Earth and Planetary Science Letters 456 (2016) 66–77

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Compositional variability in mafic arc magmas over short spatial and temporal scales: Evidence for the signature of mantle reactive melt channels

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ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 25 September 2016
Accepted 30 September 2016
Editor: M. Bickle

Keywords:
reactive melt channels
Southern Volcanic Zone
Mocho-Choshuenco
mantle transport
subduction zone processes

ABSTRACT

Understanding arc magma genesis is critical to deciphering the construction of continental crust, understanding the relationship between plutonic and volcanic rocks, and for assessing volcanic hazards. Arc magma genesis is complex. Interpreting the underlying causes of major and trace element diversity in erupted magmas is challenging and often non-unique. To navigate this complexity mafic magma diversity is investigated using sample suites that span short temporal and spatial scales. These constraints allow us to evaluate models of arc magma genesis and their geochemical implications based on physical arguments and recent model results. Young volcanic deposits ($\lesssim$18 kyr) are analysed from the Southern Volcanic Zone (SVZ), Chile, in particular suites of scoria cones on the flanks of arc stratovolcanoes that have erupted relatively primitive magmas of diverse compositions. Our study is centred on the high-resolution post-glacial tephrochronological record for Mocho-Choshuenco volcano where tight age constraints and a high density of scoria cones provide a spatially well-resolved mafic magma dataset. Two compositional trends emerge from the data. Firstly, magmas from cones on the flanks of the main edifice become more mafic with distance from the central vent. This is attributed to fractional crystallisation processes within the crust, with distal cones sampling less differentiated magmas. Secondly, there is a set of cones with distinct major and trace element compositions that are more primitive but enriched in incompatible elements relative to the central system and other 'normal SVZ' magmas. This distinct signature – termed the 'Kangechi' signature – is observed at three further clusters of cones within the SVZ. This is attributed to greater preservation of the enriched melt signature arising from reactive melt transport within the mantle wedge. Our model has important implications for arc magma genesis in general, and in particular for the spatial and temporal scales over which compositional variations are preserved in erupted magmas.

1. Introduction

Mafic magmas are critically important for our understanding of arc magma genesis. In arc settings it is widely agreed that mantle melting is dominated by flux melting due to the release of volatile-rich fluids and/or melts from the subducting slab (e.g., Elliott et al., 1997; Grove et al., 2012; Spandler and Pirard, 2013). These melts differentiate and interact with the mantle and crust as they ascend to the surface. Major volcanic centres have a characteristic spacing of order 10–100 km along-arc. As there is no particular reason why this pattern should reflect the locus of primary melt production along the slab or within the mantle wedge, it has long been assumed that some melt transport processes must be responsible for focussing melt into these major crustal processing systems (Spiegelman and McKenzie, 1987; Wilson et al., 2014). All the processes that occur between the slab and surface affect the geochemical signature of the magma; however, their respective roles and relative importance in causing the chemical diversity observed in erupted magmas remain largely unresolved.

Ideas regarding the origins of the chemical diversity in mafic arc magmas can be broadly grouped into three sets of hypotheses. These are that diversity in magma composition (i) is gener-

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http://dx.doi.org/10.1016/j.epsl.2016.09.056

ated during ascent, degassing and differentiation (e.g., Hildreth and Moorbath, 1988; Annen et al., 2006), (ii) is inherited from compositional variations in mantle source occurring either in space or time, for example changes in slab inputs (e.g., Plank and Langmuir, 1988; Watt et al., 2013; Turner and Langmuir, 2015a, 2015b), and/or (iii) emerges as a consequence of channelised melt transport in the mantle wedge (e.g., Kelemen et al., 1997; Reiners, 1998).

Hypotheses (i) and (ii) are well-established in the literature (e.g., McCulloch and Gamble, 1991; Peacock et al., 1994; Plank and Langmuir, 1988; Wallace and Carmichael, 1999; Elliott, 2003; Grove et al., 2006). Hypothesis (iii) has mainly been discussed in the context of decompression melting at mid ocean ridges (e.g., McKenzie, 1985; Kelemen et al., 1995, 1997; Spiegelman and Kelemen, 2003; Katz et al., 2004; Keller and Katz, 2016). Hence, there is some uncertainty in applying this concept to arc settings. Recent models of magma/mantle dynamics (e.g., Spiegelman and Kelemen, 2003; Hewitt, 2010; Katz and Weatherley, 2012; Keller and Katz, 2016) suggest that geochemical consequences of channelised melt transport in the mantle wedge may be more important than previously understood.

The physical mode of melt transport significantly influences the way melts are generated and how they physically and chemically interact with the mantle. These dynamic processes can thus control both the type of compositional variations emerging in a magmatic system as well as the distances over which such variations are preserved. Recent work has shown that volatile-flux melting may cause strongly channelised melt transport in an upwelling mantle column (Keller and Katz, 2016). Flux of a volatile-rich liquid enhances partial melting of peridotite. Melt produced by such flux melting increases the local mantle permeability, thus facilitating faster rates of volatile-flux, which cause even more melting. This reaction-transport feedback known as the Reactive Infiltration Instability (see references in Keller and Katz, 2016) leads to channelised melt transport in the mantle wedge. Such reactive channelling causes significant lateral variability in melt composition, with low-degree incompatible-enriched melts arising in the centre, and high-degree depleted melts on the periphery of channels (Spiegelman and Kelemen, 2003). This process has particular relevance in arc settings, where water-flux melting from slab dehydration is a dominant source of magma generation in the mantle wedge.

