

Upper mantle structure in the south central Chilean subduction zone (30° to 36°S)

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[1] Regional P and S wave travel time data were used to obtain three-dimensional seismic tomography models for V_p , V_s , and V_p/V_s above the subducting slab in central Chile and Argentina. In this region, there is an abrupt change from a normal subduction geometry south of 33°S to a flat subduction geometry to the north. We find low V_p , low V_s , and high V_p/V_s ratios in the southern half of our study area directly beneath the modern active volcanic arc, which we interpret as localized pockets of melt. In the northern half of our study area, above where the subducting Nazca plate flattens at 100 km depth, we find low V_p , high V_s , and low V_p/V_s ratios. These unusual results point to a lack of melt or hydrated mineralogies such as serpentine, both of which are characterized by high V_p/V_s values. The only mantle rocks that have low V_p/V_s and high V_s are Mg-rich compositions, such as dehydrated serpentinite or orthopyroxenite. We suggest that significant portions of the mantle overlying the flat slab consist of orthopyroxenite, formed by a transient fluxing of silica-rich fluids. Such fluids may have come from sediments that were subducted during the initiation of flat subduction at this latitude at ~ 10 Ma. This would imply that the hydration of mantle material above a flat slab can be a transient phenomenon, which leaves little residual-free water behind but significantly alters the mantle chemistry.

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1. Introduction

[2] The relationship between flat slab subduction, changes in arc volcanism, and back-arc thick-skinned deformation has been under investigation for some time. In the early 1980s, several authors [e.g., Cross and Pilger, 1982; Bird, 1984] investigated the possible relationship between a period of flat slab subduction in the Farallon plate and the basement cored uplifts of the Rocky Mountain Laramide province. Jordan and Allmendinger [1986] studied the Sierras Pampeanas in Argentina as a modern analogue to the Laramide province and suggested that both were due to shallow or flat subduction geometries. Similarly, the spatial correlation between a lack of modern arc volcanism and the location of the current flat slab in central Chile and Argentina has been noted for some time. However, exactly why flat slab subduction causes volcanism to cease and inland deformation to occur has never been completely explained. At issue is the state of the thin sliver of mantle lithosphere wedged between the top of the horizontal slab at ~ 100 km depth and the overlying crust which ranges in thickness from 35 km to over 65 km in this region [Fromm *et al.*, 2004]. It has been proposed that the asthenospheric corner flow which usually introduces hot mantle material above a normally dipping slab is

pinched out, resulting in an unusually cool environment [Gutscher *et al.*, 2000; Gutscher, 2002]. In a normal subduction zone, the downgoing slab dehydrates at 100–150 km depth, releasing water into the hot overlying mantle, inducing melting. In the case of a flat slab, it has been proposed that the slab is continuously dehydrating, but that the overlying mantle is too cool to melt [Kay *et al.*, 1988]. Gutscher *et al.* [2000] suggest that the cooling of this mantle sliver results in increased strength of the lithosphere, and thus increased interplate coupling, which could explain the transfer of stress far inland to create the basement cored uplifts of the Sierras Pampeanas. However, a hydrated mantle would likely contain significant amounts of serpentine, which would weaken it [Maggi *et al.*, 2000]. Therefore a better understanding of the amount of water present above the flat slab is needed to evaluate the possible inland stress transfer mechanism.

[3] Direct information about the rheology of the mantle sliver is difficult to attain, but the physical state and composition of this material can be constrained from the study of seismic velocities. Hydrated mantle mineralogies such as serpentine are characterized by decreases in P and S wave velocities and an increase in the ratio between P wave velocities and S wave velocities (V_p/V_s ratio). Similarly, the presence of melt lowers S wave velocities more than it lowers P wave velocities, also resulting in an increase in the V_p/V_s ratio. We use P and S wave travel times to determine the three-dimensional (3-D) velocity structure above the

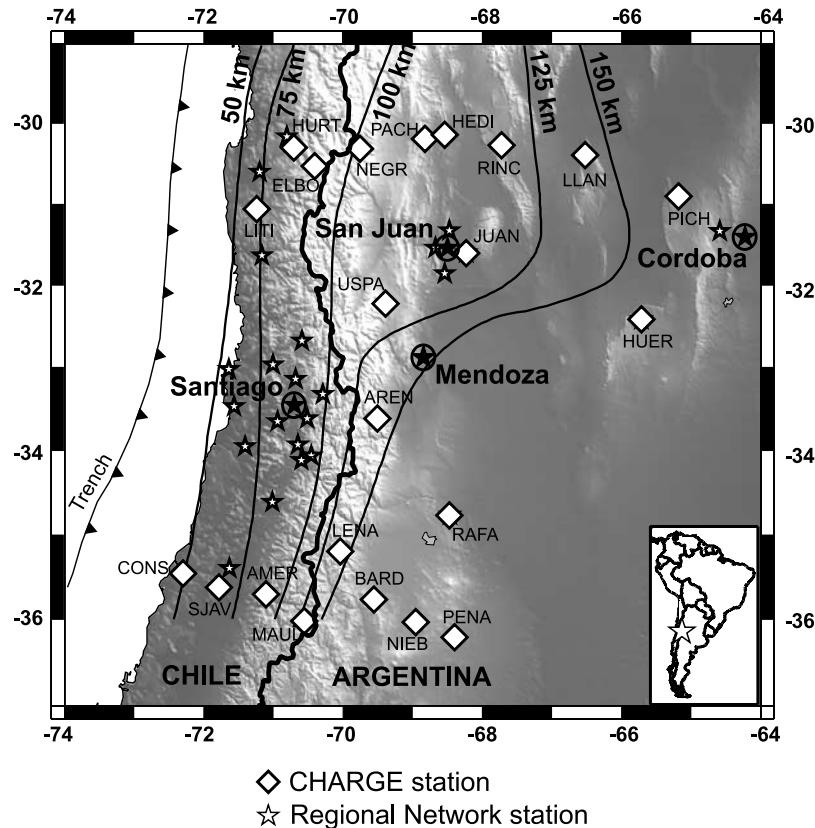


Figure 1. Map of our study area showing CHARGE seismic stations and regional seismic stations. Solid lines indicate depth contours of the subducting Nazca plate from *Cahill and Isacks* [1992].

Nazca plate between 30° and 36°S (Figure 1). The northern half of this study area overlies the central Chilean flat slab segment associated with the Sierras Pampeanas. The southern half overlies a section of Nazca plate that subducts at a normal angle. Our results to the north indicate that while P wave velocities are reduced above the flat slab, S wave velocities are increased, resulting in a dramatic decrease in the V_p/V_s ratio. The absence of low S wave velocities indicates a lack of fluids or melt above the flat slab, which explains the cessation of volcanism in this region. To the south, we find decreases in V_p and V_s and increased V_p/V_s ratios below the modern active arc consistent with the presence of melt.

2. Tectonic Setting

[4] The Andean Cordillera of Chile and Argentina can be divided into three segments. North of 28°S and south of 33°S, the modern active volcanic arc overlies regions where the subducting Nazca plate dips at a relatively constant angle of $\sim 30^\circ$. Between these areas lies the central Chilean flat slab segment, which is spatially correlated with the basement cored uplifts of the Sierras Pampeanas and the cessation of modern arc volcanism. The northern and southern transition zones between normal and flat slab subduction are very different from one another. The transition at 28°S is very gradual, starting with the formation of a small “bench” [Cahill and Isacks, 1992] at 20°S, which gradually widens until the flat slab reaches its broadest extent at $\sim 32^\circ$ S. The northern “edge” of the flat

slab region is better defined by the cessation of arc volcanism at 28°S and the increased seismic activity in the slab between 29°S and 32°S. In contrast, the transition at 33°S is fairly abrupt, going from a very broad flat slab region to a normally dipping slab in less than 2° latitude. The nature of the southern transition zone is ill defined due to a paucity of seismicity below 125 km depth, so it is possible that this change in dip is accommodated either by a tear in the slab or by a sharp bend in the downgoing plate.

[5] The history of this region of flat slab subduction has been inferred both by looking at the timing of possible causes for this flattening, and by looking at the age of observable geologic features for which this flattening is presumed responsible. While the causes of flat slab subduction are not indisputably confirmed, one likely contributing factor is the subduction of aseismic oceanic ridges. The spatial correlation between subducting or subducted bathymetric features and regions of flat slab subduction along the Andean margin has been noted repeatedly [Cross and Pilger, 1982; McGeary et al., 1985; von Huene et al., 1997; Gutscher et al., 2000; Ramos et al., 2002]. In the case of the central Chilean flat slab segment, it is the Juan Fernandez Ridge (JFR) which is subducting beneath the South American continent at a rate of about 8.4 cm/yr [Gutscher et al., 2000]. At the time of the breakup of the Farallon plate and the formation of the Nazca plate some 25 Myr ago, the JFR was being subducted obliquely at $\sim 20^\circ$ S. After the breakup, convergence between the plates became almost normal, and between 20 and 12 Ma, the JFR moved rapidly southward, reaching current latitudes

Table 1. Station Information

Station	Longitude	Latitude	Elevation, m	Seismometer
AMER	−71.104866	−35.700006	636	CMG-3ESP
AREN	−69.510923	−33.615484	2790	CMG-40T
BARD	−69.562219	−35.763946	1896	STS2
CONS	−72.298071	−35.458957	533	CMG-3ESP
ELBO	−70.407355	−30.52794	2700	STS2
FCH	−70.294324	−33.333761	2733	CMG-3ESP
HEDI	−68.543418	−30.138674	1048	CMG-3ESP
HUER	−65.717169	−32.419091	1094	STS2
HURT	−70.712179	−30.296606	1121	STS2
JUAN	−68.23297	−31.602984	635	STS2
LENA	−70.039847	−35.197973	2071	STS2
LITI	−71.245375	−31.063698	978	CMG-3ESP
LLAN	−66.527982	−30.394928	729	CMG-3ESP
LOIC	−70.147594	−35.79144	1667	STS2
MAUL	−70.558053	−36.012462	2205	CMG-3ESP
NEGR	−69.755629	−30.316928	3924	CMG-3ESP
NIEB	−68.975166	−36.033082	1521	STS2
PACH	−68.82818	−30.192981	1309	STS2
PENA	−68.397546	−36.202639	1262	STS2
PICH	−65.186806	−30.907491	543	STS2
RAFA	−68.472116	−34.774353	869	CMG-40T
RINC	−67.724484	−30.270285	1272	CMG-3ESP
SJAV	−71.780134	−35.622742	198	CMG-3ESP
USPA	−69.387578	−32.223626	2477	STS2

~10 Ma [Yanez *et al.*, 2002]. This correlates well with the eastward progression of deformation and arc volcanism, beginning between 20 and 18 Ma and increasing rapidly after 11 Ma [Kay and Abruzzi, 1996; Ramos *et al.*, 2002]. Eventually, volcanism would move over 500 km east before ending completely between 5 and 1.9 Ma [Ramos *et al.*, 2002; Kay and Mpodozis, 2002]. The timing of the uplift in the Sierras Pampeanas is not well constrained, but it is believed to have begun between 10 and 3 Ma [Jordan and Allmendinger, 1986], roughly coeval with the sweep of volcanism through this area. This evidence suggests flattening began to the north between 20 and 18 Ma, with the most dramatic changes at current latitudes occurring between 10 and 5 Ma, reaching its present configuration no later than 2 Ma.

