



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



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ARTICLE INFO

Article history:

Received 27 December 2016

Received in revised form 22 April 2017

Accepted 30 April 2017

Available online 13 June 2017

Editor: M. Bickle

Keywords:

subduction

SVZ

ambient

mantle

heterogeneity

EM1

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. $^{143}\text{Nd}/^{144}\text{Nd}$ measurements of rear-arc samples that have minimal slab influence are similar to $^{143}\text{Nd}/^{144}\text{Nd}$ in the stratovolcanoes of the adjacent volcanic fronts, suggesting that $^{143}\text{Nd}/^{144}\text{Nd}$ of arc-front volcanics are largely inherited from the ambient mantle composition. $^{143}\text{Nd}/^{144}\text{Nd}$ 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 $^{143}\text{Nd}/^{144}\text{Nd}$ 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.

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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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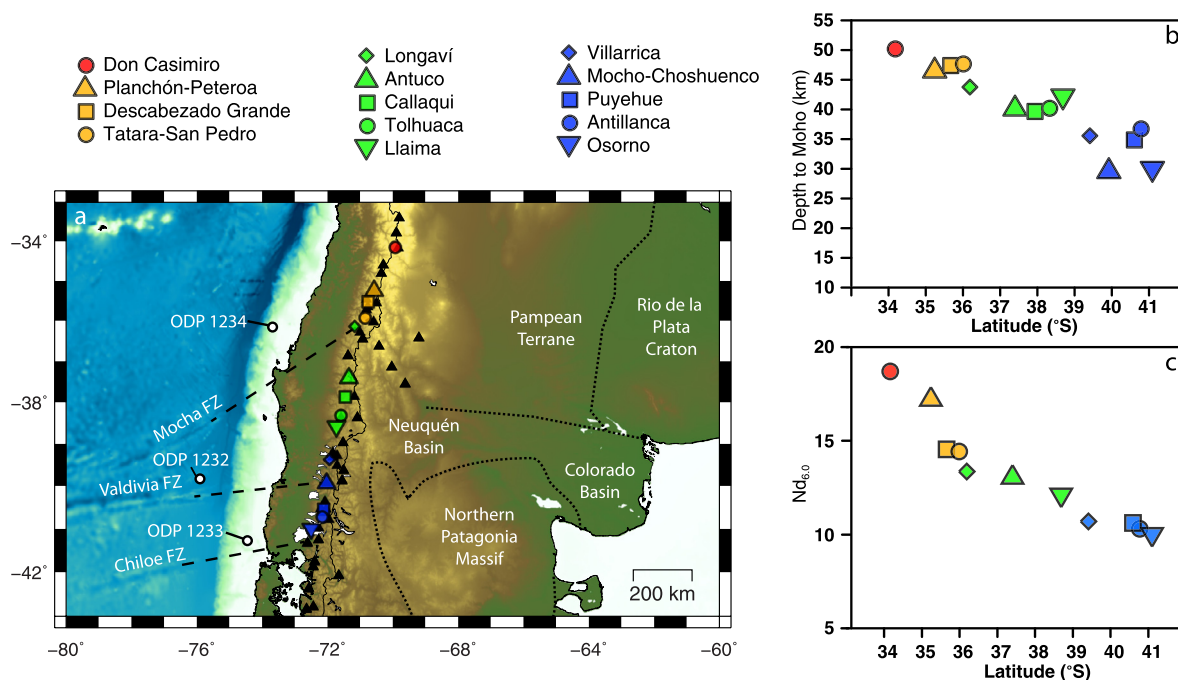


Fig. 1. Panel a) A map of the Chilean Southern Volcanic Zone (SVZ), indicating fracture zones, and their projections beneath the arc front, sediment cores, arc front volcanoes, additional eruptive centers listed in the Smithsonian Global Volcanism Program's Holocene Volcano List (small black triangles), 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 Hawkesworth, 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 H₂O/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-

mal parameter”) is nearly constant. Turner et al. (2016) found that the chemical variability among SVZ volcanoes follows the same element–element and element–ratio trends observed among arc-averaged compositions globally, and that both the SVZ volcanoes and arc segment averages have the same relationship with the thickness of the crust below the arc front. The coincidence of the SVZ and global arc data among elemental abundances and with crustal thickness argues for first-order control by the thermal structure of the mantle wedge. Numerical models support this conclusion. Although variation of the slab flux does not produce this first-order variation among arc-front stratovolcanoes, such effects may emerge in unusual tectonic environments such as ultra-slow convergence regimes (Yogodzinski et al., 2015), slab edges (Portnyagin and Manea, 2008), or subduction of hotspot tracks (Gazel et al., 2015).

The “wedge thermal structure” model does not account for the well-known isotopic variability (e.g. Fig. 2a) among arcs, however. An analogous problem arises for certain trace element ratios, such as Zr/Nb. On the basis of experimentally determined partition coefficients (McDade et al., 2003; Salters and Stracke, 2004; Gaetani et al., 2003; Green et al., 2000) typical extents of mantle melting at arcs (5–20%) lead to less than 30% variation of Zr/Nb, but average Zr/Nb for global arcs varies from 15 to 90. Some individual volcanoes display a significant fraction of this range. The ranges in concentrations of light rare earth elements are also too large to be produced only by varying extents of melting, both globally and within the SVZ. The observed ranges of multiple isotopic and trace element ratios thus require compositional heterogeneities in the mantle sources of arc magmas.

Evidence for compositional heterogeneity of the mantle is also apparent on the regional scale within the SVZ. This assessment makes use of an SVZ dataset filtered to minimize the influence of crustal processes, as outlined by Turner et al. (2016). The along-strike trends in isotope and trace element ratios in Fig. 3 are insensitive to variations in the extent of melting, so must reflect compositional differences in the mantle sources of these lavas. The well-documented variations in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ along the arc (Fig. 3a–b) (Deruelle et al., 1983; Hickey et al., 1986; Hildreth and Moorbath, 1988; Tormey et al., 1991; Jacques et al., 2013, 2014; Hickey-Vargas et al., 2016, and 65 new analyses (supplementary material)) show a maximum in $^{143}\text{Nd}/^{144}\text{Nd}$ and Zr/Nb, and minimum in $^{87}\text{Sr}/^{86}\text{Sr}$ and Th/U midway along the study area near 38°S. This result is difficult to reconcile with an origin by crustal processes, because crustal thickness decreases progressively from north to south (Fig. 1b). Indicators of extent of melting such as $\text{Nd}_{6.0}$ (Fig. 1c) change progressively, correlating with crustal thickness, but $^{143}\text{Nd}/^{144}\text{Nd}$, $^{87}\text{Sr}/^{86}\text{Sr}$, Zr/Nb, and Th/U (Fig. 3) show an inflection midway along the study area.

Hildreth and Moorbath (1988) proposed that along-strike isotopic trends within the SVZ (33–37°S) are produced from similar parental magmas that are variably overprinted in the lower crust in zones of Mixing, Assimilation, Storage, and Homogenization (MASH). Crustal assimilation significantly affects many differentiated magma compositions along the SVZ, and is most prevalent in the northern SVZ, where the crust is thickest. Most regional studies of the SVZ following Hildreth and Moorbath (1988), however, have found that potential lower crustal assimilants, as well as the general geochemical variability among mafic SVZ magmas at single volcanoes and along the arc, are inconsistent with a pervasive and long-term MASH zone (e.g. Tormey et al., 1991; Ferguson et al., 1992; Dungan et al., 2001; Jacques et al., 2013, 2014; Turner et al., 2016). The MASH model is also unable to account for southward increases in $^{87}\text{Sr}/^{86}\text{Sr}$ from ~39°S to ~42°S, which occur as the crust becomes progressively thinner and elemental signals of assimilation diminish.

