

# Causes and consequences of flat-slab subduction in southern Peru

Brandon T. Bishop<sup>1</sup>, Susan L. Beck<sup>1</sup>, George Zandt<sup>1</sup>, Lara Wagner<sup>2</sup>, Maureen Long<sup>3</sup>, Sanja Knezevic Antonijevic<sup>4</sup>, Abhash Kumar<sup>5</sup>, and Hernando Tavera<sup>6</sup>

<sup>1</sup>Department of Geosciences, University of Arizona, 1040 East 4th Street, Tucson, Arizona 85721, USA

<sup>2</sup>Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Road NW, Washington, D.C. 20015, USA

<sup>3</sup>Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, Connecticut 06511, USA

<sup>4</sup>University of North Carolina at Chapel Hill, CB #3312, Chapel Hill, North Carolina 27599, USA

<sup>5</sup>National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, Pennsylvania 15236, USA

<sup>6</sup>Instituto Geofísico del Perú, Calle Badajoz 169, Lima 15012, Peru

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## CORRESPONDENCE:

brandontbishop@email.arizona.edu

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## ABSTRACT

**Flat or near-horizontal subduction of oceanic lithosphere has been an important tectonic process both currently and in the geologic past. Subduction of the aseismic Nazca Ridge beneath South America has been associated with the onset of flat subduction and the termination of arc volcanism in Peru, making it an ideal place to study flat-slab subduction. Recently acquired seismic recordings for 144 broadband seismic stations in Peru permit us to image the Mohorovičić discontinuity (Moho) of the subducted oceanic Nazca plate, Nazca Ridge, and the overlying continental Moho of the South American crust in detail through the calculation of receiver functions. We find that the subducted over-thickened ridge crust is likely significantly eclogitized ~350 km from the trench, requiring that the inboard continuation of the flat slab be supported by mechanisms other than low-density crustal material. This continuation coincides with a low-velocity anomaly identified in prior tomography studies of the region immediately below the flat slab, and this anomaly may provide some support for the flat slab. The subduction of the Nazca Ridge has displaced most, if not the entire South American lithospheric mantle beneath the high Andes as well as up to 10 km of the lowermost continental crust. The lack of deep upper-plate seismicity suggests that the Andean crust has remained warm during flat subduction and is deforming ductilely around the subducted ridge. This deformation shows significant coupling between the subducting Nazca oceanic plate and overriding South American continental plate up to ~500 km from the trench. These results provide important modern constraints for interpreting the geological consequences of past and present flat-slab subduction locations globally.**

## INTRODUCTION

Near-horizontal subduction or flat-slab subduction of oceanic lithosphere occurs along ~10% of all subduction zones today and has been postulated to have occurred in many subduction zones in the past to explain patterns of overriding plate magmatism and deformation (Gutscher et al., 2000; Kay and Mpodozis, 2002). In this mode of subduction, the descending slab initially

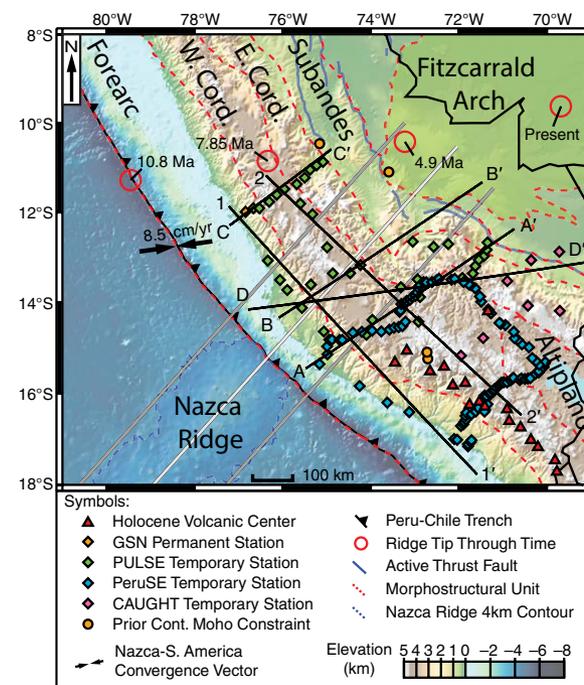
dips at a normal angle (~30°) down to a depth of ~80–100 km, then becomes horizontal for several hundred km, before descending more steeply into the mantle. Studying present-day flat-slab subduction, including the Peruvian flat slab, may provide important insights into this process. How strongly coupled the downgoing and overriding plates may be in a flat-slab system has long been debated, and our study suggests that the South American and Nazca plates are strongly coupled in the segment of the Peruvian flat slab associated with the subduction of the Nazca Ridge. The causes of flat subduction and the effects on the upper plate also remain topics of vigorous debate. Numerous studies suggest several factors are important, including the age of the subducting slab, the absolute motion of the plates, and the presence of buoyant features, such as aseismic ridges on the descending plate (e.g., Gutscher et al., 2000; van Hunen et al., 2002a). Other studies suggest these features are not sufficient and that dynamic effects and the structure of the upper plate play an important role (e.g., Gerya et al., 2009; Manea et al., 2012; O'Driscoll et al., 2012). Additional parameters potentially influencing flat subduction include changes in the viscosity and geometry of the mantle wedge separating the two plates, with relatively shallow low-viscosity regions in the mantle wedge acting to enhance slab flattening by reducing viscous resistance (Manea and Gurnis, 2007). Prior studies of the proposed Cretaceous to mid-Cenozoic Laramide flat slab beneath the western United States and the present-day Sierras Pampeanas flat slab beneath Chile and Argentina have argued that flat-slab subduction leads to both the termination of arc volcanism (e.g., Dickinson and Snyder, 1978, for Laramide; Barazangi and Isacks, 1976, for Sierras Pampeanas) and compressional thick-skinned crustal deformation in the upper plate (see Erslev, 2005, for a review of the Laramide; Jordan and Allmendinger, 1986, for the Sierras Pampeanas). However, not all instances of present-day flat subduction are associated with these features. The Mexico flat slab occurs in association with an inboard active arc and a neutral to extensional state of stress in the upper plate (Suter et al., 2001; Gérard et al., 2015), while the Peruvian flat slab is associated with a cessation of arc volcanism (e.g., Rosenbaum et al., 2005) and long spatial wavelength foreland uplift (Espurt et al., 2007). This diverse range of behavior indicates that no single set of upper-plate responses can be linked to all flat subduction occurrences (see Manea et al., 2017, for a detailed review of present-day flat-slab systems).

We present new receiver function images of the flat-slab region in southern Peru calculated using data from recent deployments of broadband seismic stations. We identify both the South American continental Moho and subducted Nazca oceanic Moho, map the depths to both discontinuities, and calculate an isopach map of the thickness separating the two. The results show up to 20 km of continental crustal thickness variation and delineate the flat slab's depth and areal extent. The new information on the geometry of the flat slab and the structure of the overlying continental crust, in conjunction with recent tomographic results, reveal new clues on the causes of flat subduction and provide details on the tectonic effects in the overlying plate.

## SOUTHERN PERUVIAN FLAT SLAB

The Nazca and South American plates have a present convergence rate in our study region of  $\sim 7$  cm/yr oriented at an azimuth of  $71^\circ$  (DeMets et al., 2010), a significant departure from the calculated 0 Ma to 5 Ma average convergence value of 8.5 cm/yr oriented along an azimuth of  $82^\circ$  (Somoza and Ghidella, 2012). The oceanic Nazca plate first subducts at an angle of  $\sim 30^\circ$ , then flattens near a depth of 100 km to become nearly horizontal in the uppermost mantle beneath South America between  $2^\circ\text{S}$  and  $15^\circ\text{S}$  and subducts at a continuous angle of  $\sim 30^\circ$  south of  $\sim 15^\circ\text{S}$  (Gutscher et al., 2000). The modern gap in active arc volcanism characterizing northern and central Peru was established between 2 and 3 Ma (Noble and McKee, 1982; Rosenbaum et al., 2005) following a significant pulse of magmatism between 16 Ma and 4 Ma (Rosenbaum et al., 2005). Approximately perpendicular to the Peruvian Trench lies the Nazca Ridge, an aseismic ridge with  $\sim 17$ – $20$ -km-thick oceanic crust (Hampel et al., 2004; Tassara et al., 2006) formed from the interaction of the Easter-Salas Hotspot and the East Pacific Rise (Coffin and Eldholm, 1994; Ray et al., 2012). Subduction of the Nazca Ridge has been linked to the cessation of volcanism and ongoing flat-slab subduction between  $\sim 9^\circ\text{S}$  and  $15^\circ\text{S}$  (Fig. 1) (e.g., Gutscher et al., 1999; Gutscher et al., 2000; Hampel, 2002; Rosenbaum et al., 2005; Antonijevic et al., 2015). Slab seismicity relocated by Kumar et al. (2016) for a 2.5 year period shows earthquakes at depths of  $\sim 100$  km in the region where the Nazca Ridge subducts and a gap in deeper seismicity  $> 100$  km along the projection of the subducting Nazca Ridge (Fig. 2).

The western margin of South America between  $9^\circ\text{S}$  and  $17^\circ\text{S}$  can be divided into seven major morphostructural units (Fig. 1, modified from Espurt et al., 2010; Carlotto, 2013). From west to east, the forearc, Western Cordillera (WC), Eastern Cordillera (EC), Subandes, and Amazonian foreland basin extend along a northwest-southeast trend throughout the study region. The Altiplano Plateau is localized in the southeastern corner of our study region, and the Fitzcarrald Arch is a broad foreland uplift aligned with the inland projection of the oceanic Nazca Ridge (Fig. 1). While uplift of the forearc (e.g., Macharé and Ortlieb, 1992; Saillard et al., 2011) and the formation of the Fitzcarrald Arch (e.g., Espurt et al., 2007; Espurt et al., 2010) have been proposed to correspond to the ongoing subduction of the Nazca Ridge, no ridge-related deformation



**Figure 1.** Tectonic features of central Peru and adjacent regions with locations of broadband seismic stations used in this study and of receiver function profiles from this study. White line marks projection of Nazca Ridge axis; gray lines mark projection of ridge edges based on Saillard et al. (2011) seafloor bathymetry. These projections correspond to the uplifted Peruvian Forearc, the intersection of the Fitzcarrald Arch foreland uplift with the Andean thrust front, and the approximate termination of the active Holocene volcanic arc near  $15^\circ\text{S}$ . Orange circles mark constraints on continental Moho depth from prior seismic studies (James and Snoke, 1994; McGlashan et al., 2008). Red circles and associated ages mark the approximate position of a point on the southern edge of the subducted Nazca Ridge through time as it passes through the PULSE area, following the Hampel (2002) model. See text for details of morphostructural units (modified from Espurt et al., 2007; Carlotto, 2013) and seismic arrays. Holocene volcanic centers from Global Volcanism Program (2013), present Nazca–South America convergence vector at  $12^\circ\text{S}$  from Somoza and Ghidella (2012), and Marotta et al. (2013).

inboard of the 500 m elevation contour of the WC has been documented within the cordillera (Wipf et al., 2008).