[6] The southern half of our study area is characterized today by comparatively “normal” subduction at a constant dip angle of ~30°. Modern volcanism is concentrated along the main Cordillera, roughly following the Chile/Argentina border, and is consistent in location and geochemistry with normal subduction-related arc volcanism.

3. Field Deployment and Data

[7] The Chile Argentina Geophysical Experiment (CHARGE) consisted of 22 broadband portable seismometers deployed in roughly two transects for 18 months starting in late 2000. The seismometers were primarily a mix of STS-2s and Guralp CMG-3ESPs (Table 1). Data were collected using RefTek 72A-08 digitizers recording at 40 samples per second and stored on 80 GB hard drives which were exchanged every 3–4 months. Timing at each station was synchronized using GPS receivers. Instrumentation for this deployment was provided by the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) of the Incorporated Research Institutions for Seismology (IRIS).

[8] The two transects of this deployment both trended roughly east-west (Figure 1). The northern line was located at ~30°S above the flat slab region. The southern line was located at ~36°S, above the normally dipping slab. Four stations were deployed between these two transects, complementing previously existing regional networks run by the University of Chile in Santiago, the Instituto Nacional de Prevencion Sismica, and the University of San Juan, Argentina, which report data to the International Seismological Centre (ISC).

[9] For this tomography study, we used a total of 142 well located events consisting of 84 events below 70 km depth, presumed to be in the subducting Nazca plate, and 58 crustal events (Figure 2). We picked *P* and *S* wave first arrivals and relocated each event using Hypocenter [Lienert and Havskov, 1995]. Only events with azimuthal gaps of less than 180° were used. *P* waves were picked exclusively on the vertical component, and *S* waves were picked on the transverse component, initially using the global catalog location to rotate the data. After relocating all the events, events were re-rotated using new hypocenter locations, and all *S* wave picks were reviewed on the transverse component. We discuss any possible *S* wave anisotropic effects in section 6.1. The impulsive *P* and *S* wave arrivals generated by the deep events were significantly easier to pick than the emergent arrivals generated by the shallow events. However, the large impulsive *P* wave arrivals from the deep events (and some close in recordings of shallow events) produced acausal precursory arrivals due to the antialiasing FIR filter applied by the RefTek 72A-08 digitizer. We removed the FIR filter effect using the method of Scherbaum and Bouin [1997] before picking the *P* wave arrival times. The acausal FIR arrival was typically less than 0.25 s before the true first arrival, which is significantly less than the final average travel time residuals of the inversions, which are between 0.45 and 0.5 s.

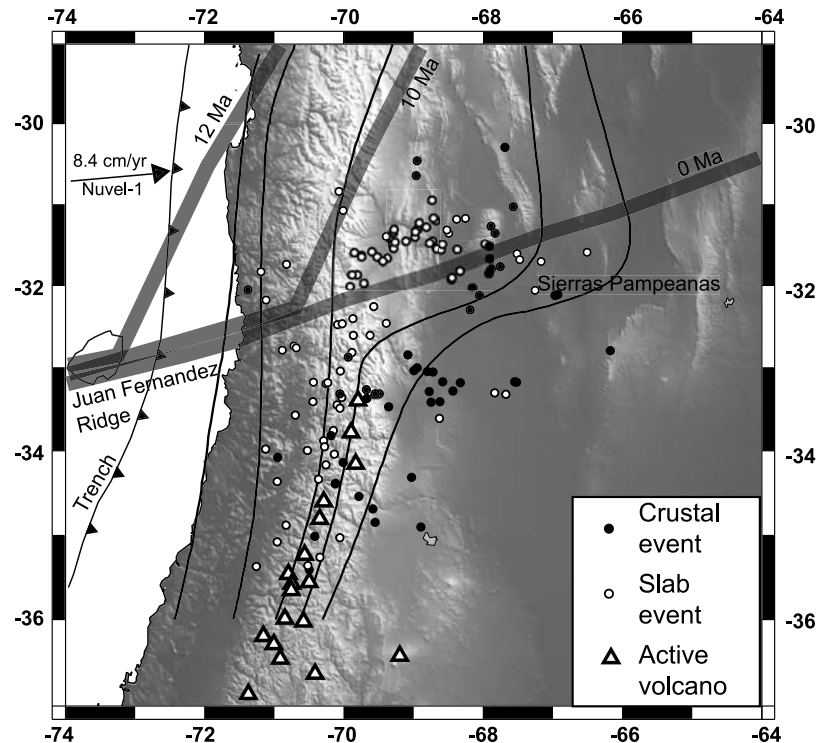


Figure 2. Map of geologic features in our study area. Slab contours are from *Cahill and Isacks [1992]*. Triangles indicate active volcanos. Open circles indicate slab events, and solid circles indicate crustal events. Shaded grey lines indicate the locations of the Juan Fernandez Ridge at the indicated times [*Yanez et al., 2001*].

[10] P and S wave arrivals for the shallow events were more difficult to pick. Most recordings were made at distances beyond the crossover distance where the Moho-refracted P_n or S_n phases become the first arrivals. These phases are very emergent and difficult to pick accurately. Complicating matters, S_n arrivals for travel paths crossing the southern back-arc region were severely attenuated and impossible to pick. In order to avoid a systematic bias caused by picking all S_n arrivals too late and to maintain a consistent data set, we do not use any S wave picks from shallow events with epicentral distances of greater than 150 km. In total, we used over 1600 P wave picks and over 900 S wave picks from CHARGE stations. After inverting for V_p , V_s , and V_p/V_s using only CHARGE station picks, we added data from the regional networks as reported to the ISC catalog. We did not include S wave picks from shallow events beyond 150 km epicentral distance in order to avoid potential bias. Adding the ISC data did not change any of the major features of the tomography, but did improve resolution. With the ISC data included, the data set consists of over 2600 P wave picks and over 1600 S wave picks.

4. Methods

[11] There is continuing debate on the best methodology for determining V_p , V_s , and the V_p/V_s ratio through seismic tomography. Each of these three quantities gives us important information on the composition and physical state of the volume being studied, yet they are each obviously not

entirely independent from one another. We can determine V_p and V_s relatively independently (assuming fixed event parameters), as they are each tied to the absolute travel times of a particular phase. Errors in P wave picks map directly to errors in the P wave velocity structure but not necessarily to errors in the S wave velocity structure, and vice versa. The V_p/V_s ratio, on the other hand, is derived from the difference in travel times between the P and S wave arrivals, and as such the accuracy of a given V_p/V_s measurement is sensitive to errors in both P and S picks and velocity structures. Further complicating the determination of V_p/V_s is the generally uneven distribution and quality of P and S wave picks. Even if all picks were made with total accuracy, an underresolved S wave anomaly that is related to a well resolved P wave anomaly would produce a spurious V_p/V_s ratio. A number of authors [e.g., *Thurber, 1993; Eberhart-Phillips and Reyners, 1997; Graeber and Asch, 1999*] have addressed this issue by inverting directly for V_p and V_p/V_s . This should guarantee that deviations in V_p/V_s are mandated by the data and are not merely artifacts of uneven resolution. Unfortunately, V_s deviations determined from this method by dividing V_p by V_p/V_s suffer from many of the same problems associated with determining V_p/V_s by inverting for V_p and V_s . In particular, large P wave anomalies in areas with better P wave coverage than S wave coverage tend to “bleed over” into the S wave anomalies via an underresolved V_p/V_s anomaly. Thus, to ensure that observed anomalies either in V_p , V_s , or V_p/V_s are not due to a bleed-over effect, it is necessary to invert directly for each quantity.

[12] To that end, in addition to inverting simultaneously for V_p and V_s , we modified the code of Zhao *et al.* [1992] to invert simultaneously for V_p and the V_p/V_s ratio. Zhao *et al.*'s method allows for the input of a priori information on crustal structure and the location of the subducting slab which improves ray tracing by allowing for sharp velocity gradients at discontinuities. The ray tracer iteratively uses Snell's law across the model discontinuities, and the pseudobending technique described by Um and Thurber [1987] to determine ray paths through the rest of the volume. A priori information about discontinuities also allows for a more accurate starting model, as initial velocities for crust and mantle follow the contours of the model Moho discontinuity. Velocity deviations are assigned to grid nodes, and are linearly interpolated between these grid nodes when velocities are calculated. We used a grid spacing of $40 \times 40 \times 20$ km in latitude, longitude, and depth, respectively. Because seismic travel time equations are nonlinear, the equations are linearized and the tomography is performed iteratively using the sparse matrix LSQR inversion method of Paige and Saunders [1982].

[13] Before the inversion in each iteration, events are relocated using the updated 3-D P and S wave velocity models, and travel time residuals recalculated based on the revised locations and velocity models. For the P and S inversion, we tested the effects of including event parameters in the inversion as opposed to relocating events through the 3-D model after each iteration, and found essentially no difference in the velocity models or the event locations between the two methods.

[14] For the simultaneous inversion of V_p and V_p/V_s , we added the derivatives for the difference in S wave travel times from P wave travel times (S - P time) to Zhao *et al.*'s [1992] original code (see auxiliary material¹). Data for the V_p/V_s inversion came from stations/event pairs with good P and S picks. To obtain predicted S - P times, we calculated P and S wave ray paths independently. Because the derivatives assume identical ray paths (see auxiliary material), we also tried calculating predicted times along identical ray paths, but the change in predicted S - P times was much smaller than our uncertainty and thus had no significant effect on the tomography results.

[15] Our starting mantle model is that of IASPEI-91 [Kennett, 1991], and our input for the slab discontinuity is from Cahill and Isacks [1992]. The tomography allows for an initial velocity deviation in the slab to more closely approximate the likely higher velocities in the cold subducting plate. We tried inverting with and without this slab deviation of 5% and found that it had no significant effect on our upper mantle results. Since our results are insensitive to initial slab deviations and we are uncertain of the exact slab structure, we decided not to include an initial slab deviation in our starting model. Our crustal thicknesses and velocities were taken from P_n [Fromm *et al.*, 2004] and receiver function studies [Gilbert *et al.*, 2003] from the CHARGE experiment. Because most of our crustal earthquake picks are from P_n arrivals, we have very poor crustal resolution. We therefore fix our crustal P wave

velocity at 6.0 km/s, as determined by Fromm *et al.* [2004], and a V_p/V_s ratio of 1.73. We tested the effects of changing the initial P and S velocities in the crust on the mantle tomography and found that differences tended to affect only amplitudes, and not the general patterns of velocity perturbations. We discuss the effects of different crustal models in section 6.1.

[16] In order to remove outliers due to mispicks, we imposed a residual cutoff of 2 s for P waves, 3 s for S waves in the P and S inversion, and 3 s for S - P times in the P and V_p/V_s inversion. These values were determined by looking at the distribution of residuals versus travel times for the initial model (Figure 3). Damping is necessary in this inversion due to the instability caused by incomplete and inconsistent data [Menke, 1989]. For details on the damping used in this inversion, see the auxiliary material.¹ There are two main ways to determine damping parameters. The traditional method sets the damping equal to the data variance divided by the model variance. This is difficult in seismic tomography because of problems quantifying error in the data prior to the inversion. The other method proposed by Eberhart-Phillips [1986] involves running the tomography for one iteration over a range of damping parameters and plotting data variance versus model variance. The ideal damping value is at the corner of the resulting "L" curve, beyond which increases in model variance do not produce significant decreases in data variance, and vice versa. In our case, this method produces an ideal damping value of 20 for both the P and S and the P and V_p/V_s inversions (Figure 4). Changing this damping value ± 10 does little to change the basic patterns in the results, but it does affect the amplitude of the deviations. These amplitudes are also affected by the number of iterations used. In order to find the optimal number of iterations, we use our previously determined damping values over 10 iterations, and again plot data variance versus model variance, this time for each iteration. In our case, 2 iterations are optimal for both the P and S and P and V_p/V_s inversions (Figure 5). Additional iterations may reduce variance more, but would serve only to increase the size of the observed anomalies. The improvement in the residuals can be seen in Figure 3. These constitute a 40.9% and a 44.3% improvement in data fit for the P and S and P and V_p/V_s inversions, respectively.