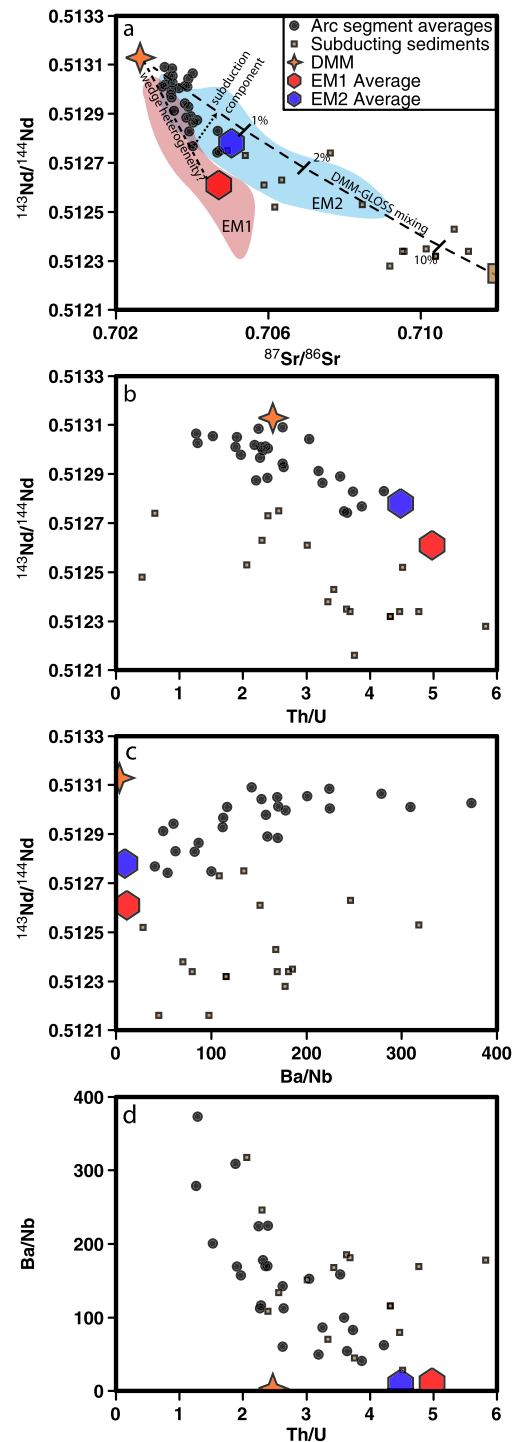


Fig. 2. Comparison of global arc averages with oceanic basalts and subducting sediment compositions. Panel a) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$. Three arc segments have sediment with $^{87}\text{Sr}/^{86}\text{Sr} > 0.712$ that have been cropped to preserve scale. The red and blue fields indicated the range of compositions erupted from ocean islands associated with EM1 and EM2 type compositions, respectively. Note that the mixing line between DMM and the GLOSS sediment average (Plank, 2013) lies at a higher $^{87}\text{Sr}/^{86}\text{Sr}$ for a given $^{143}\text{Nd}/^{144}\text{Nd}$ at all segments with $^{143}\text{Nd}/^{144}\text{Nd} < 0.51295$. Panels b–d) Average arc front Th/U and Ba/Nb values correlate with $^{143}\text{Nd}/^{144}\text{Nd}$, and with each other. On all plots, the most radiogenic end of the arc front array trends towards EM-type ocean island basalts. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

These data suggest that mantle heterogeneity has a significant effect on regional as well as global isotopic and trace element variability of arc volcanics. Heterogeneities arising from slab components are well documented (e.g. Elliott et al., 1997;

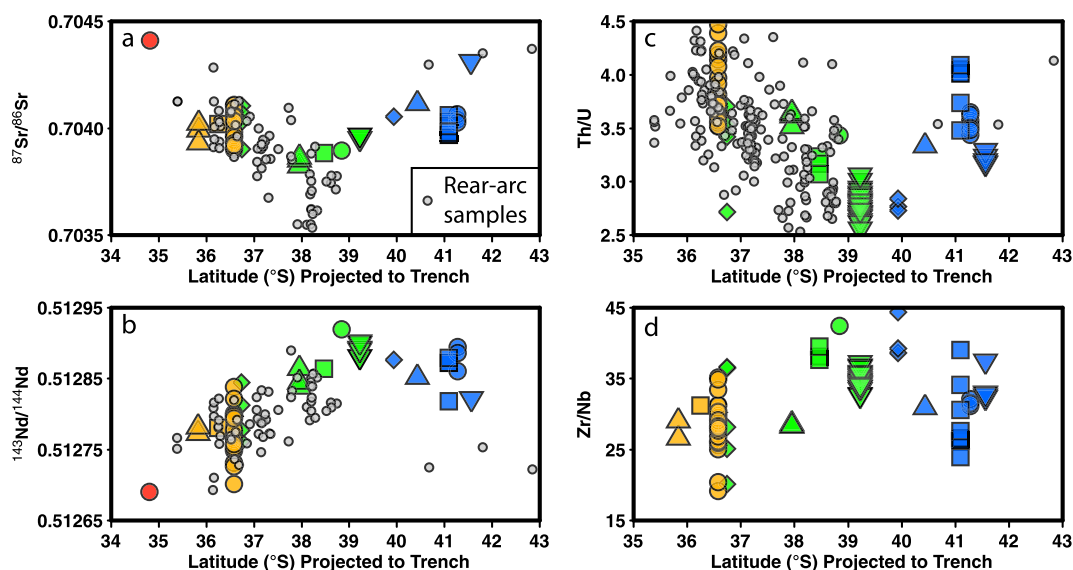


Fig. 3. Panel a) $^{87}\text{Sr}/^{86}\text{Sr}$ for samples from both the arc front (large colored symbols) and rear arc (small gray circles) projected along the angle of convergence back to the trench. Only rear-arc samples with $\text{Th}/\text{Nb} < 0.4$ were included to avoid the inclusion of rear-arc samples with large slab signatures. Samples with particularly high Th/U at very low U concentrations were also removed due to likely low-T alteration effects. Arc front data are filtered as described in Turner et al. (2016). This projection enables visualization of mantle domains perpendicular to the trench that should be connected via corner flow in the mantle wedge. Note that the least radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ values occur between 38°S and 39°S , and that both rear-arc and arc-front samples follow similar along-strike trends. Panels b–d) These ratios all follow similar along-strike trends for both the rear-arc and the volcanic front. Panel d) Zr/Nb is fractionated by the very low extents of melting found in the rear-arc, and so Zr/Nb of rear-arc samples are not representative of their source composition, they are not plotted to preserve figure scale (see text). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Plank and Langmuir, 1993; Heydolph et al., 2012, etc.), but these largely affect chemical indices that are particularly sensitive to slab fluxes such as Pb isotopes, and elements that are highly concentrated in sediments and “slab fluids.” Are the heterogeneities documented above in Nd isotopes, the REE, and Zr/Nb also derived largely from variations in the magnitudes or compositions of slab-derived fluxes, or do they instead reflect ambient mantle wedge variability that is independent of recent slab additions? Relationships derived from the global dataset and from the Chilean SVZ can be used to resolve this question.

3. Evidence from global data for ambient wedge heterogeneity

Rear-arc volcanics provide the opportunity to evaluate regional mantle heterogeneity without the overprint of slab-derived fluxes (Woodhead et al., 2001, 2012; Pearce et al., 2007; Turner and Langmuir, 2015b). Rear-arc magmas erupt at sufficiently large distances from trenches to minimize slab-derived additions, but they sample mantle sources that eventually feed the arc because of corner flow from the rear arc towards the arc front (e.g., van Keken et al., 2008). Turner and Langmuir (2015b) established a global rear-arc database, filtered on the basis of $\text{Th}/\text{Nb} (< 0.14)$ to remove samples that have detectable slab-derived contributions. Data from the Simcoe volcanic field (Leeman et al., 1990) in the Cascades have since been added to the database, though these analyses have larger uncertainties, as indicated by the error bars on Fig. 4. For the 12 arc segments with rear-arc data: (1) arc-averaged rear-arc $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ correlate strongly ($r^2 = 0.84$), (2) these isotopic data define a mixing array between depleted Mid Ocean Ridge Basalt (MORB) and EM1-type Ocean Island Basalt (OIB) (Fig. 4a), and (3) the average rear-arc $^{143}\text{Nd}/^{144}\text{Nd}$ values correlate ($r^2 = 0.71$) on a near 1:1 basis with the corresponding arc-front $^{143}\text{Nd}/^{144}\text{Nd}$ averages (Fig. 4b). These are important constraints for models of arc volcanism.

The correspondence of $^{143}\text{Nd}/^{144}\text{Nd}$ values between rear-arc volcanics with no slab contribution and the $^{143}\text{Nd}/^{144}\text{Nd}$ of the nearby arc front indicates that the composition of the ambient mantle is a primary control on $^{143}\text{Nd}/^{144}\text{Nd}$ among volcanic arcs

globally, and that slab additions have very little effect on the $^{143}\text{Nd}/^{144}\text{Nd}$ of the volcanic front. This conclusion is consistent with the observation by Morris and Hart (1983) of a similar range of $^{143}\text{Nd}/^{144}\text{Nd}$ in arcs and ocean island basalts. It should be emphasized that this does not imply that Nd behaves “conservatively” in subduction zones, as there is abundant evidence that slab-derived Nd perturbs the $^{143}\text{Nd}/^{144}\text{Nd}$ of arc-front volcanics (e.g. Elliott et al., 1997). The offsets from the 1:1 line on Fig. 4a in the direction of subducted sediment (low $^{143}\text{Nd}/^{144}\text{Nd}$, Fig. 2), which are most evident at arcs with the highest $^{143}\text{Nd}/^{144}\text{Nd}$, are likely the result of slab-derived Nd contributions to the sources of the arc-front volcanics. These effects are small, however, in comparison to the global range of $^{143}\text{Nd}/^{144}\text{Nd}$. For arcs with enriched ambient mantle, the effects are almost negligible.

