Sr and O Isotope Geochemistry of Volcán Uturuncu, Andean Central Volcanic Zone, Bolivia: Resolving Crustal and Mantle Contributions to Continental Arc Magmatism

Gary S. Michelfelder[1]; Alicia D. Wilder[2] and Todd C. Feeley[2]

1. Department of Geography, Geology and Planning, Missouri State University, Springfield, MO 65897

2. Department of Earth Sciences, Montana State University, Bozeman, MT 59717

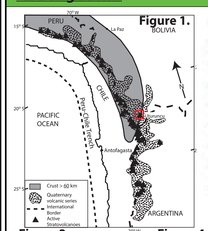
Missouri State University
Department of Geography, Geology and Planning

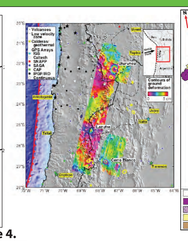
Missouri State University Volcanology, Petrology and Geochemistry Research Group

1. Abstract:

This study reports oxygen isotope values determined by laser fluorination of mineral separates and in situ Sr isotope ratios (mainly plagioclase) from andesitic to dacitic composition lava flows erupted from Volcán Uturuncu in the Andean Central Volcanic Zone (CVZ). Variation in $\delta^{18}O$ values (6.6-11.8‰ relative to SMOW) for the lava suite is large and the data as a whole exhibit no simple correlation with any parameter of compositional evolution. Plagioclase separates from nearly all rocks have $\delta^{18}O$ values (6.6-11.8‰) higher than expected for production of the magmas by partial melting of little evolved basaltic lavas erupted in the back arc regions of the CVZ. Most Uturuncu magmas must therefore contain high $\delta^{18}O$ crustal material. This hypothesis is further supported by textures and isotopic variation ($^{87}Sr/^{86}Sr$= 0.7098-0.7165) within single plagioclase phenocrysts suggesting repeated mixing followed by crustal contamination events occurring in the shallow crustal reservoir. The dacite composition rocks show more variable and extend to higher $\delta^{18}O$ ratios than andesite composition rocks. These features are interpreted to reflect assimilation of heterogeneous upper continental crust by low $\delta^{18}O$ value andesitic magmas followed by mixing or mingling with similar composition hybrid magmas with high $\delta^{18}O$ values. Conversely, the $\delta^{18}O$ values of the andesites suggest contamination of the magmas by continental crust modified by intrusion of mantle derived basaltic magmas. These results demonstrate on a relatively small scale the strong influence that intrusion of mantle-derived mafic magmas can have on modifying the composition of pre-existing continental crust in regions of melt production. Given this result, similar, but larger-scale, regional trends in magma compositions may reflect an analogous but more extensive process wherein the continental crust becomes progressively hybridized beneath frontal arc localities as a result of protracted intrusion of subduction-related basaltic magmas.

2. Background:





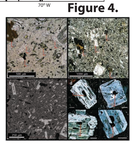
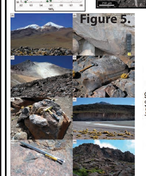
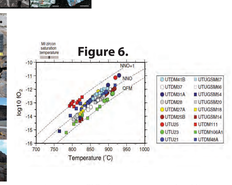


Figure 1. Map showing location of Andean Central Volcanic Zone (CVZ). Shaded area shows the region where crustal thickness exceeds 60 km; stippled region illustrates distribution of Quaternary volcanic rocks. Modified from Michelfelder et al., (2014).

Figure 2. Simplified geologic map of Cerro Uturuncu based on field mapping and satellite imagery interpretation. Modified from Sparks et al. (2008).





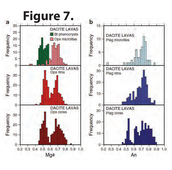


Figure 3. Modal percent phenocrysts versus SiO_2 for representative Uturuncu lava and domes.

