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Assimilative recycling of the plutonic roots of Andean arc volcanoes: Rates, physical mechanisms, and geochemical consequences

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Introduction

Interpreting the elemental and isotopic compositions of mafic arc magmas in terms of mantle processes and components and determining how these relate to the geodynamics of subduction zones are important motivations for studying of arc magmatism. In the case of continental arc volcanism, achieving this goal depends critically on a demonstration that the geochemical signature imparted by magma generation processes acting on the magma's source-region has not been modified by open-system processes during intra-crustal evolution. Ascent through 25-70 km of lithologically diverse crust leads inevitability to interactions between magma and wall rocks (dike wall erosion, assimilation via stoping, mixing with crustal melts), and to mixing of new ascending magma batches with magmas (contaminated or not) and/or cumulate crystal-mush zones already residing in the subvolcanic conduit/reservoir system. Thus, the compositions of many mafic continental arc magmas are the integrated sums of diverse polybaric, multi-component, multi-process evolution paths, wherein mantle geochemical signatures have been variably overprinted (Dungan *et al.*, 2001). One of the consequences of magma ascent in mature, long-lived continental arcs is that crust-magma interactions will be increasingly restricted to only slightly older plutonic lithologies dominated by mantle-derived components, leading to elemental overprints on primary signatures which should be accompanied by radiogenic isotope variations that may not greatly exceed the initial mantle-derived range: *i.e.*, the isotopic range defined by variably contaminated magmas may diminish with time as the crust is heated, hydrated, and hybridized by intrusions of mafic to silicic magma. Conversely, increasing contributions from isotopically evolved pre-arc crust, hence greater isotopic diversity in the eruptive products of the arc, may characterize periods of lateral arc migration. Such patterns are observed in the Andean Southern Volcanic Zone (SVZ; 33-46E S).

The Andean Southern Volcanic Zone

Distinguishing the sources and processes implicated during the addition of crustal components to continental arc magmas is an especially important endeavor in the SVZ, particularly in the northern SVZ where both extensive crust-magma interaction (Hildreth and Moorbath, 1988) and large-scale modification of the asthenospheric mantle wedge (Stern, 1991; Kay et al., 2004) have been proposed. Whereas there is strong evidence that truncation of the continental margin accompanied Neogene crustal shortening and thickening as the arc migrated to the east (36-33ES), the mechanism(s) whereby subducted crust might be transferred to the mantle wedge, the rates of such processes, and the consequences for elemental and isotopic compositions of magmas generated in this modified mantle are far less clear. The mantle window becomes increasingly clouded northward in the Quaternary SVZ by the virtual certainty that magma passage through increasingly thick, fertile and old (hence isotopically evolved) crust masks mantle signatures, which ultimately become almost impossible to rigorously assess north of 34.3ES due to the absence of erupted mafic magmas. Although some mantle source heterogeneity must be imposed by the transfer of subducted components to the asthenospheric wedge, there are no basalts in the Quaternary SVZ that unequivocally record wholesale modification of the mantle by massive incorporation of crustal material. When the segments of the Quaternary arc (Dungan et al., 2001) are compared, evolution trends on process-sensitive elemental diagrams appear to diverge from similar parental compositions, and the most robust criteria that distinguish these trends are manifested in the most evolved magmas. If these divergent patterns correctly reflect the processes and components involved in SVZ magmatism, the distinctions among segments are complex functions of intra-crustal magma evolution, not indicators of rapid transformations of the mantle by the incorporation of variable amounts of subducted crust.