The more substantial impact of slab-derived Nd at depleted arcs is likely the result of co-variations between $^{143}\text{Nd}/^{144}\text{Nd}$ and Nd abundances. Basalts from ocean islands and ocean ridges show that mantle domains with lower $^{143}\text{Nd}/^{144}\text{Nd}$ are typically enriched in incompatible elements, and the same is likely true of the ambient mantle wedges of arcs. The term “enriched ambient mantle” will thus be used to designate a mantle source with low $^{143}\text{Nd}/^{144}\text{Nd}$, high $^{87}\text{Sr}/^{86}\text{Sr}$, and high incompatible element concentrations in the following discussion. Because ambient mantle that is relatively depleted has lower Sr and Nd abundances, a given quantity of slab input will have a greater influence on depleted sources than enriched sources. The larger deviation from the 1:1 line for more depleted arc segments on Fig. 4b is consistent with this reasoning. Slab components may thus dominate the trace element signatures in magmatic outputs for arcs with depleted ambient mantle sources, but will have progressively smaller impacts as the sources become relatively enriched.

Variations in ambient mantle compositions account for the behavior of certain trace element ratios that are otherwise enigmatic. For example, the positive correlation between Pb/Nb and Zr/Nb for global arc averages (Fig. 5a) is difficult to explain by variable fluxes of subduction-related components, since they are not expected to transport large amounts of the high-field-strength elements Zr and

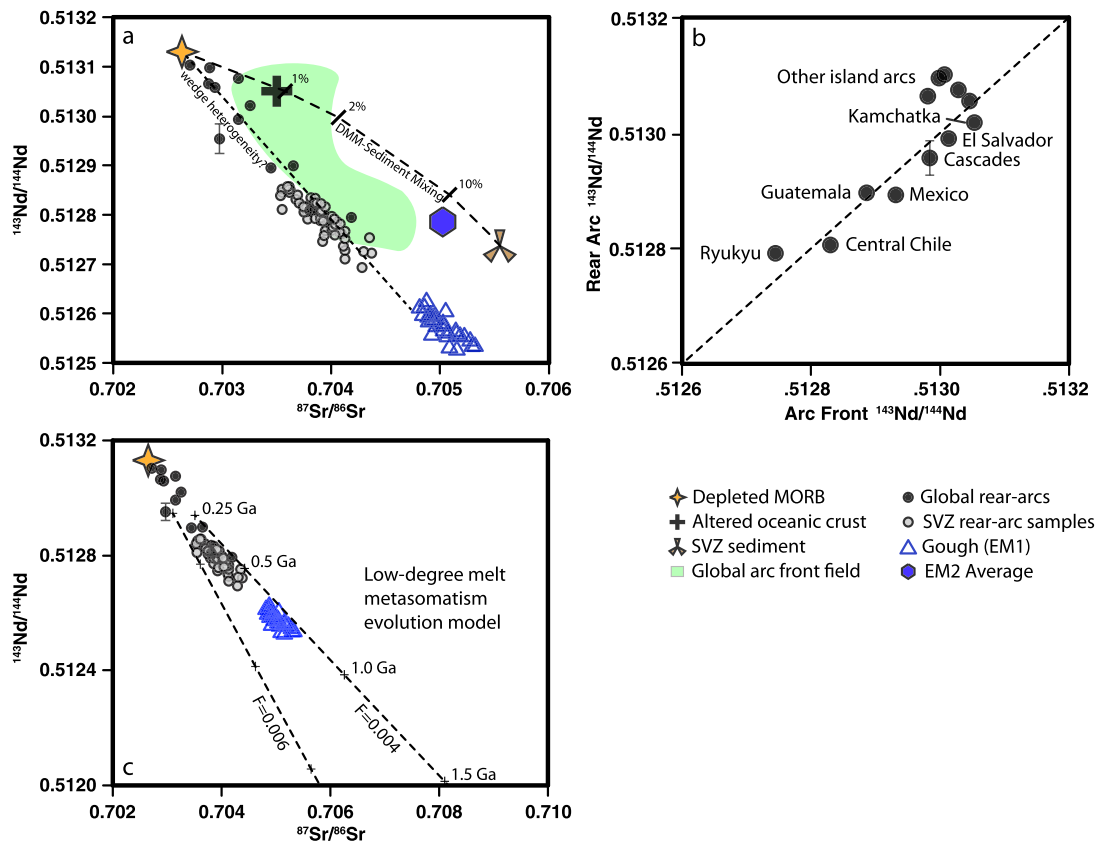


Fig. 4. Panel a) Global rear-arc segment averages (black circles, values from Turner and Langmuir, 2015b) and rear-arc samples from the SVZ (gray circles, literature data sources in main text) both form a linear array between a DMM-like composition and an EM1-like composition represented by the Gough Island basalts (blue triangles). The rear-arc samples do not trend towards the sediment or altered oceanic crust, indicating that this array is not a result of slab components in the rear arc. It can also be seen on this plot that the rear-arc array mixes exclusively towards EM1, and not EM2 type enrichment. The arc front field lies off-set from the rear-arc field towards the expected slab components, but notably the range in $^{143}\text{Nd}/^{144}\text{Nd}$ compositions is similar in both the rear-arc and arc front. Panel b) Global rear-arc $^{143}\text{Nd}/^{144}\text{Nd}$ averages correlate well with the corresponding arc-front compositions, indicating that ambient mantle heterogeneity is likely the dominant control on $^{143}\text{Nd}/^{144}\text{Nd}$ in both domains. Panel c) The dotted lines are the results of a recycling model in which low degree melts ($F = .004$ and $F = 0.006$) are extracted from the depleted mantle (Salters and Stracke, 2004) and then aged for up to 1.5 Ga using the parameters from Stracke et al. (2003). (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

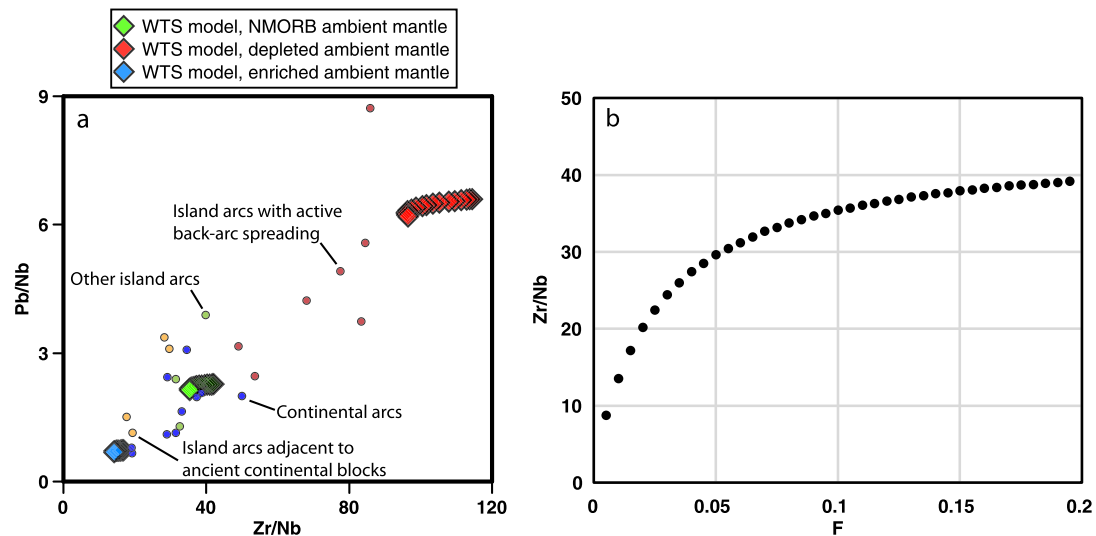


Fig. 5. Panel a) Zr/Nb vs Pb/Nb for global arc segment averages from Turner and Langmuir (2015a). Pb/Nb, which is often considered to be a good indicator of the slab or “fluid” component in an arc basalt correlates globally with Zr/Nb, a ratio of two elements not likely to be transferred in large quantities from the slab to the mantle wedge. This correlation demonstrates how trace element ratios normally attributed to variation in the flux of slab material to the mantle wedge might instead vary as a function of ambient mantle heterogeneity. The blue, green, and red diamonds are the results of a model in which the total mass flux of material from the slab into the mantle wedge are identical, but the ambient mantle wedge composition is variable. Different diamonds of the same color are generated from the same ambient mantle composition with varying extents of melting. The mantle sources of island arcs with back-arc spreading centers (red filled circles) undergo additional depletion prior to reaching the arc front, which results in high Zr/Nb and Pb/Nb (see text for details). Panel b) A demonstration of how varying extents of melting (F) influence Zr/Nb in mantle melts, calculated following Turner and Langmuir (2015b). Most arc front lavas are the result of melting where $F > 0.05$, which has a small effect of Zr/Nb. SVZ rear-arc samples are likely produced at very low F , which strongly fractionates Zr/Nb. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