Crustal seismicity in the WC is limited to  $< 10$  km depth, while that in the EC is limited to  $< 20$  km depth (Dorbath et al., 1990; Dorbath et al., 1991; Devlin et al., 2012) in contrast to seismicity observed at  $> 30$  km depth in the Subandes (Dorbath et al., 1991; Devlin et al., 2012). This suggests a comparatively shallow brittle to ductile transition depth in the WC and EC relative to the Subandes. East of the forearc, little to no seismicity is observed between this seismogenic

Supplemental Material

Causes and consequences of flat slab subduction in southern Peru

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<sup>1</sup>Department of Geosciences, University of Arizona, 1040 East 4<sup>th</sup> Street, Tucson, Arizona 85721, USA

<sup>2</sup>Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Road NW, Washington DC 20015, USA

<sup>3</sup>Department of Geology and Geophysics, Yale University, 210 Whitney Avenue, New Haven, Connecticut 06511, USA

<sup>4</sup>University of North Carolina at Chapel Hill, CB 83312, Chapel Hill, North Carolina, 27599, USA

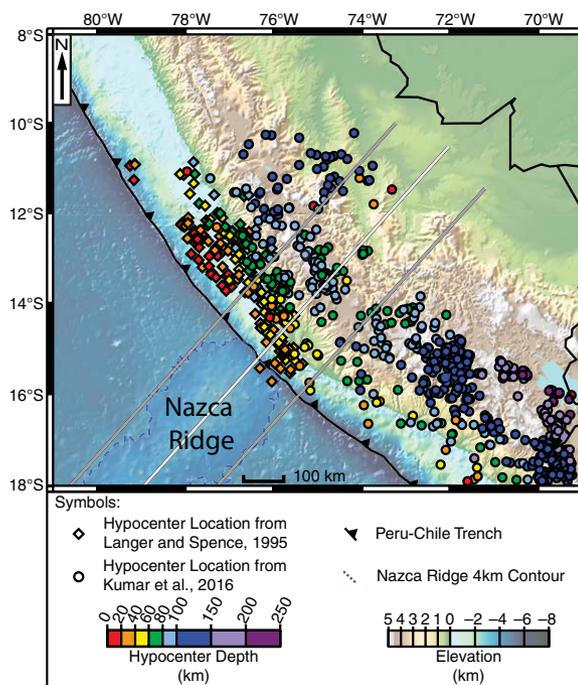
<sup>5</sup>National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236, USA

<sup>6</sup>Instituto Geofísico del Perú, Calle Baakajsa 169, Lima 15012, Peru

RECEIVER FUNCTION METHOD DETAILS

We obtained records of teleseismic direct P-phases ( $\geq 5.0$  Mw,  $30^\circ$  and  $90^\circ$  distance, 1431 usable station-event pairs), PP-phases ( $\geq 6.0$  Mw,  $90^\circ$  and  $150^\circ$  distance, 1202 usable station-event pairs), and PKP-phases ( $\geq 6.0$  Mw,  $110^\circ$  and  $160^\circ$  distance, 119 usable station-event pairs, PKP-phase was not used for PeruSE stations as overlapping station coverage provided sufficient P-, PP-phase arrivals from each seismometer for the calculation of teleseismic receiver functions (Langston, 1979) via the iterative time domain deconvolution technique (Ligorria and Ammon, 1999) using a Gaussian pulse width of 2.5 (equivalent to a low-pass filter with a corner frequency of 1.2 Hz). This gave us a total of 2752 receiver functions. In addition we obtained

<sup>1</sup>Supplemental Material. Additional details on methods and discussion of potential effects of alternate stacking parameters and multiple arrivals. Please visit <http://doi.org/10.1130/GES01440.S1> or the full-text article on [www.gsapubs.org](http://www.gsapubs.org) to view the Supplemental Material.



**Figure 2.** Map of regional slab seismicity relocated using local seismic array data by Langer and Spence (1995) (colored diamonds) and Kumar et al. (2016) (colored circles). Kumar et al. (2016) used the PULSE and CAUGHT arrays to relocate regional slab seismicity between 2010 and 2013. Langer and Spence (1995) used a local seismic array to relocate the aftershock sequence to an October 3, 1974 8.1 Mw earthquake along the Peruvian Trench, providing locations we use to better constrain the slab in the forearc. Note that the overall patterns in seismicity are similar to those in the 43-year International Seismological Centre (2011) hypocenter record plotted in Figure 6.

zone in the upper 20–30 km of the continental crust and the normal to strike-slip mechanism seismicity that begins at ~70 km depth and locally extends to >100 km (Suárez et al., 1990; Kumar et al., 2016), interpreted as earthquakes occurring within the downgoing Nazca slab (see also slab-related seismicity in Fig. 2).

■ DATA AND METHODS

We utilized data from a total of 144 broadband seismic stations to investigate the structure of central and southern Peru. Thirty-eight of these seismic stations (Fig. 1, green diamonds) were deployed (October 2010 to June 2013) for the PULSE temporary network (Wagner et al., 2010; Eakin et al., 2014). We

also used data from eight seismometers (Fig. 1, purple diamonds) deployed (October 2010 to July 2012) for the Central Andes Uplift and Geodynamics of High Topography temporary network (Beck et al., 2010; Ryan et al., 2016). Ninety-seven broadband seismic stations (Fig. 1, blue diamonds) are part of the Peru Subduction Experiment temporary network deployed between June 2008 and February 2013 (PeruSE, 2013). Finally, we used data recorded at the permanent broadband Global Seismic Network station NNA (Scripps Institution of Oceanography, 1986) located near Lima, Peru (Fig. 1, orange diamond).

We first calculated receiver functions (RFs) from the three-component broadband seismic data using an iterative time domain method (Ligorria and Ammon, 1999) and then used common conversion point (CCP) stacking (Dueker and Sheehan, 1997; Sheehan et al., 2000) to make lithospheric-scale depth cross sections (Fig. 3). To migrate the 2752 RFs that we calculated to depth, we used a simplified 1-D layer over half-space velocity model using an average crustal velocity for the region of 6.0 km/s Vp (Dorbath, 1996) to 75 km depth with a Vp/Vs of 1.75 determined from a modified Wadati plot (see Methods in Supplemental Material and Figure S1<sup>1</sup>) and consistent with adjacent regions (e.g., Phillips et al., 2012; Ryan et al., 2016). The half-space from 75 to 200 km depth was assigned a Vp of 8.1 km/s and a Vp/Vs of 1.8, equivalent to the IASP91 mantle model averaged to 200 km depth. We used bootstrapping with 400 iterations to calculate each CCP stack and required that each plotted CCP stack bin contained a minimum of four RFs to reduce the effects of noise and ensure that no single RF dominated any portion of our stack. Uncertainty in our depth calculation for features observed in the CCP stacks is strongly dependent on the uncertainty in the velocity model used to migrate the RFs from time to depth. Because detailed seismic-velocity models for the entirety of our study region are not yet available, we estimate our depth uncertainty based on departures from the simple regional starting model. Forward modeling shows that a feature at 60 km depth in our CCP stacks can be moved  $\sim \pm 0.8$  km by Vp/Vs variations of 0.01 or  $\sim \pm 2.6$  km by a 5% change in average P-wave velocity of the entire crustal column. The largest errors are associated with the forearc, where the seismic velocities and crustal thickness as well as the shallow slab structure are significantly more complex than our simple model. More detailed estimates of uncertainty require a better knowledge of the regional seismic-velocity structure than is presently available.

We used a variety of bin spacings to accommodate the variable interstation distances in our data set. The CCP stack cross section in A–A' (Fig. 3) uses rectangular bins of 15 km  $\times$  25 km; B–B' uses square bins of 25 km  $\times$  25 km (Fig. 3); C–C' uses square bins of 15 km  $\times$  15 km (Fig. 3); D–D' (Fig. 3) uses square bins of 30 km  $\times$  30 km; and 1–1' and 2–2' both use square bins of 25 km  $\times$  25 km. All cross sections use a bin sharing (spatial overlap) with dimensions of 1.5 $\times$  bin size. Further details of these methods are described in the Methods section in our Supplemental Material (see footnote 1). The CCP stacks show a complex continental crustal structure in the region, and this complexity is likely to create a number of multiple arrivals. We have examined the possible effects of multiple arrivals from the mid-crustal discontinuities on our interpreted primary Moho arrivals. Evaluation of the influence of multiple arrivals

