Elucidating geochemical heterogeneity and evolution of the explosively erupted Curacautín magma, Llaima volcano, Chile

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Introduction & Background

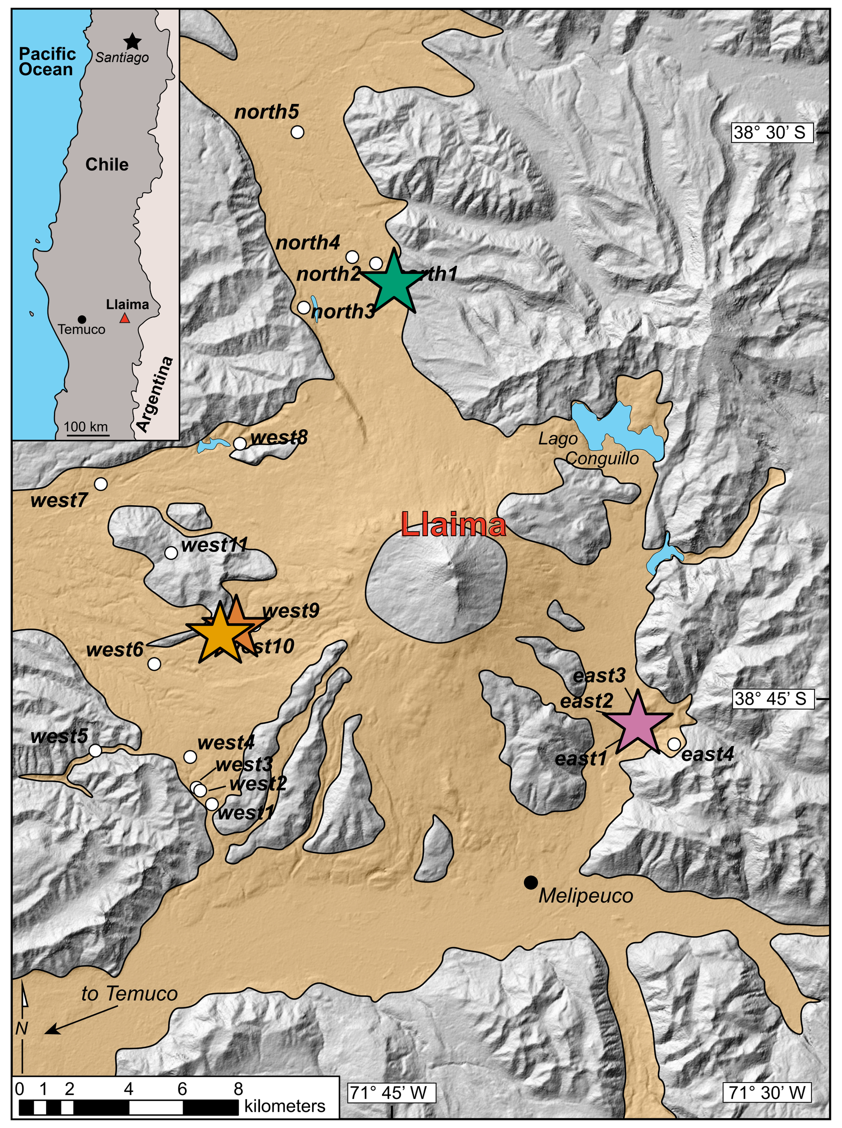
1. Problem

Mafic explosive eruptions are among Earth's most hazardous volcanic phenomena due to their rapid magma ascent rates limiting the time frame for eruption early detection and public warning systems [ref. 1-6]. Despite this concern, we do not understand how these eruptions geochemically differ from other mafic eruptions at the same volcanic center.

2. Approach

Here we present a case study focusing on the petrogenesis of the Curacautín ignimbrite, a mafic ignimbrite at Llaima Volcano, Chile, produced by a mafic explosive eruption around 12.6 ka [ref. 7]. Geochemical variability is investigated using major and trace element ratios, radiogenic isotopes, and agglomerative hierarchical clustering analysis to distinguish between fractional crystallization and source material heterogeneity.

