Subduction of the Chile Ridge: Upper mantle structure and flow

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ABSTRACT

We deployed 39 broadband seismometers in southern Chile from Dec. 2004 to Feb. 2007 to determine lithosphere and upper mantle structure in the vicinity of the subducting Chile Ridge. Body-wave travel-time tomography clearly shows the existence of a long-hypothesized slab window, a gap between the subducted Nazca and Antarctic lithospheres. P-wave velocities in the slab gap are distinctly slow relative to surrounding asthenospheric mantle. Thus, the gap between slabs visible in the imaging appears to be filled by unusually warm asthenosphere, consistent with subduction of the Chile Ridge. Shear wave splitting in the Chile Ridge subduction region is very strong (mean delay time ~3 s) and highly variable. North of the slab windows, splitting fast directions are mostly trench parallel, but, in the region of the slab gap, splitting fast trends appear to fan from NW-SE trends in the north, through ENE-WSW trends toward the middle of the slab window, to NE-SW trends south of the slab window. We interpret these results as indicating flow of asthenospheric upper mantle into the slab window.

INTRODUCTION

Spreading ridge subduction is an apparent contradiction—an impossibility if we assume ridges mark the upwelling limbs of mantle convection cells, or a geodynamic oddity if we believe that ridges spread passively, pulled apart by distant sinking slabs. And yet, there is good evidence that ridge subduction has occurred with some regularity, leaving a distinct record of rather pronounced effects on the geology and tectonics of the continental plates that overrode those ridges. Ridge subduction is invoked to explain odd tectonics and magmatism during the Neoarchean beneath the Dharwar craton of India (Manikyamba et al., 2007), during the Paleozoic in China (Jian et al., 2008), during the Mesozoic in Alaska, and during the Paleogene in the Java-Sumatra region (Whittaker et al., 2007). In fact, the very concept of ridge subduction was developed to explain Neogene tectonics and magmatism in western North America that were difficult to ascribe to Farallon plate subduction alone (Atwater, 1970; DeLong and Fox, 1977; Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989), and since then a host of observations from Central America (Johnston and Thorkelson, 1997) to Baja (e.g., Rogers et al., 1985; Michaud et al., 2006; Pallares et al., 2007) to British Columbia (Groome et al., 2003; Audet et al., 2008) to Alaska (e.g., Sisson and Pavlis, 1993; Sisson et al., 2003; Breitsprecher et al., 2003; Cole et al., 2006; Qi et al., 2007) have been associated with spreading ridge subduction beneath western North America in some way.

Beyond the clear effects on the overriding plate, ridge subduction is the last stage of destruction of one of the two oceanic lithospheres involved in the process, and, depending on the exact geometry of the ridge with respect to the consuming trench, may mark the introduction of new oceanic plate into the subduction system. In most cases, ridge subduction seems likely to result in wide separation of the subducted lithospheres that were once contiguous at their intervening ridge-transform boundary, at least at depths greater than a few hundred kilometers. Such divergence between the trailing edge of the completely consumed plate and the leading edge of the conjugate plate opens slab windows and provides gaps through which asthenospheric mantle can flow and mix (Thorkelson, 1996). The implications for geochemical cycling in the mantle, at arcs (Gutiérrez et al., 2005), and even at unsubducted portions of the spreading ridge may be profound (Klein and Karsten, 1995; Karsten et al., 1996). Given the possible effects of ridge subduction on the geology of overriding continental plates, and on mantle mixing, some direct imaging of how ridge subduction actually works is desirable. Currently, the Chile Ridge, a long-lived wide ocean basin spreading ridge, is subducting beneath southern South America, affording a perfect opportunity to examine exactly what happens when a ridge meets a trench and is recycled into the mantle.

SUBDUCTION OF THE CHILE RIDGE

The actively spreading Chile Ridge (Fig. 1) has been subducting beneath South America since mid-Miocene time (Cande et al., 1987; Breitsprecher and Thorkelson, 2009; Eagles et al., 2009). The spreading segment between the Taitao and Darwin transform faults is currently at the trench and converging with South America at a geologically determined rate of a bit over 8 cm/yr directed N79°E (Spitzak and DeMets, 1996a, 1996b). Space geodetic observations yield somewhat slower convergence rates, 6.6 cm/yr for Nazca–South America and 1.85 cm/yr for Antarctica–South America convergence (Wang et al., 2007). Past subduction of Chile ridge segments has been associated with a wide range of effects on the overriding continent,

