, 2002]. Sr and Rb cuts were loaded with a Ta₂O₅ slurry onto single Ta filament. Nd and Sm cuts were loaded onto single Re filaments using resin beads. Concentrations of Rb, Sr, Sm, Nd were determined by isotope dilution, with isotopic compositions determined on the same spiked runs. An off-line manipulation program was used for isotope dilution calculations. Typical runs consisted of acquisition of 100 isotopic ratios. The mean result of ten analyses of the standard NRbAAA performed during the course of this study is: $^{85}\text{Rb}/^{87}\text{Rb} = 2.61199 \pm 20$. Fifteen analyses of standard Sr987 yielded mean ratios of: $^{87}\text{Sr}/^{86}\text{Sr} = 0.710285 \pm 7$ and $^{84}\text{Sr}/^{86}\text{Sr} = 0.056316 \pm 12$. The mean results of five analyses of the standard nSmb performed during the course of this study are: $^{148}\text{Sm}/^{147}\text{Sm} = 0.74880 \pm 21$, and $^{148}\text{Sm}/^{152}\text{Sm} = 0.42110 \pm 6$. Fifteen measurements of the La Jolla Nd standard were performed during the course of this study. The standard runs yielded the following isotopic ratios: $^{142}\text{Nd}/^{144}\text{Nd} = 1.14184 \pm 2$, $^{143}\text{Nd}/^{144}\text{Nd} = 511853 \pm 2$, $^{145}\text{Nd}/^{144}\text{Nd} = 0.348390 \pm 2$, and $^{150}\text{Nd}/^{144}\text{Nd} = 0.23638 \pm 2$. The Sr isotopic ratios of standards and samples were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, whereas the Nd isotopic ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The estimated analytical $\pm 2s$ uncertainties for samples analyzed in this study are: $^{87}\text{Rb}/^{86}\text{Sr} = 0.35\%$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.0014\%$, $^{147}\text{Sm}/^{144}\text{Nd} = 0.4\%$, and $^{143}\text{Nd}/^{144}\text{Nd} = 0.0012\%$. Procedural blanks averaged from five determinations were: Rb 10 pg, Sr 150 pg, Sm 2.7 pg, and Nd 5.5 pg. Pb isotope analyses were conducted on a GV Instruments MC-ICP-MS [Thibodeau, *et al.*, 2007]. All Pb samples

were spiked with a Tl solution to acquire a Pb/Tl ratio of ~10 prior to analysis. Samples then entered the machine via free aspiration into a water-cooled chamber by way of a low-flow concentric nebulizer. A 2% HNO₃ blank was run before each sample, and the standard National Bureau of Standards (NBS)-981 was analyzed periodically during the sample run to insure the stability of the instrument.

4. Results and Discussion

4.1 Major and Trace Elements

Samples in this suite are mostly basaltic andesites, with a few evolved lavas and several basalts. Figure 2 shows this compositional variability with respect to other studies of primitive Puna lavas [*Déruelle, 1991; Drew, et al., 2009; Francis, et al., 1989; Kay, et al., 1994; Knox, et al., 1989; Kraemer, et al., 1999*], and Neogene volcanic rocks located between 24°S and 27°S from arc stratovolcanoes [*Matthews, et al., 1994; Rosner, et al., 2003; Trumbull, et al., 1999*] and large volume ignimbrites on the Puna plateau [*Schnurr, et al., 2007b; Siebel, et al., 2001*], in addition to the APVC, which is centered between 21°S and 24°S [*de Silva, et al., 1994; Hawkesworth, et al., 1982; Lindsay, et al., 2001; Ort, et al., 1996*]. All the lavas sampled in the suite have high potassium concentrations, which is typical of Neogene central Andean lavas.

The most primitive lavas in this suite have high MgO, Ni and Cr contents, compositions consistent with limited fractional crystallization or crustal contamination. Five of the samples are high MgO (>8.0 wt. %) and high Mg# (60-68, Table 1); a high-K lava sampled from the San Geronimo region (MC-11) has 7.88 wt. % MgO and the highest Mg# of the suite (69), and is included the “high MgO” category in the discussion below. In total, 16 of the lavas have Mg# >60, and are useful for examining the composition of the mantle source regions beneath the

Puna. The high MgO lavas have Ni concentrations 120-220 ppm and Cr concentrations 320-580 ppm, consistent with mantle-derived compositions.

All the lavas in this suite are enriched enrichments in fluid-mobile large ion lithophile (Rb, Ba) and slab-derived (Th) elements relative to high field strength elements (Ta, Nb, Ti), characteristic of typical calc-alkaline arc volcanics. Figure 3 presents trace element diagrams after Pearce [1993], showing the variability in the magnitude of these enrichments and depletions. All variability in this suite is bracketed by the patterns of the highest MgO (wt. %) samples. In Pasto Ventura region, located in the southern most Puna, the elemental geochemistry of eight lavas (all Mg# >60) sampled are very similar (Fig. 3); all exhibit a strong calc-alkaline Ta-Nb depletion. Other regions of the Puna (Salar de Arizaro, Cerro Galan region) have high MgO lavas that exhibit greater elemental variability. Multiple lavas sampled in this and other studies from the regional around Cerro Galan have the least prominent calc-alkaline trace element pattern; these observations are consistent with the suite of lavas studied by Kay et al. [1994]. The shoshonitic sample MC-11 has the greatest enrichment of trace elements overall, consistent with other studies of high-K shoshonites on the Puna [Kay, et al., 1994].