3. Curacautín Ignimbrite Geochemistry



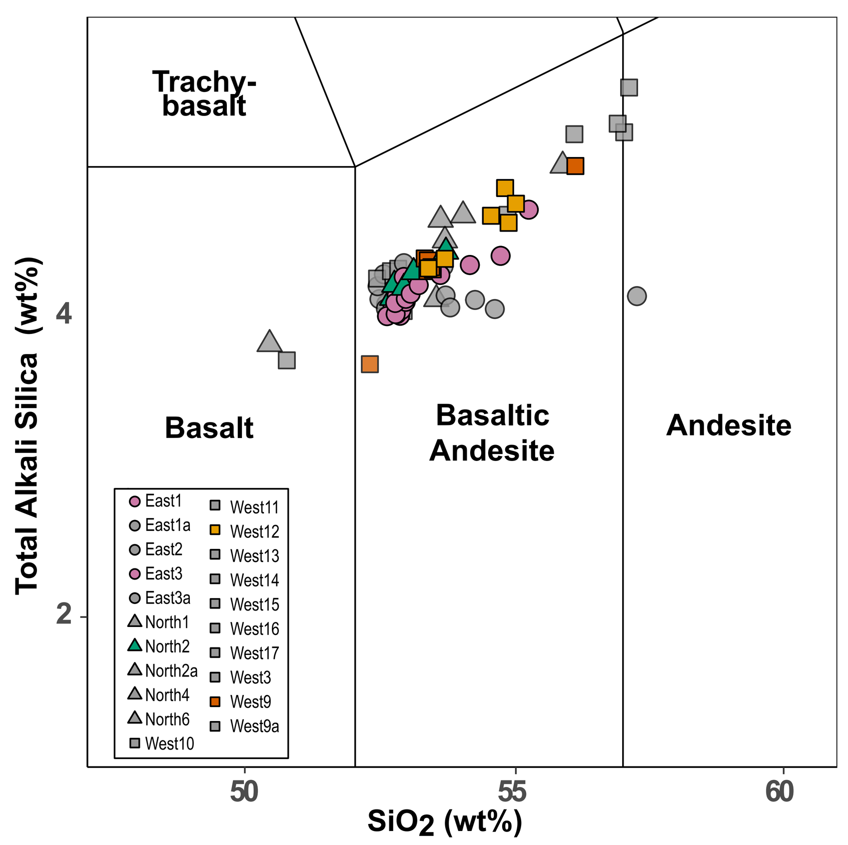


Figure 1. Map showing the location of Llaima volcano, Chile (left). Yellow polygon represents mapped extent of Curacautín ignimbrite. Locations of sampled outcrops are indicated by white circles and the four major exposures are indicated by stars. Total Alkali versus Silica [TAS] (top). Samples collected from the four key exposures are highlighted, all other samples are gray. Curacautín is primarily basaltic andesite.

