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The global chemical systematics of arc front stratovolcanoes: Evaluating the role of crustal processes

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ABSTRACT

Petrogenetic models for convergent margins should be consistent with the global systematics of convergent margin volcanic compositions. A newly developed tool for compiling and screening data from the GEOROC database was used to generate a global dataset of whole rock chemical analyses from arc front stratovolcano samples. Data from 227 volcanoes within 31 volcanic arc segments were first averaged by volcano and then by arc to explore global systematics. Three different methods of data normalization produce consistent results that persist across a wide range of Mg# [$Mg\# = Mg/(Mg + Fe)$]. Remarkably coherent systematics are present among major and trace element concentrations and ratios, with the exception of three arcs influenced by mantle plumes and Peru/N. Chile, which is built on exceptionally thick crust. Chemical parameters also correlate with the thickness of the overlying arc crust. In addition to previously established correlations of $Na_{6.0}$ with $Ca_{6.0}$ and crustal thickness, correlations are observed among major elements, trace elements, and trace element ratios (e.g. La/Yb, Dy/Yb, Zr/Sm, Zr/Ti). Positive correlations include "fluid mobile," "high field strength," and "large ion lithophile" element groups, with concentrations that vary by a factor of five in all groups. Incompatible element enrichments also correlate well with crustal thickness, with the greatest enrichment found at arcs with the thickest crust. Intra-crustal processes, however, do not reproduce the global variations. High pressure fractionation produces intermediate magmas enriched in aluminum, but such magmas are rare. Furthermore, differences among magma compositions at various volcanic arcs persist from primitive to evolved compositions, which is inconsistent with the possibility that global variations are produced by crystal fractionation at any pressure. Linear relationships among elements appear to be consistent with mixing between depleted primary magma and an enriched contaminant, but the required composition of the theoretical enriched end-member is not similar to compositions expected in the deep crust or to any known rock composition. The large-scale chemical variations among volcanic arcs are therefore likely to be generated by processes in the subducting slab or mantle wedge, rather than the crust. While crustal processes are important in the differentiation of convergent margin magmas, they do not account for the systematics presented here. Models that attribute the chemical variability of arc magmas to slab or wedge processes are also constrained to be consistent with the global chemical systematics, and are discussed in Turner and Langmuir (2015).

1. Introduction

Constraining the diverse controls on the compositions of convergent margin magmas is central to our understanding of the plate tectonic geochemical cycle, which ultimately influences all crustal and mantle reservoirs. There is widespread agreement on a general framework: a flux from the down-going slab to the mantle wedge causes melting, and produces primary magmas. These magmas are modified during ascent and differentiation in the crust. The need for multiple components derived from subducted oceanic lithosphere and sediment is also abundantly clear (Morris and Tera, 1989; Miller et al., 1994; Elliott et al., 1997). Still uncertain, however, are the relative contributions from these sources and processes, and what aspects of arc volcanic compositions they produce. Some authors have argued for primary control of a crustal filter (e.g. Hildreth and Moorbath, 1988). Others have argued for a critical role for varied extents of melting of the mantle wedge (Plank and Langmuir, 1988), for reactive transport in the mantle wedge (Kelemen, 1995; Straub et al., 2008), and more recently for control by the thermal structure of the subducting slab

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(Ruscitto et al., 2012). Many of these proposals are based on regional studies, datasets restricted to a few elemental compositions and ratios, or conceptual arguments.

Here we consider what new information and constraints a global dataset can provide to clarify our understanding of convergent margin processes. All the proposed models predict certain relationships among the compositions of erupted magmas and the physical conditions of subduction. Crustal processes, for example, should be influenced by the thickness and composition of the crust on which the arc is constructed. Variations in the extent of melting of the mantle wedge should result from changes in the wedge thermal structure. Compositional control by the subducting slab should correspond with slab age, convergence rate, and depth to slab. Reactive transport should be influenced by the thickness and thermal structure of the mantle wedge.

To evaluate these relationships, a coherent global database is necessary. The first aim of this study is to provide a high quality dataset that is inclusive and global – incorporating major element, trace element, and Sr, Nd, Hf and Pb isotope compositions of arc stratovolcanoes along volcanic fronts worldwide. The second aim is to highlight variations among chemical parameters that must be accounted for by successful models of the subduction system and to explore which subduction parameters exert a controlling influence on the global chemical variations. Competing models can then be evaluated quantitatively to determine which best account for the observed systematics.

