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Imaging a magma plumbing system from MASH zone to magma reservoir

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ABSTRACT

The Puna Plateau of the Central Andes is a well-suited location to investigate the processes associated with the tectono-magmatic development of a Cordilleran system. These processes include long-lived subduction (including shallow and steep phases), substantial crustal thickening, the emplacement of large volumes of igneous rocks, and probably delamination. To elucidate the processes associated with the development of a Cordilleran system, we pair Common Conversion Point-derived receiver functions with Rayleigh wave dispersion data from Ambient Noise Tomography. The resulting high-resolution shear wave velocity model of the southern Puna Plateau reveals the details of a lithospheric-scale magma plumbing system. Slow velocities near the crust–mantle transition are interpreted as a MASH zone (a partially molten zone where mantle-derived melts interact with the lithosphere and undergo density differentiation) with ∼4–9% melt. After differentiation, less dense and presumably more felsic melts propagate to shallower depths within the crust (∼20 km below surface) and comprise vertically (∼10 km) and laterally (∼75 km) extensive slow velocity bodies that span the frontal arc and plateau interior. These large slow velocity bodies represent a partially molten mid-crust (up to 22%) where magma can further evolve to higher silica concentrations. The periodic influx of melt from the underlying MASH zone into these mid-crustal bodies may serve as a trigger to the eruption of the voluminous ignimbrites observed in the southern Puna Plateau. Many of the active tectonic processes operating along the southern Puna Plateau are thought to be analogous to the processes that formed the North American Cordillera. Thus, these results could provide insight into some of the processes associated with the development of a Cordilleran margin.

1. Introduction

Spatially extensive subduction-related magmatic products form at Andean (Cordilleran) margins. The spatial footprint of magmatism is complicated by long-term subduction, frontal arc migration, and changes in upper plate deformation over time, all of which lead to various types of magmatic addition to the crust (DeCelles et al., 2009). The intrusion of large igneous bodies are the aggregate result of long term subduction at a Cordilleran margin and represent the roots of frontal arcs and interior volcanism generally characterized by the eruption of felsic-intermediate ignimbrites (Ducea et al., 2015c; Best et al., 2009; Freymuth et al., 2015). Despite in-depth petrological studies of Cordilleran-type frontal arcs and neighboring interior magmatism (Saleeby et al., 2003; Lipman and Bachmann, 2015; Ducea et al., 2015c; Best et al., 2016), vertically extensive seismic images of magma plumbing systems have only recently been resolved thanks to improvements in seismic coverage and imaging techniques (Ward et al., 2014; Huang et al., 2015; Kiser et al., 2016). An active type-example of these melt-forming and storing systems can be found in the South American Cordillera, where large-scale intermediate/felsic volcanism and ignimbrite flare-ups are thought to be the surface expression of batholith formation at depth (de Silva and Gosnold, 2007). Evidence is mounting from both petrological and geophysical data that large-scale igneous bodies stall in the mid-crust and undergo further crystal fractionation and mixing with crustal material as they transition from their more mafic initial composi-

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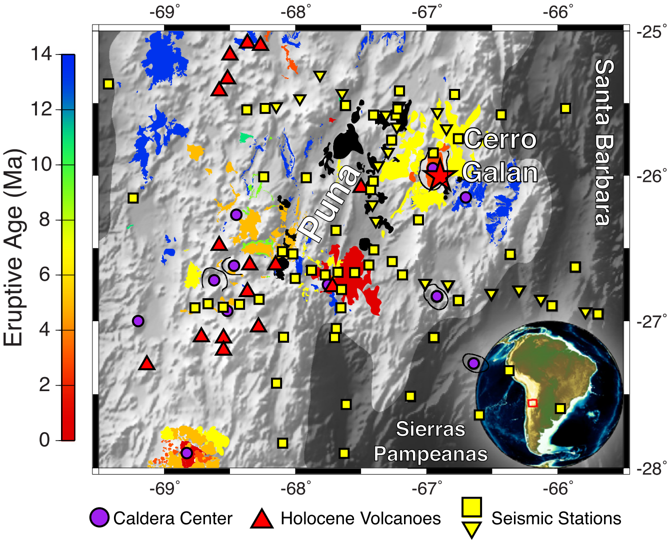

Fig. 1. The seismic station distribution (yellow squares: intermediate or broadband stations; inverted triangles: short-period stations) in the southern Puna Plateau and surrounding region. Elevations >3 km represent the southern Puna Plateau (unshaded). Only stations that had high-quality receiver functions are plotted. Irregularly shaped polygons represent ignimbrite deposits colored by eruptive age, and black semi-circular lines represent mapped ignimbrite calderas (from the Andes Ignimbrite Database, Freymuth et al., 2015 and refs. therein). Black units are basaltic deposits mapped at the surface, many of which show a geochemical signature for delamination (Kay et al., 1994; Ducea et al., 2013; Murray et al., 2015). Red star represents location of shear velocity profile in Fig. 4 within the Cerro Galan Caldera. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tions to felsic compositions (Kay et al., 2011; Ward et al., 2014; Comeau et al., 2015; Ducea et al., 2015a; Huang et al., 2015; Best et al., 2016). If these ponded magma reservoirs are laterally extensive, seismic imaging of these melt bodies is possible (Zandt et al., 2003; Ward et al., 2014).