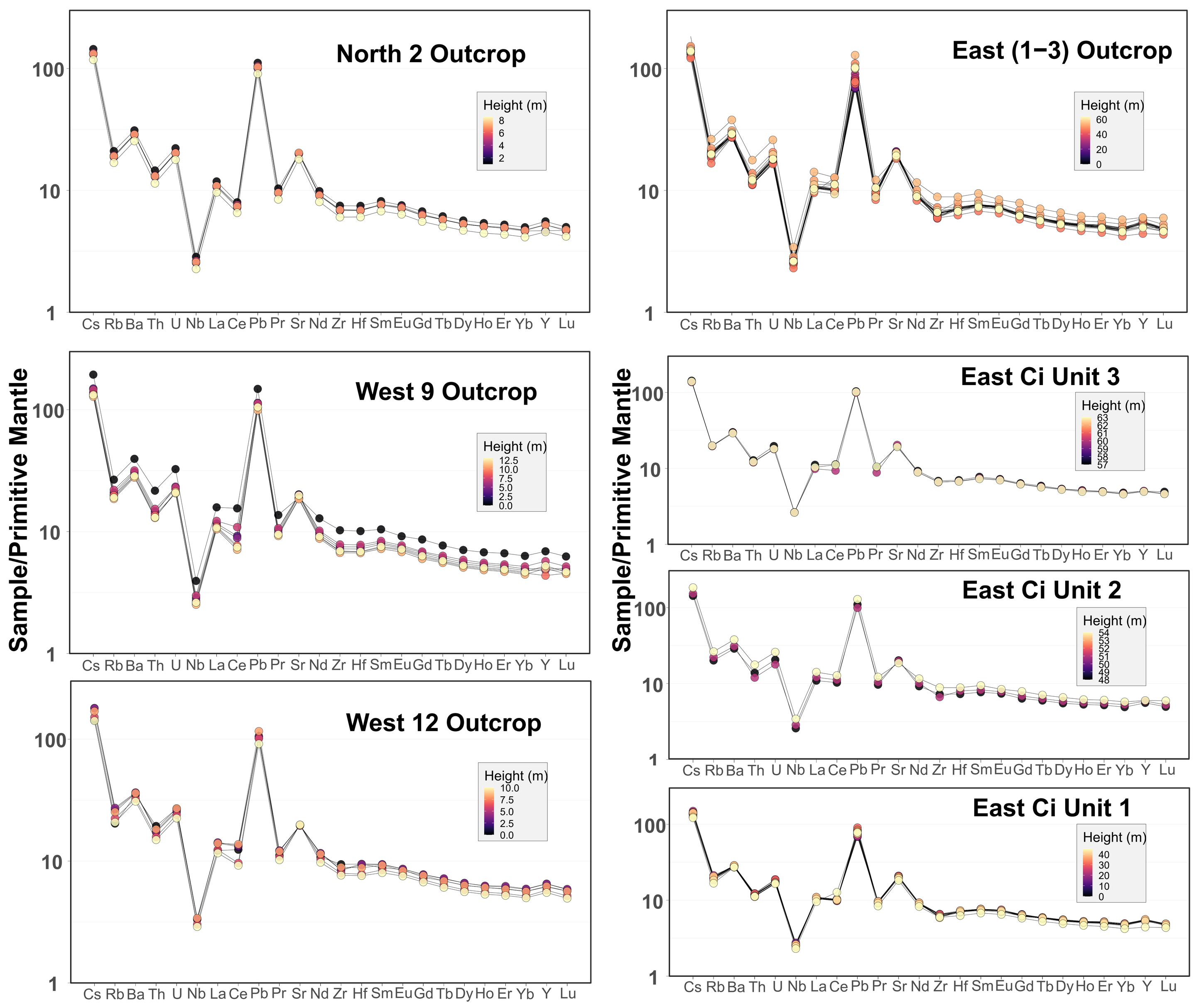


Figure 2. Trace element contents for the four stratigraphic outcrops: North 2 (top left), West 9 (middle left), West 12 (bottom left), East 1-3 (top right), and the three east units are parsed out (unit 3 is top of outcrop and unit 1 is the bottom unit). Data is colored by stratigraphic height; darker colors represent the base of the outcrop and colors get lighter with increasing stratigraphic height.