Plots of elemental ratios highlight regional variability in the magnitude of the calc-alkaline signal in this suite. Figure 4 shows how Ba/Th vs. La/Ta distinguishes lavas by region, where in the Cerro Galan area samples have less prominent calc-alkaline signatures compared to those around the Salar de Arizaro, Pasto Ventura, and the shoshonitic flows near Cerro Tuzgle. This regional pattern is consistent with the observations of Kay et al. [1994], who characterized the lavas around Cerro Galan as OIB-like ($La/Ta < 25$) or intra-plate ($La/Ta > 25$). The Th/Nb ratio is useful in identifying the magnitude of the Nb anomaly in arc rocks, in comparison to depleted mantle MORB where high Th/Nb (> 0.25) is typical of continental crust, slab sediments,

and arc basalts [Plank, 2005]. Figure 5 shows the Th/Nb vs. La/Nb trend in Puna lavas relative to the local Neogene volcanics. Within the Puna volcanics (Fig. 5a, 5b) Th/Nb values vary regionally. As observed in the Figure 3, lavas from the Pasto Ventura and Salar de Arizaro region have little variability in the magnitude of the calc-alkaline trace element signature, and the high-K MC-11 has similar Th/Nb values and a greater enrichment in all trace elements. Samples from the Antofagasta basin, Jote volcanic field, and Antofalla basin, all of which ring the western flanks of Cerro Galan, exhibit significant variability in Th/Nb values, where the highest MgO samples all have very low Th/Nb values, approaching MORB values [Plank, 2005].

Plank [2005] used the Th/La ratio in island arc basalts to trace the crustal high Th/Nb ratio through the subduction system via trench sediments and arc volcanism; by this proxy the Puna mafic lavas appear to have record little interaction with crustal material. The applicability of Th/La to fingerprint the slab sediment contribution is relatively unexplored in cordilleran arcs and likely limited by ambiguities in the magnitude of crustal overprinting [Davidson, *et al.*, 1991]. However, the mantle has Th/La <0.2 [Plank, 2005, and references therein] and thus Th/La ratios can aid in distinguishing mantle-derived magmas from those that have interacted with crustal material, be it in the mantle wedge or during migration through the crust. Th/La values for Neogene volcanics in the south central Andes vary between <0.1 and 1.4 (Figure 5a, 5c). Frontal arc volcanics and ignimbrite flows exhibit the widest variability in Th/La, consistent with mixing studies that suggest variable but commonly significant contributions from both mantle and crustal materials [de Silva, *et al.*, 2006; Hildreth and Moorbath, 1988; Ort, *et al.*, 1996]. Most Puna lavas in this and other studies have Th/La values between 0.1 and 0.2 (Fig. 5a, 5c), which supports the idea that they are useful for examining the geochemistry of the Puna mantle with little crustal overprinting.

In the rare earth element (REE) patterns (Fig. 6) the highest MgO lavas have variable enrichments in La and very similar Yb values, yielding a La/Yb ratios between 10-24; MC-11 has La/Yb of 45. All the La/Yb>40 samples are also the highest K samples, suggesting that relative degree of melting in the mantle source is controlling the La/Yb ratio. Most lavas in this suite exhibit a small Eu anomaly; the highest MgO samples have the smallest Eu anomaly; they likely had the least interaction with material at crustal levels where plagioclase is a stable phase.

Though rocks with adakite compositions have been reported in parts of the central and southern Andean arc [*Haschke, et al., 2002; Kay and Mpodozis, 2002*], the lavas in this suite do not fit the broadest geochemical definition of an adakite. The term “adakite” has been complicated by inconsistent use as both a genetic term in describing mantle-derived magmas produced by high-pressure melting of a garnet-bearing basaltic slab or lower crust (high Sr/Y, high La/Yb, and low Y and Yb concentrations), as well as a non-genetic term for “adakite-like” igneous rocks that are likely not the product of slab melting [*Castillo, 2006*]. Most importantly adakites are silicic rocks ($\text{SiO}_2 > 56\%$) with high-Al contents [*Castillo, 2006*], in addition to characteristic trace element signatures. None of the rocks in this suite display enough of the geochemical characteristics of adakites to warrant a discussion of adakitic evidence for slab melting.

4.2 Sr-Nd-Pb Isotopes

All Sr and Nd isotopic ratios in this suite are enriched relative to the bulk silicate earth, and plot within the array of other isotopic data from the central Andean volcanic zone; whole-rock $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for this suite of Puna lavas are presented in Figure 7 and Table 1. Sr isotope values range from 0.7055 to 0.7095; the subset of lavas with Mg# >60 have

nearly as wide range of values (0.7055 - 0.7084, Fig. 8a). Neodymium isotopic ratios range between $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.51223 and 0.51260 ($\epsilon_{\text{Nd}} -8$ to -0.8), and the highest Mg# lavas have both the highest and lowest Nd isotopic ratios (Fig. 8b). The most primitive lavas have both the highest and lowest values, suggesting that the source regions for these lavas are heterogeneous in $^{143}\text{Nd}/^{144}\text{Nd}$.

As with the trace element data, the Pasto Ventura region stands out in plots of regional isotopic variability and composition (Figs. 5b, 8). In both Nd and Sr, lavas in this region exhibit significant isotopic heterogeneity despite little compositional variability. In other regions, such as Salar de Arizaro and around Cerro Galan, there is a similar spread of isotopic ratios, but more evolved lavas tend to have compositional variations consistent with fractional crystallization and crustal contamination effects. In sum, the regional distribution of the isotopic data in the most primitive lavas suggests that the upper mantle source of these melts is isotopically heterogeneous, and generally evolved and enriched.

Lead isotope data from this study has little variability, suggesting that Puna Pb provinciality is homogeneous and similar to the entire suite of Neogene volcanics in this region. Figure 9 shows the Pb isotope data from this study together with previously published data from the Puna and Neogene volcanics in the region.