Nb. Variable extents of melting have only small effects on these ratios as long as the extent of melting is greater than 5% (Fig. 5b). Enrichment and depletion of mantle sources, however, significantly affects Nb concentrations and Zr/Nb ratios. Enriched MORB samples typically have Zr/Nb from 10 to 15, whereas normal MORB have Zr/Nb ~40 (Gale et al., 2013). Larger source depletions, such as those commonly observed in arcs with back-arc spreading centers, can lead to Zr/Nb > 100 (e.g. Langmuir et al., 2006). The model developed in Turner and Langmuir (2015b) can be used to demonstrate how a constant slab flux influences ambient mantle with MORB-like, extra depleted, and enriched ambient mantle compositions (colored diamonds on Fig. 5a). Higher Pb/Nb ratios in this example do not reflect a larger flux of subduction components into the mantle wedge. Instead, the proportions of slab-derived incompatible elements in mantle-wedge source regions increase as a function of progressive mantle depletion (see also, Rogers and Hawkesworth, 1989). High Pb/Nb and Ba/Nb are commonly attributed to greater fluid fluxes, but variations in these ratios are likely to be expressions of varying initial Nb concentrations in ambient mantle sources rather than variable additions of fluid-transported Pb and Ba.

4. Evidence for ambient wedge heterogeneity along the SVZ

If ambient mantle heterogeneity contributes to compositional differences among arcs, then it may also contribute to variations within single arcs, such as the SVZ. Regional studies of arcs with back-arc basins can make use of abundant rear-arc volcanics to constrain the ambient mantle composition along the length of the arc (Woodhead et al., 2001, 2012; Pearce et al., 2007; Escrig et al., 2009), but such an approach is more complicated in continental arcs where back-arc spreading is not present. The SVZ provides a useful natural laboratory in this regard, thanks to abundant primitive monogenetic rear-arc volcanism that spans much of the length of the arc.

Several studies of SVZ rear-arc volcanics (Dyhr et al., 2013; Kay et al., 2007, 2013; Varekamp et al., 2010; Søager et al., 2013; Søager and Holm, 2013) have found that the rear-arc mantle source displays prominent EM1-type heterogeneity. Data for SVZ rear-arc monogenetic volcanics, filtered to remove high Th/Nb samples and samples with <4 wt.% MgO, correlate well on the $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ diagram, plotting between a MORB-like composition and an EM1-like composition (Fig. 4a). A new observation is that the SVZ rear-arc $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ array aligns closely with the global $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ rear-arc array and extends it to some of the highest $^{87}\text{Sr}/^{86}\text{Sr}$ and lowest $^{143}\text{Nd}/^{144}\text{Nd}$ values seen worldwide. The fact that this array does not extend towards Altered Ocean Crust (AOC) or subducted sediment compositions supports the conclusion that this filtered rear-arc data does not vary as the result of slab-derived components, but rather as a result of variable ambient mantle compositions.

The global-scale correlation between $^{143}\text{Nd}/^{144}\text{Nd}$ in rear-arc and arc-front volcanics (Fig. 4b) is also present on the scale of the SVZ. Sample compositions from arc-front and rear-arc locations, projected to the trench along the vector of convergence, follow similar along-strike patterns (Fig. 3a). A maximum in $^{143}\text{Nd}/^{144}\text{Nd}$ is observed at the same position along the volcanic front and in the rear arc. Co-variations between arc-front and rear-arc compositions are also present for $^{87}\text{Sr}/^{86}\text{Sr}$ and Th/U, although $^{87}\text{Sr}/^{86}\text{Sr}$ and Th/U data are more scattered and exhibit slight offsets between the rear arc and the arc front (Fig. 3b–c). Statistical treatment of the data confirms the significance of these trends. A linear regression (for samples north of 40°S) of Th/U on trench-projected latitudes yields a slope of 0.27 per degree for the rear-arc data with $p = 3.7 \times 10^{-20}$ and a similar 0.35 per degree for the arc front with $p = 3.7 \times 10^{-26}$. The scatter apparent in the significant latitudinal

variations may reflect the impact of slab-derived fluxes on these parameters, but the similarities among the along-strike patterns of these ratios suggests an important influence by ambient mantle heterogeneity in both the rear arc and arc front.

Arc-front Zr/Nb also exhibits along-strike variability that is similar to the $^{143}\text{Nd}/^{144}\text{Nd}$ variations of the rear arc (Fig. 3d), but Zr/Nb in rear-arc lavas extends to values below 5, and does not vary regularly along strike (not plotted on Fig. 3d to preserve scale). The offset in Zr/Nb between the arc front and rear arc is likely the result of very low extents of melting in the rear arc, which produces silica under-saturated compositions and Zr/Nb values that are too low to be directly representative of their mantle sources (see Fig. 5b). Extents of melting at arc-front volcanoes, on the other hand, are generally >5% (Plank and Langmuir, 1988; Turner and Langmuir, 2015b), thereby preserving the along-strike arc-front trend in Zr/Nb. It is noteworthy that $^{87}\text{Sr}/^{86}\text{Sr}$ values in the least enriched region of the SVZ (38°S–39°S) do not drop as low in the arc front as they do in the rear arc (Fig. 3). This can be attributed to the relatively depleted ambient mantle in this region, which makes it more sensitive to slab additions.

These observations support the conclusion that SVZ arc-front $^{143}\text{Nd}/^{144}\text{Nd}$ compositions are primarily a function of the composition of the ambient mantle wedge, which varies along strike on a regional scale. Compositional variation of the ambient mantle also appears to systematically affect arc-front $^{87}\text{Sr}/^{86}\text{Sr}$, Th/U, and Zr/Nb, which follow similar along-strike patterns.

Is it possible that the systematic along-strike chemical variations result from changes in the composition or magnitude of the slab flux? New data from three sediment cores (ODP sites 1232, 1233 and 1234) taken offshore of the SVZ at 40°S, 41°S, and 36°S (Fig. 2), have average $^{143}\text{Nd}/^{144}\text{Nd}$ ranging only from 0.51273 to 0.51277 (supplementary material), indicating that along-strike variation in the subducting sediment composition cannot explain the progressive compositional variability of the arc-front volcanoes. Furthermore, trace element ratios that are most sensitive to slab contributions do not vary along the arc. The ratios Sr/Nd, Ce/Pb, and Ba/La (Fig. 6) are not readily fractionated by variable extents of melting and exhibit small differences between relatively enriched and depleted oceanic mantle reservoirs, but large differences between normal MORB mantle compositions and SVZ lavas. These ratios are particularly sensitive to changes in the slab flux, and are similar for all the volcanoes in our study region for which data are available (Fig. 6). While the particularly low Th/U at Villarrica (39.4°S) has previously been attributed to variation in slab flux caused by subduction of the Valdivia fracture zone (Jacques et al., 2013, 2014; Wehrmann et al., 2014; Dzierma et al., 2012), similar Th/U along-strike variations in the back-arc (Fig. 3c) and the similarity of Sr/Nd, Ce/Pb, and Ba/La at Villarrica and the other SVZ volcanoes (Fig. 6) suggest that the low Th/U at Villarrica may instead be inherited from the ambient mantle composition. Evidence from offshore sediment cores and trace element ratios sensitive to slab fluxes support the conclusion that variability in slab-derived fluxes do not drive along-strike compositional variability of SVZ volcanoes.

