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The importance of mantle wedge heterogeneity to subduction zone magmatism and the origin of EM1

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ABSTRACT

The composition of the convecting asthenospheric mantle that feeds the mantle wedge can be investigated via rear-arc lavas that have minimal slab influence. This "ambient mantle wedge" composition (the composition of the wedge prior to the addition of a slab component) varies substantially both worldwide and within individual arcs. $^{143}Nd/^{144}Nd$ measurements of rear-arc samples that have minimal slab influence are similar to $^{143}Nd/^{144}Nd$ in the stratovolcanoes of the adjacent volcanic fronts, suggesting that $^{143}Nd/^{144}Nd$ of arc-front volcanics are largely inherited from the ambient mantle composition. $^{143}Nd/^{144}Nd$ correlates with ratios such as Th/U, Zr/Nb, and La/Sm, indicating that these ratios also are strongly influenced by ambient wedge heterogeneity. The same phenomenon is observed among individual volcanoes from the Chilean Southern Volcanic Zone (SVZ), where along-strike variability of the volcanic front tracks that of rear-arc monogenetic volcanics. Depleted mantle wedges are more strongly influenced by slab-derived components than are enriched wedges. This leads to surprising trace element correlations in the global dataset, such as between Pb/Nb and Zr/Nb, which are not explicable by variable compositions or fluxes of slab components. Depleted ambient mantle is present beneath arcs with back-arc spreading; relatively enriched mantle is present adjacent to continents. Ambient mantle wedge heterogeneity both globally and regionally forms isotope mixing trajectories for Sr, Nd and Hf between depleted mantle and EM1-type enriched compositions as represented by Gough Island basalts. Making use of this relationship permits a quantitative match with the SVZ data. It has been suggested that EM1-type mantle reservoirs are the result of recycled lower continental crust, though such models do not account for certain trace element ratios such as Ce/Pb and Nb/U or the surprisingly homogeneous trace element compositions of EM1 volcanics. A model in which the EM1 end-member found in continental arcs is produced by low-degree melt-metasomatism of the sub-continental lithospheric mantle may be more plausible. The $^{143}Nd/^{144}Nd$ maximum along the SVZ may be a consequence of either rifting and collision of two ancient lithospheric domains or a slab tear. The correspondence of mantle wedge variations with EM1 suggests a potential role for metasomatized sub-continental lithosphere in creating EM1 sources globally.

1. Introduction

The majority of convergent margin volcanics erupt from large arc-front stratovolcanoes. These edifices are the end result of material fluxes from subducted oceanic lithosphere into the overlying mantle wedge, followed by transfer of melts to the crust, where the melts differentiate and sometimes assimilate crustal material. Slab fluxes, mantle melting processes, and crustal differentiation are all well-established controls on magma compositions (e.g., Morris and Tera, 1989; Miller et al., 1994; Elliott et al., 1997; Spandler and Pirard, 2013). While the composition of the sub-arc mantle wedge (the convecting asthenospheric mantle) prior to its metasomatism by slab-derived material is also recognized as an important factor (e.g. Pearce et al., 2007), its significance has received less attention. Understanding how variations in pre-existing wedge composition, or "ambient mantle heterogeneity," influence arc compositions is essential to understand the processes that take place and to quantify the fluxes of elements from slab to mantle and crust.

Significant variability in ambient mantle wedge compositions would be consistent with observations from ocean ridge and in-

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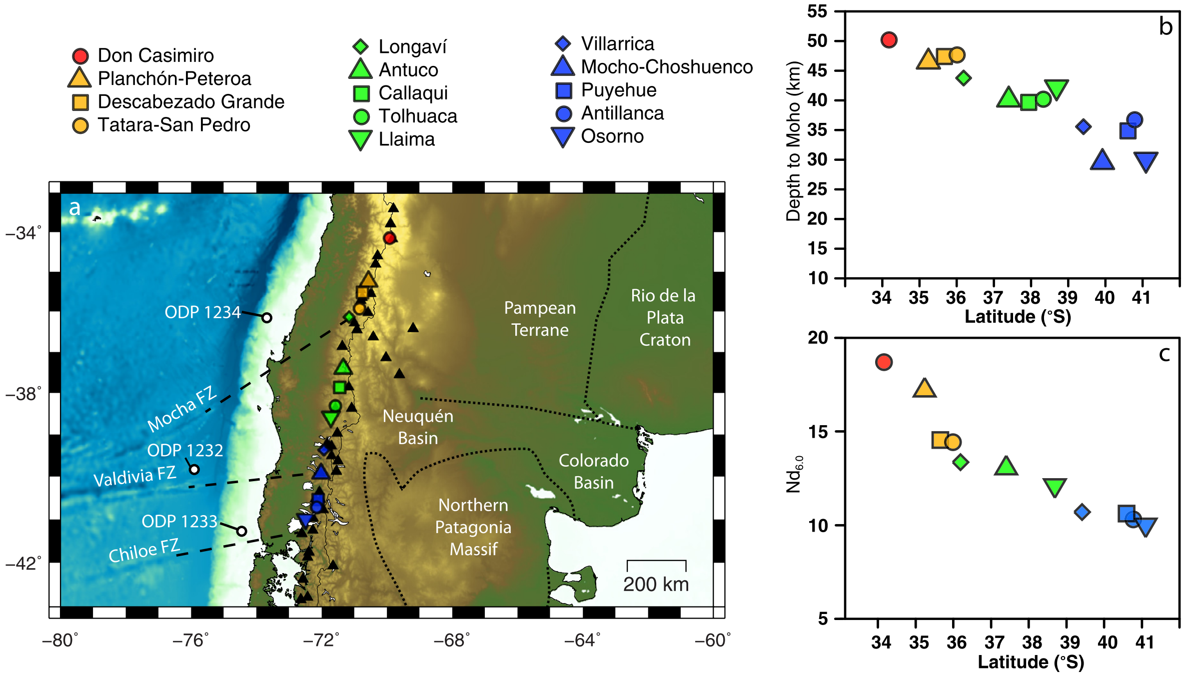