Understanding Geochemical Heterogeneity

1. Hierarchical Clustering

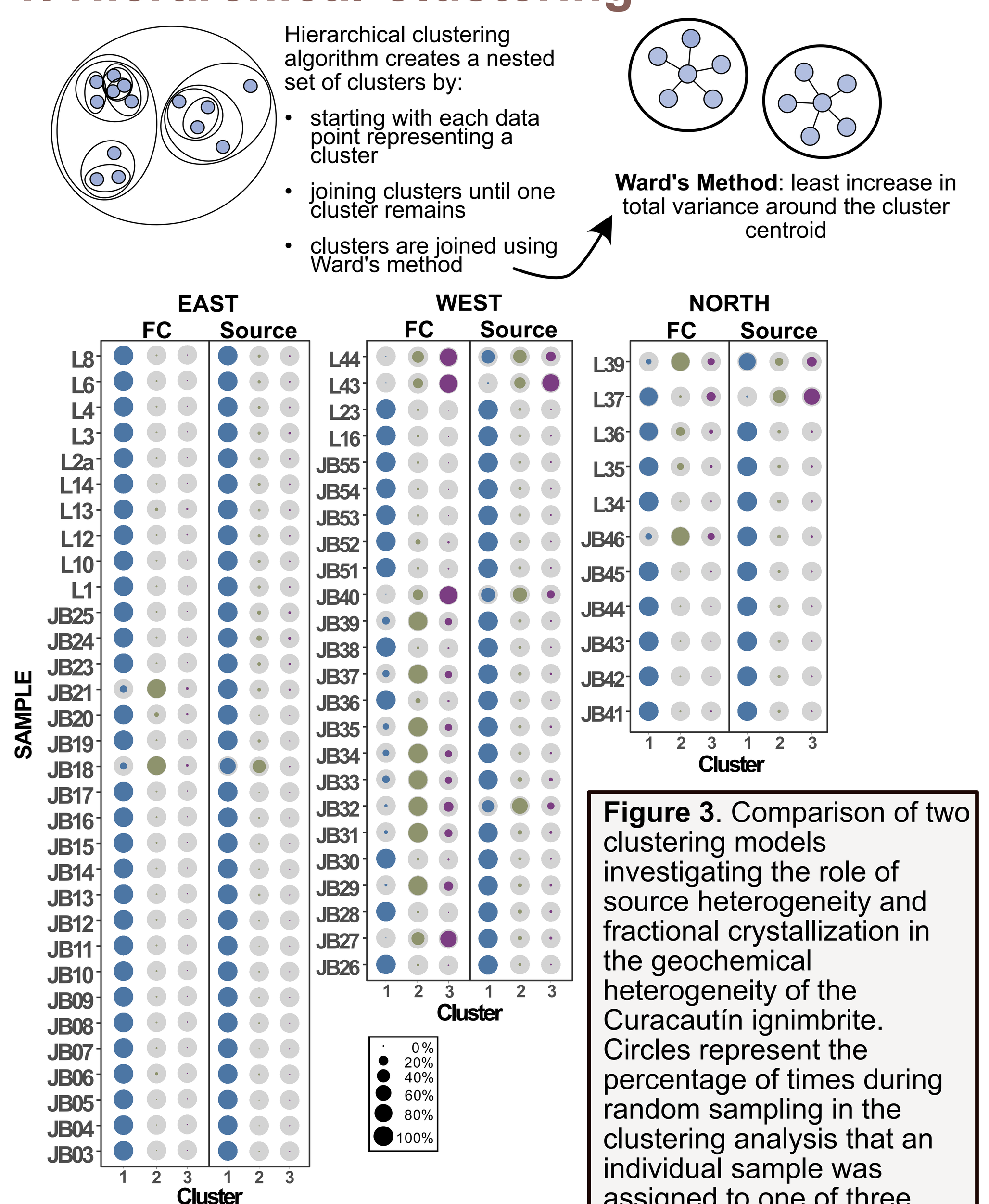


Figure 3. Comparison of two clustering models investigating the role of source heterogeneity and fractional crystallization in the geochemical heterogeneity of the Curacautín ignimbrite. Circles represent the percentage of times during random sampling in the clustering analysis that an individual sample was assigned to one of three possible clusters.

- Unratioed REE concentrations are used in the FC model because concentrations will vary as fractionation occurs
- REE are ratioed to remove effect of FC on concentrations and focus on subduction processes influence on source material compositions
- Fewer clusters are stable in the Source model
- More clusters in the FC model indicates FC is the dominant process influencing geochemical variability
- Samples that are assigned cluster 2 or 3 in Source model indicate potential mixing end members