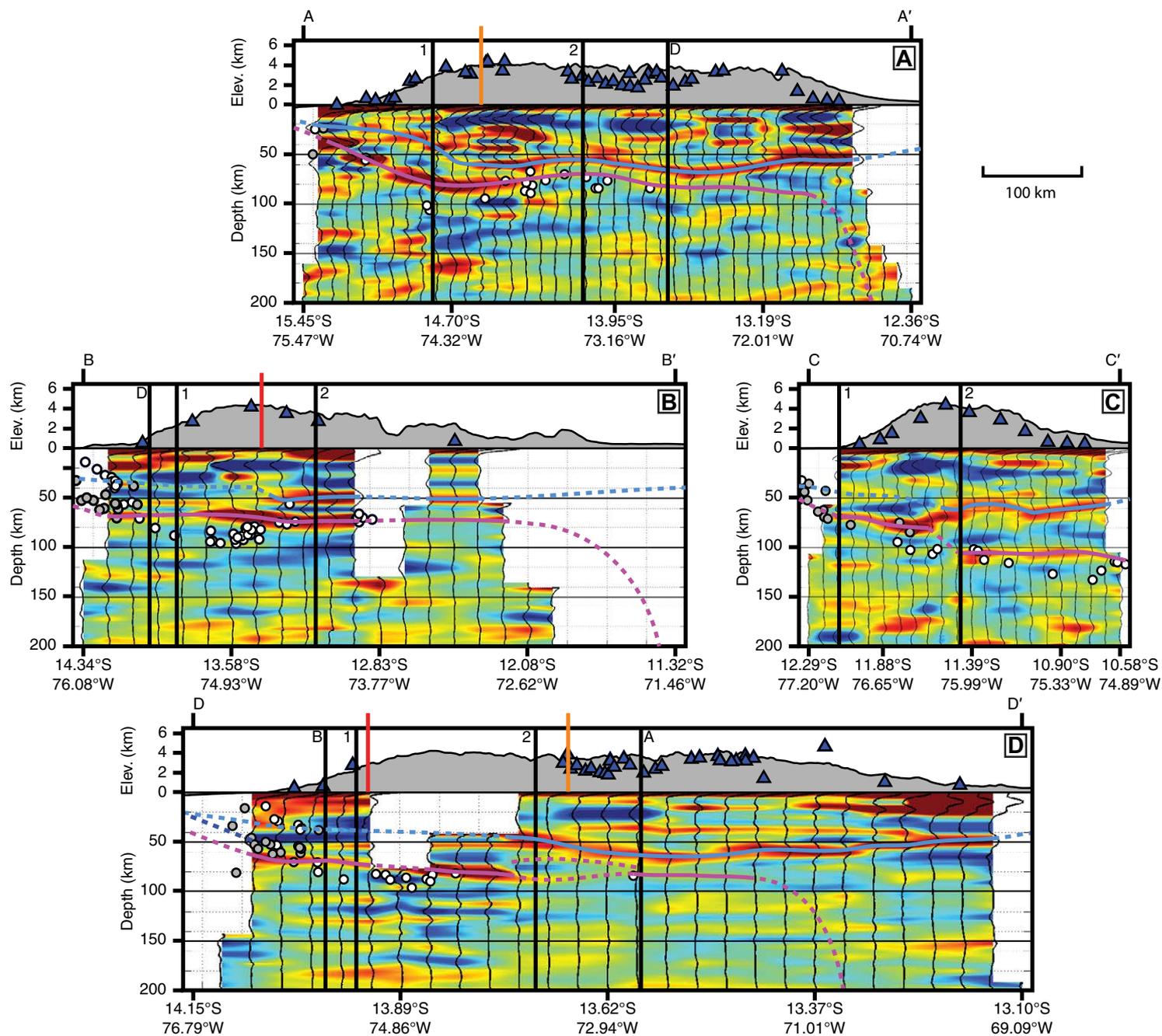


Figure 3. Receiver-function common conversion point (CCP) stack profiles. A–A', B–B', and C–C' are trench-perpendicular cross sections from south (A–A') to north (C–C'). Cross section D–D' follows a strike parallel to the 5 Ma to 0 Ma average South America plate–Nazca plate convergence vector. Receiver-function CCP stack bin size varies between profiles; line A–A' uses rectangular bins of 15 km × 25 km; B–B' uses square 25 km × 25 km bins; C–C' uses square 15 km × 15 km bins; and line D–D' uses square 30 km × 30 km bins. All profiles use 1.5× bin sharing. Light-blue lines mark interpreted continental Moho; purple lines mark interpreted subducted oceanic Moho; dashed dark-blue line at western edge of D–D' marks inferred top of subduction channel (see text). Moho and subducted oceanic Moho lines dashed where inferred, approximate location of slab re-steepening based on Scire et al. (2016) and Antonijevic et al. (2015) tomographic imaging of the Nazca Slab while trench-ward features are based on location of trench, Slab 1.0 megathrust surface (Hampel et al., 2004; Hayes et al., 2012). White dots mark slab seismicity from Kumar et al. (2016), while gray dots mark slab and megathrust seismicity from Langer and Spence (1995), projected on to each section from 30 km to each side. Black vertical lines show locations of intersecting profiles. Red vertical line marks intersection of profile with projected Nazca Ridge axis; orange vertical lines mark intersection of profile with projection of the edges of the ridge. Blue triangles mark location of seismic stations. Surface topography averaged across each profile and six parallel lines spaced at CCP stack bin width.

from these crustal interfaces on the continental Moho and subducted oceanic Moho is presented in our Supplemental Material (see footnote 1) along with examples of intersecting CCP-stack cross sections that have allowed us to better constrain the continental and subducted oceanic Moho (Figs. S2 and S3). An examination of the potential effects of bin size and sharing is presented in Figure S4. Here we focus on the depth to the continental Moho, the depth to the subducting plate's Moho, and on the interpretation of these two features combined with previous studies in the region.

## ■ INTERPRETATIONS OF CROSS SECTIONS

We first picked the continental Moho and the subducted oceanic Moho on individual CCP stacks by identifying relatively high amplitude, laterally continuous positive arrivals at or near depths predicted by previous work. The continental Moho Ps phase is generally a positive high-amplitude, continuous feature except under the forearc, where mantle hydration weakens and may even locally invert the amplitude (Bostock, 2013). The oceanic Moho Ps phase is more variable in amplitude and becomes difficult to trace inland, but recently published slab seismicity locations obtained from analysis of a subset of the seismic stations used in this study (Kumar et al., 2016) have aided us in identifying the top of the slab. We required that the RF arrivals identified as these features match constraints from prior geophysical studies and that these arrivals be laterally continuous between intersecting trench-perpendicular and trench-parallel cross sections (see Figs. S2 and S3 in the Supplemental Material [footnote 1] for examples of intersecting cross sections). The CCP cross sections in Figures 3 and 4 show our interpreted continental Moho (light-blue lines) and subducted oceanic slab Moho (purple lines) based on our receiver-function results (solid lines) and prior seismic (Hampel et al., 2004; Antonijevic et al., 2015; Kumar et al., 2016; Scire et al., 2016) and gravity (Fukao et al., 1989; Tassara and Echaurren, 2012) studies of the region (dashed lines).

Profile A–A' (Fig. 3) is a trench-perpendicular cross section located slightly south of the inboard projection of the Nazca Ridge. We observe the continental Moho's depth (given in depth below sea level) increasing from ~20 km depth at the coastline (where it may coincide with the top of the subduction channel) to more than 60 km depth beneath the WC and undulating between 55 km and 60 km depth beneath the EC and Subandes before gradually reaching less than 50 km depth in the Amazonian foreland. The subducted oceanic Moho of the Nazca plate appears at less than 50 km depth at the coast and dips at a relatively steep angle beneath the forearc to ~80 km beneath the WC before following the variations in the South American continental Moho. This undulating structure is consistent both with slab earthquake hypocenter locations (Kumar et al., 2016) and RF-constrained surface-wave results sampling this location (Ma and Clayton, 2015). The amplitude of the oceanic Moho Ps phase is very high beneath the western portion of the WC and then diminishes abruptly into a low-amplitude phase farther inboard, a characteristic observed on other trench-perpendicular cross sections. We utilize slab earthquake locations and

seismic tomography results to constrain the inboard locations and show the feature with dashed lines where it is poorly constrained (see Supplemental Material [footnote 1] for a discussion of crustal interface multiples that may potentially influence the low-amplitude oceanic Moho Ps phase and an example in Fig. S2 [see footnote 1]).

Profile B–B' (Fig. 3) is a trench-perpendicular cross section located slightly askew to the inboard projection of the Nazca Ridge axis; the vertical red line marks the intersection of the profile and the projection of this axis. The continental Moho signal is very weak or perhaps inverted beneath the forearc and much of the WC, and we show an interpretation consistent with our other cross lines and with offshore data (Hampel et al., 2004). The continental Moho signal increases in strength and depth toward the east, reaching ~50 km depth beneath the EC and the Subandes. The depth to the continental Moho along this profile is significantly shallower than the continental Moho observed to the south (see profile A–A') and north (see profile C–C'), where it reaches >60 km depths. Over the ~375 km separating the forearc and western Subandes, the subducted oceanic Moho lies at ~80 km depth, making it the shallowest part of the flat slab. This upwarp of both the continental and oceanic Mohos across the subducted Nazca Ridge is observed most clearly in the along-strike and oblique cross sections described below.

Trench-perpendicular profile C–C' (Fig. 3) crosses the Andes north of the subducted Nazca Ridge. The continental Moho in the forearc lies at ~45 km depth before increasing to more than 60 km depth beneath both the WC and EC. The gradational character of the forearc Moho arrival may indicate a structural complication or gradual rather than abrupt transition between mantle and crustal velocity materials in this location. Along this profile, the Nazca plate's subducted oceanic Moho lies at ~60 km depth near the Peruvian coast to ~80 km depth near the edge of the WC. The slab Moho appears discontinuous under the WC and is offset rapidly from ~80 km to ~110 km depth near the central portion of the WC (see Supplemental Material and Fig. S3 [footnote 1] for additional details), before flattening for ~225 km inland and then re-steepening beneath the Subandes (Scire et al., 2016). This separation between the South American crust and Nazca plate is several tens of kilometers greater than the separation we observe elsewhere in the region and is located where Antonijevic et al. (2015) hypothesized a trench-parallel slab tear from surface-wave tomography results.