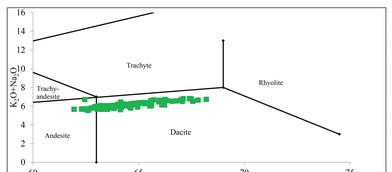
Figure 4. A. Photomicrgraphs of Uturuncu lavas. Pl, plagioclase, Opx, orthopyroxene, Sp, spinel, Bt, biotite. Note sieve texture of Pl core in top right image. D. Cross-polarised photomicrographs of plagioclase-hosted MI from various Uturuncu lavas. Scale bar is 100 microns. From Muir et al., 2014.

Figure 5. Representative views of Cerro Uturuncu geology. (A) View southeast towards the edifice of Uturuncu; (B) Typical flow folding in lava flows; (C) Hydrothermally altered remains of the edifice of Uturuncu produced by fumaroles; (D) Typical prismatically jointed block from exterior wall of a collapsed dome; (E) Andesite inclusions in an Uturuncu lava flow; (F) Typical flow front of an Uturuncu lava flow overlying APVC ignimbrite; (G) Oxidized autobrecciation found at the terminus of lava flows; (H) Pressure ridge found commonly found in lava flows over 20 m thick.

Figure. 6. Temperature and fO_2 calculated from coexisting oxides in natural dacitic lavas and domes.

Figure 7. Modal distributions of andestite and dacite plagioclase, orthopyroxene and biotite compositions from Uturuncu lavas and domes. From Muir et al. 2014.

3. Bulk Rock Geochemistry:



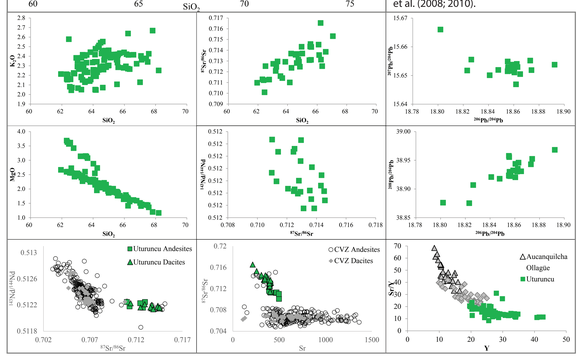
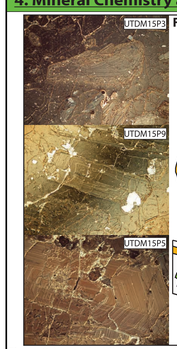
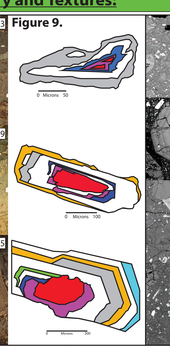


Figure 8. A. Total alkali versus silica (TAS) diagram for Uturuncu volcanic rocks. B. Major-element oxide concentrations versus SiO_2 for Uturuncu lavas and domes. C. Trace-element concentrations versus SiO_2 for Uturuncu lavas and domes. D. $^{143}Nd/^{144}Nd$ ratios versus $^{87}Sr/^{86}Sr$ ratios for Uturuncu volcanic rocks compared to andesites and dacites from the Central Volcanic Zone (CVZ). $^{87}Sr/^{86}Sr$ ratios versus Sr concentration for Uturuncu lava flows and domes compared to andesites and dacites from the CVZ. Analytical errors are with the size of the data point. CVZ andesite and dacite data from Mamani et al. (2008; 2010).