3. Subducted sediments

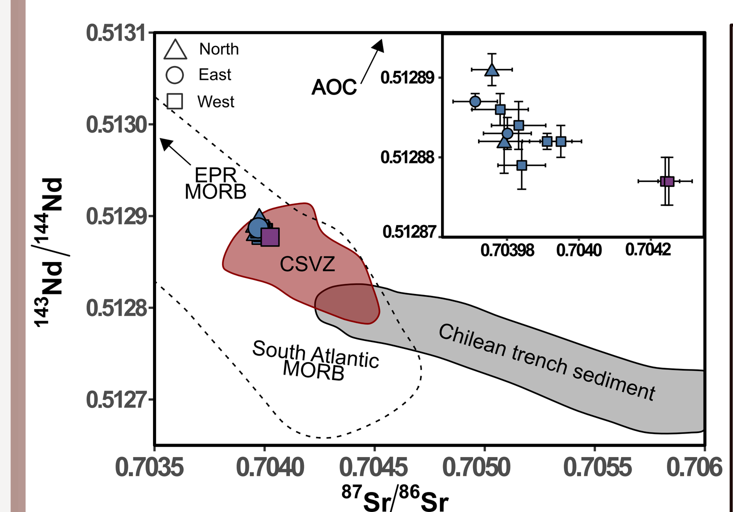


Figure 8. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$. The Curacautín samples form a group of elevated $^{143}Nd/^{144}Nd$ compared to most of the CSVZ volcanic arc, shifted to more depleted compositions. The single Source cluster 3 sample is more similar to CSVZ samples, slightly more enriched source than the rest of the Curacautín sample. Errors are 2σ.

2. Assimilation and Fractional Crystallization

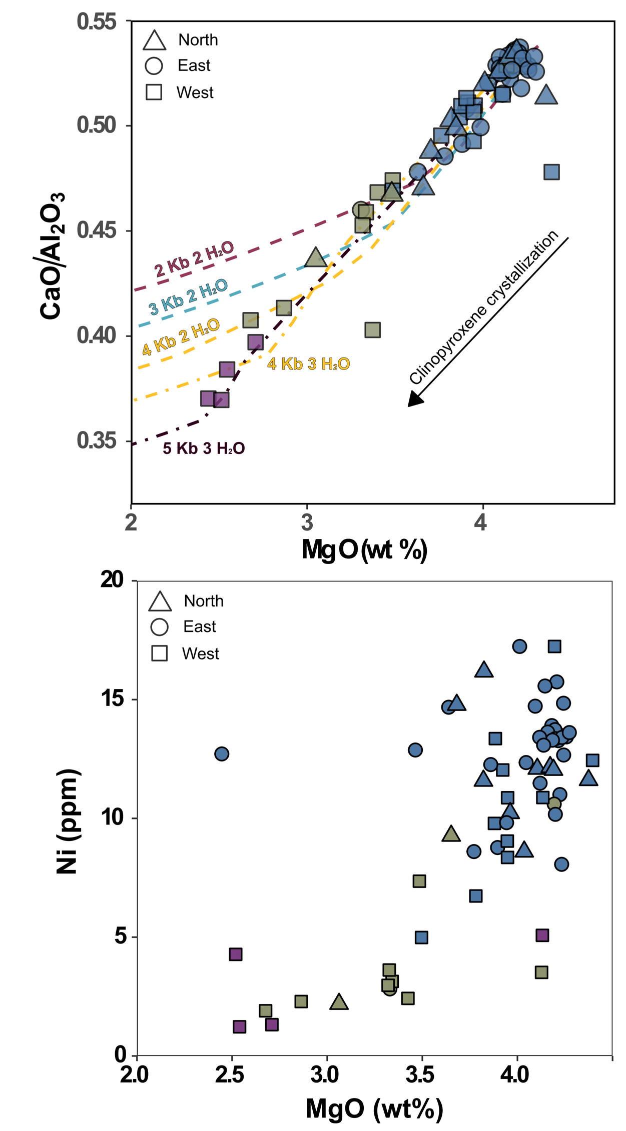


Figure 4. (top) Cluster assignments from the FC model are plotted with MCS fractionation paths to highlight FC as the dominant process influencing the geochemical variability of the samples. Colors match those assigned to the three clusters in Figure 3. The FC model cluster 1 (blue) contains the least fractionated of the samples and FC model cluster 3 (purple) is primarily the most fractionated. (bottom) Cluster assignments and compatible trace elements (e.g. Ni in Olivine) highlight multiple evolution trajectories.

