RECHARGE-ASSIMILATION-FRACTIONATION-TAPPING ("RAFT") PROCESSES AND MAGMA ENRICHMENT IN THE CENTRAL ANDES

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RESUMEN: La variación restringida de los enriquecimientos isotópicos y amplia de los enriquecimientos de elementos trazas observados en la ZVC puede ser satisfactoriamente explicada por la contaminación cortical de un magma basáltico empobrecido con la simultánea occurencia de cristalización fraccional y recarga magmática. El aumento exponencial en la concentración de elementos incompatibles en el líquido durante la crystalización fraccionale evita que la composición isotópica tenga mayores cambios. Todos estos enriquecimientos pueden ser explicados con sólo un 15% de contribución cortical al sistema magmático, sin necesidad de invocar una fuente de manto enriquecido.

KEY WORDS: Central Andes; Volcanics; Crustal contamination; Isotopes; Trace elements

INTRODUCTION

Miocene to Recent subduction-related volcanic rocks of the Central Volcanic Zone (CVZ) of the Andes occur in a region of exceptionally (ca 70 km) thick continental crust. In comparison with Andean arc volcanics from areas of thinner (<40km) crust the CVZ lavas have: extremely high abundances of incompatible elements; enriched isotope ratios (e.g. $^{87}Sr/^{86}Sr > 0.7055$, $\varepsilon_{Nd} < -2$); and generally more evolved bulk compositions (basaltic andesite to rhyolite, with minor shoshonites in the eastern part of the arc). The genesis of these rocks and, especially, how they acquired their enriched chemical character is central to the following questions:

(I) Is there widespread enrichment of the mantle beneath the Central Andes?

(II) What is the balance in the Central Andes between crustal growth by addition of magma from the mantle and crustal recycling by intracrustal contamination of mantle-derived magmas?

Proposed explanations for the CVZ lava enrichments include: (1) involvement of the magmas with enriched lithospheric mantle (Rogers & Hawkesworth, 1989); (2) enrichment of the mantle source with subducted crustal material (Stern, 1991); and (3) intracrustal contamination of formerly depleted magmas (Wörner et al., 1992). The first two explanations imply widespread mantle enrichment under the CVZ but the third requires no enriched source. The explanations also imply crustal growth which is: almost equal to (explanation 1); a little less than (explanation 2); or substantially less than (explanation 3) the mass of young CVZ igneous rocks.

In this contribution we use new techniques for quantitative geochemical modelling to test the ability of intracrustal contamination to produce the enrichments observed in the CVZ magmas.

CAN INTRACRUSTAL CONTAMINATION EXPLAIN THE ENRICHMENTS?

Although there is ample evidence that *some* intracrustal contamination has affected the CVZ lavas, previous quantitative crustal contamination models have failed to account adequately for the observed enrichments. Simple bulk mixing calculations produce conflicting results for different elements and the *combined* process of assimilation with fractional crystallization (AFC; DePaolo,1981) has been rejected by workers such as Feeley & Davidson (1992), even although the CVZ rocks are highly fractionated, because of the general lack of correlation between isotopic ratios (which change with contamination) and element abundances or ratios (which change mainly by crystal fractionation). Apart from one or two exceptional centres (e.g. Ollague) with clear chemical evidence for the operation of upper crustal AFC processes, the vast majority of CVZ centres have an extremely small range of isotopic compositions coupled with an enormous range of enriched trace element abundances.

New techniques

The new techniques of Aitcheson & Forrest (1993) allow isotopic data from real rocks to be inverted by means of simple equations which are solved to give independent estimates of the relative rates of assimilation, fractional crystallization and magma recharge. These equations also explicitly quantify the crustal component and its dependence on the rate of venting or eruption. The existence of a solution means that all of the isotopic data from the sample being studied can be reconciled by a Recharge-Assimilation-Fractionation-Tapping ("RAFT") process. Having obtained this information, and given reasonable endmember concentrations and bulk distribution coefficients, it is possible to predict the concentrations of any other elements in the liquid (sample) and thus to test (by comparison with the observed sample composition) whether the isotope data and estimates of relative rates of assimilation, fractional crystallization, etc. are also consistent with the trace element data.