5. Resolution Tests

[17] To test the resolution of our study, we calculated synthetic travel times through a checkerboard model where the velocity deviation at each grid node used in the original inversion is $\pm 5\%$. We used the same source-receiver distribution as the actual data set. These calculated times were then inverted for V_p and V_s to see how much of the original checkerboard pattern could be recovered (Figure 6). Our checkerboard pattern is best recovered for both P and S above the flat slab region. Amplitudes for V_p are somewhat underestimated whereas amplitudes for V_s are accurately recovered in this area. The overall checkerboard pattern is clearly observable in both V_p and V_s . To the south, the checkerboard pattern is well recovered for V_p , but V_s indicates some vertical smearing. Amplitudes for both V_p and V_s are well recovered in this area.

¹Auxiliary material is available at <ftp://ftp.agu.org/apend/jb/2004JB003238>.

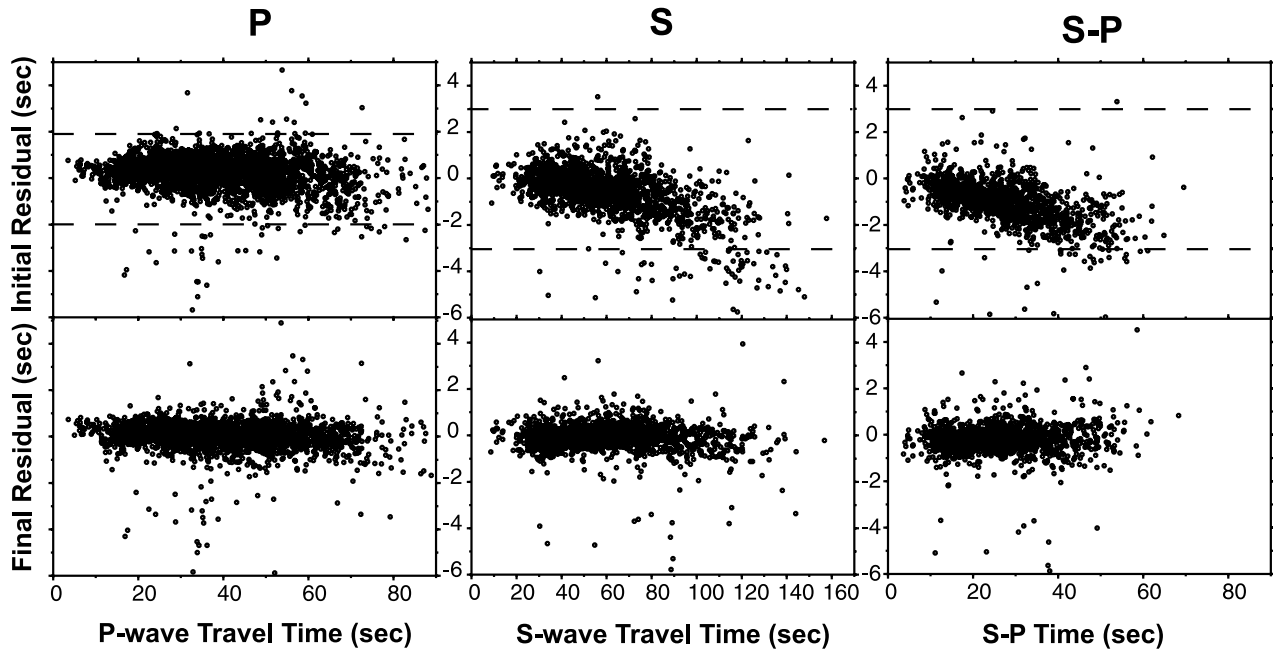


Figure 3. Residuals versus travel time plots for P , S , and $S-P$. (top) Residuals before the inversions. (bottom) Residuals after the inversions. P and $S-P$ final residuals are from the P and V_p/V_s inversion. Final residuals for S are from the P and S inversion. Dashed lines indicate residual cutoffs for P , S , and $S-P$ times.

[18] While checkerboard tests are good for observing streaking anomalies, they are not good tests for the recoverability of larger features [Leveque *et al.*, 1993]. To this end, we tested the ability of our inversion to recover a broad flat horizontal anomaly to the north similar in size and amplitude to our observed anomaly above the flat slab and a long narrow thicker anomaly to the south, similar in shape and amplitude to the low velocity zone observed there, following the method of Husen *et al.* [2003]. This test is also well suited for demonstrating the bleed-over effect discussed in section 4. We generated a synthetic data set by ray tracing through a specified model, and then inverted this synthetic data set without allowing events to be relocated. If we allow events to be relocated, the results are similar, but the bleed-over effect is less pronounced. We performed three different tests, the first with an initial anomaly only in P , the second with an initial anomaly only in S , and the third with an initial anomaly in both P and S resulting in no V_p/V_s anomaly. We performed this test using both the P and V_p/V_s inversion and the P and S inversion. The results of these tests indicate that the best way to determine S wave velocity structure is through a simultaneous inversion of V_p and V_s , and the best way to determine the V_p/V_s ratio is to invert directly for V_p and V_p/V_s (see Appendix A and Figure 7). V_p was insensitive to the inversion method.

[19] In Figure 8, we show cross sections for V_p , V_s , and V_p/V_s anomalies which we feel best reflect the true resolvability of these synthetic anomalies. V_p and V_p/V_s cross sections are from the P and V_p/V_s inversion recovering a P only anomaly (i.e., no S anomaly). V_s cross sections are from the P and S inversion recovering an S -only anomaly (i.e., no P anomaly). The V_p anomaly is best recovered, with good resolution extending east of 68°W . For V_s and V_p/V_s ,

resolution of the amplitude of the anomaly begins to degrade east of 69°W , with very little resolution east of 68°W . Vertical smearing is also more pronounced to the east in V_s and V_p/V_s than in V_p .

6. Results and Sensitivity Analysis

[20] We present results for V_p and V_p/V_s from our P and V_p/V_s inversion and V_s from our P and S inversion. Even though we invert for structure below the slab, resolution is poor, so we only show results between the crust and the top of the subducting plate. Results for V_p are virtually identical in the two inversions. Results for V_s and V_p/V_s are very similar, except for specific areas (such as the far eastern flat slab region), where there are bleed-over effects. For an example of this effect in the V_s results, see Figure 9. Figure 9 also shows initial and final event locations along the subducting flat slab. Prior work [e.g., Reta, 1992] had noted the apparent “reverse dip” of the subducting plate as determined by earthquake locations, caused by the apparent deeper depths of events below the main cordillera than those located farther east. This effect is seen when events are relocated independently using a 1-D velocity model. However, when these events are relocated in the tomography using full 3-D V_p and V_s models, these events flatten out, aligning themselves closely at approximately 100 km depth, as suggested by Cahill and Isacks [1992].

[21] We present V_p and V_s deviations from the starting model in color, and provide absolute velocity contours to facilitate interpretation (Figures 10–15). For V_p/V_s , we present absolute values in color, where cooler colors (green, blue, purple) indicate V_p/V_s values that are lower than the starting model, and where warmer colors (yellow, orange, red) indicate V_p/V_s values that are higher than the starting

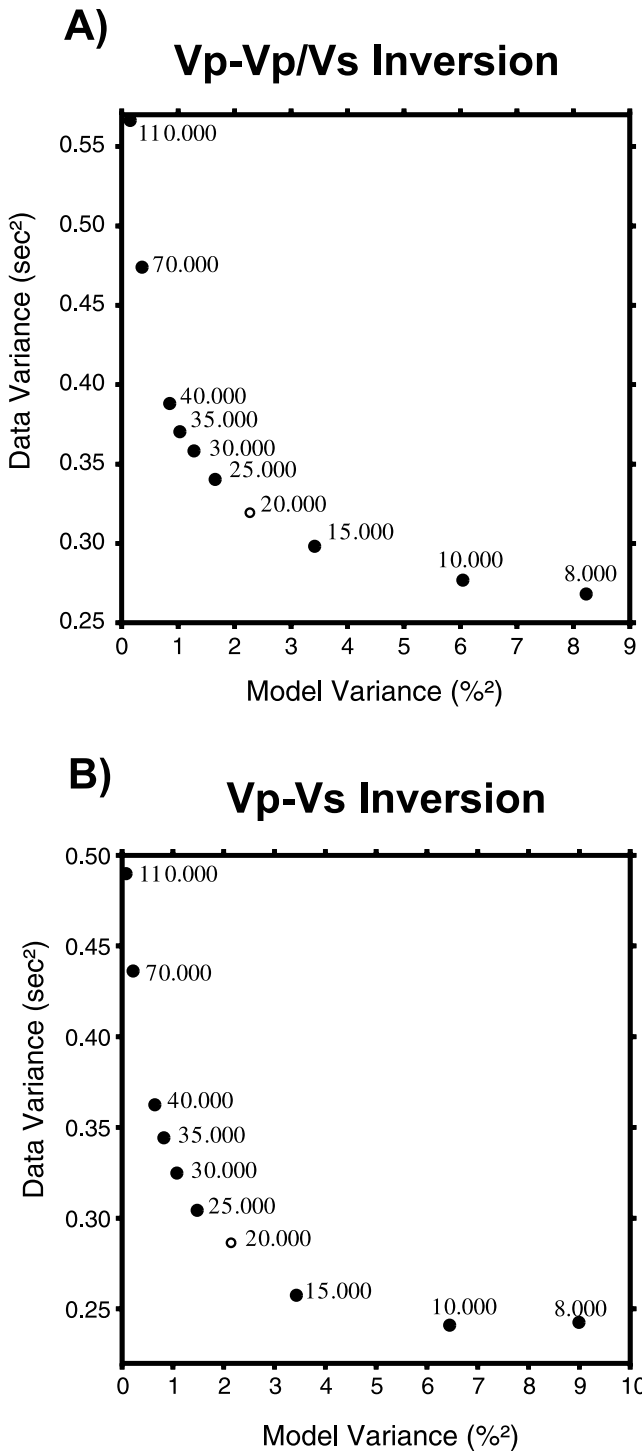


Figure 4. Model versus data variance plots for different damping parameters. Open circles indicate the optimal damping values for each inversion. (a) Model versus data variance for the inversion of V_p and the V_p/V_s ratio. (b) Model versus data variance for the inversion of V_p and V_s .

model. Green dots indicate the earthquake locations determined using the final 3-D velocity models.