5. The “Puna mantle array” and implications for Andean lithospheric foundering

If the mafic lavas in this study accurately sample the Puna upper mantle, then it has a heterogeneous isotopic architecture that is variably melted and tapped by the magma systems generating the small volume mafic flows. We propose this architecture contains a “Puna mantle array” (Fig. 10) that can be represented by two mantle end-members, both of which are

isotopically enriched relative to the depleted mantle. One has low $^{143}\text{Nd}/^{144}\text{Nd}$ ($\epsilon_{\text{Nd}} < -8$), and likely has been sequestered from the convecting mantle for some time, probably as a part of the local mantle lithosphere. It is possible that this sub-continental lithospheric mantle was generated during the activity of the Ordovician Famatinian arc [Drew, *et al.*, 2009] and thus could have been sequestered from the convecting mantle for nearly 500 Myr. The other mantle end-member has Nd isotopic values closer to the bulk silicate earth ($\epsilon_{\text{Nd}} \sim 0$). Though it is possible that isotopically depleted asthenospheric mantle is the true mantle end-member here, there is little direct geochemical evidence to suggest it makes a significant compositional contribution to the melts generated. These geochemical observations are consistent with geophysical imaging of the upper mantle in the region, which resolves broad heterogeneities beneath the Puna [Schurr, *et al.*, 2006] and heterogeneous preservation of cordilleran roots beneath the Altiplano [Beck and Zandt, 2002].

Identifying the source of Sr isotopic variability in our most primitive lavas is more problematic, for contamination from high-Sr secondary phases (calcite) and windblown dust can contaminate samples despite efforts to avoid those surface effects. However, it is possible samples with high $^{143}\text{Nd}/^{144}\text{Nd}$ and relative high $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.7080 - 0.7095) reflect a mantle source fluxed with sea water from the slab. Sea water [$^{87}\text{Sr}/^{86}\text{Sr} = 0.7092$, Elderfield, 1986] would increase the $^{87}\text{Sr}/^{86}\text{Sr}$ value of a mantle source but have little affect the Nd isotopic composition.

If the isotopic variability in this suite is not a product of cryptic crustal contamination [Glazner and Farmer, 1992], the resilience of old subcontinental lithospheric mantle ($\epsilon_{\text{Nd}} < -8$) in the midst of an active cordilleran orogen suggests that if lithospheric removal occurs in the central Andes, these foundering events do not remove all of the lithospheric mantle. Similarly,

primitive lavas from the Puna lack geochemical evidence for significant contributions from a depleted mantle source. If massive upwelling and decompression melting of the asthenosphere occurred beneath the Puna - one likely result of rapid and catastrophic loss of the lower lithosphere - either this event did not generate a large volume of asthenospheric melt, or that melt mixed significantly with the foundering or remaining lithospheric material. We propose that if these lavas are the product of delamination, small-scale convective loss (i.e. drips) of dense lithospheric material characterizes the mode of lithospheric foundering. These would drips drive local convection and upwelling of the asthenosphere, which in turn delivers significant heat to the residual lower lithosphere and drives melting of the enriched, fertile material available locally. In some regions, such as Pasto Ventura, this local mantle material is has a relatively homogeneous elemental composition, while around Cerro Galan and other parts of the Puna there is greater variability. The relative homogeneity of the local melt zone is likely controlled by the extent of lithospheric loss, inherited geochemical heterogeneities, and distance from the trench and the effect of material flux from the slab. Though the predicted geodynamic response to relatively gradual lithospheric removal is less than that of whole-scale, rapid delamination, this model remains consistent with the idea that this process is focused in space and time, occurring periodically as the cordilleran orogen evolves.

Acknowledgements

This research was primarily supported by the Convergent Orogen System Analysis (COSA) collaboration between ExxonMobil and the Department of Geosciences at the University of Arizona; the Mark and Mary Lou Zoback graduate fellowship provided additional support for KM. S. Drew and L. Schoenbohm provided samples for this study. M. Ducea, E. Mortazavi,

and A. Thibodeau provided laboratory support. Thanks to M. Ducea, P. Reiners, and P.

DeCelles for discussion, suggestions, and comments on early versions of this manuscript.

Figure captions

Figure 1. (a) Digital elevation map of the central Andes between 21°S and 27°S showing the high elevation (>3 km, orange-red on color ramp) Altiplano and Puna plateaus relative to major regional landmarks. Stratovolcanoes of the active arc currently located in the Western Cordillera. Regional extent of the Altiplano-Puna Volcanic Complex (APVC) ignimbrites after de Silva et al. [2006]. (b) Simplified geologic map of the Puna plateau, modified from Schnurr et al. [2007a], with sample locations from this study.

Figure 2: : Whole-rock geochemistry of central Andean volcanic rocks in a total alkalis versus silica classification diagram after Le Bas et al. [1986]. Samples from this study are presented as filled symbols, where the most primitive (> 8 weight % MgO) are distinguished from the rest of the suite. Patterned fields represent variability in a compilation of published data from Neogene volcanic rocks located 23°S to 27°S, see text for compilation references

Figure 3: Trace element diagrams after Pearce [1993]. The 26 lavas from this study plotted with emphasis with the highest MgO and the tightly clustered pattern of those from Pasto Ventura. Typical calc-alkaline enrichments in fluid-mobile large ion lithophiles (Rb, Ba) and slab-derived elements (Th) together with depletions in high field strength elements (Ta, Nb, Ti) vary in magnitude but are present in all samples. The patterns in the six most primitive samples bracket the observed variability, suggesting a heterogeneous source composition.

Figure 4. Ba/Ta versus La/Ta of whole rock samples from this study (filled symbols) and from other Puna studies (open symbols, same as previous compilation). All samples < 55% SiO₂ by weight. Note the regional patterns in the relative enrichment in Ba and La.