Regions with long-lived volcanic activity are thought to be underlain by a Melting, Assimilation, Storage, and Homogenization (MASH) zone at the base of the crust (Hildreth and Moorbath, 1988). The MASH zone represents a level of neutral buoyancy for mantle-derived basaltic melt where fractionation, differentiation, and mixing with lower crustal material occurs. This lower-crustal mixing zone eventually differentiates based on density, with the intermediate and felsic compositions rising to shallower depths in the crust and the mafic–ultramafic residuals or "cumulates" remaining near the base of the crust or sinking back into the mantle (Hildreth and Moorbath, 1988; Saleeby et al., 2003). Despite the petrologic evidence that these MASH zones exist beneath volcanically active regions, high-resolution seismic images of these zones are difficult to obtain.

The southern Puna Plateau was the site of a passive seismic experiment deployed from 2007 to 2009 by US, German, Argentine and Chilean institutions (Fig. 1) (Bianchi et al., 2013). Numerous seismic studies using different techniques, including teleseismic and regional body wave tomography (Bianchi et al., 2013), P- and S-wave receiver functions (Heit et al., 2014), two plane-wave tomography using earthquake-generated surface waves (Calixto et al., 2013), and body wave attenuation (Liang et al., 2014), characterize the first-order lithospheric structure and identify some important magmatic features in the region. However, the techniques utilized in these studies have some inherent resolution limitations within the crust.

We utilize a recently developed technique for the joint inversion of receiver functions and surface-wave dispersion data (Julia et al., 2000; Delph et al., 2015) from this dense array of seismic stations to obtain a 3D shear wave velocity model of this magmatically-active subduction-related continental plateau. This resulting model has better crustal resolution than previous models and illuminates a magmatic plumbing system from the base of the lithosphere to the upper levels of the crust. We interpret these images in the context of the detailed tectonic and petrologic history of the southern Puna Plateau to understand the evolution of the continental lithosphere through subduction-related processes (e.g. the compositional variation of igneous rocks, plutonic–volcanic (P:V) ratios, and lithospheric foundering). As the western margin of South America is often interpreted as a modern analogue to the North American Cordillera, these results have broad implications for long-lived magmatic arcs and the development of Cordilleran systems.

2. Methods

2.1. *Receiver function computation*

This dataset arises from the analysis of 92 short, intermediate, and broadband period range stations deployed throughout the southern Puna Plateau from the REFUCA project (19 stations, 2002–2003) and the complimentary German–American–Chilean–Argentine projects of PUDEL (PUna DELamination; Heit et al., 2007) and SLIP (Seismic Lithospheric Imaging of the Puna Plateau; Sandvol and Brown, 2007) that operated from 2007–2009. We computed 5919 receiver functions from earthquakes with magnitudes between 5.5 and 7.6 from distances between 30 and 90 degrees.

For short-period instruments, the instrument response was deconvolved from the waveforms to enhance the sensitivity to lower frequency signals in the seismograms (Niu et al., 2005). The short-period data was kept in units of velocity and subsequently incorporated into the larger dataset (Fig. 2A). All traces were then filtered to enhance the frequency range of interest and those that did not display clear first arrivals were discarded from further analysis. Radial receiver functions were computed using the iterative time-domain receiver function computation described by Ligorria and Ammon (1999). We used a Gaussian pulse width of 2.5 due to its ability to resolve robust crustal structures (vertical resolution of ∼1 km). The receiver functions were then inspected using the FuncLab package (Eagar and Fouch, 2012) for further quality control.

2.2. *Ambient noise tomography*

The ambient noise tomography dataset of Ward et al. (2013) was augmented by recently available data from the PUDEL (Heit et al., 2007), SLIP (Sandvol and Brown, 2007), and PLUTONS (West and Christensen, 2010) deployments. These datasets were processed as described by Ward et al. (2013) to obtain phase velocities at 13 periods between 8 and 50 s (Supp. Fig. S1). To assure only high quality data was used in the calculation of phase velocities, all cross-correlations with a signal-to-noise ratio <10, an interstation spacing of <3 times the wavelength at the period of interest, and unrealistic phase velocities (<1.5 km/s and >5 km/s) were discarded from the 2-D phase velocity inversion (Barmin et al., 2001). Also, any data that had residuals >3 s after the 2-D tomographic inversion were discarded. The resulting dispersion model has a spatial resolution of ∼0.25° based on the Rayleigh criterion (Barmin et al., 2001), and a 50 km Gaussian smoothing parameter was used to stabilize of the inversion. Thus, the amplitudes of anomalies <50 km may be underestimated in the phase velocity results. Because of the station geometry available previous to this study, the inclusion of the newly available data imposed few changes to the phase velocity results of Ward et al. (2013), and

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