Profile D–D' (Fig. 3) is oblique to the trench and follows the 5 Ma to 0 Ma average 82° convergence vector between the Nazca–South America plates, and it intersects with the projected axis of the Nazca Ridge (red line) and its southern edge (orange line). Although there is a large gap in coverage at crustal depths in the WC, we include this profile because it clearly shows the shallowing of the continental Moho from depths >60 km south of the Nazca Ridge to <50 km over the ridge. This variation in Moho topography is not reflected in the surface elevation along the profile, where the average elevation of the WC and EC remain ~3.5–4 km. In addition, this large variation in Moho depth occurs in a region characterized by relatively uniform Cretaceous to Late Miocene geology and tectonic shortening histories (Oncken et al., 2006; Pfiffner and Gonzalez,

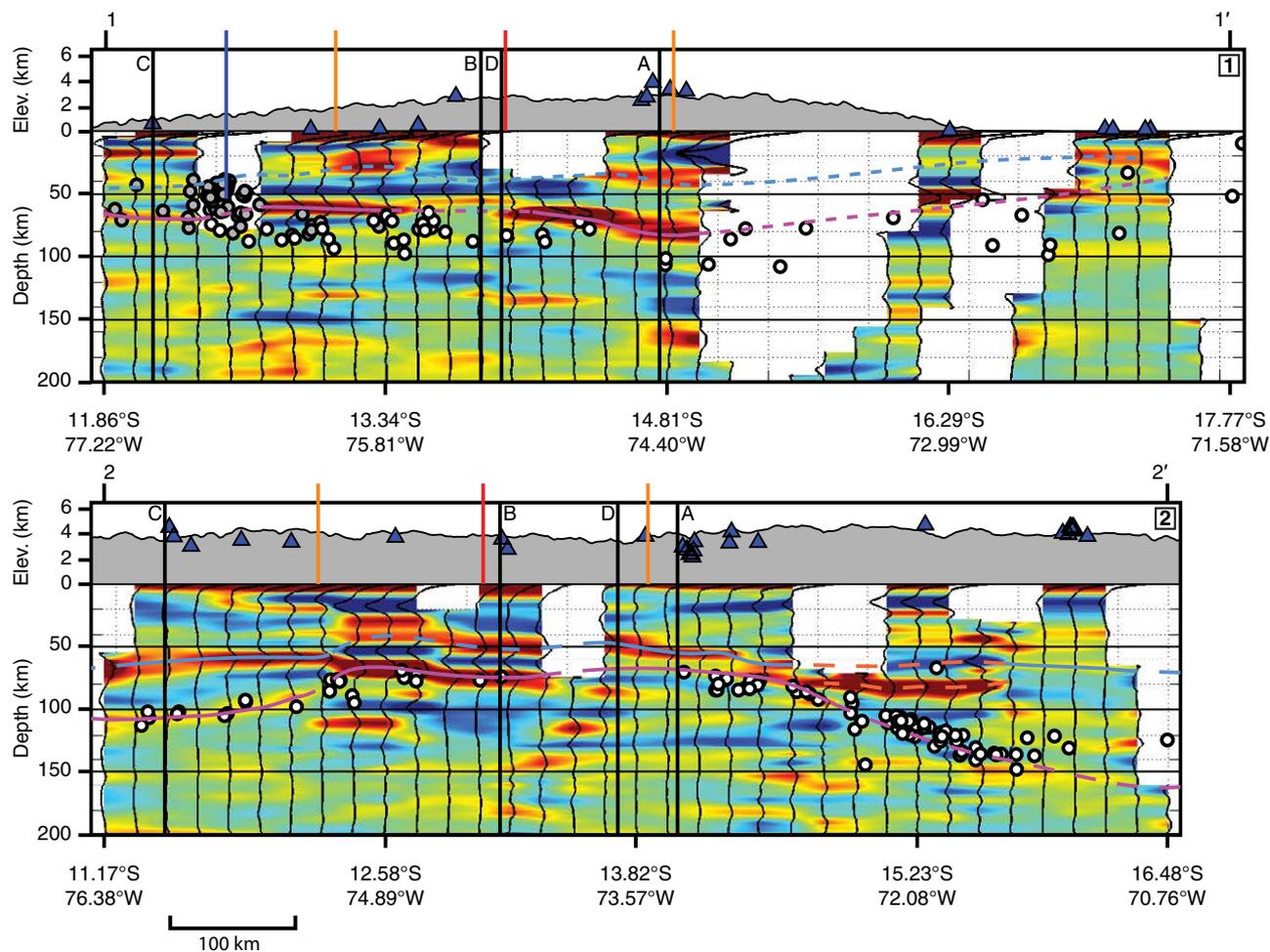


Figure 4. Receiver-function common conversion point (CCP) stack profiles. Cross sections 1-1' and 2-2' strike approximately perpendicular to the inboard projection of the Nazca Ridge Axis and trench-perpendicular cross sections A-A', B-B', and C-C'. Both cross sections use square 25 km x 25 km bins and 1.5x bin sharing. Blue vertical line in 1-1' marks location where Langer and Spence (1995) report strike-slip earthquakes within the subducting Nazca plate (see text). Dashed orange line in 2-2' marks possible inverted continental Moho and bottom of mantle low-velocity zone possibly related to magmatic arc processes (see text). All other symbols and topography features as in Figure 3.

2013), suggesting this variation may relate to the underthrusting of the Nazca Ridge. The slab Moho signal is strong under most of the WC and weakens abruptly under the dense line of stations in the central part of the high cordillera. Based on a few slab earthquakes and tomography results, we interpret the slab to remain flat ~180 km beyond the projection of the Nazca Ridge's southeastern edge, suggesting the subducted ridge may be wider or less linear than the non-subducted portion. Alternately, this may indicate that additional factors are promoting flat-slab subduction in this area. Under the forearc, a large negative arrival near 50 km depth appears to correspond to megathrust-related earthquakes (gray dots in Fig. 3, Langer and Spence, 1995) and the

down-dip projection of the top of the subducting slab (dashed dark-blue line, Hampel et al., 2004), suggesting this feature marks the top of the slab. If so, the subducted ridge has a crustal thickness of ~20 km, indistinguishable from the non-subducted portion of the oceanic ridge crust within the limits of our resolution and uncertainty.

Profile 1-1' (Fig. 4) samples the forearc, highlighting the complicated nature of the continental forearc Moho structure in this region. Aside from the area near the intersection of this line with A-A', the continental Moho appears as a diffuse or low-amplitude arrival that is much weaker than the underlying subducted slab oceanic Moho. This indicates that the velocity contrast

SUPPLEMENTAL TABLE S1. SOUTH AMERICAN MOHO CONSTRAINTS

Lat (°S)	Long (°W)	Depth (km)	Comment
This Study			
13.403300	76.603469	25.500000	RF Moho depth from sea level Theoretical CCP-stack resolution equal to 0.1 km
13.577629	76.499264	35.200000	
13.752559	76.315108	34.400000	
13.926889	76.170932	36.300000	
14.101419	76.028766	38.200000	
14.275948	75.882580	37.900000	
14.450478	75.738404	41.400000	
14.625008	75.594228	41.500000	
14.799538	75.450053	41.000000	
14.974068	75.305877	39.000000	
15.148598	75.161701	37.000000	
15.323128	75.017525	35.000000	
15.497658	74.873349	29.900000	
15.672188	74.729173	27.800000	
15.846718	74.585000	28.800000	
16.021248	74.440824	28.000000	
16.195778	74.296648	28.100000	
16.370308	74.152473	28.200000	
16.544838	74.008297	28.300000	
16.719368	73.864121	28.400000	
16.893898	73.719945	28.500000	
17.068428	73.575769	28.600000	
17.242958	73.431593	28.700000	
17.417488	73.287417	28.800000	
17.592018	73.143241	28.900000	
17.766548	73.000000	29.000000	
17.941078	72.856824	29.100000	
18.115608	72.713648	29.200000	
18.290138	72.570472	29.300000	
18.464668	72.427296	29.400000	
18.639198	72.284120	29.500000	
18.813728	72.140944	29.600000	
18.988258	72.000000	29.700000	
19.162788	71.859124	29.800000	
19.337318	71.718248	29.900000	
19.511848	71.577372	30.000000	
19.686378	71.436496	30.100000	
19.860908	71.295620	30.200000	
20.035438	71.154744	30.300000	
20.209968	71.013868	30.400000	
20.384498	70.872992	30.500000	
20.559028	70.732116	30.600000	
20.733558	70.591240	30.700000	
20.908088	70.450364	30.800000	
21.082618	70.309488	30.900000	
21.257148	70.168612	31.000000	
21.431678	70.027736	31.100000	
21.606208	69.886860	31.200000	
21.780738	69.745984	31.300000	
21.955268	69.605108	31.400000	
22.129798	69.464232	31.500000	
22.304328	69.323356	31.600000	
22.478858	69.182480	31.700000	
22.653388	69.041604	31.800000	
22.827918	68.900728	31.900000	
23.002448	68.759852	32.000000	
23.176978	68.618976	32.100000	
23.351508	68.478100	32.200000	
23.526038	68.337224	32.300000	
23.700568	68.196348	32.400000	
23.875098	68.055472	32.500000	
24.049628	67.914596	32.600000	
24.224158	67.773720	32.700000	
24.398688	67.632844	32.800000	
24.573218	67.491968	32.900000	
24.747748	67.351092	33.000000	
24.922278	67.210216	33.100000	
25.096808	67.069340	33.200000	
25.271338	66.928464	33.300000	
25.445868	66.787588	33.400000	
25.620398	66.646712	33.500000	
25.794928	66.505836	33.600000	
25.969458	66.364960	33.700000	
26.143988	66.224084	33.800000	
26.318518	66.083208	33.900000	
26.493048	65.942332	34.000000	
26.667578	65.801456	34.100000	
26.842108	65.660580	34.200000	
27.016638	65.519704	34.300000	
27.191168	65.378828	34.400000	
27.365698	65.237952	34.500000	
27.540228	65.097076	34.600000	
27.714758	64.956200	34.700000	
27.889288	64.815324	34.800000	
28.063818	64.674448	34.900000	
28.238348	64.533572	35.000000	
28.412878	64.392696	35.100000	
28.587408	64.251820	35.200000	
28.761938	64.110944	35.300000	
28.936468	63.970068	35.400000	
29.110998	63.829192	35.500000	
29.285528	63.688316	35.600000	
29.460058	63.547440	35.700000	
29.634588	63.406564	35.800000	
29.809118	63.265688	35.900000	
29.983648	63.124812	36.000000	
30.158178	62.983936	36.100000	
30.332708	62.843060	36.200000	
30.507238	62.702184	36.300000	
30.681768	62.561308	36.400000	
30.856298	62.420432	36.500000	
31.030828	62.279556	36.600000	
31.205358	62.138680	36.700000	
31.379888	62.000000	36.800000	
31.554418	61.861324	36.900000	
31.728948	61.722648	37.000000	
31.903478	61.583972	37.100000	
32.078008	61.445296	37.200000	
32.252538	61.306620	37.300000	
32.427068	61.167944	37.400000	
32.601598	61.029268	37.500000	
32.776128	60.890592	37.600000	
32.950658	60.751916	37.700000	
33.125188	60.613240	37.800000	
33.300000	60.474564	37.900000	
33.474530	60.335888	38.000000	
33.649060	60.197212	38.100000	
33.823590	60.058536	38.200000	
34.000000	60.000000	38.300000	

<sup>2</sup>Supplemental Table S1. Latitude, longitude, and depth constraints of South American Continental Moho. Please visit <http://doi.org/10.1130/GES01440.S2> or the full-text article on [www.gsapubs.org](http://www.gsapubs.org) to view Table S1.