Figure 5. (a) After Plank [2005], Th/Nb versus La/Nb plot showing the magnitude of the Nb depletion in Puna lavas relative to Neogene volcanics in the south central Andes (compilation same as Figure 2), with Th/La reference lines. The mantle has Th/La <0.2. (b) Th/Nb vs. Nd isotopic values for Puna lavas. A group of lavas in the Jote volcanic field and Antofagasta basin have the lowest Th/Nb, but this region also has some of the highest Th/La values in the suite. Note that samples from Pasto Ventura and the Salar de Arizaro have significantly less variability in Th/Nb ratio. (c) Th/La versus MgO (wt. %) for Neogene volcanics compilation.

Figure 6. REE plot after McDunough and Sun [1993]. Note that the highest MgO (wt. %) lavas have a wide variety of La concentrations, but similar Yb concentrations.

Figure 7. Epsilon Nd vs. ⁸⁷Sr/⁸⁶Sr for data in this study (symbols) and fields identifying the regional compilation of Neogene volcanics from Figure 2.

Figure 8. Sr and Nd isotopic data plotted against Mg#, where data from this study are filled symbols and published data from Puna lavas (same compilation as Figure 5) are open symbols. Note that the full range of Nd isotopic ratios observed in this suite is in the Mg# >60 lavas, and there is also significant Sr isotopic variability in these samples as well.

Figure 9. Pb isotopic data for Puna samples in this study (symbols) and fields identifying the regional compilation of Neogene volcanics. Compilation same as Figure 2.

Figure 10. Same as Figure 7, but with the proposed “Puna mantle array” showing the approximate isotopic characteristics of likely mantle end-members in the upper mantle beneath the Puna plateau.

References Cited

- Allmendinger, R. W., et al. (1997), The evolution of the Altiplano-Puna plateau of the Central Andes, *Annual Review of Earth and Planetary Sciences*, 25, 139-174.
- Beck, S., et al. (1996), Crustal-thickness variations in the central Andes, *Geol*, 24, 407-410.
- Beck, S. L., and G. Zandt (2002), The nature of orogenic crust in the central Andes, *J Geophys Res-Sol Ea*, 107, 2230.
- Castillo, P. (2006), An overview of adakite petrogenesis, *Chinese Science Bulletin*, 51, 257-268.
- Coira, B., and S. M. Kay (1993), Implications of Quaternary volcanism at Cerro Tuzgle for crustal and mantle evolution of the Puna Plateau, central Andes, Argentina, *Contrib Mineral Petrol*, 113, 40-58.
- Davidson, J. P., et al. (1991), The source of central Andean magmas; Some considerations, *Andean Magmatism and its Tectonic Setting: Geological Society of America Special Paper*, 265, 233-243.
- de Silva, S. (1989), Altiplano-Puna volcanic complex of the central Andes, *Geol*, 17, 1102-1106.
- de Silva, S., et al. (1994), Effusive silicic volcanism in the Central Andes: The Chao dacite and other young lavas of the Altiplano-Puna Volcanic Complex, *J. Geophys. Res.*, 99, 17805-17825.
- de Silva, S., et al. (2006), Large scale silicic volcanism: The result of thermal maturation of the crust, *Advances in geosciences: River Edge, New Jersey, World Scientific Press, Proceedings of the Asia-Oceania Geosciences Society*, 215–230.
- de Silva, S. L., and W. D. Gosnold (2007), Episodic construction of batholiths: Insights from the spatiotemporal development of an ignimbrite flare-up, *Journal of Volcanology and Geothermal Research*, 167, 320-335.

- DeCelles, P. G., et al. (2009), Cyclicity in Cordilleran orogenic systems, *Nat Geosci*, 2, 251-257.
- Déruelle, B. (1991), Petrology of Quaternary shoshonitic lavas of northwestern Argentina, *Geological Society of America Special Paper*, 265, 201-216.
- Drew, S., et al. (2009), Mafic volcanism on the Puna Plateau, NW Argentina: Implications for lithospheric composition and evolution with an emphasis on lithospheric foundering, *Lithosphere*, 1, 305-318.
- Ducea, M., et al. (2002), Melt depletion and subsequent metasomatism in the shallow mantle beneath Koolau volcano, Oahu (Hawaii), *Geochem Geophys Geosy*, 3, 1015.
- Ducea, M. N. (2001), The California Arc: Thick Granitic Batholiths, Eclogitic Residues, Lithospheric-Scale Thrusting, and Magmatic Flare-Ups, *GSA Today*, 11, 4-10.
- Elderfield, H. (1986), Strontium isotope stratigraphy, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 57, 71-90.
- Francis, P., and C. Hawkesworth (1994), Late Cenozoic rates of magmatic activity in the central Andes and their relationships to continental-crust formation and thickening, *Journal of the Geological Society*, 151, 845-854.
- Francis, P., et al. (1989), Petrology and geochemistry of volcanic rocks of the Cerro Galan caldera, northwest Argentina, *Geol. Mag.*, 126, 515.
- Glazner, A., and G. Farmer (1992), Production of isotopic variability in continental basalts by cryptic crustal contamination, *Science*, 255, 72-74.
- Haschke, M., et al. (2006), Central and Southern Andean Tectonic Evolution Inferred from Arc Magmatism, *The Andes: Active Subduction Orogeny*, 17.
- Haschke, M., et al. (2002), Repeated crustal thickening and recycling during the Andean orogeny in north Chile (21 degrees-26 degrees S), *J Geophys Res-Sol Ea*, 107, 3019.
- Hawkesworth, C., et al. (1982), Isotope and trace element evidence for late-stage intra-crustal melting in the High Andes, *Earth and Planetary Science Letters*.
- Hildreth, W., and S. Moorbath (1988), Crustal contributions to arc magmatism in the Andes of central Chile, *Contrib Mineral Petrol*, 98, 455-489.
- Johnson, D. M. (1999), XRF Analysis of Rocks and Minerals for Major and Trace Elements on a Single Low Dilution Li-tetraborate Fused Bead, *Advances in X-ray Analysis*, 41, 843-867.
- Kay, R. W., and S. M. Kay (1993), Delamination and delamination magmatism, *Tectonophysics*, 219, 177-189.