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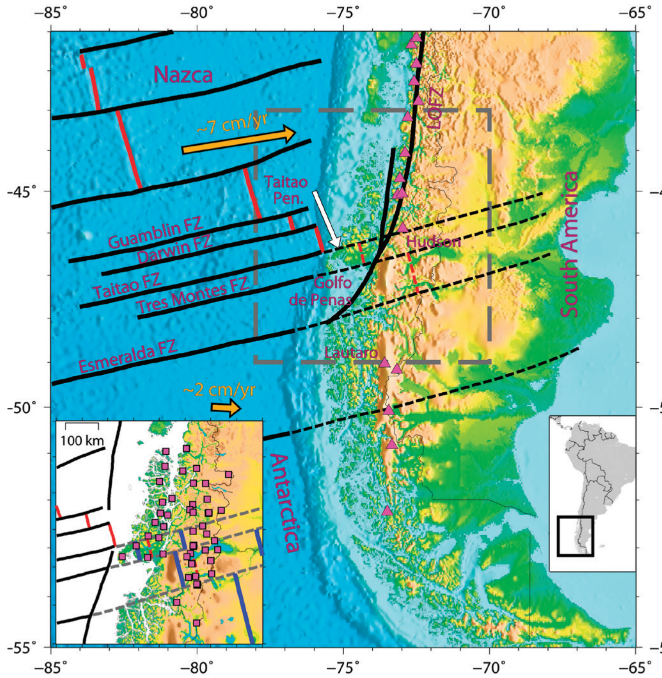

Figure 1. Actively spreading ridge segments (red) and transform faults/fracture zones (black); projections of subducted Chile Ridge structures (dashed black lines). Purple triangles are arc volcanoes; note gap in volcanic arc between Hudson and Lautaro. Relative convergence velocities from Spitzak and DeMets (1996a, 1996b) and Wang et al. (2007). Heavy dashed gray lines mark study area shown in inset, lower left: Chile Ridge Subduction Project station sites (squares). Slab window boundaries predicted from marine paleomagnetic data, subduction rates, and slab dip marked by heavy blue lines (Murdie and Russo, 1999). Inset, lower right: study region. FZ—fault zone; LOFZ—Liquiñe-Ofqui fault zone.

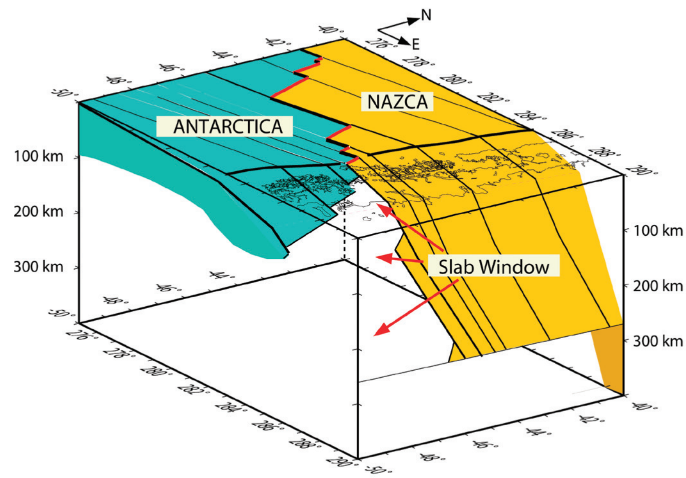

Figure 2. Development of slab windows, as projected from Chile Ridge surface structure and magnetic anomalies (e.g., Fig. 3) (Murdie and Russo, 1999). Separation of the trailing edge of the Nazca plate and the leading edge of the Antarctic plate opens a slab window once ambient temperatures are high enough to prevent lithosphere formation.