SUPPLEMENTAL TABLE S2. NAZCA SLAB CONSTRAINTS

Lat (°S)	Long (°W)	Depth (km)	Comment
This Study (RF Based)			
12.879711	77.039867	065.600000	RF subducted oceanic Moho depth from sea level Theoretical CCP-stack resolution equal to 0.1 km
13.054240	76.891811	065.300000	
13.228769	76.743755	065.000000	
13.403300	76.603469	072.400000	
13.577629	76.499264	079.800000	
13.752559	76.315108	071.800000	
13.926889	76.170932	074.200000	
14.101419	76.028766	071.200000	
14.275948	75.882580	071.300000	
14.450478	75.738404	073.200000	
14.625008	75.594228	071.600000	
14.799538	75.450053	073.300000	
14.974068	75.305877	069.900000	
15.148598	75.161701	069.900000	
15.323128	75.017525	069.900000	
15.497658	74.873349	069.900000	
15.672188	74.729173	069.900000	
15.846718	74.585000	069.900000	
16.021248	74.440824	069.900000	
16.195778	74.296648	069.900000	
16.370308	74.152473	069.900000	
16.544838	74.008297	069.900000	
16.719368	73.864121	069.900000	
16.893898	73.719945	069.900000	
17.068428	73.575769	069.900000	
17.242958	73.431593	069.900000	
17.417488	73.287417	069.900000	
17.592018	73.143241	069.900000	
17.766548	73.000000	069.900000	
17.941078	72.856824	069.900000	
18.115608	72.713648	069.900000	
18.290138	72.570472	069.900000	
18.464668	72.427296	069.900000	
18.639198	72.284120	069.900000	
18.813728	72.140944	069.900000	
18.988258	72.000000	069.900000	
19.162788	71.859124	069.900000	
19.337318	71.718248	069.900000	
19.511848	71.577372	069.900000	
19.686378	71.436496	069.900000	
19.860908	71.295620	069.900000	
20.035438	71.154744	069.900000	
20.209968	71.013868	069.900000	
20.384498	70.872992	069.900000	
20.559028	70.732116	069.900000	
20.733558	70.591240	069.900000	
20.908088	70.450364	069.900000	
21.082618	70.309488	069.900000	
21.257148	70.168612	069.900000	
21.431678	70.027736	069.900000	
21.606208	69.886860	069.900000	
21.780738	69.745984	069.900000	
21.955268	69.605108	069.900000	
22.129798	69.464232	069.900000	
22.304328	69.323356	069.900000	
22.478858	69.182480	069.900000	
22.653388	69.041604	069.900000	
22.827918	68.900728	069.900000	
23.002448	68.759852	069.900000	
23.176978	68.618976	069.900000	
23.351508	68.478100	069.900000	
23.526038	68.337224	069.900000	
23.700568	68.196348	069.900000	
23.875098	68.055472	069.900000	
24.049628	67.914596	069.900000	
24.224158	67.773720	069.900000	
24.398688	67.632844	069.900000	
24.573218	67.491968	069.900000	
24.747748	67.351092	069.900000	
24.922278	67.210216	069.900000	
25.096808	67.069340	069.900000	
25.271338	66.928464	069.900000	
25.445868	66.787588	069.900000	
25.620398	66.646712	069.900000	
25.794928	66.505836	069.900000	
25.969458	66.364960	069.900000	
26.143988	66.224084	069.900000	
26.318518	66.083208	069.900000	
26.493048	65.942332	069.900000	
26.667578	65.801456	069.900000	
26.842108	65.660580	069.900000	
27.016638	65.519704	069.900000	
27.191168	65.378828	069.900000	
27.365698	65.237952	069.900000	
27.540228	65.097076	069.900000	
27.714758	64.956200	069.900000	
27.889288	64.815324	069.900000	
28.063818	64.674448	069.900000	

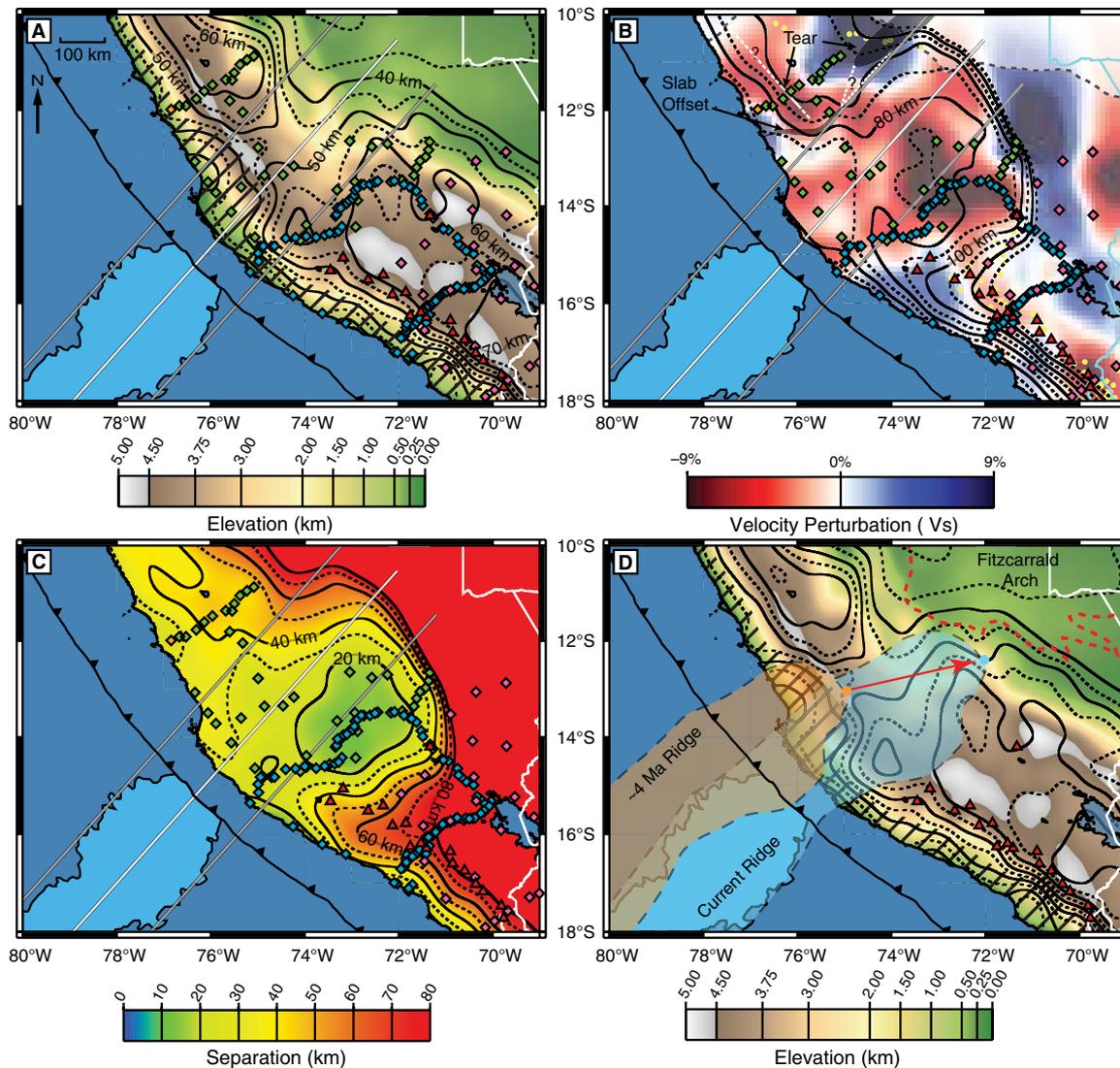


Figure 5. Maps showing our results. Map symbols in A, B, and C are the same as in Figure 1. (A) Moho depth map of the South American continental Moho incorporating receiver-function (RF) constraints (CAUGHT stations not included in Fig. 1) from this study and Ryan et al. (2016) along with additional seismic constraints (James and Snoke, 1994; McGlashan et al., 2008) and gravity constraints from Tassara and Echaurren (2012) (see Fig. S2A [footnote 1] for locations of constraint on these features). Solid contours mark 10-km-depth increments, dashed contours mark 5 km increments. (B) Slab depth contour map for subducted Nazca plate to 130 km depth overlain on S-wave teleseismic tomography results from Scire et al. (2016) (130-km-depth slice). Slab Moho contours between 50 and 110 km depth are from our RF study; contours <50 km are based on slab seismicity (Hayes et al., 2012) and contours >110 km are based on slab seismicity (Dougherty and Clayton, 2015; Kumar et al., 2016) and tomography (Scire et al., 2016). Slab tear marked by white solid line seen in RF profile C-C' (Fig. 3), slab offset seen in profile 1-1' (Fig. 3); tear feature to northeast presented in Scire et al. (2016). See text for discussion. (C) Separation between South American continental Moho shown in A and subducted Nazca oceanic Moho shown in B. Solid and dashed contours alternate marking 10 km increments. Note that active volcanic centers terminate near the 40 km contour. The area of least separation between the continental Moho and slab Moho occurs well inboard of the trench and extends south of the inland projection of the southeastern edge of the Nazca Ridge. (D) Simplified outline of shallowest segment of flat slab and present location of Nazca Ridge (transparent blue) and location of same features (transparent orange) at 4 Ma following Hampel (2002) convergence vector plate reconstruction. Red arrow shows motion of the northeastern end of the shallow segment over the past 4 m.y. Black contours are continental Moho as in Figure 5A. Present position of shallow segment links the current position of the subducting Nazca Ridge to the southwestern most part of the Fitzcarrald Arch and taken together with the ridge's migration history suggest the shallow segment of the subducted Nazca plate passed directly through the region of South American continental crust with a shallow continental Moho (see text for discussion).