Fig. 1. Panel a) A map of the Chilean Southern Volcanic Zone (SVZ), indicating fracture zones, and their projections beneath the arc front, sediment cores, arc front volcanoes, additional eruptive centers listed in the Smithsonian Global Volcanism Program's Holocene Volcano List (small black triangles), and a simplified representation of the various continental terranes. Panel b) Depth to Moho beneath each of the SVZ arc-front volcanoes included in this study (Tassara and Echaurren, 2012). Panel c) $Nd_{6.0}$ values from Turner et al. (2016). Note that both Moho depth and $Nd_{6.0}$ increase from north to south, in general agreement with the wedge thermal structure model of Turner and Langmuir (2015b) and Turner et al. (2016).

traplate volcanics, which have wide ranges in their trace element and radiogenic isotope compositions. As concentrations of some elements (e.g. Ba, K) vary by two orders of magnitude in mid-ocean ridge basalts (MORBs, Gale et al., 2013), ambient mantle wedge compositions might be expected to encompass similar ranges. Mantle xenoliths from arc settings (e.g., Chin et al., 2014), which sample the sub-arc mantle, provide direct evidence for widespread mantle heterogeneity. Arc magmas with OIB-like enrichments have been identified in the Cascades, Mexico, Central America, and the Andes (e.g., Leeman et al., 1990; Gómez-Tuena et al., 2003; Rogers and Hawksworth, 1989; Kay and Abbruzzi, 1996; Muñoz et al., 2013; Heydolph et al., 2012; Jacques et al., 2013). Several workers (e.g., Ewart and Hawkesworth, 1987; Woodhead et al., 1993; Langmuir et al., 2006) have further demonstrated that island arcs with back-arc spreading centers tend to be derived from ambient mantle sources that are especially depleted, presumably owing to processing of mantle material beneath the spreading center prior to its emplacement beneath the arc front.

A few studies have attempted to assess variations in the ambient mantle compositions among different arcs. Pearce (1983) argued for relatively enriched ambient mantle sources in continental arcs on the basis of trace element abundances, and proposed that the association of enriched lavas with continental settings implies that the melts are partially derived from the sub-continental lithospheric mantle (SCLM). Ambient mantle sources for the arcs of the South Pacific vary in their isotope compositions, with a clear distinction between "Indian" and "Pacific" domains (Pearce et al., 2007). Plank (2005) constrained ambient mantle wedge compositions of various arcs by projecting from known sediment and arc basalt compositions. Cooper et al. (2012) used a similar approach in their evaluation of H_2O/Ce ratios.

Here we extend this evaluation by considering the influence of ambient mantle wedge compositions among subduction zones globally, and within the Chilean Southern Volcanic Zone (SVZ) from 34°S to 41°S. The data demonstrate an association of enriched sources with continental arcs, indicate an end-member that is compositionally similar to EM1-type OIBs, and implicate metasomatized SCLM as the origin of this end-member. Note that this analysis refers specifically to the major volumes of arc magmas produced from stratovolcanoes, and not to the sporadic, rarer occurrences of boninites, shoshonites and other exotic compositions, which are not considered here.

2. General observations that require heterogeneity in the mantle wedge

Turner and Langmuir (2015a, 2015b) showed that the averaged compositions of arc-front stratovolcanoes exhibit positive correlations among almost all incompatible element concentrations. Correlations are present even among trace elements that are traditionally placed into different groups on the basis of their expected behaviors within the subduction system (e.g. fluid-mobile, high-field-strength). Turner and Langmuir (2015a) showed that the compositional variations of these filtered and averaged mafic to intermediate magmas are not the consequences of intra-crustal processes. Turner and Langmuir (2015b) postulated that first-order global-scale variability of arc compositions might be produced by either of two mechanisms: 1) variations of elemental fluxes from slabs to the mantle wedges as a consequence of differences in the temperatures of the subducted slabs, or 2) differences in the thermal structures of mantle wedges that lead to differences in the pressures and extents of mantle melting. For the latter hypothesis, increasing lithospheric thickness leads to higher maximum pressures and lower maximum temperatures in the sub-arc mantle wedge, suppressing the extent of melting and producing different residual mineral assemblages, with increasing residual garnet.

Using major and trace element data from the Chilean Southern Volcanic Zone (SVZ, Fig. 1a), Turner et al. (2016) were able to distinguish between these two mechanisms because crustal thickness along the SVZ varies from 30 to 50 km (Fig. 1b), which should lead to variation in the thermal structure of the mantle wedge, while the slab thermal structure (as indicated by the slab "ther-