including highly variable structure of the continental forearc (Cande and Leslie, 1986; Cande et al., 1987; Bangs et al., 1992; Lagabrielle et al., 2004; Ranero et al., 2006), as well as important differences between structures, morphology, and evolution in foreland areas north and south, and backarc areas well east of the present triple junction (Ramos, 1989; Flint et al., 1994; Cembrano et al., 2002; Lagabrielle et al., 2004). Obduction of a Plio-Pleistocene ophiolite sequence (Forsythe and Nelson, 1985; Nelson et al., 1993; Bourgois et al., 1996; Lagabrielle et al., 2000; Veloso et al., 2005, 2007; Shibuya et al., 2007) and recent volcanism on the Tres Montes Peninsula anomalously close to the trench (Forsythe et al., 1986; Lagabrielle et al., 1994, 2000) are both attributed to the ridge subduction. A pronounced gap in the active Patagonian volcanic arc (Fig. 1) (Cande and Leslie, 1986; Ramos and Kay, 1992; Gutiérrez et al., 2005), eruption of back-arc–like plateau basalts in eastern Chile and western Argentina (Charrier et al., 1979; Ramos and Kay, 1992; Kay et al., 1993; Gorring et al., 1997; Espinoza et al., 2005, 2008; Guivel et al., 2006), anomalous isotopic signatures from rocks dredged from Chile Ridge ridge segments at or adjacent to the trench (Klein and Karsten, 1995; Karsten et al., 1996), and anomalous seismicity, gravity (Murdie et al., 1993, 2000), and upper mantle flow (Murdie and Russo, 1999) have also been deemed consequences of the subduction of the Chile spreading ridge.

Implicit in the slab window idea is the assumption that spreading between the trailing and leading edges of the subducted ridge continues after subduction, but that no new lithosphere is formed after subduction, leading to a progressively widening gap between the two edges of the former ridge (Fig. 2) (Delong and Fox, 1977; Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989; Thorkelson, 1996; Gorring et al., 1997; Thorkelson and Breitsprecher, 2005). Although the exact form of slab window mantle flow is unknown, such mantle flow should be detectable via shear wave splitting analysis, and we have attempted to characterize the Chile Ridge subduction slab window flow field using splitting observations of extant regional data (Murdie and Russo, 1999) and larger-scale upper mantle flow indicators (Alvarez, 1982; Russo and Silver, 1994, 1996; Russo et al., 1996; Anderson et al., 2004).

As part of the ongoing Chile Ridge Subduction Project (CRSP), we deployed 39 broadband seismometers (Fig. 1) from late 2004 to early 2007 in the region where the Chile Ridge subducts. The basic goals of the seismic deployment were (1) to detect whether a Patagonian slab window between subducted Nazca and Antarctic lithosphere exists; (2) if so, to resolve its shape and extent; (3) to determine the form of asthenospheric mantle flow in the vicinity of any slab window; and (4) to confirm that a slab window allows direct contact between mantle flow associated with ridge spreading processes and the base of the overriding (i.e., South American) lithosphere. Such interaction would explain many aspects of the anomalous forearc and backarc volcanism that has been associated with the Patagonian slab window. The geodynamic implications of ridge subduction are important: Subduction of actively spreading ridges implies that mantle convection return flow is not strongly localized at oceanic spreading ridges (ridges spread passively, unforced by convective upwelling). Any indication that upwelling mantle flow is occurring in the geodynamically equivocal setting of ridge subduction would be important information for understanding global geodynamics.

TRAVEL-TIME INVERSIONS AND STRUCTURE OF THE SUBDUCTED SLABS

We used P-waves recorded at 39 stations of the CRSP seismic network to determine anomalous travel times that can be ascribed to local upper mantle structure. Suitable events for this study come from a well-distributed set of backazimuths (Supplemental Data Figs. DR1 and DR2[1]), a result of operating the network stations for a minimum of two years. A well-distributed group of source events ensures even sampling of the upper mantle structure, with raypaths crossing at as many angles as possible, allowing us to isolate structure at depth.

Results of the P-wave travel-time inversions are shown in Figure 3, with images at depths of 100 and 200 km. Travel-time anomalies mapped into velocity structure at these depths are color-coded: blue represents fast velocities, and red shows regions with velocities that are slow relative to a commonly used model of seismic velocities that varies only with depth. The subducted Nazca slab is clearly visible in Figure 3 as a high-velocity region in the northern part of the maps, and this anomaly shifts eastward at depth, as we would expect for a slab with an eastward dip. Because of the event-station distribution, we are unable to resolve the subducted Antarctic lithosphere very well (few stations were deployed in the SW of the study region over the shallow Antarctic slab; see Fig. 3). However, the very low velocities present at the depth projections of the expected slab window are clearly visible, and we take this as first-order evidence that the slab window exists. We note that the high-velocity anomalies we associate with the Nazca slab are clearly bounded by the downdip projection of the Taitao transform fault that now forms the southern edge of the subducted Nazca plate, as predicted (Murdie and Russo, 1999; Breitsprecher and Thorkelson, 2009). Note also that the low seismic velocity anomalies present in the slab