4. Mineral Chemistry and Textures:





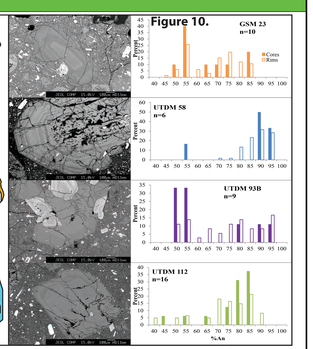
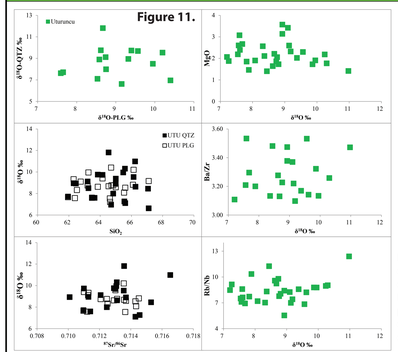


Figure 9. Nomarski differential interference contrast (NDIC) images and interpretative line drawings of representative plagioclase crystals from rocks of Cerro Uturuncu. The images demonstrate the variety of equilibrium and disequilibrium textures associated with this complex magmatic system. The line drawings illustrate dissolution surfaces or zones. See text for description for each crystal.

Figure 10. Histograms of anorthite mole percent showing the distribution of plagioclase rim and core anorthite compositions for representative lava flows and domes. Samples were selected at random to illustrate the variation between lava flows and domes and to express the complexity of the Cerro Uturuncu subvolcanic plumbing system.

5. Oxygen Isotope Geochemistry:



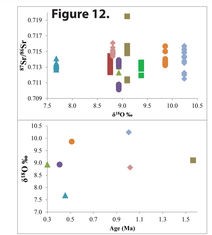
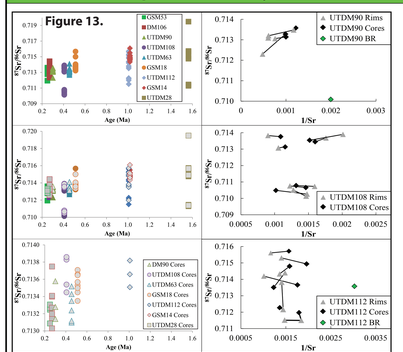
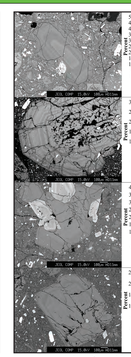


Figure 11. Oxygen isotope values for plagioclase and quartz phenocrysts from Uturuncu lavas and domes compared to major and trace element concentrations.

Figure 12. A. In situ Sr isotope ratios from plagioclase phenocrysts versus O isotope values. B. Stratigraphic corelation of O isotope values for Uturuncu lavas and domes.

6. In Situ Sr Isotope Geochemistry:





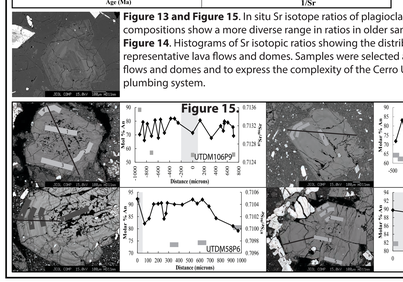


Figure 13 and Figure 15. In situ Sr isotope ratios of plagioclase cores and rims from Uturuncu lavas and domes. Core compositions show a more diverse range in ratios in older samples and are more restricted ratios in younger samples.

Figure 14. Histograms of Sr isotopic ratios showing the distribution of plagioclase rim and core isotopic variation for representative lava flows and domes. Samples were selected at random to illustrate the variation between lava flows and domes and to express the complexity of the Cerro Uturuncu subvolcanic plumbing system.

7. AFC and Mixing Models:

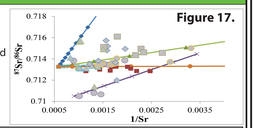
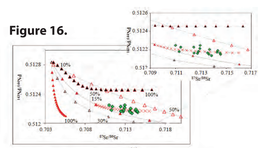
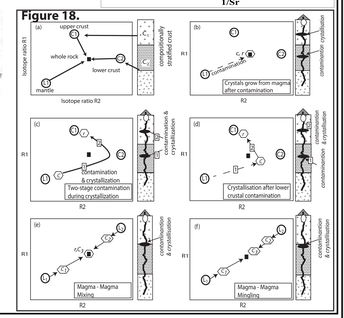


Figure 16. (A) Nd Isotope and Sr isotope constraints on bulk mixing and assimilation fractional crystallization (AFC) models for Uturuncu lava flows and domes. (B) $^{87}Sr/^{86}Sr$ ratios versus Rb/Sr ratios for Uturuncu lava flows, domes and inclusions with AFC models of primary melts discussed in text and in Michelfelder et al., 2014.

