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The thermal effect of fluid circulation in the subducting crust on slab melting in the Chile subduction zone

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ABSTRACT

Fluids released from subducting slabs affect geochemical recycling and melt generation in the mantle wedge. The distribution of slab dehydration and the potential for slab melting are controlled by the composition/hydration of the slab entering a subduction zone and the pressure–temperature path that the slab follows. We examine the potential for along-strike changes in temperatures, fluid release, and slab melting for the subduction zone beneath the southern portion of the Southern Volcanic Zone (SVZ) in south central Chile. Because the age of the Nazca Plate entering the subduction zone decreases from ∼14 Ma north of the Guafo Fracture Zone to ∼6 Ma to the south, a southward warming of the subduction zone has been hypothesized. However, both north and south of Guafo Fracture Zone the geochemical signatures of southern SVZ arc lavas are similar, indicating 3–5 wt.% sediment melt and little to no contribution from melt of subducted basalt or aqueous fluids from subducted crust. We model temperatures in the system, use results of the thermal models and the thermodynamic calculation code Perple_X to estimate the pattern of dehydration-derived fluid release, and examine the potential locations for the onset of melting of the subducting slab. Surface heat flux observations in the region are most consistent with fluid circulation in the high permeability upper oceanic crust redistributing heat. This hydrothermal circulation preferentially cools the hottest parts of the system (i.e. those with the youngest subducting lithosphere). Models including the thermal effects of fluid circulation in the oceanic crust predict melting of the subducting sediment but not the basalt, consistent with the geochemical observations. In contrast, models that do not account for fluid circulation predict melting of both subducting sediment and basalt below the volcanic arc south of Guafo Fracture Zone. In our simulations with the effects of fluid circulation, the onset of sediment melting occurs under the volcanic arc, but dewatering of the subducting sediment and basalt is focused farther seaward (below the landward boundary of the stagnant mantle wedge corner). Thus, the sediment melt could enter the mantle wedge, contributing to the composition of the southern SVZ magmas, yet remain separate from the fluid derived from sediment dewatering which could migrate updip within the slab or into the wedge corner. Preferential hydrothermal cooling of the hottest segments of the system can help explain how there can be fairly uniform magma composition along the arc, despite large along-arc differences in the age of the subducting plate.

1. Introduction

In a subduction zone, the temperature distribution is an important control on metamorphic reaction progress, fluid generation, hydration of the mantle wedge, and melt generation (e.g., Wada et al., 2012; Völker and Stipp, 2015). The age of the subducting plate, convergence rate, and dip of the subducting slab have long been recognized as key controls on subduction zone temperatures (e.g., Kirby et al., 1991). More recently, the important thermal consequences of vigorous fluid circulation redistributing heat in subducting crust have been recognized (e.g., Spinelli and Wang, 2008). The effects of this fluid circulation on subduction zone temperatures are most pronounced for hot systems (i.e. those with young subducting lithosphere) (Rotman and Spinelli, 2013). Because water circulating in the oceanic crust preferentially cools the hottest segments of a subduction zone, it can reduce along-arc variability in subduction zone temperatures (e.g., Rotman and Spinelli, 2014). In this study, we use the results of the thermal models that in-

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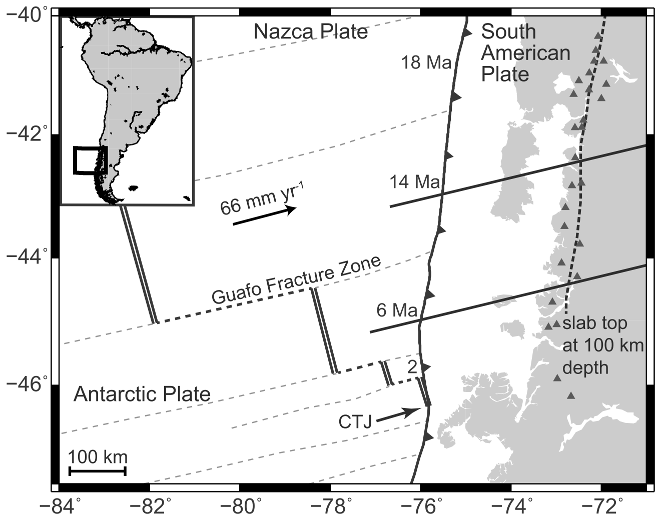

Fig. 1. Map of the study area, the south central Chile subduction zone; inset map shows location in South America. The barbed line is the deformation front between the Nazca/Antarctic Plates and the South American Plate. The pairs of parallel lines are the Chile Rise, with dashed lines indicating fracture zones offsetting ridge segments. The triple junction at the intersection of Chile Rise and the trench is indicated with CTJ. Numbers along the trench indicate the age of the Nazca Plate entering the subduction zone. Transects for the thermal modeling are shown by solid lines in the 6 Ma and 14 Ma segments. Gray triangles onshore are the locations of volcanoes in the southern segment of the Southern Volcanic Zone (i.e. southern SVZ). The dashed line along the volcanic arc shows the location at which the top of the subducting slab is at 100 km depth.

clude the effects of fluid circulation in oceanic crust combined with petrological models to predict mineral stability, water content, and the locations for the onset of melting within the subducting slab in southern Chile, a system with large along-strike changes in the age of the subducting lithosphere including some segments with extremely young subducting lithosphere (Fig. 1). We constrain the influence of fluid circulation in oceanic crust on subduction zone temperatures using the contributions from the subducting material to the magmatic source in southern Chile inferred from geochemical analyses of arc lavas (e.g., D'Orazio et al., 2003; Kilian and Behrmann, 2003; Shinjoe et al., 2013).

