The nature of sub-slab slow velocity anomalies beneath South America

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Introduction

The supporting information in this document contains details about the tomography data and methodology used for this study as well as the process used for testing its robustness. We also include a rough calculation of plate motion used to support the time aspect of our interpreted model.
This study incorporates data from 394 broadband and short period seismic stations deployed throughout Chile and Argentina between 1999 and 2015, including stations from 10 different temporary networks and 6 different permanent networks [Albuquerque Seismological Laboratory (ASL)/USGS, 1988, 1993; GEOFON Data Centre, 1993; Beck et al., 2000; Beck and Zandt, 2007; Sandvol and Brown, 2007; Gilbert, 2008; Roecker and Russo, 2010; Waite, 2010] (Figs. 2 and S6, Table S1). Direct P phases are picked from 508 earthquakes with magnitude 5.0 and greater between 30˚ and 90˚ from the stations and PKIKP phases are picked from 170 earthquakes with similar magnitudes between 155˚ and 180˚ from the stations (supporting information Fig. S1A). Earthquakes used in this study come primarily from the North American subduction systems, the South Sandwich subduction zone, and the southwestern Pacific subduction systems, leading to an uneven backazimuthal distribution of travel paths (supporting information Fig. S1B).

Residuals from broadband stations are picked on the vertical component in up to four frequency bands (0.5 to 1.5 Hz, 0.2 to 0.8 Hz, 0.1 to 0.4 Hz, and 0.04 to 0.16 Hz) while residuals from short period stations are picked on the vertical component only in the 0.5 to 1.5 Hz band. In total, 22,674 direct P phases and 7,591 PKIKP phases are included in the inversion, with 45% in the 0.5 to 1.5 Hz band, 28% in the 0.2 to 0.8 Hz band, 15% in the 0.1 to 0.4 Hz band, and 12% in the 0.04 to 0.16 Hz band. Picks are dominated by the highest frequency band (0.5 to 1.5 Hz) due to the inclusion of short period data and the improved pick quality from more impulsive arrivals.

P-wave arrivals were determined relative to the IASP91 velocity model [Kennett and Engdahl, 1991] using a multi-channel cross correlation algorithm [VanDecar and Crosson, 1990; Pavlis and Vernon, 2010]. Travel time residuals were demeaned for each event to determine relative residuals and were corrected for variations in crustal thickness across the study area using a regional crustal model [Tassara and Echaurren, 2012]. An additional correction is applied to stations in the forearc to account for faster than average seismic velocities in the crust as imaged by several local P-wave studies [Graeber and Asch, 1999; Koulakov et al., 2006; Schurr et al., 2006] and ambient noise tomography [Ward et al., 2013].

We use finite-frequency teleseismic tomography [Dahlen et al., 2000; Schmandt and Humphreys, 2010]. The finite-frequency approximation uses frequency-dependent sensitivity kernels to determine the sampled volume surrounding the geometrical ray path rather than assuming an infinitesimally thin sampling ray. We approximate sampling to occur only within the first Fresnel zone, with differential sensitivity calculated using the Born theoretical “banana-doughnut” kernels [Dahlen et al., 2000]. For a more detailed discussion of the finite-frequency teleseismic tomography methodology used in this study, see Schmandt et al. [2010].

The tomographic inversion is a smoothed and damped least squares inversion of relative travel time residuals within a parameterized model space to determine velocity perturbations from the IASP91 reference model within the modeled volume. Smoothing and damping parameters are determined using a tradeoff analysis between the variance reduction of the inversion and the L2 model norm (supporting information Fig. S2). Based on the tradeoff curve, we choose a smoothing parameter of 5 and a damping parameter of 6, yielding a variance reduction of 53%. Station-side and event-side corrections are additionally incorporated in the inversion to account for velocity perturbations outside of the modeled volume.

The model space is parameterized into an irregularly spaced grid of discrete nodes, covering an area at the surface approximately 2400 km (east to west) x 3200 km (north to south) centered on (33.5˚S, 69˚W) from 60 km to 1010 km depth. In the shallowest layer,
horizontal node spacing gradually dilates away from the center of the model from 35 km in the center to 56 km on the edges. In the deepest layer, horizontal node spacing similarly dilates from 54 km to 88 km (east to west) and 109 km (north to south). Vertical node spacing dilates with depth from 35 km between the shallowest nodes and 70 km between the deepest. The node spacing is chosen to optimize the crossing ray paths allowed by our station geometry, as determined by measurements of node hit quality. Hit quality is a quantitative measure of backazimuthal distribution of rays sampling a given node, with a node awarded a perfect hit quality of 1 if it has at least six rays sampling it from the six 30° backazimuthal bins as well as at least six PKIKP phase rays.