these surfaces to obtain a map showing the separation between the continental and subducted oceanic Mohos (Fig. 5C). All maps have been filtered using a low-pass spatial filter passing spatial wavelengths greater than 650 km and rejecting wavelengths less than 50 km, with a cosine taper over wavelengths between these two values. We applied this filter to eliminate any features smaller than 50 km × 50 km, which are effectively below the lateral resolution of our

array. The South American continental Moho depth map (Fig. 5A) shows the close correspondence between the shallow Moho beneath the WC (see profiles D-D' and 2-2' above) and the likely location of the subducted Nazca Ridge (region bound by gray lines in Fig. 5A). Here continental Moho depths ~60 km typically associated with the high Andes shallow to ~50 km, strongly suggesting that the thick crustal root of the cordillera has been partially displaced by

the subducting ridge. This location also corresponds to the shallowest section of flat subduction and may relate to the subduction of the main body of the over-thickened Nazca Ridge. The southeastern edge of the ridge is likely to correspond to the increase in continental Moho depth to >60 km. This depth increase may partially reflect the eastward displacement of crustal material as ridge subduction progresses.

Compilation of our subducting slab depth map (Fig. 5B) is complicated by differing criteria used by different authors to determine slab depth. In the region sampled by our array, we have used the subducted oceanic Moho from our RF results to constrain slab depth. In this region, the top of the slab itself is likely to be ~8 to ~20 km above the mapped slab Moho depth. In the areas outside our array coverage, we have used Slab1.0 (Hayes et al., 2012) to define the slab above 95 km and seismicity (Dougherty and Clayton, 2015; Kumar et al., 2016) along with tomography-based contours (Scire et al., 2016) to define the slab below 95 km depth. Both Hayes et al. (2012) and Scire et al. (2016) use different criteria to define their slab locations (slab surface and center of high-velocity slab anomaly, respectively). To reduce potential artifacts resulting from the incorporation of these disparate data sets, we maintained a gap of at least 25 km where the data sets gave differing values, allowing for a gradual shift between what are presumably nearly parallel surfaces in the subducting plate. We further avoid interpretation of the slab Moho surface near the edge of individual data sets (especially the rapid re-steepening of the surface to the east) and focus on only large-scale features. For the locations of the slab-depth constraints used in the calculations of Figure 5B, see Supplemental Figure S5B (footnote 1).

We also note the similarity of our slab contours at and below 90 km depth to those determined independently by Antonijevec et al. (2015) using surface-wave tomography and slab earthquake locations. Differences above 90 km depth likely reflect greater vertical resolution by receiver functions than that possible with surface-wave tomography. The southeastern corner to the flat slab, in a region well sampled by our array, extends well beyond the southern margin of the Nazca Ridge projection and directly above a prominent sub-slab low-velocity zone image at 130 km depth by teleseismic S-wave tomography (Fig. 5B) (Scire et al., 2016) and surface-wave tomography (Antonijevec et al., 2016). These low velocities could be produced by increased temperature, the presence of partial melt, and/or the presence of hydrous phases, implying that more buoyant material is present in this area than in the surrounding mantle (Antonijevec et al., 2016; Scire et al., 2016). The correspondence between the 100- and 120-km contours and the edge of the low-velocity anomaly is consistent with the southern margin of the flat slab being partially supported by this material. We further note that this location corresponds to an area of complicated mantle anisotropy identified in shear-wave splitting results; this area contrasts with observations immediately to the north and south of the ridge (Eakin et al., 2015), further indicating the mantle beneath the subducted ridge is distinct from other parts of the upper mantle.

The slab, where it re-steepens to the southeast, appears to be continuous despite the rapid change in slab dip. This contrasts with the behavior we ob-

serve northwest of the Nazca Ridge where smaller changes in slab dip are associated with a clear down-drop of the slab from 70 km to 100 km depth. A trench-perpendicular fold or fault zone, imaged by our RFs at ~80 km depth, which may develop into a slab tear at 120 km to 300 km depth as imaged by teleseismic tomography (Scire et al., 2016), accommodates this down-drop. This feature intersects a second, trench-parallel apparent offset that we image on profile C–C' at the same location as Antonijevec et al. (2015) inferred a tear from surface-wave tomography. This offset corresponds to the southern margin of the “sag” in the flat slab proposed by Gutscher et al. (1999). These proposed tears and/or faults would allow the continuation of flat subduction NW of the subducted Nazca Ridge, but at a depth >20 km deeper than along the ridge itself. While our observations are consistent with the “sag” feature of Gutscher et al. (1999), we lack the coverage to test for the hypothesized “Lost Inca Plateau,” which Gutscher et al. (1999) proposed as a second, buoyant subducted oceanic feature to explain the northern segment of the Peruvian flat slab.

Figure 5C shows a map of the separation between the South American continental Moho and the slab Moho based on the previous maps. The subducted ridge requires a minimum of ~17 km of separation between these two surfaces to accommodate the over-thickened oceanic crust. This suggests that the southern edge of the ridge is in contact with the overriding continental crust, consistent with a comparison of the continental Moho contours and the 70 km and 80 km slab Moho contours (Fig. 5D). These slab contours closely follow the complex geometry of the continental Moho, suggesting coupling between the two features. Figure 5D also shows the present position of the Nazca Ridge in blue and the simplified outline of the <80 km depth segment of the flat slab (transparent blue) and the position of the ridge and this <80 km depth segment at ca. 4 Ma (transparent orange). Assuming that the shallowest part of the observed flat slab, characterized by a subducted oceanic Moho lying at <80 km depth, has remained at this depth or shallower over the past 4 m.y., we find an interesting relationship between the shallow slab and the overriding continental crust. Figure 5D indicates that this shallow segment passed directly beneath the region of the WC and EC with anomalously thin crust. We return to this possibility later in the following discussion.

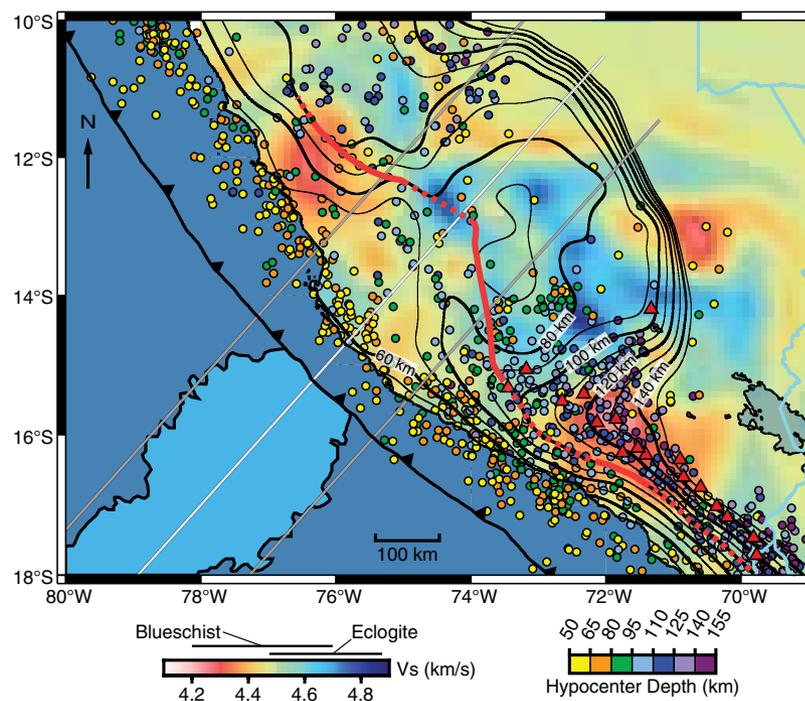
## DISCUSSION

Our results have important implications for the possible explanation for flat-slab subduction and its effects on the overriding plate. We suggest that continued flat subduction in central Peru, while related to the subducting Nazca Ridge, cannot be solely attributed to buoyancy of the ridge's comparatively thick crust and is likely to be associated with additional buoyancy from mantle anomalies below or within the subducted Nazca plate. We also suggest that the near-horizontal subducting ridge has significantly thinned both the South American lithospheric mantle and the South American crust. We discuss these major results below.

## Causes of Flat-Slab Subduction in Southern Peru

Numerical and analogue modeling of flat-slab subduction (e.g., van Hunen et al., 2002a; Martinod et al., 2005; Espurt et al., 2008; Currie and Beaumont, 2011; Manea et al., 2012) has repeatedly shown that over-thickened oceanic crust is insufficient to account for flat-slab subduction extending for >300 km from the trench without the contribution of factors related to the overriding plate. Exceptions to this (e.g., van Hunen et al., 2004; Arrial and Billen, 2013) require a significantly delayed basalt-to-eclogite conversion of the subducting crust—a proposition that is readily testable through the relative amplitude of Ps conversions from the subducted oceanic Moho recorded in RFs and directly analogous to the interpretation of changing subducted oceanic Moho seismic character discussed by Rondenay et al. (2008) in Cascadia and Alaska. The strong velocity contrast between basaltic crust and the underlying mantle lithosphere of the oceanic plate should produce a high-amplitude Ps conversion. This contrast would be increased if the crust is hydrated and the mantle was relatively dry, as proposed for the lithosphere under the thick crust of the Nazca Ridge where the ridge remains seismically active (Kumar et al., 2016). A crust with a significant eclogitized component should have a much weaker velocity contrast with the underlying mantle lithosphere, yielding a lower amplitude Ps conversion.