- Kay, S., and C. Mpodozis (2002), Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab, *Journal of South American Earth Sciences*, 15, 39-57.
- Kay, S. M., et al. (1994), Young mafic back arc volcanic rocks as indicators of continental lithospheric delamination beneath the Argentine Puna plateau, central Andes, *J. Geophys. Res.*, 99, 24,323-324,339.
- Knox, W., et al. (1989), Geochemical evidence on the origin of Quaternary basaltic andesites of the Puna, northwestern Argentina, *Asociacion Geologica Argentina, Revista*, XLIV, 194-206.
- Kraemer, B., et al. (1999), Incorporation of the Paleogene foreland into the Neogene Puna plateau: The Salar de Antofalla area, NW Argentina, *Journal of South American Earth Sciences*, 12, 157-182.
- LeBas, M. J., et al. (1986), A chemical classification of volcanic rocks based on the total alkali-silica diagram, *Journal of Petrology*, 27, 745.
- Lindsay, J., et al. (2001), Magmatic evolution of the La Pacana caldera system, Central Andes, Chile: Compositional variation of two cogenetic, large-volume felsic ignimbrites, *Journal of Petrology*, 42, 459-486.
- Lucassen, F., et al. (2007), Pre-Cenozoic intra-plate magmatism along the Central Andes (17-34° S): Composition of the mantle at an active margin, *Lithos*, 99, 312-338.
- Lucassen, F., et al. (2006), Nd, Pb, and Sr isotope composition of juvenile magmatism in the Mesozoic large magmatic province of northern Chile (18-27 degrees S): indications for a uniform subarc mantle, *Contrib Mineral Petrol*, 152, 571-589.
- Mamani, M., et al. (2008), Composition and structural control of crustal domains in the central Andes, *Geochem. Geophys. Geosyst.*, 9, Q03006.
- Matteini, M., et al. (2002), Geodynamical evolution of Central Andes at 24 degrees S as inferred by magma composition along the Calama-Olacapato-El Toro transversal volcanic belt, *Journal of Volcanology and Geothermal Research*, 118, 205-228.
- Matthews, S., et al. (1994), Lascar Volcano, Northern Chile; evidence for steady-state disequilibrium, *Journal of Petrology*.
- McDonough, W., and S. Sun (1993), The composition of the Earth, *Chemical Geology*, 120, 223-253.
- Ort, M., et al. (1996), Generation of a crust-mantle magma mixture: Magma sources and contamination at Cerro Panizos, central Andes, *Contrib Mineral Petrol*, 123, 308-322.
- Otamendi, J., et al. (2009), Generation of Tonalitic and Dioritic Magmas by Coupled Partial Melting of Gabbroic and

- Metasedimentary Rocks within the Deep Crust of the Famatinian Magmatic Arc, Argentina, *Journal of Petrology*.
- Pearce, J., and I. Parkinson (1993), Trace element models for mantle melting: application to volcanic arc petrogenesis, *Geological Society London Special Publications*, 76, 373.
- Plank, T. (2005), Constraints from thorium/lanthanum on sediment recycling at subduction zones and the evolution of the continents, *Journal of Petrology*, 46, 921.
- Ramos, V. A. (2009), Anatomy and global context of the Andes: Main geologic features and the Andean orogenic cycle, *Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision*, Kay, S.M., Ramos, V.A., and Dickinson, W.R., eds, *Geological Society of America Memoir 204*, 31-65.
- Risse, A., et al. (2008), $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of mafic volcanism in the back-arc region of the southern Puna plateau, Argentina, *Journal of South American Earth Sciences*.
- Rogers, G., and C. Hawkesworth (1989), A geochemical traverse across the north Chilean Andes - evidence for crust generation from the mantle wedge, *Earth and Planetary Science Letters*, 91, 271-285.
- Rosner, M., et al. (2003), Slab-derived boron isotope signatures in arc volcanic rocks from the Central Andes and evidence for boron isotope fractionation during progressive slab dehydration, *Geochim. Geophys. Geosyst.*, 4, 9005.
- Schnurr, W., et al. (2007a), Digital Geological Map of the Southern and Central Puna Plateau, NW Argentina, *The Andes: Active Subduction Orogeny*, supplemental.
- Schnurr, W. B. W., et al. (2007b), Twenty-five million years of silicic volcanism in the southern central volcanic zone of the Andes: Geochemistry and magma genesis of ignimbrites from 25 to 27 degrees S, 67 to 72 degrees W, *Journal of Volcanology and Geothermal Research*, 166, 17-46.
- Schurr, B., et al. (2006), Evidence for lithospheric detachment in the central Andes from local earthquake tomography, *Tectonophysics*, 415, 203-223.
- Siebel, W., et al. (2001), Geochemistry and isotope systematics of small- to medium-volume Neogene-Quaternary ignimbrites in the southern central Andes: evidence for derivation from andesitic magma sources, *Chemical Geology*, 171, 213-237.
- Thibodeau, A., et al. (2007), The strange case of the earliest silver extraction by European colonists in the New World, *Proceedings of the National Academy of Sciences*, 104, 3663.
- Thorpe, R., et al. (1984), Relative Roles of Source Composition, Fractional Crystallization and Crustal Contamination in the Petrogenesis of Andean Volcanic Rocks [and Discussion], *Philosophical Transactions of the Royal Society of London. Series A Mathematical and Physical Sciences*, 310, 675-692.