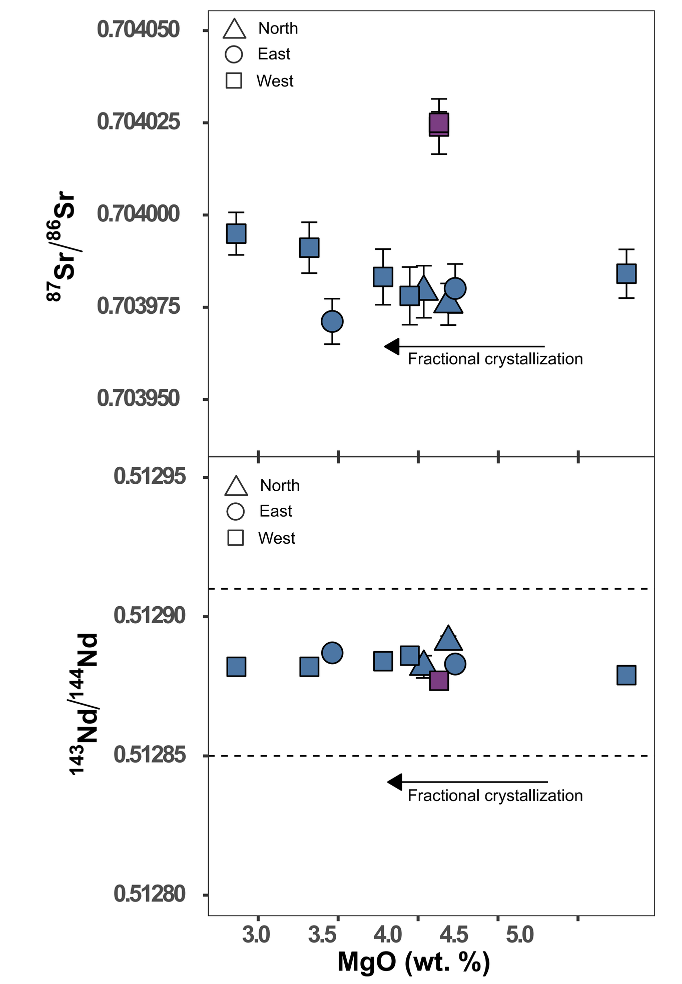


Figure 5. MgO versus (top) $^{87}Sr/^{86}Sr$, (bottom) $^{143}Nd/^{144}Nd$ for Curacautín ignimbrite. The data can be explained by crystal fractionation indicated by the horizontal arrow. The only suggestion of contaminant assimilation is the deviation in $^{87}Sr/^{86}Sr$ between cluster 1 samples and the cluster 3 sample. Errors are 2σ.