6.1. Flat Slab Region

[22] Above the flat slab in the northern half of our study area, we find a continuous layer characterized by low P

wave velocities, high S wave velocities, and an unusually low V_p/V_s ratio, as can be seen in the cross sections in Figure 10 and the map view slice at 85 km depth in Figure 14. This feature extends some 300 km E-W, 120 km N-S and appears to be between 20 and 40 km thick. P wave velocities in this region range from 7.4 to 8.0 km/s, with the

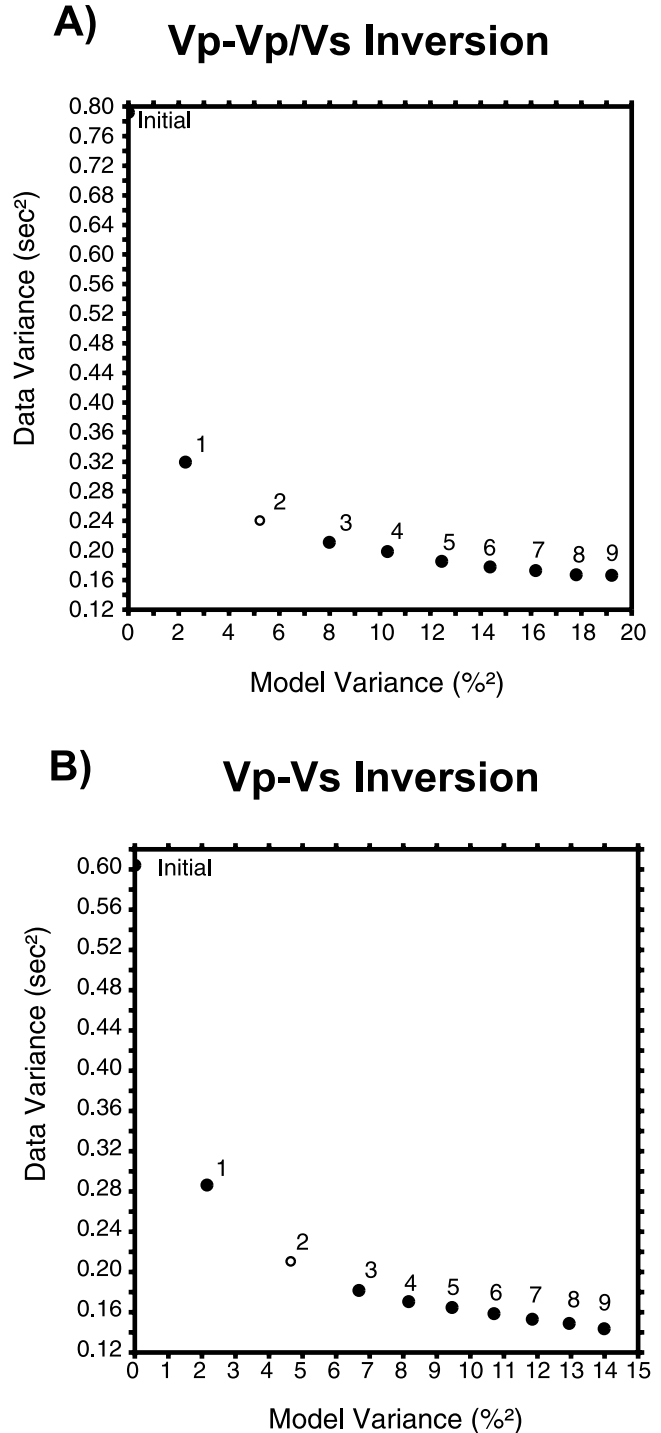


Figure 5. Model versus data variance plots with fixed damping parameters over multiple iterations. Open circles indicate the ideal number of iterations. (a) Model versus data variance for the inversion of V_p and the V_p/V_s ratio. (b) Model versus data variance for the inversion of V_p and V_s .

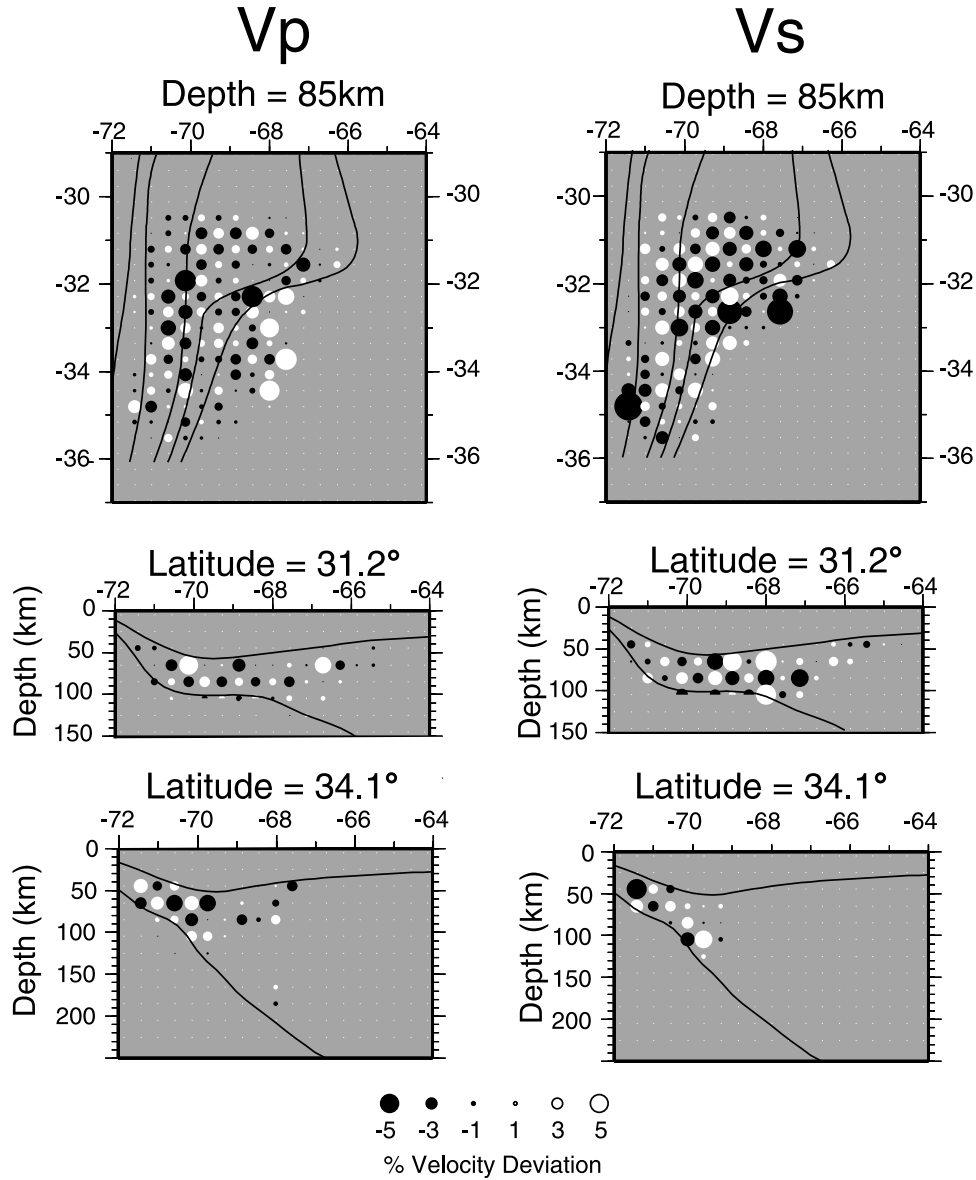


Figure 6. Checkerboard resolution test for V_p and V_s . Input velocity deviation is $\pm 5\%$.

most common velocities lying between 7.6 and 7.8 km/s. At 80–100 km depth, this is 3.1–5.5% lower than IASPEI-91 (~ 8.046 km/s), and is similar or even somewhat lower than values found by *Myers et al.* [1998] under the Altiplano in Bolivia (~ 7.8 km/s). Unlike typical volcanic arcs, however, the S wave velocities above the flat slab are higher than usual. Absolute S wave velocities range between 4.5 and 4.8 km/s with the most common velocities lying between 4.6 and 4.7 km/s, where IASPEI-91 is ~ 4.488 km/s. This corresponds to a 2.5–4.7% increase over the starting model.

[23] The obvious result of decreased P wave velocities and increased S wave velocities is a decrease in the V_p/V_s ratio. We find V_p/V_s ratios between 1.63 and 1.76, with the most common values lying between 1.68 and 1.72. IASPEI-91 at this depth is ~ 1.79 . This corresponds to a 3.9–6.1% decrease in V_p/V_s from the starting model. While absolute values are often less well resolved in tomographies, general patterns of deviations are generally

consistent. In our case, the pattern of low V_p , high V_s , and low V_p/V_s has been remarkably consistent over a range of methods, starting models, and parameters. Even a conservative velocity deviation of $\pm 1.5\%$ for V_p and V_s , respectively, results in a V_p/V_s ratio of 1.739. A 2% deviation produces a V_p/V_s ratio of 1.722.

[24] We tested the sensitivity of our results to crustal structure by inverting over a range of crustal thicknesses and velocities, and by testing the effect of fixing the crust versus allowing the crustal velocities to change during the inversion. In the case of a fixed crust, the effect of increasing crustal P wave velocities while keeping V_p/V_s fixed, or thinning the crust (for example, by using a flat Moho at 40 km depth) was to decrease the amplitude of the V_p/V_s deviation. In general, P wave velocities remained slow, S wave velocities remained fast, but due to the very low amplitudes in V_p , the V_p/V_s ratio ranged from 1.70 to 1.77. However, constraints from P_n studies [*Fromm et al.*, 2004] indicate that increases in crustal P wave velocities