Whereas there is little evidence for systematic along-strike variability in slab fluxes along the SVZ, there are substantial variations for lavas from certain volcanoes. Sr/Nd in Tatara San Pedro lavas, for example, varies from less than 30, to almost 70, which likely indicates that the slab flux can vary significantly at any given location (Jweda, 2014). The variation at Tatara San Pedro is most likely larger than at other volcanoes due to the uniquely large number of samples collected, which span the >900 ka lifetime of this complex. Chemical variability related to variations in slab-derived fluxes is also apparent at neighboring Nevado de Longaví volcano (Sellès et al., 2004), though only among samples with low MgO contents that do not pass the data-filtration criteria

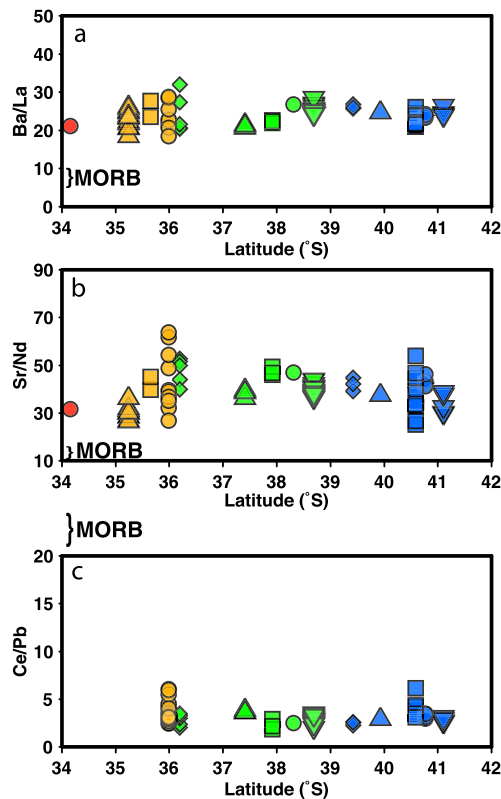


Fig. 6. The ratios Ba/La, Sr/Nd, and Ce/Pb for samples from SVZ stratovolcanoes along the volcanic front. These ratios are sensitive to variations in the slab component, but are similar in all mid ocean ridge basalts and ocean island basalts. There is no systematic along-strike variability in these ratios, suggesting variation in the slab component is not responsible for the systematic along-strike variability observed in the ratios shown on Fig. 3. Certain volcanoes exhibit large ranges in the some of these ratios, which suggests that the slab component in the mantle source of a given volcano might vary over time. Note that data in this figure has been filtered to remove samples affected by crustal processes such as assimilation, crystal fractionation, and magma mixing, as detailed in Turner et al. (2016).

(Turner et al., 2016). Variations in fluxes at individual volcanoes are useful for exploring inputs of diverse components. Short-term variations in slab-derived fluxes are important for individual volcanoes, but they apparently are not large enough to substantially overprint variable ambient mantle signals along the SVZ. These data suggest that locally slab fluxes are not well mixed and can give rise to substantial heterogeneity within a volcanic complex. Over time these variations are averaged out to accurately reflect the ambient wedge composition.

5. A quantitative model for the trace element effects of ambient mantle enrichment

The largely qualitative observations noted above require testing with a more quantitative approach. To construct a quantitative model we make use of the observations that arc ambient mantle seems to be enriched by components with affinities to EM1-type OIB (see Fig. 2 and Fig. 4a), and that most EM1-type OIBs share similar trace element compositions (Willbold and Stracke, 2006). A starting composition for the enriched ambient mantle end-member has been calculated by inverting for the source composition of the EM1-type Gough Island basalts, adjusting Th/U, Nd/Hf, and La/Sm to near-end-member values (6, 8.3, and 5.5) reported for EM1 by Willbold and Stracke (2006). Details of the inversion process are available in the supplementary material. The trace element composition of the depleted MORB source from Workman and Hart (2005) was used for the depleted ambient mantle end-

member, but with $^{87}\text{Sr}/^{86}\text{Sr} = 0.7028$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.5130$ and $\text{Th}/\text{U} = 2.2$. This depleted end-member (open crosses on Fig. 7) falls within the MORB field (blue fields on Fig. 7) on all plots, justifying its use as a plausible depleted mantle source. A model ambient mantle source was calculated for each SVZ volcano by mixing enriched and depleted mantle sources. Mixing proportions for each volcano were constrained by Nd isotopes of rear-arc volcanics. Calculated proportions of enriched mantle vary linearly from 90% at 34°S, to 10% at 39°S, and then back to 70% at 44°S. A fixed slab component composition, consisting of 1.5% sediment melt and 6% AOC melt (Turner and Langmuir, 2015b), was added to the estimated ambient mantle sources at each volcano. The consequences of melting the resulting mantle sources are determined by mantle source P–T conditions estimated for each volcano (Turner et al., 2016).

This model reproduces the observed correlations among trace element abundances, trace element ratios, and radiogenic isotope ratios of the SVZ arc-front stratovolcano samples (Fig. 7), as well as along-strike patterns that do not correlate with slab age or crustal thickness (Fig. 8). On plots of $^{143}\text{Nd}/^{144}\text{Nd}$ vs. both $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 7a) and $^{176}\text{Hf}/^{177}\text{Hf}$ (Fig. 7b), the mixing line between DMM and EM1 (dashed line) matches the trend among the rear-arc volcanics. The addition of a constant slab component to the variable ambient mantle wedge results in a separate arc-front model trend which matches the arc-front data. The $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ plot is based on the data of Jacques et al. (2013, 2014), and is characterized by sub-parallel arrays between rear-arc and arc-front. The $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ arrays are of essentially the same form as those on the plot of $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 7a). The first-order isotopic variability is largely the result of ambient mantle heterogeneity in both the rear arc and arc front. The offset between rear-arc and arc-front compositions results from adding a constant amount of melt derived from the slab to the arc-front mantle source. Incorporating variation in the ambient mantle composition along with variation in P–T conditions of melt generation reproduces co-variations of $^{143}\text{Nd}/^{144}\text{Nd}$, Zr/Nb and Th/U (Fig. 7c–d), the along-strike variations of these ratios (Fig. 8), and the along-strike variations of incompatible element abundances (Fig. 9).

Similar $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ systematics are observed for samples from the Central American Volcanic Arc (Heydolph et al., 2012), and the eastern Mexican volcanic belt (Straub et al., 2015). Straub et al. interpret these isotopic variations as variable recycling of material into the subduction zone (via subduction of sediments, AOC, and continental subduction erosion). As Straub et al. point out, however, there is high variability in $^{143}\text{Nd}/^{144}\text{Nd}$ even among the Mexican samples for which continental material cannot have contaminated the source, as indicated by MORB-like Th/La values. Straub et al. suggest this may be the result of subducted seamounts that have been recycled through the arc, though the fact that similar samples are present in multiple other arc settings and are widespread across the SVZ support a more generalizable origin for this enriched component.

Certain SVZ volcanoes do not conform to model predictions. These deviations may be explained by small adjustments in the proportions of slab-derived components added to the source, without changing total slab flux. Osorno volcano has higher $^{87}\text{Sr}/^{86}\text{Sr}$ relative to $^{143}\text{Nd}/^{144}\text{Nd}$ in comparison to other SVZ volcanoes (Fig. 7a), but this can be accommodated with the same total slab-derived flux by adjusting the proportion of sediment melt (from 25% to 30% of the total slab flux) relative to AOC melt transferred to the mantle source. This anomaly may be related to the remarkably shallow estimated slab depth of ~80 km beneath Osorno (Tassara and Echaurren, 2012). This exception is a useful reminder that compositions and magnitudes of the slab-derived fluxes may vary locally along the SVZ, despite the fact that we have not iden-