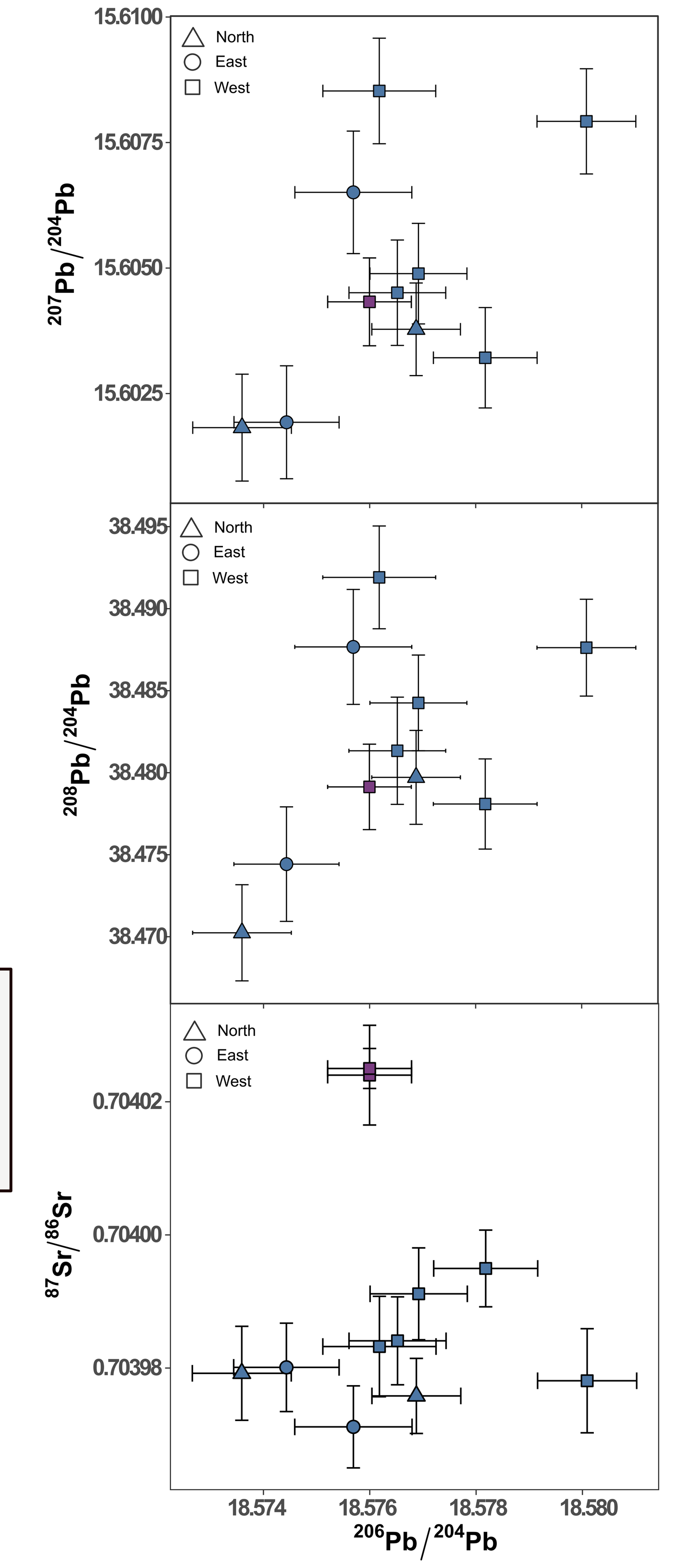


Figure 6. $^{206}Pb/^{204}Pb$ versus (top) $^{207}Pb/^{204}Pb$, (middle) $^{208}Pb/^{204}Pb$, and (bottom) $^{87}Sr/^{86}Sr$. Source clustering model does not explain variability in $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, or $^{206}Pb/^{204}Pb$, but does capture variability in $^{87}Sr/^{86}Sr$. Errors are 2σ.

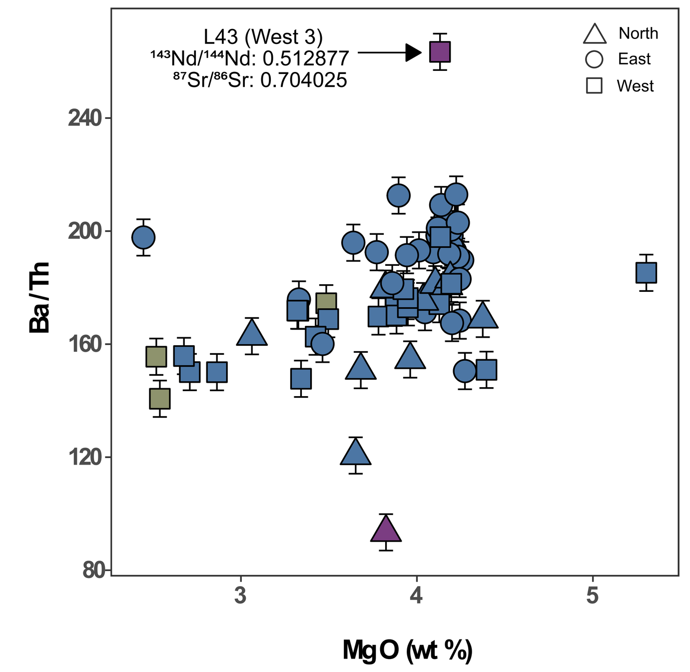


Figure 7. MgO versus Ba/Th (right). Vertical trend in Ba/Th with little variability in MgO (wt. %) at 4.1 wt. % reflecting mixing with L43, potentially enriched in Ba by assimilation of young crustal roots. Errors are 2σ.