Magmas erupted at arc volcanoes are chemically and isotopically diverse across a range of temporal and spatial scales (e.g., Carr et al., 1990; Stern, 2004; Ramos and Kay, 1992; Druitt et al., 1999; Gertisser and Keller, 2003; Ripepe et al., 2005; Singer et al., 2008; Watt et al., 2013; Jacques et al., 2014; Turner and Langmuir, 2015a, 2015b; Rawson et al., 2016). Interpretations of the origin of this diversity are often non-unique when using solely geochemical arguments. However, if samples of materials on appropriate spatial and temporal scales are used physical arguments can be additionally applied. For example, investigating along-arc or across-arc variations using samples erupted over short timescales (e.g., less than tens of millennia) removes some potential drivers which operate on much longer timescales, such as changing regional stress fields or long-term variations in slab parameters. However, many prior studies of arc-scale or global trends have used limited datasets that have poorly constrained chronology and spatial relationships (e.g., Hildreth and Moorbath, 1988; Plank and Langmuir, 1988; Jacques et al., 2014). This can lead to potential biases in the data, including underestimating the full magma diversity at a single volcanic centre; over-emphasising the volumetric significance of geochemical variability; and confusing spatial trends for temporal trends.

Here, we focus on a region where mafic magma diversity is seen over short temporal (∼1 kyr) and spatial (1–10 km) scales. Our particular focus is on the mafic products of post-glacial (≲18 kyr) eruptions from the Mocho-Choshuenco Volcanic Complex (40°S, 72°W), in the Southern Volcanic Zone of Chile (33.3°S–46°S; SVZ: Fig. 1). Mocho-Choshuenco is a large, late Quaternary (<350 kyr) stratovolcano that has erupted melts of basaltic-andesite to rhyolite composition in post-glacial times (Rawson et al., 2015). The central part of the SVZ (37°S–45°S) is an ideal case study since the regional tectonics and arc inputs are relatively invariant along strike and typical for an arc setting. The subduction angle (20–30°), dip (25–35°), convergence rate (7–9 cm/yr), sediment thickness, sediment lithology and crustal thicknesses (∼35 km) are all spatially quasi-uniform (e.g. Stern, 2004; Syracuse and Abers, 2006; Lucassen et al., 2010). This setting allows us to reduce the number of potential physical and chemical variables that could control observed mafic magma diversity.

Mocho-Choshuenco has a high number and density of mafic cones (∼40 scoria cones, situated up to ∼15 km from the central vent), which have erupted relatively primitive but compositionally diverse magmas. This spatially well-resolved sample set has the potential to reveal km-scale melt compositional variability – a signal that is otherwise easily overlooked. A high-resolution post-glacial tephrochronological record for Mocho-Choshuenco additionally provides tight age constraints for the deposits, all of which have erupted within the last 18 kyr (Rawson et al., 2015).

2. Methods and samples

Whole-rock major and trace element analyses were carried out on a suite of 120 post-glacial tephra samples from Mocho-Choshuenco, including 44 scoria cone samples. Major elements were analysed by X-ray fluorescence spectrometry (XRF) at the Department of Geology, University of Leicester, and trace elements by Inductively Coupled Plasma-Mass Spectrometry on a Thermo Finnigan Element 2 Sector-Field instrument at the Department of Earth Sciences, University of Oxford. See Supplementary Material for the detailed methodology and full set of analyses.

To capture the compositional range of the broader SVZ we compiled whole-rock data from the literature, and augmented this by analysing 109 additional samples (method as above) from Llaima, the Caburgua-Huelemolle Small Eruptive Centers (CHSEC), Villarrica, Quetrupillan, Puyehue-Cordón Caulle, Casablanca, Osorno and Huanquihue. We only compiled/analysed samples known to have erupted in post-glacial times (≲18 kyr) and from volcanic centres between 37°S and 45°S. Volcanoes within the Northern and Transitional segments of the SVZ (33.3°S to 37°S) are excluded due to the thicker continental crust in that part of the arc, which may impart a stronger crustal signature to the magmas (e.g., Hildreth and Moorbath, 1988). Volcanoes south of 45°S are excluded because of the potential influence of the Chile Rise, an oceanic ridge that marks the boundary between the Nazca and Antarctic Plates (e.g., Gutiérrez et al., 2005). We refer to this filtered dataset as 'SVZ' hereafter.

Within this SVZ dataset we distinguish deposits within three volcanic groups for further discussion: the Puyuhuapi volcanic group; the CHSEC ca. 20–35 km north-east of Villarrica and the peripheral cones within the Carrán-Los Venados volcanic field (Fig. 1). The Puyuhuapi volcanic group is a chain of Holocene basaltic cinder cones (44°18′S, 72°32′W; about 500 km south of Mocho-Choshuenco). These cones were constructed on two NE-SW trending fissures, each with four associated cones (e.g., Lahsen et al., 1994). The CHSEC (∼39°30′S, 71°50′W; 60 km north of Mocho-Choshuenco) field comprises small scoria cones and associated flows of probable post-glacial age (Fontijn et al., 2016 described an event from CHSEC at 10.38 ± 0.04 cal ka BP). The cones are grouped into five clusters and three individual centres: Huelemolle, Cordillera Cañi, Caburgua, La Barda and Relicura and the