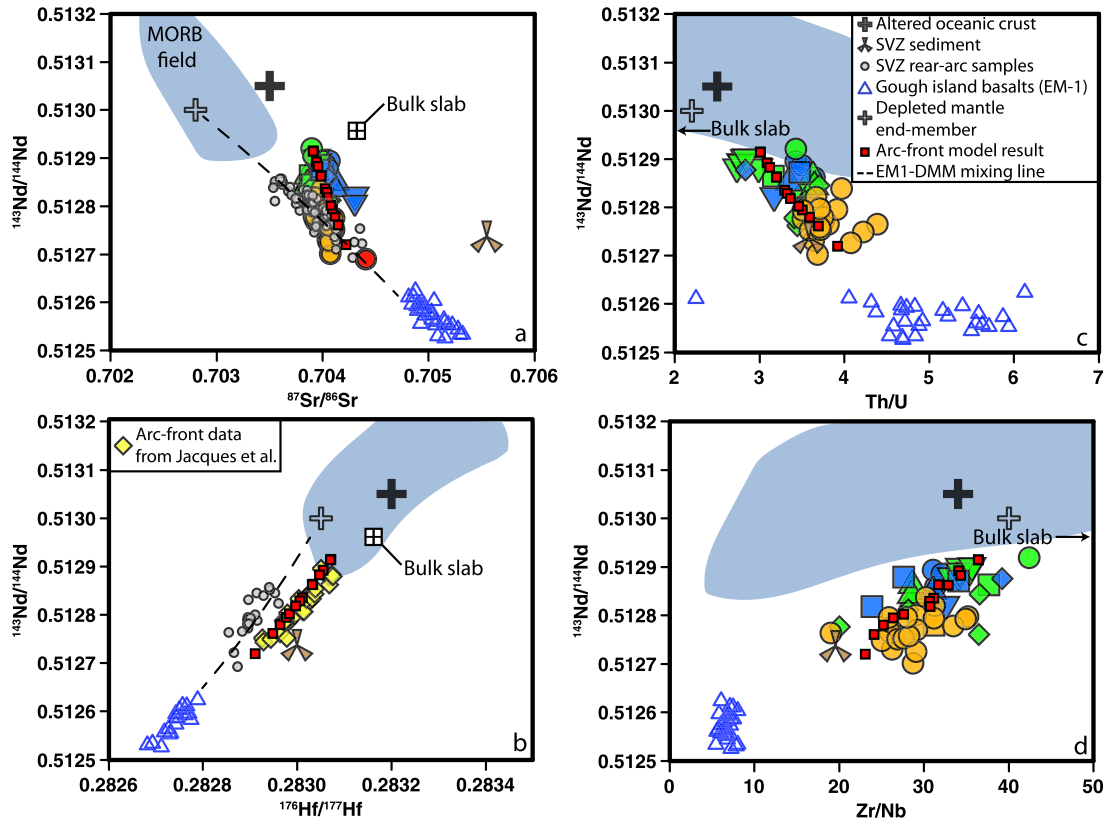


Fig. 7. Illustration of the results of a quantitative model (model results plotted as red squares) based on a variable ambient mantle source with a constant slab component that is able to reproduce the variability among the SVZ arc front stratovolcanoes, as well as the offset between the arc front and rear-arc samples. Other symbols as in Figs. 3 and 4. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

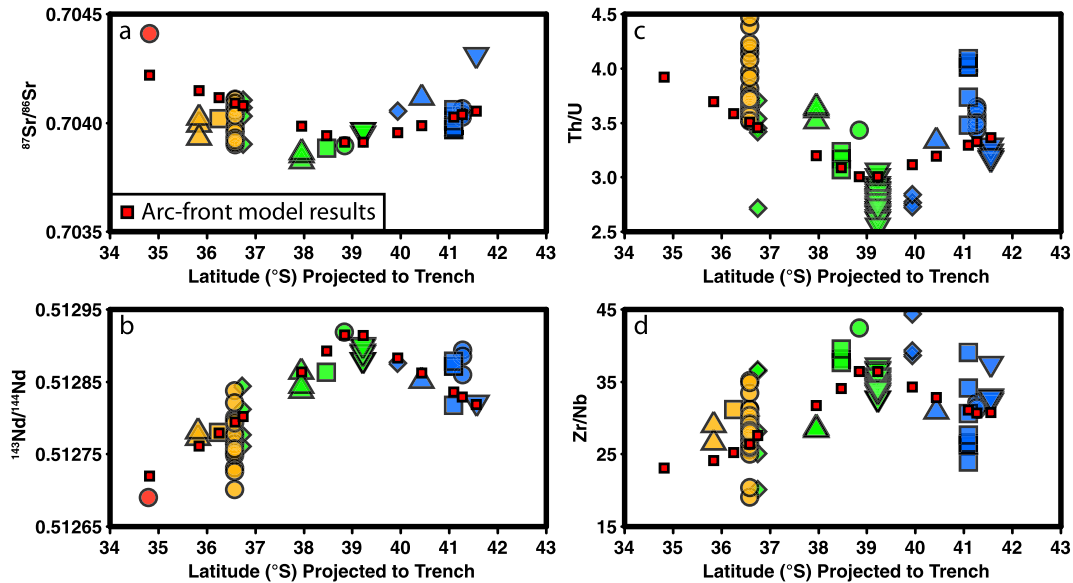


Fig. 8. Results of a quantitative model (red squares) compared to along strike variations of volcano compositions. The ambient mantle source varies due to the addition of an EM1 component with a composition derived from Gough Island basalts. The proportion of the enriched component in the ambient mantle is constrained by the Nd isotope compositions of rear-arc samples. The combination of constant slab component, consistent with a constant slab thermal parameter in this region, a variable mantle wedge, and the wedge thermal structure model of Turner and Langmuir (2015b) is able to reproduce the along-strike variations in average volcano compositions. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

tified systematic differences in subduction-related fluxes along the arc.

Instead, the systematic along-strike compositional differences among SVZ stratovolcano sources are primarily due to variations in ambient mantle wedge compositions. Our results do not

support a first-order role for variations in slab-derived components, in contrast to proposals by some other workers (Dzierma et al., 2012; Jacques et al., 2013, 2014; Wehrmann et al., 2014). A similar model may be applicable to Ryukyu, Guatemala/El Salvador, Mexico, and the Cascades, as associated rear-arc volcanic

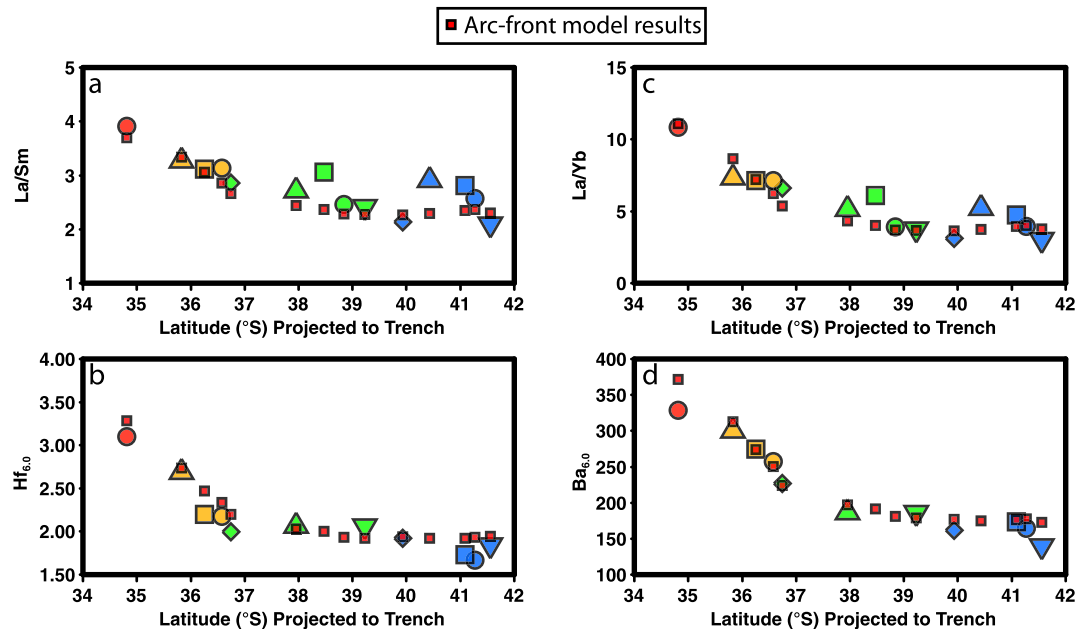


Fig. 9. Further results of the quantitative model compared along strike variations in trace element ratios. Symbols as in Fig. 8. The combination of constant slab component, variable wedge thermal structure, and variable wedge composition reproduces the along strike variability along the SVZ.

compositions trend towards EM1 in each of these regions (Fig. 4a). We speculate that this model might be successful for other arcs characterized by low $^{143}\text{Nd}/^{144}\text{Nd}$ in arc-front magmas, such as the Aegean, Java/Bali, and Honshu arcs. Correlations of global arc-segment-averaged $^{143}\text{Nd}/^{144}\text{Nd}$ with trace element ratios that are controlled by compositional variations in ambient mantle wedges (Fig. 1) suggest that global applications for this model should be considered. Testing of models that incorporate variable thermal structures in mantle wedges in combination with EM1-linked variations among ambient mantle wedge compositions in diverse subduction environments will provide tests of this model's generality.

6. Implications for the origin of EM1

The model of SVZ along-strike compositional variability depends on a component of ambient mantle enrichment that resembles EM1-type OIBs. The origin of EM1-type heterogeneity in the mantle has long been debated. Some recent studies link the origin of EM1 to recycling of lower crustal material (LCC) into the convecting mantle, either by subduction erosion or delamination (e.g. Willbold and Stracke, 2010). Willbold and Stracke (2010) use a two-stage model in which material with the composition of the continental crust is extracted from the bulk earth at 4.55 Ga, then differentiates into a range of LCC compositions at 3.7 Ga, later to be recycled. Rudnick and Gao (2003) have estimated the composition of the LCC by averaging compositions of lower crustal xenoliths, and if this composition is used (with some modifications) in the model of Willbold and Stracke (2010), the resulting recycled material successfully reproduces the isotopic composition of EM1 end-member OIBs with 2–3% mixing into the mantle source.