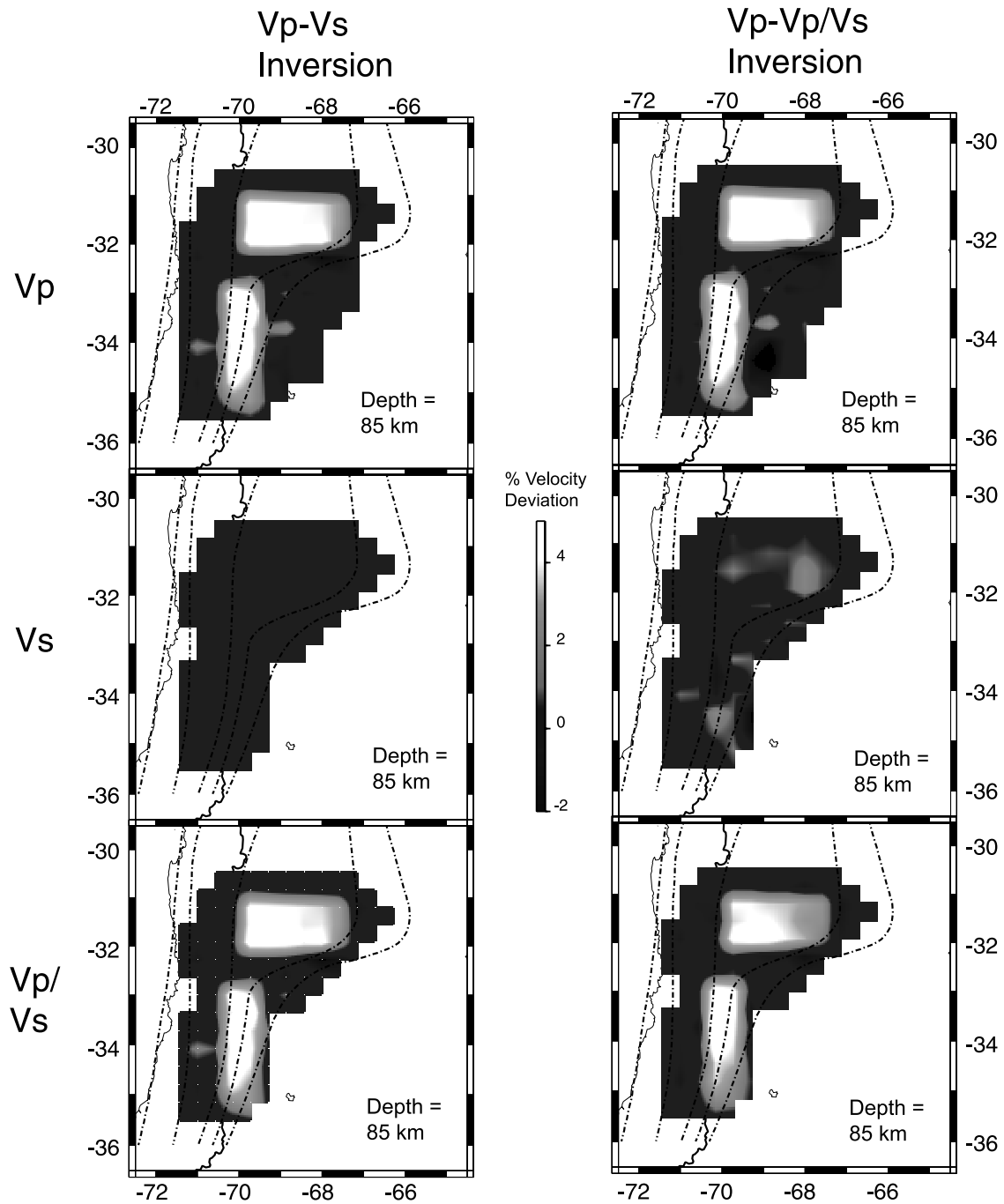


Figure 7. Map view of the results of the first recovery test for a V_p only anomaly. (right) Recovery of V_p , V_s , and V_p/V_s using the P and V_p/V_s inversion. Note the bleed over of the V_p anomaly into V_s where V_p is better recovered than V_p/V_s . (left) Same test done with the P and S inversion. Note the lack of bleed over into V_s .

must be coupled with increases in crustal thickness. Thus if we use a higher P wave velocity, we must also use a thicker Moho, and vice versa. The net effect is that if our crust has a velocity/thickness combination that is plausible with respect to the Pn data, our V_p , V_s , and V_p/V_s results remain stable. We also looked at the effect of fixing the crustal P wave velocity while varying the crustal V_p/V_s ratio. While the general pattern of low V_p , high V_s and low V_p/V_s persists above the flat slab, decreasing the crustal V_p/V_s ratio has the

effect of raising the observed V_p/V_s ratio above the flat slab to between 1.69 and 1.77, with typical ratios ranging between 1.71 and 1.74. However, receiver function studies [Gilbert *et al.*, 2003] indicate that the V_p/V_s ratio below the main cordillera above the flat slab may be higher than 1.80. Raising the crustal V_p/V_s ratio to 1.79 in this study has the effect of lowering the V_p/V_s ratio above the flat slab to between 1.60 and 1.69. Thus we feel our estimate of 1.68–1.72 is conservative.

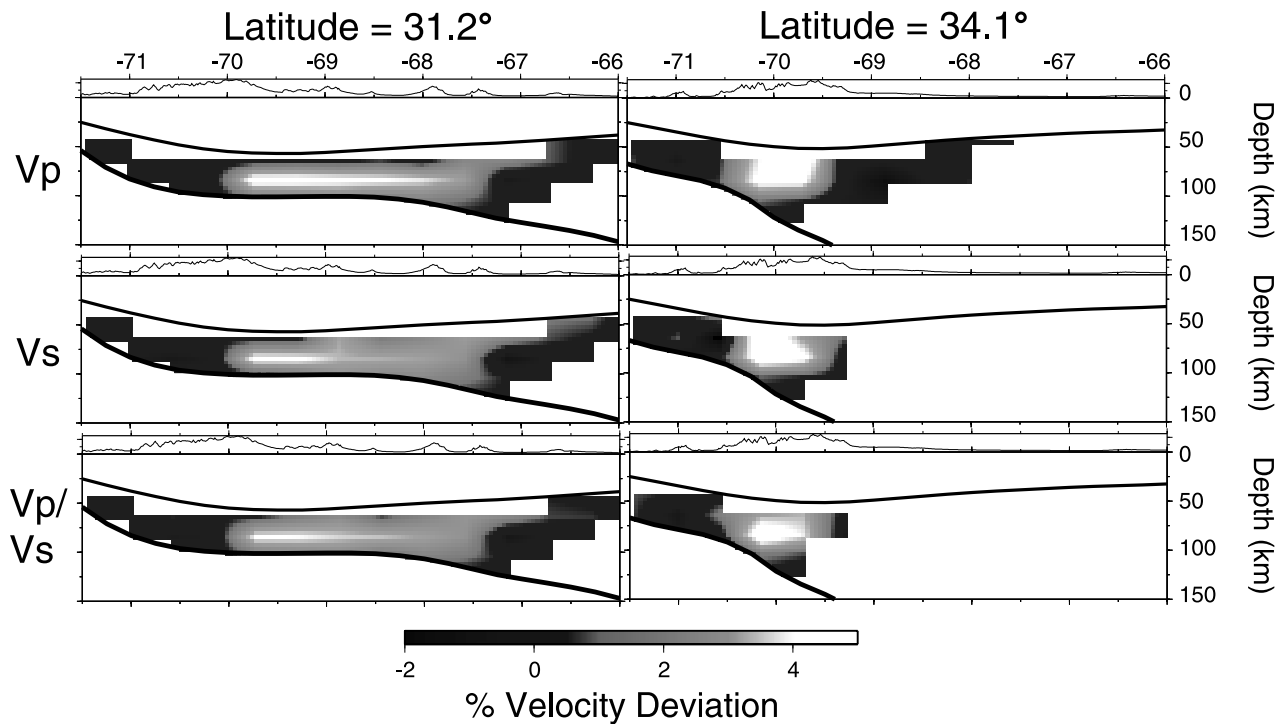


Figure 8. Cross sections of recovery tests for V_p , V_s , and V_p/V_s which most accurately represent the true resolvability of these synthetic anomalies. V_p and V_p/V_s are from the P only test using the P and V_p/V_s inversion. V_s is from the S -only anomaly test using the P and S inversion.

[25] If we allow the inversion to vary the crustal structure, we again find the same general pattern of low V_p , high V_s , and low V_p/V_s , but much of this pattern is smeared into the crust. The result is an extremely low V_p/V_s ratio in the crust and an only moderately low V_p/V_s ratio in the mantle above the flat slab. As discussed earlier, independent receiver function analyses, which have much better resolution on crustal structure than this inversion, indicate a much higher V_p/V_s ratio in the crust, especially west of 67°W . Thus we believe our low V_p/V_s ratio in the crust to be due to smearing of this anomaly from the mantle sliver into the overlying structure due to poor vertical resolution above the Moho.

[26] We also investigated the possibility that our high S wave velocities are due to anisotropy associated with the alignment of olivine crystals in the mantle overlying the flat slab. For the most part, the good azimuthal distribution of rays above the flat slab makes it unlikely that our result is due to anisotropy. We calculated the average V_p/V_s ratio as a function of back azimuth using Wadati diagrams with picks from deep events north of 33° . Results are shown in Figure 16, along with the number of S wave data points in each partition. If azimuthal anisotropy were the cause of changes in V_p/V_s , we would expect to see 180° periodicity in the results, meaning wedges opposite each other would have similar V_p/V_s values. While we do see variations in V_p/V_s , we do not observe this periodicity. We also tried inverting picks from deep events with fixed event parameters as a function of back azimuth, first using only picks with back azimuths between 0° and 180° where the V_p/V_s ratio is low and then using only picks with back azimuths between 180° and 330° where the V_p/V_s ratio is high. We find that the latter mostly samples the westernmost portion

of the study below the main cordillera where both V_p and V_s are low, but to the extent that there is coverage above the flat slab, we observe the same characteristic low V_p/V_s ratio. In the former, the flat slab is well sampled, and again, we observe the same low V_p/V_s ratio. This suggests that the differences in V_p/V_s observed in the Wadati diagrams is due to structure, not anisotropy. We recognize that this method may not be sensitive to anisotropy where the fast axis is aligned vertically and the slow axis is horizontally isotropic. However, the fast axis tends to preferentially align itself in the direction of shear [Zhang and Karato, 1995], and it is unlikely above the flat slab that we have any mechanism for vertical shearing. As such, we do not consider this to be a likely cause of our observed results. Seismic recordings at JUAN, located above the center of the flat slab, of events located directly below the station show less than 0.3 s of shear wave splitting (M. Anderson, personal communication, 2004), which is within noise levels for this study. In general, we cannot find any evidence of anisotropy and therefore do not think it has significant effects on the results of this study. This is consistent with the findings of Russo and Silver [1994], who found most of the anisotropy in this region to be located below the Nazca plate.

[27] One notable exception to the pervasive low- V_p , high- V_s , low- V_p/V_s regime above the flat slab lies beneath the main Cordillera between 70°W and 70.5°W . Here we find a small shallow low-velocity zone in both P and S wave velocities, corresponding to a moderately high V_p/V_s ratio. This anomaly can be seen in the 65 km depth map view in Figure 13 and in the cross sections of Figure 10. This small anomaly is reminiscent of the low-velocity,

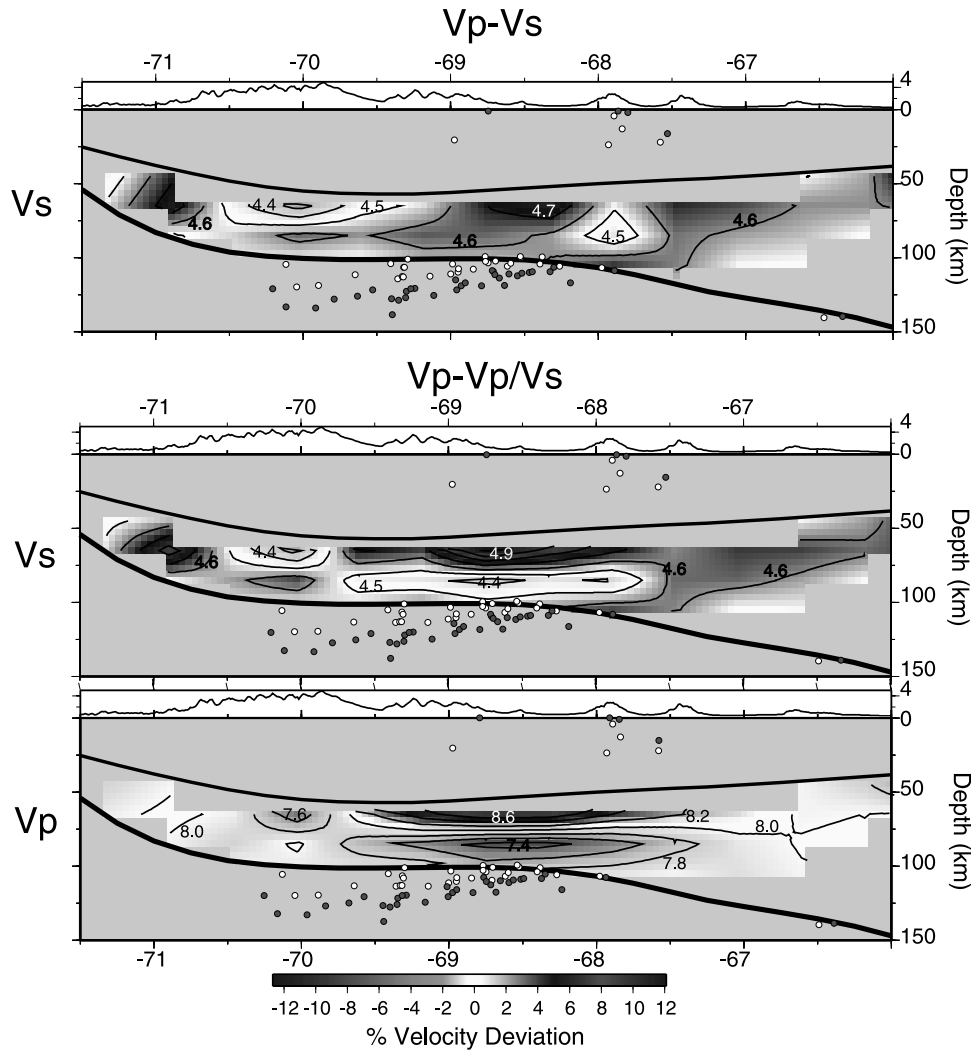


Figure 9. Bleed-over effect in CHARGE results at 31.1°S. (top) Cross section of V_s deviations from the P and S inversion. (middle) Cross section of V_s deviations from the P and V_p/V_s inversions. (bottom) Cross section of V_p from the P and V_p/V_s inversion. Notice how the low- V_p anomaly between 69°W and 68°W bleeds over into the V_s anomaly in the P and V_p/V_s inversion. This low- V_s anomaly is not present in the results from the P and S inversion. Open circles indicate final event locations, and solid circles indicate initial event locations.