Application to the CVZ

We used these new techniques to test the ability of crustal contamination of a typical depleted arc basalt to produce the isotopic and trace element enrichments observed in the northern part of the CVZ. We used a depleted parental magma composition similar to that at Okmok in the Aleutian arc (Nye & Reid, 1986) with ε_{Nd} =+8.5 and $^{87}Sr/^{86}Sr$=0.7033. We estimated the contaminant composition from our analyses of basement rocks and crustal xenoliths from the northern Altiplano of Bolivia and Chile and allowed this composition to vary within reasonable limits to reflect crustal heterogeneity. Bulk distribution coefficients were based on various proportions of the minerals olivine, orthopyroxene, clinopyroxene, amphibole and garnet in the fractionating assemblage, plus published distribution coefficients for the different elements in these minerals with respect to basaltic melts. Note that Sr will behave incompatibly since in general there is no evidence for plagioclase removal from the liquids.

Results

For every sample we have investigated so far it has been possible to reconcile all of the isotopic data by the RAFT process, although the relative rates of assimilation, fractionation and recharge obtained vary slightly

	$\bar{M}_a : \bar{M}_c : \bar{M}_r$	Crust/magma Max.	Min.
VOLCAN PARINACOTA (18°S)			
Side crater eruption (BA*)	0.17: 1 :0.25	0.20	0.16
Side crater eruption (BA)	0.15: 1 :0.15	0.15	0.14
"Healing flow", old crater (BA)	0.15: 1 :0.15	0.16	0.15
(Cone collapse, sealing, new cone buildup)			
Andesite from old cone	0.22: 1 :0.40	0.24	0.18
GENERALIZED LEAST-ENRICHED NORTH CVZ COMPOSITION			
N. CVZ "baseline" compositions	0.15: 1 :0.48	0.17	0.12

Table 1: Examples of results of RAFT calculations for samples from the northern CVZ. $\bar{M}_a$:$\bar{M}_c$:$\bar{M}_r$ are the relative rates of assimilation, fractional crystallization and magma recharge. The crust/primitive magma mass ratio is that for the whole system. The maximum value corresponds to no venting prior to sample formation, while the minimum value is that at maximum venting rate, here assumed to equal the rate of recharge. BA is basaltic andesite, * is sample PAR-11 (see Fig.1).

from sample to sample. Table 1 illustrates some of these results for samples from a single centre (Parinacota, 18°S, N. Chile) and for a generalized least-enriched "baseline" composition for centres along the volcanic front in the northern CVZ. When these results are used to predict the trace element patterns of the samples we find that there is excellent agreement between the calculated and observed patterns, demonstrating that RAFT can also explain the trace element enrichment patterns in the CVZ (e.g. Fig.1). In general even the most extreme enrichments can be achieved with as little as 15% crust in the system. The RAFT equations may also be used to compute how much liquid remained in the system at the time of sample formation. These calculations indicate that, in general, at the time of eruption of the CVZ samples less than 10% of the systems were still liquid; >90% of the system had already crystallized as cumulates which presumably remained hidden in the lower crust.
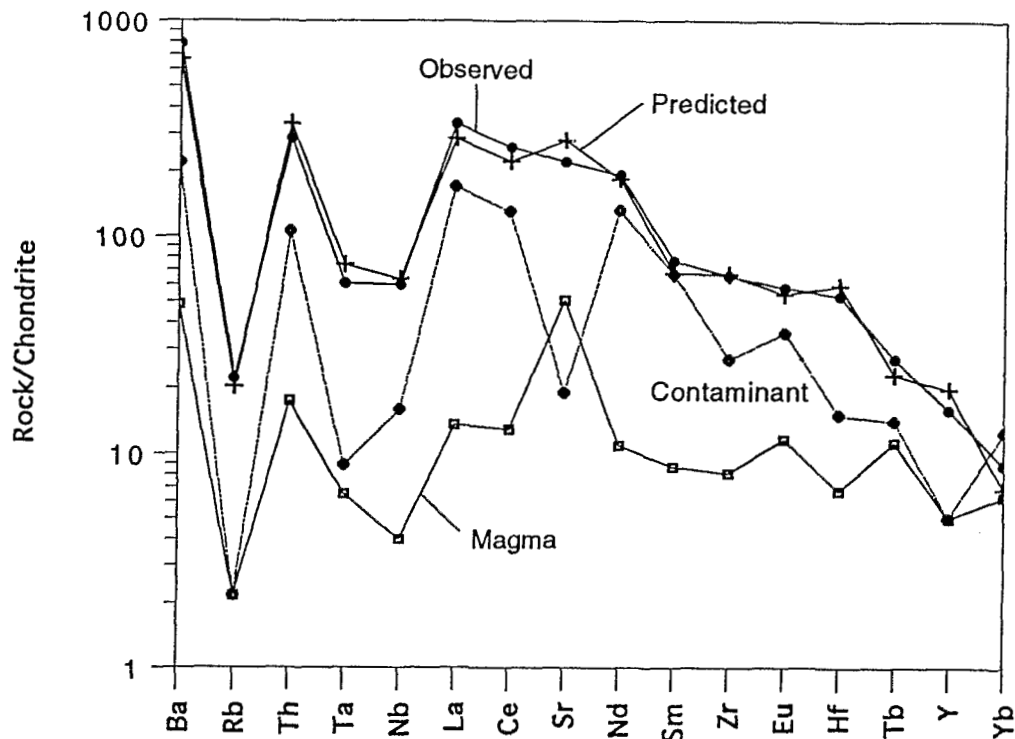