Figure 17. AFC and magma mixing models for plagioclase phenocryst cores from select Uturuncu lavas and domes. Dacite D= 1.5 and andesite D= 3.0.

Figure 18. Hypothetical models to produce core compositions observed.





8. Conclusions:

1. **The range in $\delta^{18}O$ values of Uturuncu lavas and domes are above accepted mantle values suggesting that the magmas underwent significant differentiation prior to eruption. The variation of the $\delta^{18}O$ values between erupted units and between the quartz and plagioclase phenocryst suggest that the magma interacted with a variety of different contaminants during magma migration.**
2. **In situ Sr isotope ratios from plagioclase phenocrysts record the pathway of magma migration through the crust. Core Sr isotopic ratios from old lavas and domes erupted from Uturuncu exhibit more variation than cores observed in the youngest lavas and domes suggesting hybridization of the crust over time.**
3. **AFC and mixing models suggest that even though whole rock trends are linear, mixing played a minor role in the generation and accumulation of plagioclase phenocryst. Only samples DM90 and DM112 show textural and compositional evidence of extensive mixing.**

9. Acknowledgements:

The authors wish to thank Frank Ramos for use of and assistance with the thermal ionization mass spectrometer at New Mexico State University; the staff at the Geoanalyitical lab at Washington State University and all members of the PLUTONS Research group for insightful discussions, especially Shan de Silva, Matt Pritchard and Duncan Muir. Jamie Kern for assistance mapping and collecting samples in the field, and the residents of Quetena Chico, Bolivia and Lipiko Tours for logistical support and hospitality. Support for this work came from the U.S. National Science Foundation EAR-0901148 to TCF and grants to GSM from the Department of Earth Sciences at Montana State University.

10. References Cited:

Mamani, M., Tassara, A., and Woerner, G., 2008, Composition and structural control of crustal domains in the central Andes: Geochemistry Geophysics Geosystems, v. 9.

Mamani, M., Worner, G., and Sempere, T., 2010, Geochemical variations in igneous rocks of the Central Andean orocline (13o S to 18o S): Tracing crustal thickening and magma generation through time and space: Geological Society of America Bulletin, v. 122, no. 1-2, p. 162-182.

Michelfelder, G., Feeley, T., Wilder, A., and Klemetti, E., 2013, Modification of the Continental Crust by Subduction Zone Magmatism and Vice-Versa: Across-Strike Geochemical Variations of Silicic Lavas from Individual Eruptive Centers in the Andean Central Volcanic Zone: Geosciences, v. 3, no. 4, p. 633-667.

Michelfelder, G. S., Feeley, T. C., and Wilder, A. D., 2014, The Volcanic Evolution of Cerro Uturuncu: A High-K, Composite Volcano in the Back-Arc of the Central Andes of SW Bolivia: International Journal of Geosciences, v. 5, no. 11, p. 1263.

Muir, D. D., Blundy, J. D., Hutchinson, M. C., and Rust, A. C., 2014, Petrological imaging of an active pluton beneath Cerro Uturuncu, Bolivia: Contributions to Mineralogy and Petrology, v. 167, no. 3, p. 1-25.

Sparks, R. S. J., Folkes, C. B., Humphreys, M. C. S., Barfod, D. N., Clavero, J., Sunagua, M. C., McNutt, S. R., and Pritchard, M. E., 2008, Uturuncu volcano, Bolivia: Volcanic unrest due to mid-crustal magma intrusion: American Journal of Science, v. 308, no. 6, p. 727-769.