high- V_p/V_s ratio results commonly found beneath active volcanic arcs, and indeed this anomaly underlies the early Miocene volcanic arc. In map view at 65 km depth, it appears to form a continuous feature from the south below the active arc to the north above the flat slab. However, for reasons discussed in section 6.3, we believe this feature is not due to the same causes as those responsible for low velocities and high V_p/V_s ratios below normal arc settings but rather has a distinct genesis that happens to have similar seismic effects.

6.2. Transition Zone

[28] In the region between the anomalous low- V_p , high- V_s , low- V_p/V_s zone to the north and the modern active arc to the south lies the transition zone where the slab rapidly changes from a flat geometry to a normally dipping one. While we cannot resolve whether the slab is torn or continuous in this region, we can image the area immedi-

ately above it. We find an ENE trending feature characterized by high V_p , high V_s , and relatively high V_p/V_s ratios that extends from the southern edge of the flat slab to the northern edge of modern arc volcanism. This feature is most clearly seen in the 85-km-depth map of the P wave velocity anomalies (Figure 14), extending from between 33°S and 34°S in the west at 71°W to between 32°S and 33°S in the east at 69°W. It is approximately 80 km wide and 280 km long and between 20 and 40 km thick (Figure 11).

[29] The high- V_p , high- V_s , high- V_p/V_s velocities in this region are consistent with cooled depleted mantle peridotites (Figure 17). This can occur when asthenospheric corner flow is pinched out by the shallowing of the slab in the transition zone. The high velocities indicate that this material is no longer hydrated or melted to any significant extent because the presence of melt or hydrated mineralogies would decrease both P and S wave velocities. Immediately above this region, below the main cordillera, is an area of

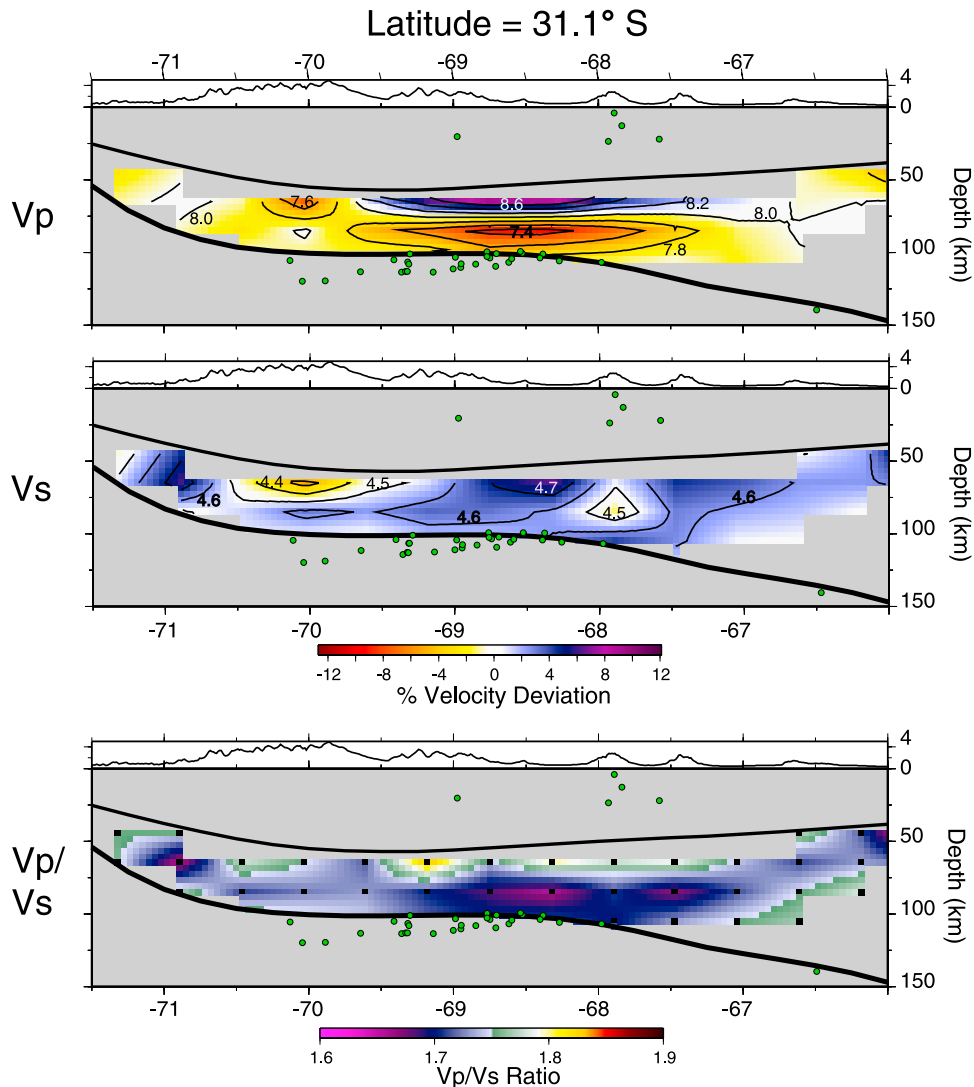


Figure 10. Results for V_p , V_s , and V_p/V_s at 31.1°S latitude. The Moho is from a P_n study by *Fromm et al.* [2004]. The slab contours are from *Cahill and Isacks* [1992], and the green dots indicate event locations. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

pronounced low V_p , low V_s , and high V_p/V_s , which can be seen in the 65-km map view plots (Figure 13) at 32.5°S and 69.5°W . This area is north of the modern active arc, so the anomaly is unlikely to be entirely due to the presence of melt. The high- V_p , high- V_s anomaly immediately below this area may indicate it is too cool for melt to exist. Instead, it may be a large volume of serpentinized mantle material that was formed when the last of the water from the normally subducting slab was released and moved up through the lower part of the mantle wedge to pool beneath the thickened arc crust. It is probably not coincidence that this pronounced feature lies directly at the “corner” of the transition zone, and the complicated slab geometry in this region may aid in trapping the fluid-rich serpentinites in this area.

6.3. Southern Region

[30] Results from the southern half of this study above the normally subducting slab are consistent with results from

other subduction zones around the world [e.g., *Graeber and Asch*, 1999; *Nakajima et al.*, 2001; *Zhao et al.*, 1992; *Zhang et al.*, 2004]. The mantle is characterized by a low- V_p , low- V_s , high- V_p/V_s zone immediately below the active arc (Figures 12, 13, and 14). The exact dimensions of this region are ill defined, but it appears to extend the full length of the active volcanic arc our study area, averaging 80 km E-W and 20–40 km in thickness. While resolution to the south is not as good as to the north as evidenced by the checkerboard test, we still find resolvable localized P and S velocities of ~ 7.8 and ~ 4.3 km/s, respectively, indicating velocity reductions of 3% and 4.2%. We also find corresponding V_p/V_s ratios of ~ 1.81 , a 1.1% increase over IASP91. These deviations are very similar in amplitude to those found in Bolivia beneath the Western Cordillera and the Los Frailes volcanic field [*Myers et al.*, 1998].

[31] This pattern of low V_p , low V_s , and high V_p/V_s can generally be interpreted as either a serpentinization of

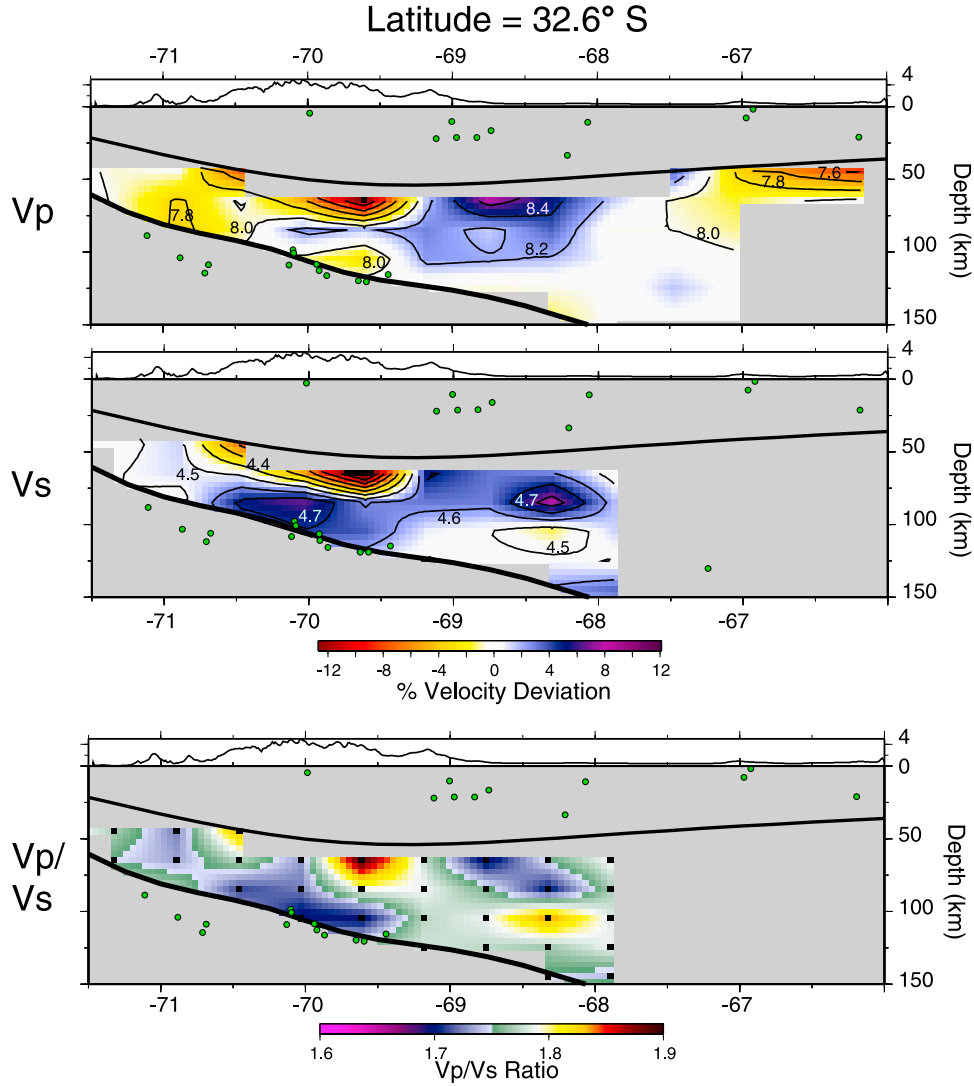


Figure 11. Results for V_p , V_s , and V_p/V_s at 32.6°S latitude. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