We observe a rapid decrease in Ps conversion amplitude ~300–400 km inboard of the trench along our profiles A–A', B–B', and D–D', indicating a significant fraction of the subducting Nazca Ridge has been eclogitized well trenchward of the point where the Nazca slab resumes steep subduction in tomographic results (Antonijevic et al., 2015; Scire et al., 2016). This decrease in Ps amplitude corresponds to a transition in S-wave velocity structure at 75 km depth from relatively slow velocities typical of sub-eclogite-facies material to high velocities typical of eclogite-facies material (Fig. 6). We further note that the slab seismicity from Kumar et al. (2016) appears to correspond primarily to areas where a strong subducted oceanic Moho Ps conversion is present (see Figs. 3 and 4). This region with a strong subducted oceanic Moho Ps conversion also has an inboard extent that approximately matches that of a supra-slab ultra-low velocity layer likely related to slab dehydration identified by Dougherty and Clayton (2015). The depth of this transition from a strong subducted oceanic Moho Ps conversion to a weak conversion and its relationship to slab dehydration is consistent with recent studies of instances of subducted oceanic material exhumed from pressures equivalent to 70–100 km (Beinlich et al., 2010; Dragovic et al., 2012; Klemd et al., 2015) and with petrologic models that indicate that dehydration of subducted oceanic crust predominately occurs rapidly at the blueschist/eclogite transition (Hacker, 1996; John et al.,



**Figure 6.** Comparison of subducted oceanic Moho slab contours and replotting surface-wave tomography at 75 km depth from Antonijevic et al. (2015) model. Earthquakes from International Seismological Centre (2011) catalogue ( $\geq 4.5$  magnitude, 50–150 km depth, from 1970 to 2013). Red line marks location of rapid decrease in slab Moho Ps arrival amplitude, indicating decrease in slab crust-mantle velocity contrast; line also corresponds to inboard edge of Dougherty and Clayton's (2015) dehydration-related slab top low-velocity layer. This boundary also corresponds to the transition from S-wave velocities characteristic of blueschist-facies materials (velocity range from Cao and Jung, 2016) to eclogite-facies materials (Worthington et al., 2013). See text for discussion.

2012; Baxter and Caddick, 2013). This interpretation is also consistent with the inference by Kumar et al. (2016) that the rapid decrease in slab seismicity in the Peruvian flat slab in the vicinity of the subducted Nazca Ridge is a result of the ridge's subducted oceanic crust largely being dehydrated by 80 km depth. Our results suggest that numerical models of flat slabs that model a rapid eclogite transition occurring 300 km to 350 km from the trench (e.g., van Hunen et al., 2002a; Currie and Beaumont, 2011) are an accurate representation of the processes occurring within the Peruvian flat slab.

In Figure 6, we summarize the relationship between this "eclogitization front," the slab Moho contours, long-term (>40 year) patterns of slab seismicity from the International Seismological Centre (2011) catalogue (note similarity to patterns shown in Fig. 2 from short-term (~2.5 years) seismicity relocated using local arrays), and the S-wave velocity structure at 75 km depth from surface-wave tomography (Antonijevec et al., 2015). Two important relationships are revealed in Figure 6. First, the shallowest part (<80 km depth) of the flat slab resides roughly between the projected locations of the edges of the subducted Nazca Ridge and extends ~500 km inboard of the trench. While the precise shape and size of the subducted portion of the Nazca Ridge cannot be known with certainty, reconstructions (e.g., Hampel, 2002; Rosenbaum et al., 2005) indicate that as the ridge formed at the intersection of the Easter-Salas Hotspot and the East Pacific Rise, the Tuamotu Plateau is likely the Nazca Ridge's conjugate and of comparable size. Given the size and position of the Tuamotu Plateau relative to the East Pacific Rise and given plate motion reconstructions, the present-day location of the end of the subducted Nazca Ridge is likely located ~400–500 km farther down-dip in the slab (Hampel, 2002) than the present inboard limit of flat subduction. This suggests that much of the ridge has been subducted and is presently located within the section of the slab that descends nearly vertically into the mantle (Scire et al., 2016). Second, the flat segment extends several hundred kilometers beyond the eclogitization front, indicating that additional forces (in addition to the positive buoyancy of the subducted oceanic crust) must be acting to maintain the flat geometry. Both our observations and those of Ma and Clayton (2015) using a similar data set show that some of the shallowest segments of the flat slab occur along the projection of the Nazca Ridge beyond 350 km from the trench in the area with at least partially eclogitized oceanic crust. Additionally, the southern edge of the flat slab appears to extend farther south than the projected southern edge of the ridge. While numerical models of flat subduction incorporating active over-thrusting of the overriding plate (van Hunen et al., 2002a; Currie and Beaumont, 2011) suggest that over-thrusting can promote flat-slab subduction, the correspondence of the shallowest inboard part of the flat slab to the Nazca Ridge and a region of slow S-wave velocities in the mantle immediately beneath the shallow flat slab (Fig. 5B) suggest that a second source of buoyancy may also be acting on the slab, in addition to any dynamic effects, in agreement with findings by Antonijevec et al. (2016). The origin of this low-velocity feature remains unclear (Antonijevec et al., 2016; Scire et al., 2016).

While this sub-slab, low-velocity feature's origin is unknown, our observations and those of prior studies allow us to better understand its present-day

relationship with the flat slab. Comparison of our subducted oceanic Moho depth over this region (~80 km) and the most intense negative velocity anomaly in tomographic results (concentrated between ~100 and 200 km though potentially extending to ~400 km depth; Antonijevec et al., 2016; Scire et al., 2016) indicates that it is separated from the oceanic crust by at least 20–30 km of high-velocity slab lithosphere. This indicates the anomaly is unlikely to be due to hydration-related serpentinization of the slab's lithosphere, a mechanism invoked for other flat-slab occurrences (e.g., Kopp et al., 2004). Our observations support the interpretation of this feature as a region of anomalously hot mantle material (Antonijevec et al., 2016; Scire et al. 2016) or a portion of the mantle containing melt (Antonijevec et al., 2016). Calculations by Antonijevec et al. (2016) indicate the low-velocity material can be explained by a mantle temperature anomaly of 200 °C or the presence of at least 1% partial melt. We emphasize that either possibility would decrease the density of mantle beneath this segment of the flat slab, helping to promote continued flat subduction.

The existence of complicated shear-wave splitting anisotropy in the mantle along the projection of the ridge (Eakin et al., 2015) further indicates that mantle beneath the ridge differs significantly from that to the north or south. Based on this correlation, we suggest that low-velocity, low-density upper mantle beneath the ridge may be a contributing factor to its continued buoyancy, somewhat analogous to other low-density mantle anomalies observed along the Juan Fernandez Ridge and associated Sierra Pampeanas flat slab (e.g., Kopp et al., 2004; Porter et al., 2012), though affecting the base of the oceanic lithospheric mantle rather than its top.

There are two end-member possibilities for the geodynamic evolution of this flat-slab geometry. One is that the flat geometry is initiated as soon as the ridge enters the subduction zone as implicitly assumed in Hampel (2002), Rosenbaum et al. (2005), and others. The other possibility is that the leading segment of the ridge is subducted at a normal angle until a sufficient volume of buoyant crust (or mantle) is subducted to compensate for the negative buoyancy of the lower part of the slab (Espurt et al., 2008). In the case of southern Peru, plate reconstructions show the ridge entered the trench ca. 11 Ma (Fig. 1) but the volcanic arc was not extinguished until 4 Ma (Rosenbaum et al., 2005), a delay of 7 m.y. between the initial subduction of the buoyant ridge and the formation of flat subduction under the arc that is consistent with the analogue modeling studies of Espurt et al. (2008) and numerical modeling studies by Hu et al. (2016). We have used the 5–0 Ma average convergence rate of 8.5 cm/yr (Somoza and Ghidella, 2012) to restore the approximate position of what is now the 80-km-depth contour of the Nazca subducted oceanic Moho to its position at ca. 4 Ma (orange transparency in Fig. 5D). Assuming that the slab material represented by this contour has remained at <80 km depth since its subduction, we find that this shallow feature should have lain directly below the WC volcanic arc, indicating that it is likely associated with the final closure of the volcanic arc mantle wedge ca. 4 Ma. This association suggests that the current inboard hinge separating flat and steep slab subduction has progressed inboard since the full establishment of flat subduction at ca. 4 Ma with little re-steepening within the flat segment itself.

## Coupling of the Nazca and South American Plates

The shallow depth of the subducted Nazca Ridge and the corresponding deep continental Moho, especially to the southeast of the ridge (see Fig. 5), suggest that strong mechanical coupling occurs between the Nazca and South American plates. The WC and EC southeast of the ridge are characterized by a number of short-wavelength changes of >5 km in Moho depth (see Fig. 5A). Variations on this scale over such short lateral distances are difficult to attribute to variations in crustal thickening due to variations in structural shortening amounts, which occur over a much larger spatial wavelength in this region (Oncken et al., 2006; Pfiffner and Gonzalez, 2013), or to variations in magmatic addition, as these features include areas free of Cenozoic arc volcanism (Rosenbaum et al., 2005; Mamani et al., 2010). These changes in Moho depth appear to interlock with changes in the depth to the subducted slab oceanic Moho (see Fig. 5B). The correspondence of these slab and continental features leads to the remarkably uniform, <20 km separation between the continental and oceanic Mohos in this area (see Fig. 5C), suggesting the overriding continental crust and subducting slab have deformed one another. When combined with the arch-like structure apparent in the continental Moho directly above the shallowest part of the flat slab (discussed in detail in the subsequent two sections), we take this as evidence for significant displacement of upper-plate material, and by extension, we infer strong mechanical coupling of the plates in response to the subduction of the Nazca Ridge.

The shallow depth and potential mechanical coupling in this portion of the Peruvian flat slab contrast with some other modern flat-slab occurrences where the subducting plate lies well below the continental Moho, as in Chile (e.g., Porter et al., 2012), or a weak layer separates the plates, preventing significant coupling, as in Mexico (e.g., Kim et al., 2012). In central Peru, however, a number of observations suggest that strong coupling occurs between the two plates along the southern edge of the subducted Nazca Ridge. These observations include coseismic slip to 75 km depth associated with a 1996–1997 earthquake sequence (Spence et al., 1999), increased subduction erosion along the trench removing on the order of 100 km of the forearc (e.g., Clift et al., 2003; Hampel et al., 2004), and vertical uplift of the Peruvian forearc both near the trench (Hagen and Moberly, 1994) and inland of the present shoreline (e.g., Macharé and Ortlieb, 1992; le Roux et al., 2000; Wipf et al., 2008; Saillard et al., 2011). To further understand this coupling, we examine its effects on the lithospheric mantle and lower crust of the upper plate in more detail.