An SVZ plutonic-volcanic transect (35-38ES) and the significance of 36ES

Within this transect, the boundary at 36ES between the Palomo-Tatara and Longaví-Osorno segments (Dungan et al., 2001) marks the eastward stepping of the arc away from the present-day eastern limit of the Central Valley, a consequent shift of the Quaternary arc onto thicker continental crust (Andres Tassara, personal communication), and marked changes in magmatic associations and compositions of evolved magmas. High-SiO_2 rhyolite, which is nearly unknown south of 36ES, abruptly appears as a volumetrically significant magma type from the Tatara San Pedro complex (TSPC) to Laguna Del Maule (all at –36ES). The subducted oceanic Mocha Fracture Zone (MFZ) projects under the arc at this latitude (Sellés et al., 2004; Rodríguez et al., 2005), and the age of the subducted plate is older north of the MFZ. Although the arc appears to have remained nearly stationary since 17 Ma at 38ES, from 36ES to 35ES the ages of plutonic rocks record a –30 km eastward shift in position between 17-15 Ma and 11-7 Ma, and the Quaternary arc is superimposed on the –10 Ma plutons. The Sr and Nd isotopic compositions of Miocene batholiths (–18-7 Ma) underlying the SVZ in the region of 35-38ES are dominated by values that are not substantially different from those of spatially associated Quaternary mafic magmas (Lucassen et al., 2004), although there is a subtle increase in the $^{143}Nd/^{144}Nd$ of Quaternary magmas southward from the TSPC to Volcán Lliama (38.6ES). Despite the absence of important temporal or spatial changes in the isotopic compositions of these late Tertiary plutons, the chemistry of the batholithic rocks apparently mirrors distinctly different *elemental* contamination trends in some overlying Quaternary volcanoes (*e.g.*, Tatara-San Pedro complex at 36ES versus Antuco-Sierra Velluda at 37.3ES). Whether this reflects assimilation in the upper crust, mixing with deep crustal melts comparable in composition to the granitoid batholiths, or both, is undetermined, but this does not detract from the apparent importance of inherited 'crustal' signatures derived from the young plutonic roots of the arc, wherein isotopic and elemental indices of open-system evolution are seemingly 'decoupled' due to the importance of mantle-derived components in these plutons.

Recycling of the mafic-ultramafic magmatic roots of the arc

Observations derived from multiple suites of basaltic lavas of the Quaternary Tatara-San Pedro complex (TSPC: 36E S, Andean Southern Volcanic Zone - SVZ; Dungan *et al.*, 2001; Dungan and Davidson, 2004) raise questions about the nature and sources of assimilated components, the dynamic processes associated with assimilation, and conventional interpretations of whole-rock chemistry and isotopic compositions of arc basalts. Dungan and Davidson (2004) suggest that: **(1)** *partial assimilation* of magmatic cumulates containing hornblende and phlogopite, wherein grain-boundary melting and disaggregation of stoped blocks (*e.g.*, Heliker, 1995) leads to incorporation of incompatible element-enriched melts and variable loss of refractory xenocrysts, is a common phenomenon with a large impact on contaminated basalt chemistry, **(2)** that the textures and mineral compositions of xenocrysts retained during assimilative recycling of nominally refractory lithologies offer numerous clues to their origins, and **(3)** the extremely short residence times of such olivine xenocrysts (2-25 years) suggest that there are few thermo-mechanical barriers to this process. Elemental trends consistent with open-system evolution are not correlated with minor isotopic variations in TSPC basaltic suites of varying age (600 to 100 ka).

Conclusions and implications

As continental arc volcanic centers have substantially evolved *average* compositions, the complementary mass of refractory to evolved plutonic material will be comparable to or even greater than the erupted mass. Where arc volcanism is spatially focused for 10^6-10^7 years, the 'percolation column' (Hildreth and Moorbath, 1988) beneath the arc will retain enough heat and volatiles along with this mass that the efficiency of assimilative recycling of even refractory lithologies will be enhanced. Assimilation of plutonic lithologies that are close in age to the host, or mixing with partial melts thereof, will engender isotopic shifts that may not exceed the range defined by the original mantle-derived signal. The absence of isotopic evidence for assimilation in erupted magmas should not be interpreted uncritically as proof that such magmas have passed through the crust without modification of their elemental mantle signatures.

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