mantle peridotites or as an indicator of melt. There is virtually no difference between the seismic signatures of melt and those of hydration, so we must look to other information in order to determine which is the cause of a particular low-velocity, high- V_p/V_s ratio area. Temperature is the key determining factor in most cases. Serpentine is generally unstable at temperatures above 700° [Bose and Ganguly, 1995; Hacker et al., 2003], and melt is unlikely at cooler temperatures, even if water is present. Temperature above a subducting slab is dependent on many factors including rate of subduction, age of the subducting plate, and the amount of frictional heating between the downgoing plate and the overlying mantle [Peacock, 1996]. Given an age of ~50 Ma and a convergence rate of ~80 mm/yr, temperatures at the location of this low- V_p , low- V_s , high- V_p/V_s anomaly are expected to be well above the stability field for serpentinite [Peacock, 1996; Hyndman and Peacock, 2003]. Therefore we believe these results indicate localized pockets of melt, probably induced by the

introduction of water into the mantle by the subducting slab. The percent melt represented by these velocity reductions is dependent on the assumed geometry of the melt inclusions. If we assume ellipsoidal melt geometry as done by Schmeling [1985], the percent melt is likely to be between 1% and 1.5% (see Figure 17). However, recent work with more realistic melt geometries [e.g., Hammond and Humphreys, 2000] indicates that shear velocities are likely more affected by small percent melts than previously predicted, resulting in higher predicted V_p/V_s ratios. This would imply that our results either represent a smaller percent melt than that indicated by Schmeling [1985] and the amplitude of our P wave anomaly is exaggerated or, more likely, our S wave anomaly is underresolved in amplitude. If we assume the latter case is true and our P wave amplitudes are correct, Hammond and Humphreys [2000] predict between 0.6% and 1.1% melt, depending on geometry.

[32] In contrast, the low-velocity, high- V_p/V_s region located above the flat slab which we mentioned in

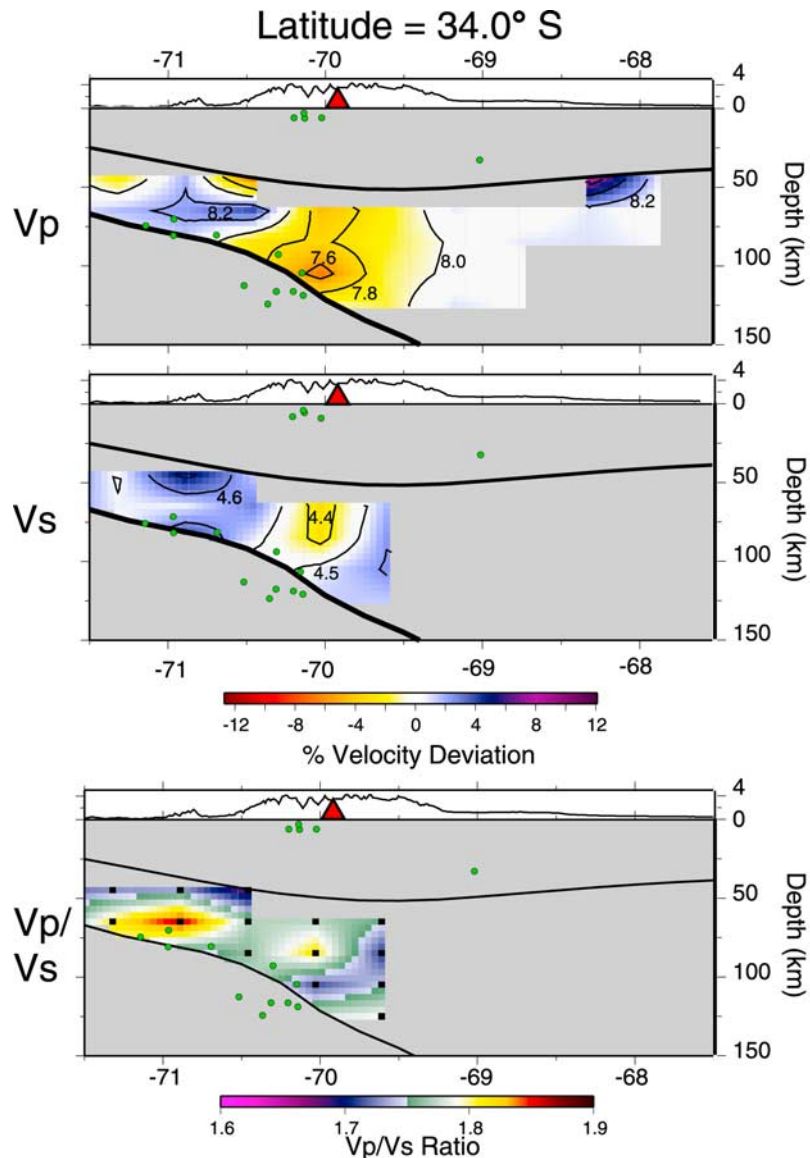


Figure 12. Results for V_p , V_s , and V_p/V_s at 34.0°S latitude. The red triangles indicate the locations of active volcanism. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

section 6.1 is unlikely to be due to melt. Although this feature looks spatially continuous with the low-velocity, high- V_p/V_s zone to the south, it exists only at shallow levels (65 km), and is located in an area believed to have unusually cool temperatures within the stability field of serpentine [Gutscher *et al.*, 2000; Kay *et al.*, 1988; Hacker *et al.*, 2003]. The northern anomaly is therefore unlikely to be melt, and is probably due to a 15–20% hydration of mantle peridotites (see Figure 17). Although this area is not forearc, the hydration processes may be similar to those responsible for the hydration of the Cascadia forearc [Bostock *et al.*, 2002; Brocher *et al.*, 2003]. The apparent continuity of the low-velocity, high- V_p/V_s zone from south to north may simply be a consequence of the fact that fluids released at depths of ~ 100 km are causing both anomalies, but the different ambient temperatures result in melt in one

case and hydration in the other. Alternatively, the northern anomaly may be due to leftover hydrated mantle from earlier normal geometry subduction.

7. Discussion

[33] While the tomography results to the south beneath the active arc are very similar to tomographic results from other subduction zone studies [e.g., Myers *et al.*, 1998; Graeber and Asch, 1999; Nakajima *et al.*, 2001; Zhao *et al.*, 1992; Zhang *et al.*, 2004], the results to the north are unusual and do not lend themselves to simple interpretation. Normally, the pervasive low V_p values found above the flat slab might have been interpreted as the presence of hydrous mineralogies or melt, as both are commonly found in subduction zones and both result in P wave velocity

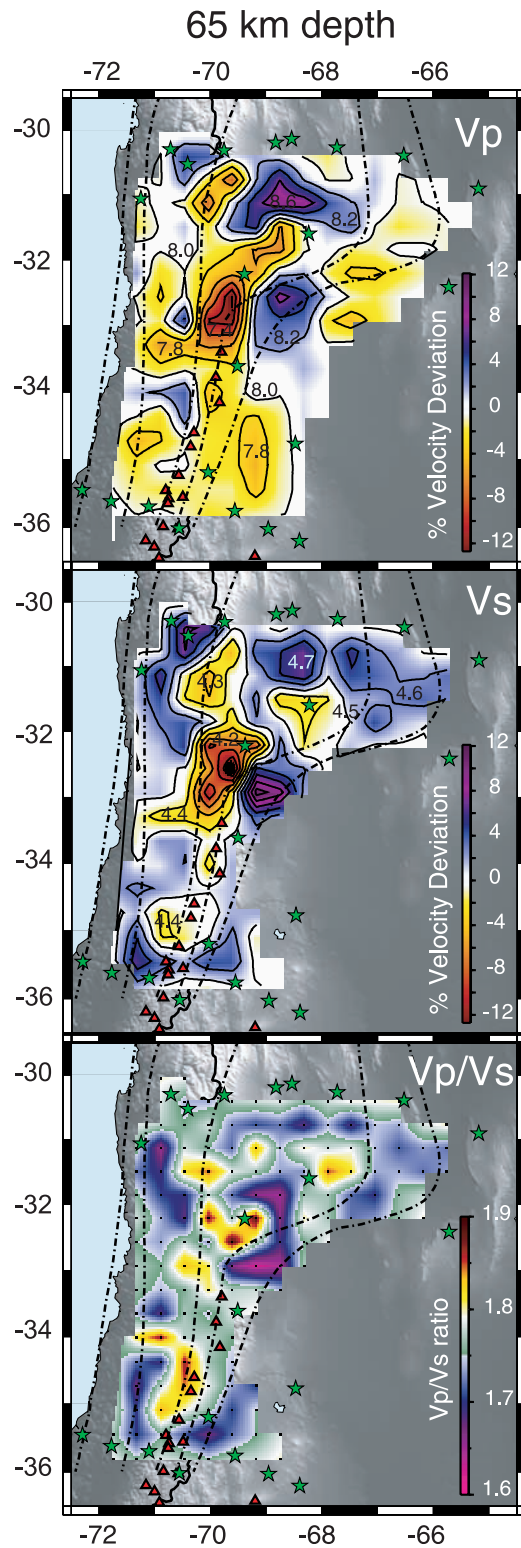


Figure 13. Map views of results for V_p , V_s , and V_p/V_s at 65 km depth. Slab contours are from *Cahill and Isacks [1992]*, green stars are CHARGE stations, and red triangles are active volcanoes. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