Trumbull, R., et al. (1999), Evidence for Miocene to Recent contamination of arc andesites by crustal melts in the Chilean Andes (25–26° S) and its geodynamic implications, *Journal of South American Earth Sciences*, 12, 135-155.

Whitman, D., et al. (1996), Lithospheric structure and along-strike segmentation of the Central Andean Plateau: seismic Q, magmatism, flexure, topography and tectonics, *Tectonophysics*, 259, 29-40.

Yuan, X., et al. (2002), Moho topography in the central Andes and its geodynamic implications, *Earth and Planetary Science Letters*, 199, 389-402.

Table 1. Elemental and isotopic data.

locale	San Geronimo		Salar de Arizaro					Salar de Rio Grande	Salar de Hombre Muerto		Salar de Antofalla			
SampleID	MC11*	MC12*	MC13*	MC17*	MC18*	AZ1	AZ4	AZ7	RG1	HM1	HM2	AF1	AF2	ALB-01
rock type**	BTA	BTA	BTA	BA	BA	BA	BTA	B	B	A	D	TA	A	BTA
SiO2	54.43	55.66	54.35	54.38	54.66	56.04	52.80	51.87	51.25	62.92	66.69	61.50	57.85	52.31
TiO2	1.339	1.164	1.207	1.200	1.074	1.065	1.101	1.082	1.121	0.905	0.768	1.066	1.306	1.416
Al2O3	13.46	14.88	16.30	17.28	15.96	16.42	16.64	16.08	15.80	15.90	15.50	15.67	15.84	15.71
FeO*	6.32	5.90	6.86	7.91	6.88	6.82	7.72	8.09	7.42	4.71	3.60	4.97	6.56	7.84
MnO	0.106	0.094	0.111	0.133	0.121	0.115	0.136	0.142	0.127	0.065	0.041	0.069	0.097	0.129
MgO	7.88	6.31	5.52	4.91	6.38	5.48	5.27	8.06	6.14	2.41	1.48	2.86	4.36	8.19
CaO	6.23	6.60	7.76	7.96	7.91	7.40	8.30	8.68	8.90	4.40	3.01	4.75	6.09	7.73
Na2O	2.52	2.92	3.65	3.00	3.30	3.51	3.45	3.16	3.10	3.84	3.72	3.83	3.75	3.31
K2O	5.20	3.34	1.94	1.89	1.79	2.02	1.77	1.35	1.76	2.94	3.71	3.07	2.10	1.88
P2O5	0.862	0.529	0.377	0.315	0.297	0.287	0.358	0.232	0.276	0.250	0.237	0.352	0.362	0.398
Sum	98.34	97.69	98.08	98.99	98.39	99.17	97.55	98.75	95.90	98.34	98.75	98.13	98.32	98.92
LOI(%)	0.93	1.13	1.36	0.68	1.09	0.40	1.52	0.82	2.07	-0.06	0.03	0.08	0.41	0.30
Ni	179	116	79	34	97	75	34	127	83	23	14	38	65	191
Cr	341	253	183	68	261	217	83	361	223	46	22	64	108	323
Sc	16	16	17	19	21	20	24	27	22	11	7	11	17	21
V	138	149	180	190	187	184	191	222	199	116	87	124	171	179
Ba	1923	910	541	440	448	495	462	277	400	721	860	755	596	486
Rb	181.7	113.3	46.1	33.1	46.7	60.0	40.4	34.4	39.4	110.8	154.4	103.5	65.9	47.5
Sr	966	730	698	789	620	639	756	487	503	496	503	659	577	680
Zr	475	236	201	199	173	182	186	144	174	216	249	239	229	189
Y	24.09	18.77	17.82	27.70	19.46	18.85	29.50	21.38	19.92	13.73	13.36	15.95	20.21	21.23
Nb	36.78	22.01	13.86	12.62	9.14	10.97	11.56	7.78	8.92	10.96	10.22	12.38	14.40	27.44
Ga	19	21	20	19	18	22	20	20	18	23	24	23	23	19
Cu	33	24	42	21	44	39	26	52	48	21	23	24	32	42
Zn	95	100	98	92	87	90	79	89	101	94	80	90	106	84
Pb	31.86	25.29	8.89	6.73	7.96	9.18	4.30	6.04	8.15	17.06	19.08	15.67	12.99	8.27