Model quality was further tested with a series of synthetic recovery tests using our ray distribution to qualitatively assess model resolution and distinguish recoverable structures from inversion artifacts. In general, anomaly recovery within the well-sampled portions of the model space (hit quality > 0.2) is good, although we observe some along-path smearing and amplitude loss. Both smearing and amplitude loss are stronger on the edges of the model space.

Our initial synthetic recovery test is a standard checkerboard pattern, with alternating two-nodes-per-edge blocks of positive and negative anomalies, separated by neutral zones with a perturbation of 0% (supporting information Figs. S3,S4). The input anomalies are +8% and -8% V_p respectively. On average, ~40% of the anomaly amplitude is recovered within the well-sampled portion of the model space. In these regions, the broad checkerboard pattern is well recovered. However, significant vertical smearing is apparent by the recovery of non-zero velocity anomaly within neutral input layers, while high-amplitude anomalies tend to smear into the neutral spaces between alternating blocks (supporting information Figs. S3A, S3D). Additionally, there is significant along-path smearing along the edges of sampled model space due to a lack of backazimuthal coverage in those nodes. This artifact is more prevalent at depth and in the upper 150 km.

Further recovery tests were performed to test the quality of prominent anomalies seen in our model solution. The first, an input of a +5% slab anomaly (~150 km thick) extending from the surface to the 660 km discontinuity with a gap between 200 and 500 km depth between 31˚S and 33˚S, shows weak smearing of the fast slab anomaly into the gap (supporting information Fig. S5A) indicating that a hole in the slab is not sufficient to produce a slow anomaly. This is further supported by a similar recovery test with synthetic slow anomalies (-5%) mimicking the observed slow anomalies discussed in the text (supporting information Fig. S5B). A high-amplitude slow input anomaly is necessary to produce similar amplitude slow anomalies in the recovered model.

Text S2.

To calculate the approximate age of the subducted ridge segment, we measure the length of the reconstructed hotspot track [Yáñez et al., 2002] and use reconstructed convergence rates between the Nazca and South America Plates at (32˚S, 73˚W) [Somoza and Ghidella, 2012]. In these calculations, we assume 1) trench-perpendicular convergence, 2) all convergence is taken up by subduction, and 3) the material is generated at a hot-spot that is stationary relative to the Nazca Plate.

**Hot-spot age at trench**

\[
\begin{align*}
l &= \text{length}_{\text{hot-spot-trench}} = 750 \text{ km} \\
r_5 &= \text{convergence rate}_{5-0 \text{Ma}} = 88 \frac{\text{km}}{\text{myr}} \\
r_{11} &= \text{convergence rate}_{11-5 \text{Ma}} = 108 \frac{\text{km}}{\text{myr}}
\end{align*}
\]
\[ l = r_5 \times 5 \text{myr} + r_{11} \times (\text{age} - 5 \text{myr}) \]
\[ 750 \text{km} = 88 \frac{\text{km}}{\text{myr}} \times 5 \text{myr} + 108 \frac{\text{km}}{\text{myr}} \times (\text{age} - 5 \text{myr}) \]
\[ \text{age} = 7.87 \text{myr} \approx 8 \text{myr} \]

**Hot-spot age at bend**

\[ l_1 = \text{length}_{\text{hot-spot-trench}} = 750 \text{km} \]
\[ l_2 = \text{length}_{\text{trench-bend}} = 1100 \text{km} \]
\[ r_5 = \text{convergence rate}_{5-0 \text{Ma}} = 88 \frac{\text{km}}{\text{myr}} \]
\[ r_{11} = \text{convergence rate}_{11-5 \text{Ma}} = 108 \frac{\text{km}}{\text{myr}} \]
\[ r_{16} = \text{convergence rate}_{16-11 \text{Ma}} = 114 \frac{\text{km}}{\text{myr}} \]
\[ r_{20} = \text{convergence rate}_{20-16 \text{Ma}} = 138 \frac{\text{km}}{\text{myr}} \]
\[ l_1 + l_2 = r_5 \times 5 \text{myr} + r_{11} \times 6 \text{myr} + r_{16} \times 5 \text{myr} + r_{20} \times (\text{age} - 16 \text{myr}) \]
\[ 750 \text{km} + 1100 \text{km} = 88 \frac{\text{km}}{\text{myr}} \times 5 \text{myr} + 108 \frac{\text{km}}{\text{myr}} \times 6 \text{myr} + 114 \frac{\text{km}}{\text{myr}} \times 5 \text{myr} + 138 \frac{\text{km}}{\text{myr}} \times (\text{age} - 16 \text{myr}) \]
\[ \text{age} = 17.39 \text{myr} \approx 17 \text{myr} \]