## Effects of Flat-Slab Subduction on the Upper Plate

### *Displacement of the Continental Lithospheric Mantle*

The thick (>50 to ~60 km) continental crust beneath the WC and EC that overlies the subducted oceanic Moho of the Nazca Ridge observed at 70–80 km depth leaves little room for continental mantle lithosphere. Assuming the

crustal thickness of the subducted ridge is comparable to the 17–20 km thickness of its unsubducted equivalent (Hampel et al., 2004; Tassara et al., 2006), less than 3 km of continental mantle lithosphere may separate these features. Crustal shortening estimates for the WC and EC of ~30% for the Cretaceous through Cenozoic (Pfiffner and Gonzalez, 2013) would require proportional thickening of the mantle lithosphere. The present configuration of the subducted slab and overriding continental crust requires that much of the South American mantle lithosphere has been thinned prior to, or as a consequence of, ridge subduction. Thinning as a consequence of ridge subduction is consistent with shear-wave splitting for local S events and indicates that the subducting ridge actively deforms the mantle lithosphere as it moves with respect to South America (Eakin et al., 2014). These lines of evidence suggest the removal of a significant part of the mantle lithosphere is a response to ridge subduction in central Peru. The inboard extent of this removal is difficult to constrain; however, given both the thinning of the South American crust near the Shira Uplift in the Subandes (James and Snoke, 1994) and the re-steepening of the Nazca slab near 71°W (Scire et al., 2016), it is possible that the lithospheric mantle remains thicker beneath the Subandes and Fitzcarrald Arch.

### *Displacement of WC and EC Crust along the Subducted Nazca Ridge*

With the exception of the region along the projected axis of the subducting Nazca Ridge, we find that the South American Moho beneath the WC and EC extends to depths greater than 55 km and locally to depths greater than 65 km. These Moho depths are similar to those reported for the central to northern Altiplano immediately to the south (e.g., Dorbath et al., 1993; Tassara et al., 2006; McGlashan et al., 2008; Phillips et al., 2012; Ryan et al., 2016) and somewhat surprising given the differences in tectonic shortening between the two regions (~120 km to ~150 km for central Peru [Gotberg et al., 2010; Pfiffner and Gonzalez, 2013] versus up to ~250 km for the central Altiplano [e.g., Oncken et al., 2006]). The similarity in Moho depth despite differing shortening histories may support models in which crustal flow moves material from the Altiplano to the regions to the north (e.g., Kley and Monaldi, 1998; Gotberg et al., 2010) or those that reflect the effects of regional variations in magmatic addition (e.g., Mamani et al., 2010; Chapman et al., 2015).

It is interesting to note that the one location where we find significant disagreement between the gravity-derived Moho of Tassara et al. (2006) and the seismically observed Mohos reported by both Lloyd et al. (2010) and in our own results occurs directly over the shallowest part of the flat slab. Both our results and larger patterns in continental crustal thickness observed by Lloyd et al. (2010) indicate the continental Moho is much shallower (by ~20 km) near 13°S, 75°W (see decrease in Moho depth beneath WC and EC in Fig. 5C) than the calculation by Tassara et al. (2006) from gravity data (prior to the availability of regional seismic constraints). This location marks both the intersection of the projected axis of the subducting Nazca Ridge, where we observe the subducted oceanic Moho of the Nazca plate at depths of less than 75 km, and

the high elevations of the WC and EC. We suggest that the unexpectedly shallow slab combined with the unusually thick oceanic crust of the subducting ridge may have complicated interpretation of the gravity data at this location.

The migration history of the tip of the Nazca Ridge over the past 10 m.y., based on the plate reconstruction of the mirror image of the Tuamotu Plateau (Fig. 1) (Hampel, 2002; Rosenbaum et al., 2005), suggests an apparent kinematic problem with the formation of this crustal arch: if the Nazca Ridge produced flat subduction immediately upon entering the subduction zone, it should have passed at an equally shallow depth to the north, where crust >60 km thick remains (Fig. 5). We have already discussed the possibility that this apparent conflict is due to a delay in the start of flat subduction following initial subduction of the ridge. Alternately, progressive development of faulting and tearing along the northern edge of the ridge may have reduced the downward force exerted on the ridge by the rest of the slab and allowed this segment to shallow. This alternative is somewhat less likely given the continuity of the slab observed to the east and southeast (Schneider and Sacks, 1987; Phillips and Clayton, 2014; Dougherty and Clayton, 2015; Scire et al., 2016), in the overall plate subduction direction, that would be the dominant sources of downward slab pull.

While we prefer the scenario presented above to explain the relationship between the overriding continental crustal structure and the subducting ridge, we are unable to conclusively rule out two other possibilities that could also account for thicker crust north of the subducting ridge: (1) re-thickening of crust north of the ridge via crustal flow or (2) crustal underplating of material tectonically eroded from the near-trench forearc. High temperatures in the lower continental crust (~1000 °C at 40 km depth) have been reported immediately south of the subducting ridge (Chapman et al., 2015). These temperatures are sufficiently high to induce the formation of partial melt in the middle to lower crust (Clark et al., 2011) and above temperatures necessary to induce ductile flow (Jamieson and Beaumont, 2013). This raises the possibility that ductile flow at mid-crustal levels may have supplied a path for material to pass over the shallowly subducting slab and fill in the region to the north as the ridge migrates. This requires that the crust of the overriding plate remained at a high temperature following the onset of flat subduction. This requirement may be fulfilled; numerical models incorporating temporal transitions from normal to flat subduction (van Hunen et al., 2002a, 2002b; Arrial and Billen, 2013) indicate the crust of the upper plate above a flat slab may cool only slightly even >10 m.y. after the onset of flat subduction. Alternately, material may have been available to re-thicken the continental crust north of the ridge through underplating of tectonically eroded forearc materials. Significant forearc subduction erosion has been documented to the north of the Nazca Ridge (Clift et al., 2003; Hampel et al., 2004) and dated to a period following subduction of the ridge. This tectonically eroded material may have allowed extensive underplating to occur north of the ridge.

Although both of these mechanisms may be possible explanations for the presence of thick continental crust north of the subducting Nazca Ridge, they require processes that are not yet documented in central Peru and are more

complicated than our preferred model, in which the ridge only begins to affect the continental crust at ca. 4 Ma when the mantle wedge is finally closed and volcanism ceases in this region (Rosenbaum et al., 2005). We also note that all four mechanisms discussed above require the modification of the continental crust by the subducting Nazca Ridge and strong coupling between the two plates.

## CONCLUSIONS

We have used CCP receiver function analysis and prior geophysical studies to constrain the depth to both the South American plate's continental Moho and the Nazca plate's subducted oceanic Moho in the southern segment of the Peruvian flat slab. The schematic plate-scale 3D model for the region in Figure 7 shows what we find to be the key features of the southern segment of the Peruvian flat slab. In this trench-parallel view, the subducted oceanic Moho of the Nazca slab is very close to the base of the continental crust, leaving very little room for continental mantle lithosphere between the two. Specifically, the oceanic Moho is separated from the overriding continental crust by less than 40 km, and locally less than 20 km. Given the 17–20 km thickness of the Nazca Ridge's crust, less than 3 km of mantle lithosphere may locally separate the subducted Nazca Ridge and the base of the overriding continental crust. The thickness of the continental crust varies significantly over the subducted

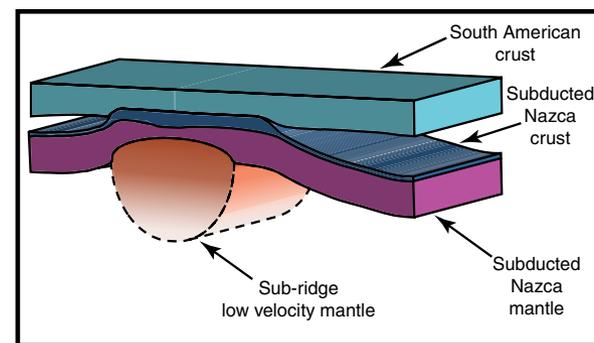


Figure 7. Schematic 3D model of the Nazca Ridge's subduction in central Peru. This is a trench-parallel view based primarily on cross section 2-2' in Figure 4. Continental crust (light blue) beneath the high cordilleras is generally separated from the subducted oceanic crust of the Nazca plate (dark blue), but thinned due to deformation caused by the shallow subduction of the Nazca Ridge's comparatively thick crust. The continental lithospheric mantle is not shown for clarity but generally occupies the space between the continental crust and subducted oceanic crust. The subducted oceanic crust is separated by the lithospheric mantle of the subducting plate (purple) from low-velocity material (orange to light orange) located beneath the subducting Nazca Ridge. This low-velocity material is likely to be relatively low density due to thermal (including partial melt) or compositional effects.

Nazca Ridge, suggesting that the ongoing subduction of the Nazca Ridge has driven deformation of the continental crust of the Western and Eastern Cordilleras, thinning it by ~5–10 km. This thinning may have displaced lower-crustal material to the southeast of the ridge, locally causing thickening in advance of the ridge. This clear thinning and possible displacement indicates that the subducting and overriding plates are strongly mechanically coupled around the subducting ridge.

Our results show that the shallowest part of the flat slab corresponds to the inboard projection of the Nazca Ridge and extends considerably inboard of the blueschist-to-eclogite transition of the ridge's over-thickened crust. This indicates that an additional source of buoyancy is required to support the flat slab; this support may be provided in part by a body of thermally or compositionally (partial melt) buoyant sub-slab mantle material beneath the flat slab, consistent with low seismic velocities observed previously in the region. The origin of this buoyant material is unclear; however, the >30 km separation between the observed slab Moho and this buoyant material suggests it is present deep within the slab's lithospheric mantle or in the underlying asthenosphere and is not a product of hydration and serpentinization at the base of the Nazca oceanic crust. These results may provide further insights for interpreting past flat subduction episodes such as the Laramide event in the western United States and introduce additional parameters to investigate in numerical modeling studies of flat subduction.

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