1.1. Southern Chile tectonics and volcano geochemistry

This study focuses on the subduction zone north of the Chile Rise-Trench triple junction (Fig. 1). First, we provide some broader regional context by contrasting the subduction zones north and south of the triple junction. The Chile Rise, separating the Nazca Plate to the east from the Antarctic Plate to the west, entered the subduction zone near the southern tip of South America at ∼14 Ma; since then, the Chile Rise-Trench triple junction has migrated north along the trench to its current latitude, ∼46°S (Fig. 1) (Cande et al., 1987). North of the triple junction, the Nazca Plate is subducting beneath the South American Plate at ∼66 $\mathrm{mm\,yr^{-1}}$; within our study area, the age of the Nazca Plate entering the subduction zone ranges from <2 Ma to 14 Ma (Tebbens et al., 1997). The volcanoes in this region are classified as the southern portion of the Southern Volcanic Zone (southern SVZ). South of the triple junction, Chile Rise has been subducted, and ∼12–24 Ma Antarctic Plate is subducting under South America at ∼19 $\mathrm{mm\,yr^{-1}}$ (DeMets et al., 2010). The volcanoes south of the triple junction comprise the Austral Volcanic Zone.

The volcanoes north and south of the Chile triple junction are geochemically distinct, highlighting differences in their magmatic sources. South of the triple junction, melting of the subducted slab likely contributes substantially to the magmatic source for the Austral Volcanic Zone (e.g., Stern and Kilian, 1996). These volcanoes have erupted adakitic andesites and dacites with low Y concentrations and high Sr/Y ratios (Stern and Kilian, 1996; D'Orazio et al., 2003). This is consistent with the expectation that melts from subducted oceanic crust should be depleted in heavy rare earth elements, and have high Sr concentrations (Yogodzinski et al., 2001). Melting of the subducting slab south of the Chile triple junction is consistent with the high subduction zone temperatures expected for this system with extremely slow convergence and subduction of young lithosphere (Peacock et al., 1994). Very young subducting lithosphere adjacent to slab windows following the subduction of Chile Rise could be particularly susceptible to melting (e.g., Peacock et al., 1994). In contrast, north of the Chile triple junction, the volcanoes of the southern SVZ appear to have a mantle source that is not contaminated by melt of subducted mid-ocean ridge basalt (MORB) (D'Orazio et al., 2003; Kilian and Behrmann, 2003). There is no adakite formation in the southern SVZ; the basaltic to dacitic calc-alkaine rocks there have distinctly higher Y concentrations and lower Sr/Y ratios than rocks from the Austral Volcanic Zone (D'Orazio et al., 2003).

Although arc lavas of the southern SVZ do not have a geochemical signature of MORB melt, they do have signatures of sediment melt (Kilian and Behrmann, 2003; Shinjoe et al., 2013). Plots of $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$ versus $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ of arc lavas from the southern SVZ indicate that they are derived from a depleted mantle source and contain 3–5 wt.% sediment melt, but no contribution of fluid from subducted sediment (Kilian and Behrmann, 2003). Low U/Th ratios for the southern SVZ rocks are also indicative of a lack of oceanic crust derived fluid signatures in the magmatic source (Kilian and Behrmann, 2003). Similarly, on a plot of K/Nb versus B/Nb, southern SVZ rocks lay off of the trends between depleted mantle and either fluid from oceanic crust or fluid from subducted sediment (Fig. 2) (Shinjoe et al., 2013). Shinjoe et al. (2013) estimate the composition of the mantle source for the southern SVZ rocks to be comprised of depleted mantle plus 3 wt.% subducted sediment melt. The calculated boron concentration in the sediment before melting, 14 ppm (Shinjoe et al., 2013), is lower than typically found in seafloor sediment (∼50–150 ppm; e.g., Morris et al., 1990). The low boron concentration also indicates that subducted sediment has lost boron (which is fluid-mobile) through dehydration before melting (e.g., Bebout et al., 1999).

Within the southern SVZ, there are large differences in the age of the subducting Nazca Plate that may be expected to yield substantial differences in subduction zone temperature. In this area, the largest offset of Chile Rise is ∼300 km at the Guafo Fracture Zone, which approximately bisects the southern SVZ (Fig. 1). South of the Guafo Fracture Zone, the subducting plate is <6 Ma, including a ∼40 km long segment with ∼2 Ma lithosphere in the trench and a ∼60 km long segment with the mid-ocean ridge essentially in the trench (Tebbens et al., 1997). North of Guafo Fracture Zone, the subducting Nazca Plate is >14 Ma. The subduction zone thermal parameter, ϕ:

$$\phi = A\nu \sin\theta$$

where A is age of the subducting plate, ν is convergence rate, and θ is subducting slab dip (Kirby et al., 1991), provides a simple measure of the thermal state of subduction zones. South of the Guafo Fracture Zone, ϕ in the southern SVZ ranges from 75–225 km; this is on par with the Cascadia subduction zone and hotter than all other subduction zones (e.g., Syracuse et al., 2010). In the southern SVZ north of the Guafo Fracture Zone, ϕ is 530 km; this is similar to Peru, Ecuador, Columbia, Mexico, and Nankai (Syracuse et al., 2010). Despite the large along-strike difference in ϕ across the Guafo Fracture Zone, there is no systematic along-strike variation in the composition of arc lavas in the southern SVZ volcanoes (e.g., Fig. 2).