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**Figure S1: Data distribution.** A) Earthquake distribution relative to the center of our station array (blue star). Events with direct P arrivals used in this study (between 30° and 90° from stations) are shown in red and events with PKIKP arrivals used in this study (between 155° and 180° from stations) are shown in green. B) Backazimuthal distribution of rays used in the study.
**Figure S2: Tradeoff analysis.** Tradeoff analysis between variance reduction and L2 model norm of inversions with varying damping (D1-D10) and smoothing (S1-S10) weights. The final inversion was run with damping and smoothing parameters of 6 and 5, respectively (yellow star).
Figure S3: Checkerboard test results in map view. Results of the checkerboard test are shown in map view at A) 200 km, B) 320 km, C) 455 km, and D) 605 km depth. E) shows the color scale for the velocity perturbations. The area is the same as Figure 2. The dashed black line in the output outlines the 0.2 “hit quality” contour that indicates well-sampled portions of the model space. The input model is shown on the left with the output results on the right. Note that the input at depths 200 km and 605 km are neutral, yet there are non-zero output results, indicating some degree of vertical smearing.
Figure S4: Checkerboard test results in cross section. Results of the checkerboard test are shown in latitudes A) 26°S, B) 32°S, and C) 38°S, and D) Cross section along longitude 64°W. E) Color scale for the velocity perturbations. Cross sections match those in Figure 4. The dashed black line in the output outlines the 0.2 “hit quality” contour that indicates well-sampled portions of the model space. The input model is shown on the left with the output results on the right.
Figure S5: Slab tear resolution test. Three resolution tests shown at latitude 32°S. A) Input represents a slab hole with no slow velocities. The lack of slow velocities in the output indicates that the slow velocities in the results are not an artifact of the hole. B) Input includes sub-slab slow velocities. This result indicates that sub-slab slow velocities alone are not
sufficient to produce slow velocities within and above the slab hole. C) Input includes slow velocities. This result indicates that slow velocities in the true model are necessary to see slow velocities as in the results. D) Color scale for the velocity perturbations. The dashed black line in the output outlines the 0.2 “hit quality” contour that indicates well-sampled portions of the model space. The input model is shown on the left with the output results on the right.

**Figure S6: Detailed station map.** Map showing the distribution of stations used in this study, with different symbols denoting different seismic networks, deployment types, and instrument types as denoted in the legend. The inset shows the map’s location within South America, as map bounds are different than others shown in the paper.
<table>
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<tr>
<th>Experiment name</th>
<th>Code</th>
<th># of stations</th>
<th>Instrument type</th>
<th>Operating time</th>
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<tr>
<td>GTSN</td>
<td>GT</td>
<td>1</td>
<td>Broadband</td>
<td>1994 – present</td>
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<tr>
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<td>G</td>
<td>1</td>
<td>Broadband</td>
<td>1995 – present</td>
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<tr>
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<td>IU</td>
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<td>Broadband</td>
<td>1998 – present</td>
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<tr>
<td>ISSA</td>
<td>ZP</td>
<td>70</td>
<td>Short period</td>
<td>1999 – 2000</td>
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<tr>
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<td>ZP</td>
<td>20</td>
<td>Broadband</td>
<td>1999 – 2001</td>
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<tr>
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<td>YC</td>
<td>24</td>
<td>Broadband</td>
<td>2000 – 2002</td>
</tr>
<tr>
<td>PUNA</td>
<td>X6</td>
<td>44</td>
<td>Broadband</td>
<td>2007 – 2009</td>
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<tr>
<td>SIEMBRA</td>
<td>ZL</td>
<td>44</td>
<td>Broadband</td>
<td>2007 – 2009</td>
</tr>
<tr>
<td>Eastern Sierras Pampeanas</td>
<td>XH</td>
<td>12</td>
<td>Broadband</td>
<td>2008 – 2010</td>
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<tr>
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<td>11</td>
<td>Broadband</td>
<td>2009 – present</td>
</tr>
<tr>
<td>Chile RAMP</td>
<td>XY</td>
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<td>Broadband</td>
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<td>3A</td>
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<td>2010</td>
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<td>ZE</td>
<td>30</td>
<td>Short period</td>
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<tr>
<td>IMAD – France/Chile</td>
<td>XS</td>
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<td>Broadband</td>
<td>2010 – 2011</td>
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<td>Villarica Experiment</td>
<td>YM</td>
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<td>Broadband</td>
<td>2010 – 2012</td>
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<tr>
<td><strong>West Central Argentina Network</strong></td>
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<td>Broadband</td>
<td>2011 – present</td>
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<tr>
<td>Red Sismologica Nacional</td>
<td>C1</td>
<td>25</td>
<td>Broadband</td>
<td>2014 – present</td>
</tr>
</tbody>
</table>

**Table S1. Station network metadata.** Seismic networks used in this study, sorted by operating time. Experiment names in bold represent permanent networks. Codes represent FDSN network codes. Codes in bold represent data retrieved from the GFZ-Potsdam data portal; all other data was retrieved from the IRIS database. Number of stations refers to number of stations used in this study rather than total number of stations within the network. Available references are included in Text S1.