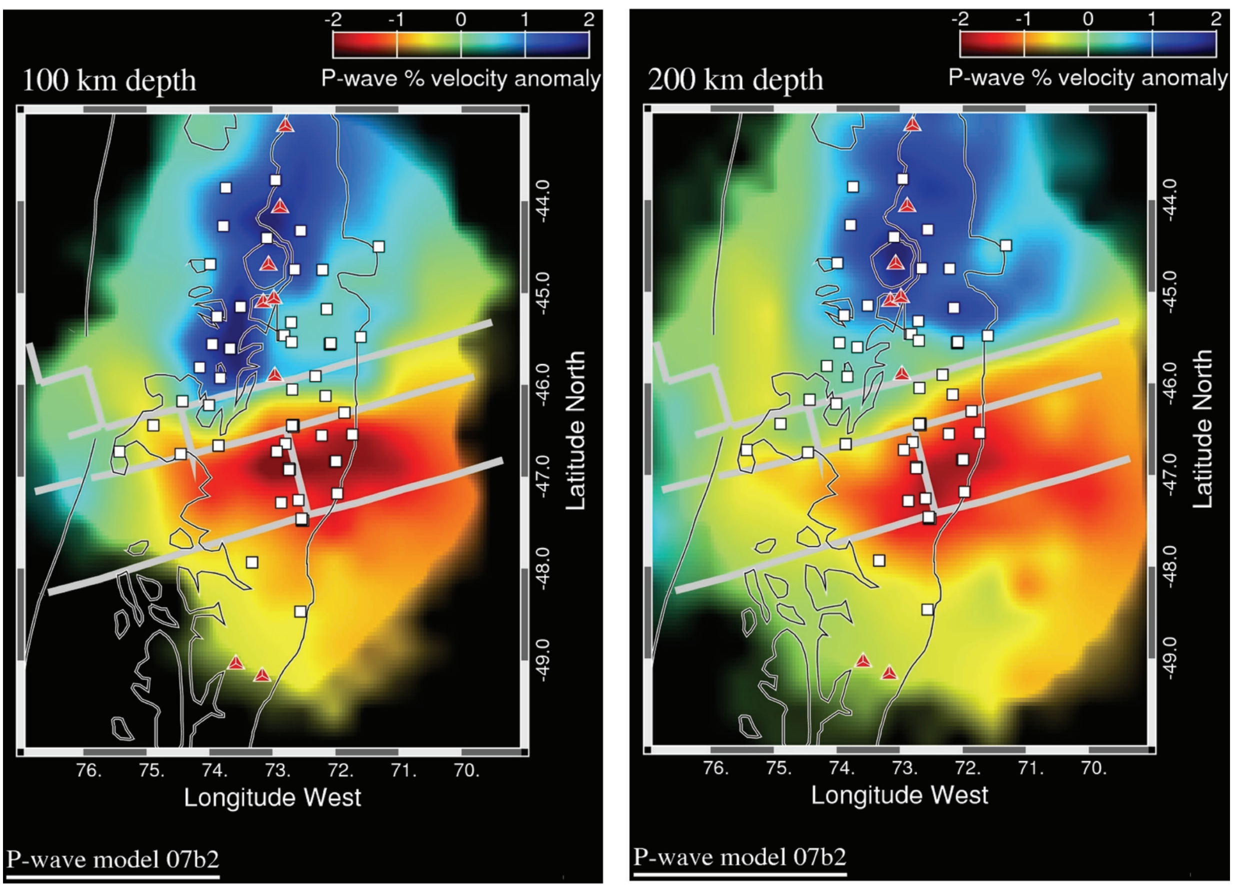

Figure 3. Map views of P-wave velocity anomalies at 100 km (left) and 200 km (right). Velocity anomaly relative to radial Earth model IASP91 (Kennett and Engdahl, 1991) shown as a perturbation percentage; see key at upper right of each map. High velocities are blue; low velocities red; where resolution is poor, colors fade to black. The subducted Nazca lithosphere is visible as the linear NNE-trending fast anomaly, and the slow velocities of the slab window are red. Structure of the Chile Ridge projected to depth shown by heavy gray lines. Stations of the CRSP seismic network are white squares, and red triangles show locations of active arc volcanoes; note the gap in the arc in the region of the slab window. Thin white lines are Chile coastline and political border with Argentina and also mark the subduction trench westward of the coastline. At 200 km depth, note broadening and eastward shift of the high-velocity anomalies associated with the Nazca slab. Slow velocities of the slab windows also shift eastward and broaden at depth, as expected given increasing separation of the trailing edge of the Nazca slab from the leading edge of Antarctica (see Fig. 2).