There are problems, however, with the model of LCC recycling as the source of EM1-like components in both OIB and subduction zone settings. The compositions of lower crustal xenoliths are highly variable (Rudnick and Gao, 2003), and the variation in these recycled compositions (or variation in the timings of the two-stage model) produce a wide range of compositional trajectories (Willbold and Stracke, 2010). This model may be a plausible way to produce the isotopic compositions of EM-type OIBs, which have a range in trajectories varying from EM1 to EM2. The global and SVZ rear-arc compositional arrays add important new obser-

vations, because they are nearly linear. If rear-arc compositional variation were due to subduction erosion of LCC material, a coherent linear trend globally would not be expected, as recycled LCC material likely has diverse compositions and ages. Age is a critical parameter in the Willbold and Stracke model, and much recycled LCC material at arcs would be far younger than the Archean source used in the OIB model of Willbold and Stracke.

The LCC model also fails for certain trace element ratios. While the composition of LCC is not well constrained, the continental crust in general is known to be enriched in “fluid mobile” elements, such as Pb, relative to other elements that are equally incompatible during mantle melting and differentiation. The estimated Ce/Pb ratio of the continental crust (3.9; Rudnick and Gao, 2003) is far lower than a recent estimate of the mantle (33.3; Salters and Stracke, 2004). Similarly low values in the LCC xenolith average of Ce/Pb = 5 (Rudnick and Gao, 2003) suggest that these elements are not strongly fractionated during differentiation. Mixing LCC material, which has high abundances of these elements, back into the mantle should have a large impact on mantle ratios. A 2.5% addition of LCC to the depleted mantle source results in Ce/Pb = 10.2, while Gough basalts almost all have Ce/Pb between 20 and 25. Similar problems exist for Nb/U, which is ~45 in the mantle, ~25 in the lower crust, ~34 in the LCC model, whereas the Gough basalts have Nb/U between 40 and 60. Finally, the trace element compositions of LCC xenoliths are highly variable, while the trace element abundances in OIBs are surprisingly uniform (Willbold and Stracke, 2006) which is also at odds with a model of LCC recycling for the generation of EM1.

An alternative is that the EM1-like components are derived from Sub-Continental Lithospheric Mantle (SCLM) that has been metasomatized by infiltration of low-degree melts from a normal depleted upper mantle source (e.g. McKenzie and O’Nions, 1995; Hoernle et al., 2011; Geldmacher et al., 2008). This scenario predicts a less variable end-member composition than does the LCC recycling model. Aging of a SCLM source that has been enriched by low-degree melts results in a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ trajectories that are consistent with the data (Fig. 4c). Chin et al. (2012, 2014) provide evidence from mantle xenoliths for modal metasomatism in an arc environment, and note that the extent of refertilization appears to increase with depth. Such

melt-metasomatism of SCLM should generate dense garnet pyroxene and eclogitic material which may be reincorporated into the convecting mantle (Foley, 2008). Some studies have found that SCLM is not consistent with the composition of EM1, because SCLM tends to have low $^{187}\text{Os}/^{188}\text{Os}$ (e.g. Shirey and Walker, 1998), while the EM1 end-member appears to have $^{187}\text{Os}/^{188}\text{Os} > 0.1450$ (e.g. Escrig et al., 2005). An SCLM source that has been metasomatized by mantle melts, however, will acquire high Re/Os and higher $^{187}\text{Os}/^{188}\text{Os}$ over time. Direct observations of these lithologies clearly indicate a uniformly high $^{187}\text{Os}/^{188}\text{Os}$ (Hauri, 2002; Carlson et al., 1996), as well as Sr, Nd, and Pb isotopic compositions similar to EM1 (Gibson et al., 2005). A model in which EM1-type compositions are largely generated via low-degree melt infiltration of the SCLM is thus viable, and avoids the issues of LCC recycling models.

Several previous workers have proposed a SCLM component to account for source enrichments in South American volcanics in particular. Gibson et al. (2005) argue that melts of the SCLM sampled in South-West Africa and South America (including samples from the Rio de la Plata Craton, which is directly east of the northern SVZ) provide good candidates for the EM1 end-member composition. An SCLM source for Andean mantle enrichment was also proposed by Rogers and Hawkesworth (1989), Kay and Abbruzzi (1996) and Muñoz et al. (2013) for Northern Chile (22°S), the “flat slab” region to the north of the SVZ (30°S to 32°S), and the Cenozoic volcanism from 33 to 34°S. Kay and Abbruzzi (1996) specifically suggest that such material might also contribute to EM1-type enrichments in OIBs. Søager and Holm (2013) provide evidence for eclogite melt contributions to some SVZ rear-arc volcanics, and Kay et al. (2013) present additional isotope and trace element evidence for metasomatized SCLM as the source of SVZ rear-arc EM1-like compositions. Several authors have converged on the connection between EM1-like compositions and a source located within the SCLM for Andean volcanism. The enriched isotopic compositions and similar $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ trajectories of other arcs built on or near (Ryukyu) old continental crust may indicate that a similar component is present in each of these locations.

7. Mechanisms for ambient mantle heterogeneity in subduction zones

Several hypotheses have been put forward to explain apparent SCLM-driven enrichments in the ambient mantle sources of arc magmas. Rogers and Hawkesworth (1989) proposed Proterozoic SCLM is reincorporated into the sources of arc magmas in Northern Chile as the result of eastward migration of the arc front. Kay and Abbruzzi (1996) suggest that SCLM was mechanically removed and then reincorporated into the asthenosphere between 30°S to 32°S as the angle of plate subduction shallowed over time. Muñoz et al. (2013) note that temporal variation in the SCLM component from 33°S to 34°S coincides with plate thickening, which may result in under-thrusting of SCLM beneath the active arc. Hickey-Vargas et al. (2016) suggest that the enriched signature of some SVZ lavas is imparted within the lithosphere beneath the arc volcanoes, noting that the SCLM signature appears to be enhanced at monogenetic volcanoes that do not overlie the regional fault system. Heydolph et al. (2012) found that an increase in the apparent SCLM signature corresponded to crustal thickness in Central America, which they suggest also corresponds to increasing lithospheric thickness and increased magma-SCLM interaction during magmatic ascent. The Ryukyu island arc is characterized by EM1-type enrichments (Hoang and Uto, 2006), but it is not underlain by SCLM. Huang et al. note that the EM1 signal increases in the volcanics that lie closer to the Sini-Korean cratonic region, and is thus consistent

with SCLM material being transported from the cratonic region into the mantle wedge via corner flow.

All of the aforementioned proposals describe viable mechanisms for incorporating SCLM into the sources of arc magmas, and it is possible that a distinct mechanism is responsible for incorporating SCLM into arc magmas in each of these instances. But there is also a common factor in all of the regions in which the SCLM component is present, which is that all of the locations are adjacent to old continental cratons. This common feature suggests that a more general process may be responsible. It is also notable that the physical parameters that support each of the previously proposed mechanisms do not always result in magmas contaminated by SCLM. Ambient mantle enrichment is not always tied to the height of the lithospheric mantle column, as is evident from the increase in ambient mantle enrichment from 39°S to 42°S in the SVZ, where the upper plate thins, and the enrichment at Ryukyu, which is an island arc. It is also not uniquely associated with the flat slabs called upon by Kay and Abbruzzi (1996), and can occur in regions where there is no evidence for a flat slab. The presence of a continental cratonic block behind the arc front, however, appears to be a ubiquitous feature where ambient mantle enrichment occurs. The extent of enrichment correlates between arc-front volcanics and volcanics which lie immediately behind them, both on a global (Fig. 4) and regional (Fig. 3) scale. These co-variations indicate the presence of large-scale domains in which the average ambient mantle composition correlates over tens, or even hundreds of kilometers.

We propose therefore that metasomatized SCLM material is commonly delivered from the bases of continental lithospheric blocks into the ambient mantle wedges of arcs by corner flow. This processes can account for the proximity of enriched arc-front volcanics to ancient continental blocks and the persistence of enriched ambient mantle over large-scale domains. Dense SCLM material that has been metasomatized by low-degree melts may delaminate due to gravitational instability. Alternatively, corner flow may continuously erode the base of the lithosphere, reincorporating SCLM material into the asthenosphere. Enriched SCLM blocks that have been reincorporated into the convecting asthenosphere are then transported into the sub-arc mantle where they are sampled by arc volcanoes (Fig. 10). Smaller-scale processes may produce local fluctuations in ambient mantle enrichment, but continuous delivery of enriched SCLM by corner flow uniquely explains the ubiquitous spatial relationship of enriched volcanics to continents.