La	73.77	58.31	40.74	33.94	33.06	35.26	34.72	20.20	26.10	44.38	53.66	54.04	45.48	39.38
Ce	150.10	115.30	81.17	71.47	67.92	70.73	72.10	43.87	55.68	87.45	103.88	105.86	92.89	75.84
Th	15.85	14.03	6.16	5.01	5.22	7.98	5.20	3.05	3.38	13.23	17.65	14.53	8.86	6.43
Nd	68.83	51.28	37.85	36.39	32.09	32.64	35.38	23.89	28.74	37.77	42.95	45.09	43.37	32.91
U	3.75	4.18	1.29	0.93	1.17	1.42	1.04	0.91	0.80	2.80	4.08	2.49	1.63	1.49
Pr	18.00	13.62	9.79	8.99	8.27	8.54	9.03	5.76	7.15	10.17	11.89	12.33	11.27	8.85
Sm	13.30	9.56	7.47	7.61	6.38	6.30	7.35	5.38	6.05	6.72	7.26	7.81	8.24	6.34
Eu	3.08	2.17	1.92	1.94	1.64	1.61	1.83	1.46	1.66	1.59	1.53	1.81	1.96	1.77
Gd	9.15	6.90	5.85	6.51	5.19	5.01	6.32	4.84	5.15	4.81	5.11	5.71	6.51	5.33
Tb	1.15	0.88	0.79	0.99	0.75	0.71	0.97	0.74	0.76	0.63	0.64	0.75	0.89	0.79
Dy	5.58	4.33	3.94	5.73	4.16	3.82	5.69	4.29	4.09	3.11	3.08	3.76	4.54	4.45
Ho	0.92	0.73	0.70	1.09	0.76	0.70	1.10	0.82	0.76	0.56	0.53	0.64	0.80	0.82
Er	2.13	1.70	1.64	2.78	1.95	1.80	2.98	2.16	1.96	1.34	1.27	1.46	1.97	2.09
Tm	0.28	0.23	0.23	0.38	0.27	0.26	0.42	0.30	0.27	0.18	0.17	0.19	0.26	0.29
Yb	1.64	1.33	1.31	2.29	1.64	1.55	2.59	1.85	1.63	1.07	0.97	1.08	1.52	1.74
Lu	0.25	0.20	0.20	0.35	0.26	0.24	0.40	0.29	0.25	0.16	0.15	0.16	0.23	0.26
Hf	12.77	6.43	5.22	5.17	4.52	4.81	4.87	3.89	4.62	5.79	6.74	6.38	6.10	4.58
Ta	2.03	1.39	0.79	0.71	0.58	0.68	0.68	0.51	0.55	0.76	0.76	0.77	0.96	1.67
Cs	7.85	3.76	0.95	0.50	1.14	1.37	0.72	0.96	1.00	3.67	6.08	2.19	1.43	1.47
Sc	15.3	13.6	15.0	18.5	20.4	20.4	23.7	27.5	21.5	10.2	7.2	10.4	15.2	21.0
Mg#***	69	66	59	53	62	59	55	64	60	48	42	51	54	65
⁸⁷ Sr/ ⁸⁶ Sr(0)	0.708046	0.708269	0.706781	0.706787	0.707271	0.706432	0.706485	0.70549	0.706867	0.708797	0.709284	0.708036	0.70832	0.705749
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512254	0.51223	0.512439	0.512378	0.512311	0.512529	0.51258	0.51259	0.512536	0.512448	0.512363	0.51248	0.512437	0.512580
εNd	-7.49	-7.96	-3.88	-5.07	-6.38	-2.13	-1.13	-0.94	-1.99	-3.71	-5.36	-3.08	-3.92	-1.13
²⁰⁶ Pb/ ²⁰⁴ Pb	18.74099	18.73075	18.87958	18.92396	18.98098	18.89099	18.96033	18.89727	18.77795	18.87389	19.03484	18.96242	18.94922	18.95657
²⁰⁷ Pb/ ²⁰⁴ Pb	15.70293	15.68827	15.64033	15.63497	15.66287	15.63611	15.64467	15.63718	15.63994	15.66733	15.68765	15.67573	15.66526	15.65459
²⁰⁸ Pb/ ²⁰⁴ Pb	39.20095	39.00297	38.86289	38.82893	38.89336	38.8583	38.86585	38.74685	38.73998	39.04708	39.26717	39.13935	39.01588	38.96154
latitude	-24.25915	-24.2364	-24.8684	-24.699933	-24.705483	-25.143	-24.871	-24.819	-24.825	-25.371	-25.741	-25.901	-25.861	-25.9568
longitude	-66.396733	-66.423783	-68.0886	-67.9827	-67.933067	-67.61	-68.086	-68.039	-68.052	-67.243	-67.198	-67.711	-67.721	-67.70942