[1]GSA Data Repository Item 2010263, supplemental text and figures DR1–DR5, can be accessed online at www.geosociety.org/pubs/ft2010.htm; copies can also be obtained via e-mail to gsatoday@geosociety.org.

gap are actually slower than the typical seismic velocity of the asthenosphere, so these slow regions really do represent anomalously slow—and therefore most likely relatively warm—asthenospheric mantle.

SHEAR WAVE SPLITTING AND UPPER MANTLE FLOW

Although we have established that a slab window is present between subducted Nazca and Antarctic lithosphere, and that seismic velocities in this gap are consistent with the presence of warm asthenosphere, the question remains whether upper mantle flow beneath the subducted lithosphere (Russo and Silver, 1994) is perturbed by these structures. We use observations of shear wave splitting to evaluate this issue. The most common interpretation of teleseismic shear wave splitting is based on development of a linear preferred orientation of natural upper mantle minerals, predominantly olivine, with a tendency for aggregates of these minerals to align in the shear plane parallel to the direction of tectonic extension (Gueguen and Nicolas, 1980; Christensen, 1984; Nicolas and Christensen, 1987; Ribe, 1989a, 1989b; Ribe and Yu, 1991; Zhang et al., 2000).

Shear wave splitting observed at the CRSP seismic network is strong (mean δt is 2.98 s) and variable. Although the results we present here are preliminary (see Fig. DR3; footnote 1)—only phases from larger-magnitude, deeper earthquakes have been analyzed—they are likely already robust in the sense that more measurements will probably add only marginally to the total already in hand, given the relative difficulty of generating high-amplitude core phases at the requisite distances ($\Delta > 88°$; Silver and Chan, 1991). We used SKS, SKKS, S´S´, and PKS phases to determine the splitting fast directions and delay times shown in Figure 4.

We assume that the heterogeneous structure visible in the travel-time inversions may have a strong effect on the orientations of upper mantle fabrics in the triple junction region. In order to separate these potential effects on observed shear wave splitting, we traced rays through a three-dimensional upper mantle velocity model derived from the travel-time inversions (Figs. DR4 and DR5; footnote 1) to determine which parts of the study area were actually sampled by waves arriving from different source events around the globe. We chose the 200 km piercing points (halfway from the 410 km depth of olivine transformation to the surface) along these rays and projected this point to the surface as the point at which to display splitting results (Fig. 4). The variable splitting at CRSP stations reflects variable anisotropy in the upper mantle below. The shear wave phases we used to make the measurement integrate splitting due to anisotropy all along their paths through the upper mantle, so, conceivably, the anisotropy could be in the overlying South American crust and upper mantle, in the upper mantle wedge for those stations sited eastward enough to overlie a significant thickness of the wedge, within the subducted Nazca and Antarctic slabs, and beneath the slabs. Given the large delay times, and by analogy with results elsewhere in South America and the world, the predominant anisotropic source to these splits is likely beneath the slab (Russo and Silver, 1994; Fouch and Fischer, 1996; Anderson et al., 2004; Pozgay et al., 2007; Abt and Fischer, 2008; Hoernle et al., 2008). The local/regional earthquake shear wave splitting due to crustal and upper mantle