Scan to Learn More

4. Fluid Flux and Degree of Melting

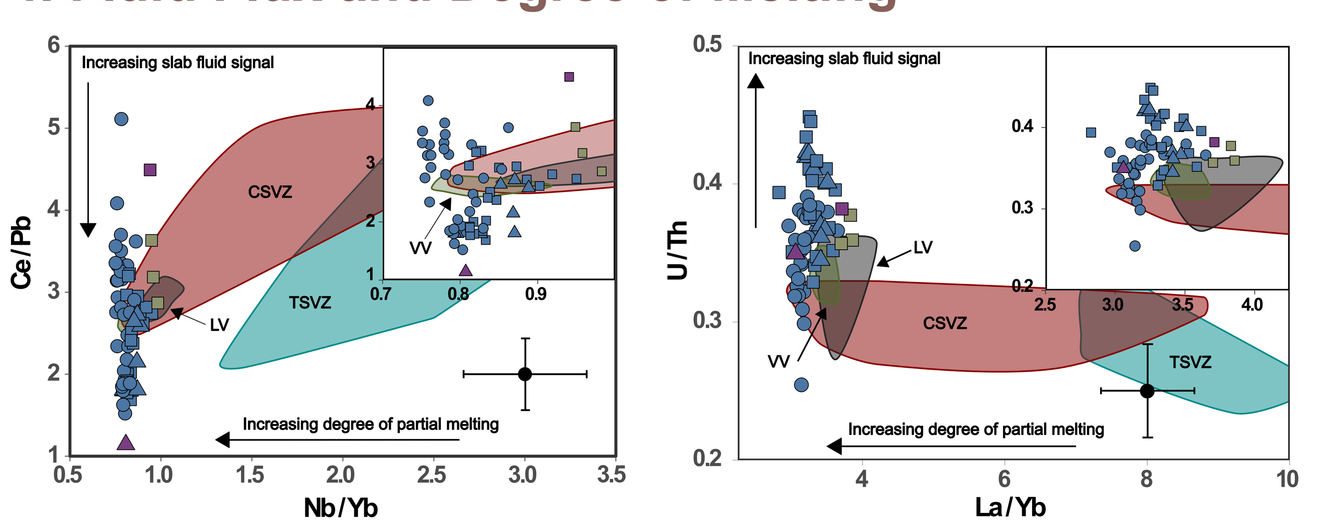


Figure 9. Nb/Yb versus Ce/Pb (left). The Curacautín samples define a vertical trend with variation in Ce/Pb, potentially reflecting mixing between a high slab fluid source and an end member with less slab fluid influence, and the lowest Nb/Yb of the CSVZ (red), TSVZ (blue), Villarrica (green), and other published Llaima (gray) data, reflecting the highest degrees of melting or derivation from a more depleted source material. La/Yb versus U/Th (right). The Curacautín samples show some vertical spread in U/Th and overlap with the lowest La/Yb values in the CSVZ volcanic arc consistent with a higher slab component and higher degree of melting/more depleted source material. Errors are 2σ.

Interpretations

- MELTS fractional crystallization models capture CPX crystallization at 5000 bars with 3 wt. % H_2O in the melt
- L43 (West 3) slightly elevated $^{87}Sr/^{86}Sr$ in comparison to other Curacautín samples and high Ba/Th reflecting an mixing end member representing assimilation of young crustal roots
- No evidence for sediment derived melt in Curacautín mantle source
- High slab-derived fluid flux can be explained by subduction of the more hydrated crust in the Valdivia Fracture Zone
- High fluid flux causes elevated degree of partial melting in the mantle wedge
- Fractional crystallization is the primary process driving geochemical variability
- A secondary mixing signal is highlighted in the clustering analysis, MgO versus selected trace elements, and radiogenic strontium
- We propose assimilation of young crustal roots and high slab-derived fluid flux in the mantle wedge influenced the melt source material of the Curacautín magma.

The signature of slab-derived fluid flux (e.g., Ce/Pb, U/Th) of the Curacautín samples is higher than any other CSVZ deposits, potentially influencing eruption dynamics of the Curacautín magma.

Acknowledgments

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References

[1]Coltelli *et al.*, 1998. *Geology*. [2]Sable *et al.*, 2006. *JVGR*. [3]Szramek *et al.*, 2006. *JVGR*. [4]Szramek, 2016. *JGR: Solid Earth*. [5]Arzilli *et al.*, 2019. *Nature Geoscience*. [6]Valdivia *et al.*, 2021. *BullVolc.* [7]Marshall *et al.*, 2021. *JVGR.*