Earth and Planetary Science Letters 470 (2017) 96–107

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Effects of crustal thickness on magmatic differentiation in subduction zone volcanism: A global study

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## ARTICLE INFO

*Article history:*
Received 17 October 2016
Received in revised form 3 April 2017
Accepted 13 April 2017
Available online xxxx
Editor: M. Bickle

*Keywords:*
magmatic differentiation
calc-alkaline
elevation
crustal thickness
Fe-depletion
arc volcanism

## ABSTRACT

The majority of arc magmas are highly evolved due to differentiation within the lithosphere or crust. Some studies have suggested a relationship between crustal thickness and magmatic differentiation, but the exact nature of this relationship is unclear. Here, we examine the interplay of crustal thickness and magmatic differentiation using a global geochemical dataset compiled from active volcanic arcs and elevation as a proxy for crustal thickness. With increasing crustal thickness, average arc magma compositions become more silicic (andesitic) and enriched in incompatible elements, indicating that on average, arc magmas in thick crust are more evolved, which can be easily explained by the longer transit and cooling times of magmas traversing thick arc lithosphere and crust. As crustal thickness increases, arc magmas show higher degrees of iron depletion at a given MgO content, indicating that arc magmas saturate earlier in magnetite when traversing thick crust. This suggests that differentiation within thick crust occurs under more oxidizing conditions and that the origin of oxidation is due to intracrustal processes (contamination or recharge) or the role of thick crust in modulating melting degree in the mantle wedge. We also show that although arc magmas are on average more silicic in thick crust, the most silicic magmas (>70 wt.% $SiO_2$) are paradoxically found in thin crust settings, where average compositions are low in silica (basaltic). We suggest that extreme residual magmas, such as those exceeding 70 wt.% $SiO_2$, are preferentially extracted from shallow crustal magma bodies than from deep-seated magma bodies, the latter more commonly found in regions of thick crust. We suggest that this may be because the convective lifespan of crustal magma bodies is limited by conductive cooling through the overlying crustal lid and that magma bodies in thick crust cool more slowly than in thin crust. When the crust is thin, cooling is rapid, preventing residual magmas from being extracted; in the rare case that residual magmas can be extracted, they represent the very last melt fractions, which are highly silicic. When the crust is thick, cooling is slow, so intermediate melt fractions can readily segregate and erupt to the surface, where they cool and crystallize before highly silicic residual melts can be generated.

## 1. Introduction

The continental crust is enriched in silica and depleted in iron relative to a parental basaltic magma and, at least since the Proterozoic, much of it originated in subduction zone settings through arc magmatism. Melting of the mantle wedge above subducting oceanic lithosphere generates basalts, which then rise into the upper plate lithosphere where they undergo cooling and crystallization to produce evolved residual melts that go on to make the crust. Both the processes of mantle melting and intracrustal differentiation influence the compositions of arc magmas (Arndt and Goldstein, 1989; Herzberg and Rudnick, 2012; Jagoutz, 2010; Jagoutz and Schmidt, 2012; Kelemen, 1995; Lee, 2014; Lee and Bachmann, 2014; Lee et al., 2006; Plank, 2005; Plank and Langmuir, 1988; Rudnick, 1995; Turner and Langmuir, 2015a, 2015b).

A number of studies have suggested that crustal thickness plays a role in controlling the composition of arc magmas. Plank and Langmuir (1988) and Turner and Langmuir (2015a, 2015b) have shown that crustal thickness controls the composition of parental arc basalts by modulating the degree of mantle melting. Superimposed on mantle source effects are the effects of intracrustal differentiation, where fractional crystallization and other processes generate more evolved melts (Hildreth and Moorbath, 1988; Jagoutz and Schmidt, 2012; Lee and Bachmann, 2014). Progressive intracrustal differentiation eventually masks most of the

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http://dx.doi.org/10.1016/j.epsl.2017.04.025

