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Temporal variations in the influence of the subducting slab on Central Andean arc magmas: Evidence from boron isotope systematics

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ABSTRACT

The Pampean flat-slab segment in the southern Central Andes represents an ideal setting at which to investigate how changes in the tectonic configuration of a subduction zone (convergence angles and rates, seamount subduction and shallowing slab angle) affects the recycling of subducted components to arc magmas. To constrain sources, particularly of slab-derived fluids and their contribution to arc magmatism, boron isotope and select major and trace element compositions were determined for pyroxene- and zircon-hosted melt inclusions obtained from a suite of Paleocene to Miocene arc magmatic rocks, from the southern Central Andes. Considerable changes in δ^{11}B values and boron concentrations are observed with time. Significantly lower δ^{11}B values (average $= -1.9 \pm 2.2‰$ (1σ)) and B/Nb ratios (average $= 3.3 \pm 1.3$ (1σ)) were obtained for melt inclusions from Oligocene arc rocks (~ 24 Ma) compared to those from the Paleocene (~ 61 Ma) (averages $= +1.6 \pm 0.8‰$ and 17.8 ± 1.4 (1σ), respectively) and the Miocene ($\sim$18 Ma) (averages $= +4.7 \pm 1.9‰$ and 11.9 ± 5.5 (1σ), respectively).

A slab-derived fluid with a δ^{11}B composition of $+1.5‰$, primarily derived from altered oceanic crust on the down-going slab, affected the source of the Paleocene arc magma. The source of the Oligocene arc magmas received less boron derived from the subducting slab ($\lesssim$1% fluid addition) than the Paleocene and Miocene arc magmas (up to 3.5% fluid addition). This is consistent with a greater depth to the slab-mantle interface and is potentially related to the widening of the volcanic arc and more distal position of these samples relative to the trench during this time period. The higher δ^{11}B values (up to $\sim$9‰) obtained for the Miocene melt inclusions record an increase in the influence of serpentinite-derived fluids on the source of arc magmas after $\sim$19.5 Ma. This is approximately coeval with the subduction of the Juan Fernandez Ridge (JFR), suggesting that the oceanic lithosphere associated with the subducting JFR in the Early Miocene was hydrated and serpentinised, similar to the present day ridge. As serpentinisation increases the buoyancy of the slab this finding supports the link between the intersection of the JFR with the Andean margin and the onset of flat-slab subduction.

1. Introduction

Convergent margins with shallow subducting angles (i.e., $<10°$ at ca. 100 km depth), often referred to as 'flat-slab zones', are frequently linked with an absence of active arc volcanism (Gutscher et al., 2000). Variations in the subduction angle of the Nazca plate beneath the South American continent has resulted in the segmentation of the Andean margin into volcanically active and inactive zones (e.g., Jordán et al., 1983). The southern Central Andes (Pampean flat-slab segment) represent a region which is currently volcanically inactive. Over the latter part of the Cenozoic the angle at which the oceanic plate subducts beneath this section of the Andean margin has shallowed, although the exact timing and cause is debated. Several mechanisms have been proposed, including; (1) the intersection of the Juan Fernandez Ridge (JFR), an intraplate volcanic seamount chain, which began intersecting the Andean margin during the Early Miocene (Gutscher et al., 2000; Pilger, 1981; Yañez et al., 2002, 2001); (2) the curvature of the subducting

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slab (Cahill and Isacks, 1992); and (3) the trench-ward motion of the thickened Andean lithosphere (Manea et al., 2012).

The intersection of the JFR with the Central Andean margin coincides with the location of the current flat-slab segment (Anderson et al., 2007). The JFR originates from a narrow mantle plume and is suggested to have begun intersecting the Andean margin at ∼20 Ma, migrating south along the margin at a rate of ∼200 km/Ma to its current position at 32.5°S (Yañez et al., 2002). Geophysical evidence suggests the current oceanic lithosphere associated with the JFR has been strongly hydrated and serpentinised (Kopp et al., 2004; Marot et al., 2013). Serpentinisation of the oceanic mantle lithosphere is an important mechanism for generating increased buoyancy in the subducting plate and hence can account for the development of flat-slab subduction (Kopp et al., 2004). Whether the oceanic lithosphere associated with the JFR has always been serpentinised, and whether this caused the development of flat-slab subduction in the southern Central Andes during the Early Miocene remains unclear.

In this study we address these outstanding uncertainties by using specific geochemical tracers present in arc magmatic rocks (boron concentrations and isotope ratios) to identify the subduction and dehydration of serpentinite at sub-arc depths. In addition we examine how the contributions of other slab components (altered oceanic crust (AOC), oceanic and continentally derived sediments) to the source of arc magmas have changed with the altering geodynamic setting.

Boron (B) concentrations and isotope ratios have been identified as sensitive indicators of subducting slab components in arc magmatic rocks (e.g., Palmer, 1991; Rosner et al., 2003; Tonarini et al., 2011). Volcanic rocks from both island and continental arcs have much higher B concentrations than MORB, and high ratios of B over incompatible, fluid-immobile elements (e.g., B/Nb, B/Zr), compared to other tectonic settings (e.g., intra-plate volcanism; Ryan et al., 1996). The high concentration of B in comparison to other incompatible, but fluid-immobile elements suggest that the B must be derived from fluids released from the subducting slab, rather than resulting from partial melting or fractional crystallisation. Generally positive δ^{11}B values have been reported for volcanic arc rocks, for example from the Izu (Straub and Layne, 2002), Kurile (Ishikawa and Tera, 1997), Lesser Antilles (Smith et al., 1997), Mariana (Ishikawa and Tera, 1999), South Sandwich (Tonarini et al., 2011) and Kamchatka (Ishikawa et al., 2001) arcs, with a decrease in B concentrations and δ^{11}B values observed from the arc front to the back-arc (e.g., Ishikawa and Tera, 1997; Leeman et al., 2004; Rosner et al., 2003; Ryan et al., 1995) reflecting the decrease in fluid flux during increased subduction of the slab and the preferential release of ^{11}B to slab derived fluids.