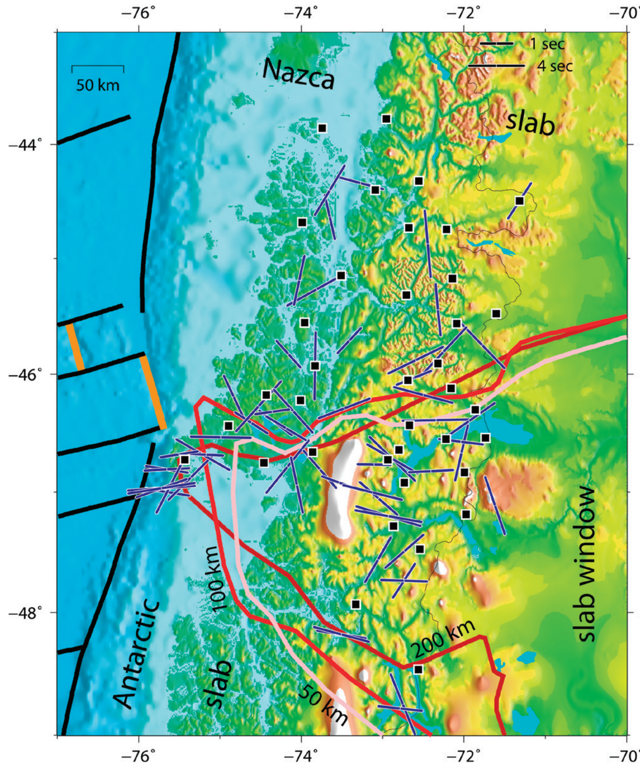

Figure 4. Map of shear wave splitting measurements. Blue bars trend in the fast polarization direction; lengths are proportional to delay times. Fast trends are variable, but splitting delays are uniformly high (mean = 2.98 s), which is near the global maximum for teleseismic splitting. Strong, variable splitting indicates a variable upper mantle flow field beneath South America and the subducted Nazca and Antarctic slabs. Patagonian slab window boundary defined by P-wave tomography (Fig. 3), shown at three depths: heavy pink, red, and dark red lines.

wedge anisotropy trend predominantly N-S in the study region (R.E. Murdie and R.M. Russo, 2010, personal commun.), significantly different from those of the teleseismic shear wave splitting, indicating that the teleseismic signal is primarily a deeper upper mantle anisotropy, as also expected from the much greater delay times (2–3 s) of the teleseismic data compared to the local splitting delays (0.05–0.3 s).

The presence of a Patagonian slab window complicates the South American upper mantle flow field, which is visible in the splitting fast trends sampling upper mantle near and within the slab gap: North of the subducted ridge, fast shear wave polarization trends—and hence, upper mantle flow beneath the Nazca slab—are predominantly parallel to the slab strike (trench parallel). South of the triple junction, they align more E-W and in many cases parallel the ENE-WSW trend of the subducted Taitao transform fault that now forms the southern boundary of the Nazca slab. Note the fanning of the splitting fast trends from waves sampling the western portions of the slab window: Splitting fast shear wave directions rotate from NW-SE trends, north of the western slab window opening, to ENE-WSW within the window, to NE-SW in the southern portion of the window (Fig. 4). We interpret these results to indicate that the gap between the Nazca and Antarctic slabs visible in the travel-time inversions allows asthenospheric upper mantle to flow into the separation between the subducted

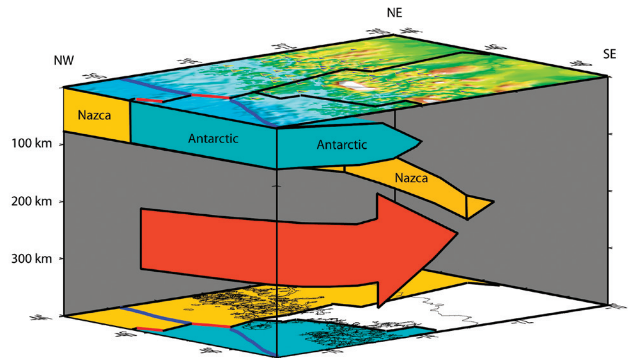

Figure 5. Schematic 3-D block diagram of upper mantle flow in the vicinity of the slab window delineated by the travel time inversions (Fig. 3); view from SW. Top map shows relief and locations of Chile Ridge structures before and after subduction. Bottom shows coastline and Chile Ridge structures over color-coded slab plates: Nazca plate—yellow; Antarctic plate—blue-green; same colors for portions of the slab visible in the block diagram itself. Red arrow generally parallels shear-wave splitting fast trends and upper mantle flow in the vicinity of the slab window opening. The northern, shallower portion of the slab window is not visible from this viewpoint.

lithospheres (Fig. 5). The majority of fast shear wave directions for stations north of the slab window trend closer to N-S than otherwise; e.g., predominantly trench-parallel, which appears to be the basic upper mantle flow direction for western South America north of the triple junction (Russo and Silver, 1994, 1996; Anderson et al., 2004).

CONCLUSIONS

Travel-time inversions demonstrate that the subduction of the Chile Ridge beneath South America has resulted in the opening of an asthenosphere-filled gap between the trailing edge of the Nazca plate and the leading edge of the Antarctic plate. These results provide the first imaging of a forming slab window, representing the first direct evidence for the existence of structures postulated to explain tectonics and magmatism on a variety of continents throughout Earth's history. Observations of shear wave splitting, resulting from systematic orientation of upper mantle mineral fabrics due to flow, indicate that the slab window perturbs the regional sub-slab upper mantle flow field. Asthenospheric flow into the gap between subducted lithospheric slabs beneath South America appears to be the likely cause of the observed shear wave splitting.

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