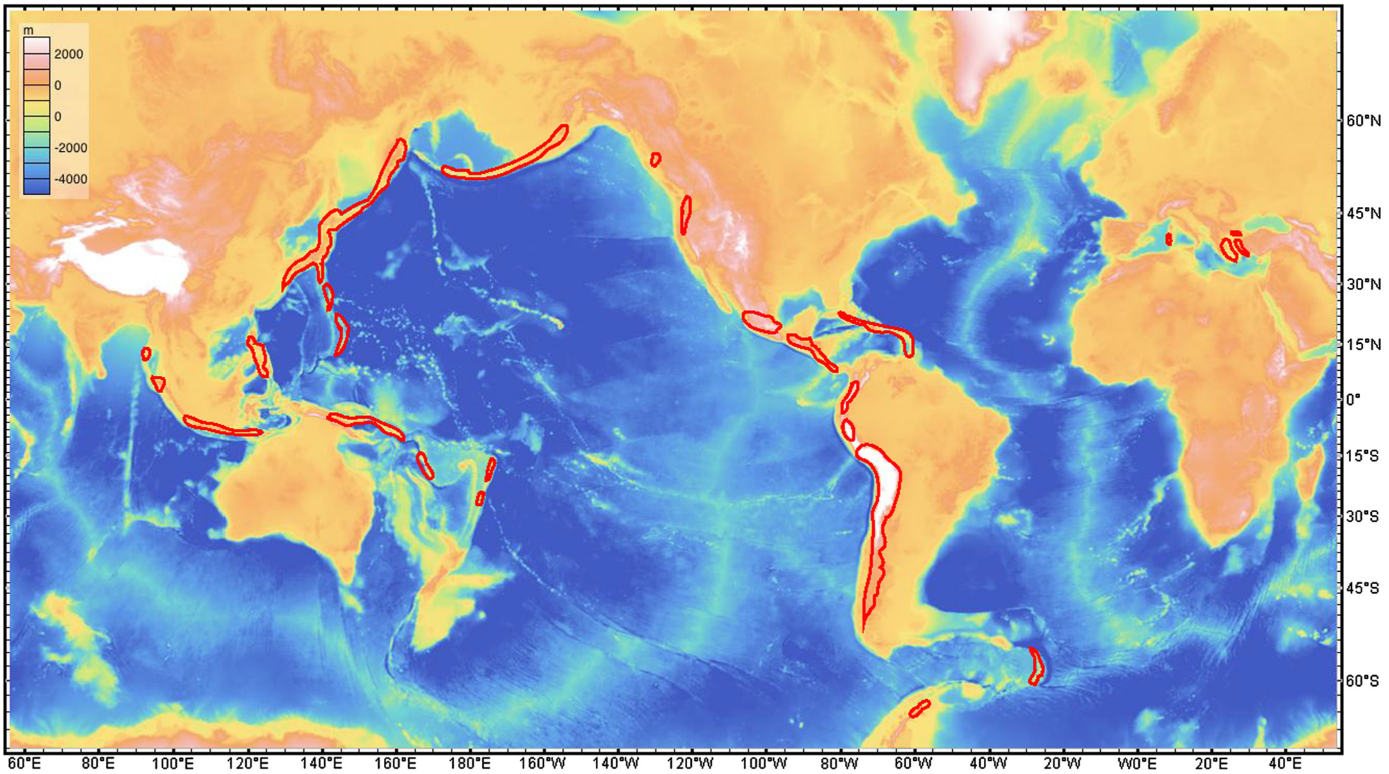

**Fig. 1.** Elevation (m) map of the Earth with locations of compiled arc lavas outlined in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

original mantle signatures, such that by the time magmas evolve to compositions typical of average continental crust, intracrustal differentiation overwhelms much of the source signal. For example, the andesitic (silicic) nature of continental crust is a result of intracrustal differentiation, and not so much due to mantle source effects, which generate basalts. Crustal thickness has also been invoked to explain the composition of more evolved arc magmas, with suggestions that thick crust favors more silicic compositions (Chapman et al., 2015; Dhuime et al., 2015; Lee et al., 2015b; Mantle and Collins, 2008).

In this paper, we explore the effects of crustal thickness on intracrustal differentiation by examining how the average composition of arc magmas varies globally with arc elevation, which we use as a proxy for crustal thickness. We find that arc magmas in thick crust have higher silica content, are more depleted in iron and more enriched in incompatible elements than magmas that traverse thin arc crust. Our observations indicate that arc magmas traversing thick crust have experienced more crystal fractionation. The greater extent of iron depletion in arc crust in thick magmatic arcs reflects earlier onset of magnetite saturation, which suggests that arc magmas traversing thick crust, such as in continental arcs, are more oxidized than arc magmas traversing thin crust, such as in island arcs. Importantly, these signatures that typify arc magmas in thick crust are the same signatures that characterize average continental crust.

## 2. Global arc database

We examined only Pleistocene to Holocene age volcanic rocks to insure that rock compositions reflect recent volcanism and are comparable to estimates of modern-day crustal thickness. Whole-rock compositions of lavas ($n = 52259$) were compiled from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/) for all presently active volcanic arcs using precompiled data for individual arc segments (Fig. 1). Compiled data were filtered to include subaerial arc front volcanic rocks ($n = 36{,}947$) with geolocation data, a designated lithologic name (e.g. basalt, rhyolite), and major element oxide sums within the range 98–101.5 wt.% to exclude altered rocks. These data, along with meta-data, such as volcano name, magmatic arc name and coordinates, are provided in the supplemental information. Our compilation differs from other recent arc lava compilations (Plank and Langmuir, 1988; Turner and Langmuir, 2015a, 2015b), which excluded low ($<4$ wt.%) MgO samples for the purpose of investigating the effects of the mantle source on the compositions of primitive magmas. The objective of those studies, in particular, was to quantify the composition of primitive arc magmas by extrapolating crustal differentiation trends to a fixed MgO content (6 wt.% MgO) rather than characterizing average compositions of arc magmas "as is". In this paper, we are interested in the extent of crustal differentiation, so all magma compositions were retained to obtain an average arc magma composition. We note that the majority of arc magmas have MgO contents $<6$ wt.%, owing to crustal differentiation.

A number of studies have compared magma compositions with crustal thickness as constrained seismically by the depth of the Moho (Chapman et al., 2015; Hildreth and Moorbath, 1988; Mantle and Collins, 2008; Plank and Langmuir, 1988; Turner and Langmuir, 2015a, 2015b), but because seismic studies are not available everywhere, the geographic coverage of such comparisons is not comprehensive. To cover all active arcs, we assume that over long enough lengthscales, the Earth is isostatically compensated, particularly beneath active arcs where the crust is hot and weak. Lee et al. (2015b) showed that elevations of mountains correlate to first order with Moho depth (Laske et al., 2013), indicating that high elevations are isostatically compensated by crustal thickness, with mantle contributions of second order. We use the empirical correlation of elevation versus crustal thickness in Lee et al. (2015b) to convert elevation to crustal thickness and estimate lithostatic pressure at the base of the crust (assuming an average crustal density of 2870 kg/m$^3$).