Past studies have carried out global evaluations of arc volcanoes, but were more limited in the parameters considered. Early studies emphasized variations perpendicular to the volcanic front. (Dickenson and Hatherton, 1967; Condie and Potts, 1969). Leeman (1983) found a global correlation between crustal thickness and some major element ratios as well as Sr isotopic compositions, interpreted as the result of enhanced interaction between melts and crust during transport. Plank and Langmuir (1988) demonstrated strong correlations for arc front lavas between major elements and crustal thickness, and weaker correlations with other subduction parameters. These trends were found to be inconsistent with generation by intra-crustal processes, and attributed to variations in the extent of melting of the mantle wedge. Ruscitto et al. (2012) proposed that the H_2O/Ce ratio of primitive melt inclusions varied with proxies for the thermal state of the subducting slab.

This paper presents a more inclusive global dataset to evaluate the importance of crustal processes on mafic and intermediate (>4 wt.% MgO) magma compositions. We find, in accordance with previous work, compelling correlations between the thickness of overlying arc crust and the compositions of these magmas. Various models, such as Annen et al. (2006), have suggested that deep crustal processes may be ubiquitous in the evolution of arc magmas. It is a primary goal of this paper to investigate whether such processes are 1) supported by the global geochemical data and 2) may be responsible for the global geochemical trends. A companion paper, Turner and Langmuir (2015), extends this analysis to incorporate the full suite of subduction parameters in an effort to provide a comprehensive view of global arc volcanism and the outstanding questions that remain unresolved.

Arc magmas are generally more evolved than ocean ridge magmas due to differentiation processes in the crust. We seek to determine whether variations in crustal differentiation at convergent margins can produce signals that might be confused with those from primary magma compositions. We additionally provide evidence that stratocone magmas from global arcs do not generally differentiate at lower crustal levels.

2. The database

Stratovolcanoes are the primary magmatic flux at convergent margins and define the volcanic fronts of continental and island arcs. Here we study volcanic front magmas as designated largely by Syracuse and Abers (2006). While smaller eruptive centers, mostly monogenetic cones, are abundant in continental arc settings, their eruptive volume is subsidiary to continental stratovolcanoes. For island arcs these small cones are either not present or are poorly sampled, and so samples from monogenetic cones are excluded from our database to avoid potential bias. Stratovolcanoes not on a volcanic front have also been excluded. Where dates were available, samples older than 200 ka were excluded in order to mitigate the potential effects of temporal variation in chemistry, and to eliminate samples that are not stratigraphically contiguous with the modern volcanism.

The raw data used in this study were primarily extracted from the GEOROC geochemical database (http://georoc.mpch-mainz.gwdg.de/georoc/ accessed September 2013), with minor additions for some arc segments (Appendix 1A). While GEOROC contains the most complete set of published analyses of arc lavas worldwide, additional processing was necessary to produce a suitably "clean" database. First, GEOROC suffers from occasional data entry errors and misattributed data. These outliers can have large effects on arc averages and apparent correlations among chemical parameters. Second, GEOROC contains no internal tools to filter out less accurate analytical methods. The GEOROC data compilation algorithm preferentially orders analytical methods for various elements, but when no high precision method is available, data gathered via any lower quality or unattributed methods are inserted automatically. These problems lead to outliers on plots of raw compiled GEOROC data, even among data matching published sources.

To produce a reliable dataset, all outliers were cross-referenced against the original publications. In some instances, chemical analyses of a single volcanic center were available from multiple publications, making it possible to identify analytical errors for certain elements from a given source. Where identified, outlying data due to probable analytical errors were removed. Data reported with low precision by rounding were removed in instances where concentrations are low. Where raw data files were modified, original data entries have been deactivated but retained and tagged in the raw data files for reference. In addition, data were automatically removed if collected prior to 1975, listed as "Extensively Altered," or if XRF data report a loss on ignition greater than 2%.

After assembly of the clean dataset, data compilation scripts were developed to filter the data. For the elements Sc, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Ge, Rb, Sr, Y, Zr, and Ba, data were included where the method was either isotope dilution mass spectrometry, ICP-MS, XRF, AES, or INAA, with preference given in that order. The remaining trace elements include data measured only by isotope dilution mass spectrometry, ICP-MS, INAA, or DCPAES, again with preference given in that order. Sufficient data existed for the Colombia and Ecuador region only if ICPOES data were also included for all trace elements, so lower precision data were allowed for this segment only.

2.1. Filtering the database

Most arc magmas have undergone cooling and crystal fractionation during transfer from the melt region to the surface, and many other magmas are the products of either magma mixing or excess crystal accumulation within the crust (e.g. Eichelberger et al., 2006). One goal of this study is to assess the chemical variability of arc magmas independently of these effects, which requires additional data filtration. To ensure the observations from filtering methods are robust, a variety of filtering methods were tested.