notes

* collected May 2008

** B = basalt; BA = basaltic andesite; BTA = basaltic trachy-andesite; A = andesite; TA = trachyandesite; D = dacite

***Mg# = [mol Mg/(mol Mg + mol Fe)]*100 assuming all Fe²⁺

Table 1 (continued). Elemental and isotopic data.

locale	Nacimientos (Antofagasta basin)			Jote (Antofagasta basin)	Pasto Ventura basin							
SampleID	NS1	NS2	NS3	J1	PV1	PV2	PV3	PV4	PV5	PV6	PV7	PV8
rock type*	BA	BA	A	B	BTA	BTA	BTA	BTA	BTA	BA	BA	BTA
SiO2	53.60	53.98	59.23	51.40	53.15	52.23	52.71	53.27	54.87	52.16	52.23	54.31
TiO2	1.131	1.039	1.113	1.572	1.094	1.149	1.126	1.066	0.950	1.105	1.086	1.114
Al2O3	14.83	14.43	16.24	15.46	15.07	15.70	15.56	15.30	15.43	15.74	15.91	15.20
FeO*	7.80	7.65	6.53	8.94	7.29	7.77	7.77	7.43	6.93	8.13	8.10	7.61
MnO	0.137	0.138	0.090	0.143	0.123	0.131	0.129	0.127	0.122	0.141	0.144	0.128
MgO	9.25	9.17	3.41	8.43	7.00	7.40	7.96	7.82	6.45	7.92	7.80	7.53
CaO	7.39	7.57	6.16	7.99	8.10	8.37	8.17	7.94	7.68	8.76	8.71	7.43
Na2O	2.94	2.85	3.45	3.29	3.29	3.46	3.58	3.55	3.26	3.29	3.34	3.51
K2O	1.71	1.62	2.09	1.68	1.95	1.77	1.69	1.76	2.26	1.71	1.63	2.04
P2O5	0.266	0.244	0.275	0.343	0.344	0.346	0.313	0.296	0.268	0.312	0.308	0.325
Sum	99.06	98.68	98.58	99.24	97.41	98.32	99.01	98.56	98.23	99.26	99.27	99.20
LOI(%)	-0.25	-0.22	0.17	0.57	1.44	1.31	0.65	0.80	0.63	0.44	-0.07	0.49
Ni	217	184	35	190	129	139	150	148	87	124	115	148
Cr	545	573	64	326	353	276	392	386	287	397	378	345
Sc	24	25	15	23	21	23	23	22	22	24	26	21
V	185	186	160	204	180	196	202	194	191	214	214	188
Ba	401	375	521	437	518	471	438	454	468	424	475	593
Rb	47.1	43.8	58.2	43.1	56.8	47.6	43.3	47.6	75.4	42.0	43.4	50.3
Sr	542	542	525	658	711	768	1482	815	562	665	734	684
Zr	155	145	280	172	205	170	191	189	155	158	175	199
Y	20.87	20.98	20.32	22.68	20.76	20.39	18.19	18.09	18.54	19.87	23.60	18.74
Nb	16.98	15.74	11.57	22.63	13.63	13.71	10.34	10.16	10.34	11.22	12.44	13.34
Ga	18	16	22	19	19	21	22	20	21	20	20	21
Cu	51	50	36	51	47	51	55	53	51	58	41	50
Zn	87	78	108	94	84	87	90	89	76	85	81	86
Pb	8.98	8.65	9.96	8.16	11.13	9.24	8.03	8.65	12.86	8.98	7.19	9.13
La	28.36	25.29	41.77	34.42	36.07	34.70	30.62	30.47	32.90	31.05	34.66	38.06
Ce	57.26	51.51	86.52	69.97	71.15	68.67	62.42	62.05	63.87	62.34	68.99	74.84
Th	5.34	4.61	9.34	5.21	7.29	6.81	5.80	6.05	11.80	6.06	6.61	7.61
Nd	26.67	24.36	41.46	33.35	33.78	32.81	31.47	31.29	29.19	30.40	33.96	35.08
U	1.25	1.09	1.41	1.15	2.19	1.50	1.29	1.44	2.40	1.26	1.40	1.27
Pr	6.92	6.24	10.67	8.53	8.72	8.37	7.86	7.80	7.67	7.66	8.54	9.03
Sm	5.26	4.91	8.39	6.45	6.57	6.44	6.31	6.23	5.82	6.10	6.86	6.66
Eu	1.42	1.39	1.87	1.80	1.70	1.74	1.69	1.69	1.53	1.67	1.90	1.75
Gd	4.61	4.46	6.58	5.54	5.44	5.38	5.06	4.93	4.82	5.16	5.66	5.25
Tb	0.72	0.69	0.88	0.82	0.77	0.75	0.70	0.70	0.69	0.74	0.86	0.74
Dy	4.15	4.05	4.52	4.62	4.34	4.19	3.84	3.80	3.83	4.08	4.82	4.03
Ho	0.82	0.82	0.81	0.89	0.81	0.77	0.72	0.71	0.74	0.78	0.94	0.74
Er	2.18	2.19	1.91	2.28	2.06	2.01	1.79	1.79	1.94	2.03	2.41	1.85
Tm	0.31	0.31	0.26	0.32	0.28	0.28	0.25	0.25	0.26	0.28	0.34	0.26
Yb	1.90	1.94	1.57	1.94	1.71	1.64	1.48	1.51	1.60	1.70	2.04	1.59
Lu	0.30	0.30	0.24	0.30	0.26	0.25	0.22	0.23	0.25	0.26	0.31	0.24
Hf	3.87	3.68	7.23	4.30	5.13	4.42	4.81	4.87	4.24	4.19	4.66	5.07
Ta	1.13	1.06	0.64	1.54	0.87	0.87	0.63	0.63	0.75	0.71	0.77	0.79
Cs	1.63	1.65	1.51	1.34	2.09	1.66	1.27	1.41	2.57	1.07	0.67	1.25
Sc	24.2	25.7	15.2	23.7	20.0	21.9	22.2	21.0	23.0	26.0	29.0	19.7
Mg#***	68	68	48	63	63	63	65	65	62	63	63	64
⁸⁷ Sr/ ⁸⁶ Sr(0)	0.705849	0.705543	0.709521	0.706108	0.70657	0.705465	0.707932	0.708401	0.706561	0.706186	0.705400	0.705844
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512516	0.512496	0.512279	0.512429	0.512366	0.512587	0.512479	0.512556	0.512412	0.512575	0.512597	0.512529
εNd	-2.38	-2.77	-7.00	-4.08	-5.31	-0.99	-3.10	-1.60	-4.41	-1.23	-0.80	-0.94
²⁰⁶ Pb/ ²⁰⁴ Pt	18.8312	18.83992	19.04474	18.97661	18.89649	18.98954	18.87577	18.84064	18.9247	18.99888	19.01626	18.90042
²⁰⁷ Pb/ ²⁰⁴ Pt	15.65526	15.6557	15.68221	15.66781	15.66558	15.6605	15.65271	15.65796	15.67863	15.65677	15.65247	15.65589
²⁰⁸ Pb/ ²⁰⁴ Pt	38.79381	38.78373	39.14805	38.96385	39.04852	39.10941	39.00766	38.96256	39.16369	39.05156	39.05077	39.02271
latitude	-25.987	-25.973	-25.857	-26.311	-26.738	-26.729	-26.759	-26.758	-26.859	-26.851	-26.85	-26.838
longitude	-67.548	-67.541	-67.4	-67.32	-67.225	-67.281	-67.288	-67.279	-67.304	-67.311	-67.319	-67.312