Figure 1: Chondrite-normalized spider diagram illustrating the calculated composition of sample PAR-11, the youngest basaltic andesite erupted at Parinacota, which was computed using the RAFT equations with the end member compositions shown in the figure, the results in Table 1, and assuming a fractionating assemblage of 9% olivine, 63% clinopyroxene, 7% orthopyroxene, 18% amphibole and 3% garnet. The measured composition is also shown for this sample and agrees closely with the computed composition, demonstrating that the RAFT process can explain both the isotopic and trace element enrichments in the sample. Compositions are normalized to the chondrite composition given by Anders & Ebihara (1982).

BUFFERING OF CVZ ISOTOPIC COMPOSITIONS BY THE RAFT PROCESS

The RAFT equations can readily predict the evolution of the isotopic and trace element composition in a magma, given reasonable endmember compositions, bulk distribution coefficients and relative rates of assimilation, fractional crystallization, etc. In the CVZ magmas the incompatible element concentrations

increase exponentially due to crystal fractionation. The isotopic composition of the liquid therefore soon becomes <u>buffered</u> against further change by the high concentration of that element in the liquid. For liquids (such as most CVZ magmas) erupted only after this concentration buffer was in force, a narrow range of enriched isotopic compositions and a wide range of high incompatible element concentrations are inevitable. On a plot of isotopic ratio vs. element concentration the samples will define an elongate field parallel to the concentration axis. Broadly similar end member compositions, fractionating minerals and physical nature of the magmatic plumbing systems will cause liquids to be buffered at about the same isotopic composition. This is presumably why the isotopic compositions of CVZ volcanoes are so similar from centre to centre.

CONCLUSIONS

(1) Crustal contamination of a depleted arc basalt can satisfactorily explain the isotopic and trace element enrichments observed in the CVZ if fractional crystallization and magma recharge were also occurring. There is thus no need to invoke an enriched mantle source for these magmas, although the existence of such a source cannot be excluded.

(2) A restricted range of isotopic compositions occurs together with a wide range of enriched trace element concentrations because crystal fractionation causes incompatible element abundances to rise exponentially in the liquid and this quickly buffers the isotopic composition of the liquid against further change.

(3) Some 85% of the total mass of CVZ igneous rocks, including hidden cumulates, represents new (i.e. mantle-derived) continental crust. The calculations suggest that less than 10% of the magmatic system is visible at the surface. Together this suggests that magmatism has caused an increase in the crustal thickness of about 5 km under the Central Andes.

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