The range of compositions erupted at single volcanoes and among individual volcanoes and surrounding small eruptive centers (e.g. Hickey-Vargas et al., 1989, 2002, 2016), suggests that small-scale heterogeneities are also present. In some cases, melt infiltration may result in modal metasomatism that produces lithologies with low-T solidi, which will be sampled preferentially by low extents of melting. Some small eruptive centers (and some eruptive episodes from stratovolcanoes) may tap mantle sources with a larger component of decompression rather than flux melting, thereby producing low extents of mantle melting and melts that are enriched in EM1-like components. Repeated melt extraction of a mantle source, or an eruptive episode for which the slab flux deviates to higher than the local average, may result in relatively depleted compositions.

8. Variations in the SCLM along the SVZ

A final question concerns the systematic along-strike variability in ambient mantle compositions along the Andean arc. Why does the ambient mantle wedge composition vary with this pattern? We speculate that this may be a product of the long-term tectonic history of the South American continent and its relation-

In a mature continental arc, refertilized lithospheric mantle is returned into the asthenosphere, and then pulled into the sub-arc mantle wedge by corner flow.

In oceanic arcs with back-arc spreading, the ambient mantle is depleted by melt extraction, then pulled into the sub-arc mantle wedge by corner flow.

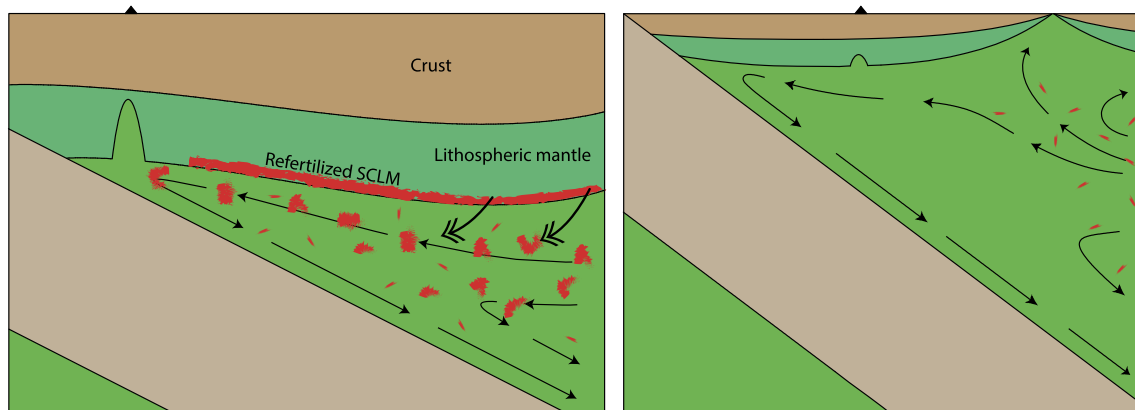


Fig. 10. A cartoon demonstrating the primary mechanisms by which ambient mantle heterogeneity is produced in subduction zones. For many arcs emplaced near older continental crust, enriched sub-continental mantle lithosphere is eroded and contributes to the composition of the mantle wedge (e.g. S. America, Mexico). For arcs with back-arc basins, melting in the back-arc basin depletes the mantle wedge leading to exceptionally depleted wedge compositions (e.g. Tonga, Marianas, Scotia). Other arcs (e.g. Aleutians) would have intermediate wedge compositions.

ship to Patagonia. There is a general consensus that the northern cratonic regions of South America (the Rio de La Plata Craton) and the Northern Patagonia Massif were isolated, or temporarily rifted apart, until a continental collision that terminated in the Early Permian (~281 Ma, Rapelini et al., 2010), although the details are contentious (Pankhurst et al., 2006, 2014; Ramos, 2008; Rapelini et al., 2010). The “suture region” between the Rio De La Plata craton and the Northern Patagonia Massif lies along the Nequén and Colorado Basins (Fig. 1), which extend along the 39th parallel – directly aligned with the latitudes from which the most depleted SVZ magmas have erupted in the rear arc and the arc front. The processes of rifting and collision between these continental blocks may have resulted in large-scale delamination of refertilized lithologies residing at the base of the lithospheric mantle along this suture (e.g. Lee et al., 2011 and references therein). The depletion of the SVZ ambient mantle at 39°S relative to the volcanics to north and the south may be due to the fact that dense, metasomatized material at the base of the South American lithosphere was partially extracted along this suture region, but remains intact along the rest of the continent, incrementally feeding the underlying asthenosphere. If true, the metasomatized SCLM material lost during this collision is an example of a large mass with an EM1-type composition that was recycled deeply into the mantle, and a potential source for EM1-type OIBs.

An alternative explanation for the along-strike mantle variability is the upwelling of depleted mantle through a slab tear in the region from 38–39°S. Tomographic modeling based on aftershocks of the 2010 Maule earthquake (Pesicek et al., 2012) is supportive of this scenario. If a slab tear is present, upwelling of relatively depleted mantle in this region may have diluted an originally enriched mantle wedge composition.

9. Conclusions

Heterogeneity in the ambient mantle wedge appears to contribute in a general and important way to the compositions of subduction zone volcanics (Fig. 10). For arcs built on continents, the mantle feeding the arc has been enriched by an EM1 component that is pervasive in the deep subcontinental lithosphere. For arcs that are distant from continents but have no back-arc spreading, an average mantle composition is present. And where

back-arc spreading occurs for extensional arcs well removed from continents, the wedge composition can become highly depleted. The extent of variability of ambient mantle wedge compositions is thus likely to be of a similar magnitude as observed in the mantle sources of oceanic basalts. Ambient mantle composition largely determines $^{143}\text{Nd}/^{144}\text{Nd}$ in arc magmas, and strongly influences $^{87}\text{Sr}/^{86}\text{Sr}$ by setting the baseline to which subduction components are added. Differences in mantle wedge composition influence the relative impacts of slab-derived components on arc magma compositions, as equivalent mass additions to more depleted ambient mantle translate into apparently greater subduction-related signatures.

If crustal thickness strongly influences wedge thermal structure (Turner and Langmuir, 2015b; Turner et al., 2016; see also Karlstrom et al., 2014), variations in extents of melting may amplify the effects of ambient wedge heterogeneity. Arcs built on continental crust tend to have a thicker lithosphere, and hence lower extents of melting. Arcs built on oceanic crust far from continents have thin lithospheres, and hence higher extents of melting. The net effect is that low extents of melting and enriched ambient mantle tend to be coupled, leading to high concentrations of incompatible elements at continental arcs, while higher extents of melting and depleted ambient mantle lead to the much lower incompatible elements observed at oceanic arcs, particularly those with back-arc spreading. If true, the effects of heterogeneity in the ambient mantle wedge combined with different extents of melting controlled by the thickness of the lithosphere largely contribute to the diversity of arc magmas worldwide.

The composition of the ambient mantle wedge varies between 34–41°S along the Andean SVZ, as evidenced by chemical variations in the SVZ volcanic front that parallel trends among rear-arc volcanics. The combination of ambient mantle wedge variations and variations in the P–T conditions of melting can explain why elements that are most sensitive to the extent of mantle melting vary monotonically along the arc, while other isotopes and trace element ratios have more complex patterns.

Chemical variability among averaged arc compositions and the volcanics of the SVZ support an important role for ambient wedge heterogeneity and partial melting. This is *not* to say that there are no differences in the compositions or quantities of slab-derived components expressed by arc magmas. Contrasts in slab-derived

components are evident in various trace element and isotopic ratios from one arc to another, and often reflect variations in sediment compositions and fluxes (Plank and Langmuir, 1993). Recognizing the effects of partial melting and wedge heterogeneity will hopefully enable future determinations of subduction recycling to be more robust than would otherwise be possible.

Finally, the model presented here also has implications for how various components are added to the continental crust. It has been proposed that a significant portion of the Phanerozoic continental crust was produced in intra-oceanic arcs, though all modern-day oceanic arcs are heavily depleted in incompatible elements relative to bulk continental crust (Gazel et al., 2015 and references within). One possible way to reconcile these contradictory observations is a model by which intra-oceanic volcanism is at times more enriched due to an increase in slab temperatures and the melting of especially enriched oceanic crust (e.g. Gazel et al., 2015). Based on modern convergent margins, however, the tectonic conditions for such an event are rare. The results presented here suggest that an enriched component is a natural consequence of building an arc on pre-existing continental crust, because of the incorporation of enriched mantle derived from the SCLM. It appears that the similarity of continental arc compositions to the bulk continental crust composition is not the result intra-crustal processing, or preferential incorporation of slab melts, but rather the result of low extents of melting of an enriched mantle source. An alternative model for the production of continental material is thus that a larger proportion of continental crust was simply produced via continental, rather than intra-oceanic arc volcanism.

Acknowledgements

This work was supported by NSF grant EAR-0948511. We thank our reviewers and Penny Wieser for extensive and insightful comments that significantly improved this work. Thanks also to Lauren Leydon-Hardy who edited and improved the writing quality of multiple versions of this manuscript.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.epsl.2017.04.051>.

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