Here we present boron isotope and select major and trace element compositions of pyroxene- and zircon-hosted melt inclusions for Cenozoic arc magmatic rocks from the southern Central Andes. Melt inclusions were analysed as they are protected by the surrounding host phenocryst phase from the effects of post depositional alteration, such as hydrothermal alteration (common at this locality; e.g., Bissig et al., 2001), as well as from late stage processes occurring in the melt during magma ascent (e.g., Schiano, 2003; Schmitt et al., 2002; Sobolev, 1996). The obtained melt inclusion data is combined with U–Pb and Ar–Ar ages (Jones, 2014) to constrain changes in the influence of the subducting slab on the source of southern Central Andean arc magmas with time, and to evaluate the potential causes of flat-slab subduction.

2. Geological setting

The study area is located between 29.5 and 31°S in the Pampean flat-slab segment of the southern Central Andes and spans the Principal and Frontal Cordillera of Chile and Argentina (Fig. 1). Subduction of oceanic crust beneath the South American plate has been active since the Jurassic and has produced a series of volcanic arcs (e.g., Charrier et al., 2007; Ramos et al., 2002; Stern, 2004). Convergence rates and the relative plate motions between the oceanic (Farallon and Nazca) and South American plates have changed over time (Somoza and Ghidella, 2012) (Fig. 2). Convergence rates between the oceanic Farallon and the South American plate are thought to have been relatively slow during the Paleocene (∼5 cm/yr), with an increase in the Mid Eocene to rates of ∼8 cm/yr (Somoza and Ghidella, 2012). This convergence rate is suggested to have remained fairly constant between the Mid Eocene and Late Oligocene, with the Farallon plate being subducted in a north-easterly (NE) direction (Pardo Casas and Molnar, 1987; Pilger, 1984; Somoza and Ghidella, 2012) (Fig. 2). The oceanic lithosphere being subducted during this time interval was most likely Late Cretaceous in age (Somoza and Ghidella, 2012) and subducting at a normal angle (>30°) (Ramos and Folguera, 2009).

A significant change in the tectonic configuration of the Andean margin occurred during the Late Oligocene (∼ 25 Ma) due to the break-up of the Farallon plate into the Nazca and Cocos plates (Lonsdale, 2005). This resulted in both an increase in convergence rates (up to ∼15 cm/yr) and a change in convergence direction from oblique (NE-SW) to orthogonal (ENE-WSW) (Pardo Casas and Molnar, 1987; Somoza, 1998) (Fig. 2). The westward migration of the South American plate is also thought to have been initiated after ∼30 Ma (Silver et al., 1998). This reconfiguration has been linked to a period of major uplift, increased magmatic activity, and a broadening of the magmatic arc (Pilger, 1984). The high convergence rates were sustained up until ∼ 20 Ma, and followed by a gradual decline to present day values (∼7 cm/yr) (Pilger, 1984; Somoza and Ghidella, 2012). It is suggested that progressively older, Late Cretaceous oceanic lithosphere, originating from the Farallon-Phoenix spreading ridge, was subducted along the South American margin between ∼24 and ∼16 Ma (Somoza and Ghidella, 2012).

Shallowing of the Nazca plate in the southern Central Andes (∼28–33°S) to an angle of ∼10° at ∼100 km depth is suggested to have been initiated ∼18 Ma, as inferred from; (1) the initiation of high angle thrust faulting in the main Andean Cordillera (Maksaev et al., 1984); (2) the broadening of the magmatic arc to the east (Kay and Abbruzzi, 1996; Kay et al., 1987, 1991); (3) the termination of back-arc volcanism (Kay and Mpodozis, 2002); and (4) the initiation of deformation in the Argentinean Precordillera (Jordan et al., 1993). The shallowing of the subducting slab over the latter part of the Miocene caused the migration and expansion of the volcanic arc to the east and the eventual cessation of arc volcanism in the Late Miocene (∼6 Ma) (Kay et al., 1987; Ramos et al., 1989; Trumbull et al., 2006). Hence the temporal and spatial distribution of arc volcanism tracks the changing angle of subduction during this time period.

3. Sample selection

Samples of Cenozoic arc magmatic rocks were collected from the Principal and Frontal Cordillera of Chile and Argentina between 29.5 and 31°S (Fig. 1). A subset of eight samples (Table 1) were selected from a larger suite of samples previously characterised and age dated (Jones, 2014). The selection of samples for melt inclusion analysis was based on a number of criteria; (1) in order to assess contributions from slab-derived fluids to the source of the arc magmas and limit the effects of crustal contamination the least evolved samples available were selected; (2) from the most mafic samples those containing suitable melt inclusions for analysis, in suitable phenocryst phases, were selected; (3) finally samples were selected in order to cover the time frame of interest (Paleocene–Miocene). Cenozoic plutonic and volcanic rocks in the