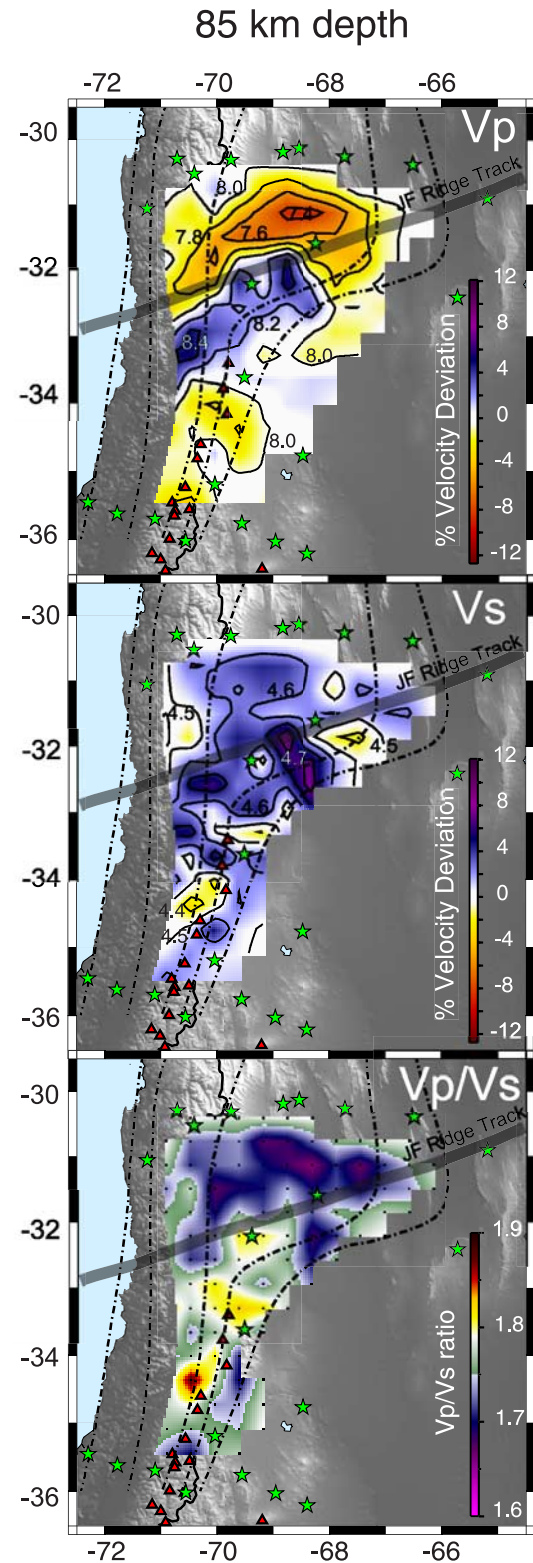


Figure 14. Map views of results for V_p , V_s , and V_p/V_s at 85 km depth. Shaded lines show the path of the Juan Fernandez Ridge. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

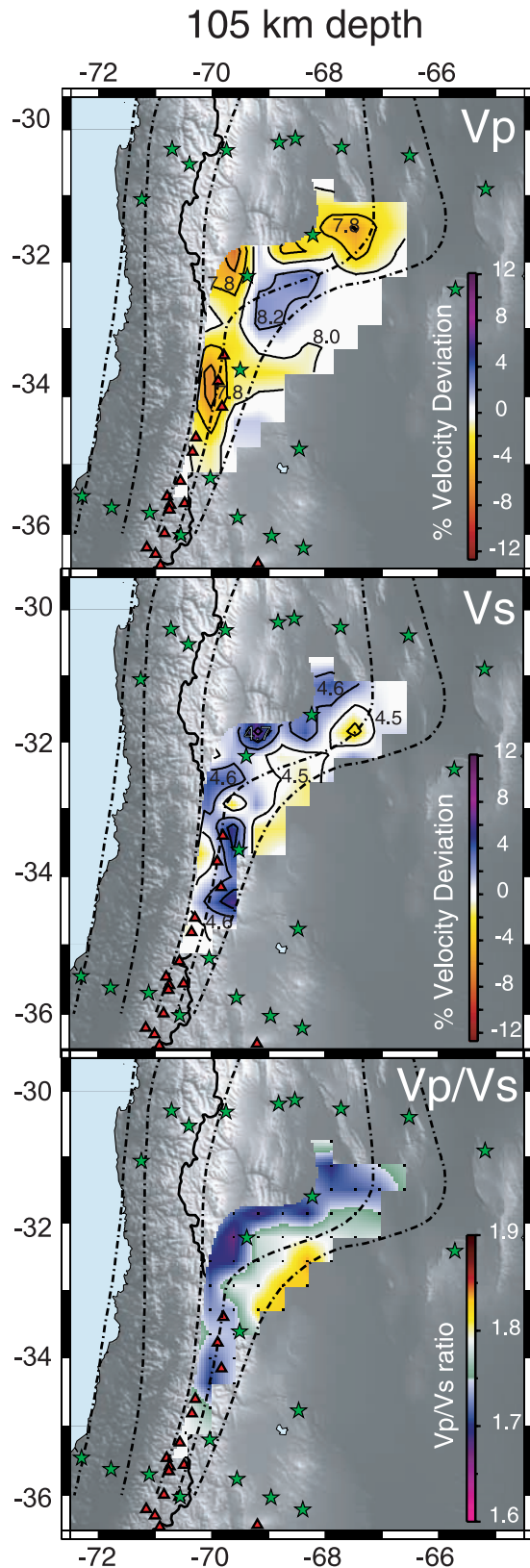


Figure 15. Map views of results for V_p , V_s , and V_p/V_s at 105 km depth. V_p and V_s colors are in percent velocity deviations. Numbers on the contours indicate absolute velocities in km/s. V_p contours are in 0.2 km/s increments. V_s contours are in 0.1 km/s increments. V_p/V_s ratio colors are absolute values. Black dots show the locations of grid nodes.

reductions [Hacker *et al.*, 2003; Carlson and Miller, 2003; Christensen, 1996; Hyndman and Peacock, 2003]. In fact, many previous tomography studies of subduction zones investigate only P wave velocity structure, and interpret their low- V_p findings as melt or hydrated mineralogies without the benefit of supporting V_s or V_p/V_s results [e.g., Husen *et al.*, 2003; Zhao *et al.*, 1995]. However, the equally pervasive high V_s values found in our study contradict this interpretation as both melt and hydrated mineralogies would serve to decrease V_s , not increase it. This combination of low V_p and high V_s is reflected in the unusually low V_p/V_s ratio which characterizes large volumes of material above the flat slab.

[34] While low V_p/V_s values in the crust are not uncommon [e.g., Nakajima *et al.*, 2001; Zhang *et al.*, 2004], low V_p/V_s values in the mantle are very rare. One exception is Zhang *et al.* [2004], who find evidence of low- V_p/V_s zones in the subducted Pacific plate beneath northern Japan at depths of over 150 km. They interpret these as regions of dehydrated serpentine, where the water released from the crystal structure collects as free water in pore spaces. The effect of free water in pore spaces is dependent on the geometry of the pores, but according to Sato and Ito [2002], spheroidal pore spaces produce decreased V_p/V_s ratios. This interpretation cannot be applied to our findings, as the presence of free water in spheroidal pore spaces has the effect of decreasing V_s , not increasing it.

[35] In order to determine which mineralogies might exhibit our observed seismic behavior, we investigate the seismic properties of common upper mantle end-member compositions using the method of Hacker *et al.* [2003]. Figure 17a shows the V_s and V_p/V_s properties for the Mg and Fe end-member compositions of the most common mantle mineralogies: olivine, orthopyroxene, and clinopyroxene. It is clear that in all cases, the Mg end-member is closer to our flat slab result than the Fe end-member. The best fit is to pure enstatite, the Mg end-member of orthopyroxene.

[36] We then investigated specific compositions which are likely to be found in a subduction zone environment (Figure 17b). A 95% enstatite, 5% ferrosilicate orthopyroxene composition comes fairly close to our observed high V_s , low V_p/V_s values. Orthopyroxenites have been found to constitute minor populations in mantle xenoliths [Smith *et al.*, 1999; Ertan and Leeman, 1996] and are generally interpreted as being samples of metasomatized mantle due to the interaction of silica-rich fluids with mantle peridotites. These fluids react with olivine to form orthopyroxenites at temperature conditions between 700°C and 1000°C [McInnes, 1996] which are above the stability field of serpentinite at these pressures [Hacker *et al.*, 2003] but are below the solidus. This provides information about the temperature above the slab at the time this metasomatization occurred but does not constrain any subsequent changes in temperature.

[37] It is possible that this metasomatization of olivine to orthopyroxene occurred on a massive scale above the flat slab. Fluids involved in this process can no longer be present in large quantity because this would result in a decrease in the S wave velocities [Sato and Ito, 2002; Hacker *et al.*, 2003]. This implies the transit time of the fluid through the lower portion of the overlying mantle must be short, and that this fluxing by silicious fluids was a

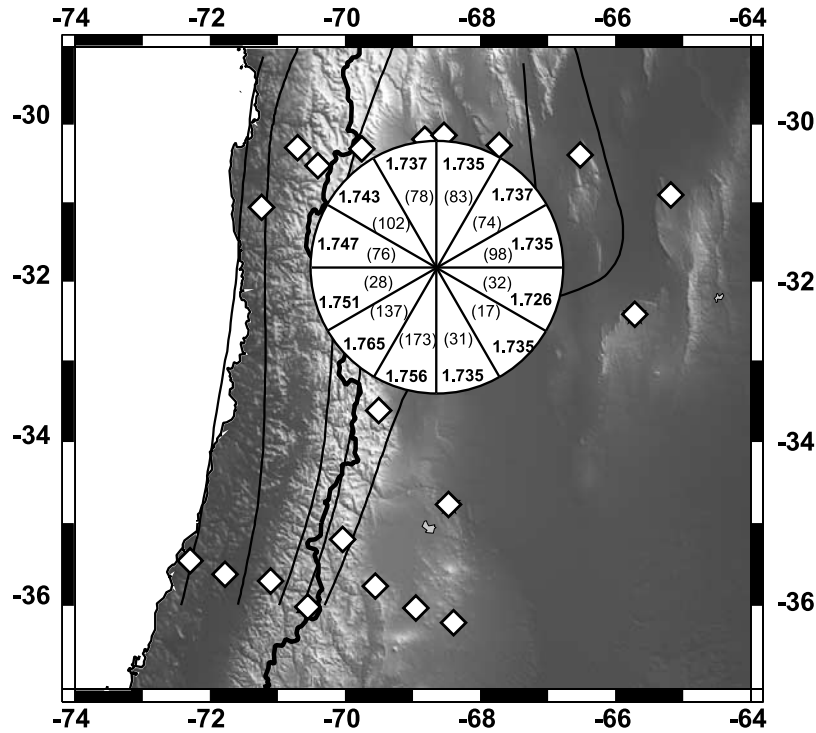


Figure 16. Average V_p/V_s values plotted as a function of back azimuth as determined by Wadati diagrams. The bold numbers indicate V_p/V_s values. The numbers in parentheses indicate the number of S wave picks used in determining these V_p/V_s ratios.

transient phenomena. Possible sources of the large quantity of required silica are subducted sediments and material eroded from an accretionary forearc. *Kay and Mpodozis* [2002] find rare earth element patterns in volcanic material erupted between 20 and 16 Ma above the flat slab, which indicate the subduction of large quantities of forearc continental crust during this time. In addition, the subduction of the corner of the Juan Fernandez Ridge beginning at 10 Ma [*Yanez et al.*, 2001] may have facilitated the transport of an unusually large quantity of sediments and forearc material across the entire width of the flat slab.

[38] We also note the spatial correlation between the southern edge of the low- V_p , high- V_s , low- V_p/V_s region and the track of the Juan Fernandez Ridge in the last 10 Myr, and the spatial correlation between the cessation of arc volcanism and the southern edge of the high- V_p , high- V_s , high- V_p/V_s region in the transition zone. We therefore postulate that changes in mantle structures as one moves from the south to the north through our study area are proxies for changes which occurred over time in the northernmost portions of our study area in the past 10–20 Myr. Initially, the mantle would have been characterized by hydration and melt above a normally dipping slab, resulting in low- V_p , low V_s , and high- V_p/V_s anomalies as we now see to the south. As the slab began to flatten, either between 19 and 16 Ma as suggested by *Kay and Mpodozis* [2002], or just in advance of the Juan Fernandez Ridge some 10 Myr ago [*Gutscher et al.*, 2000], the asthenospheric corner flow was pinched out, and the dehydration of the descending plate was reduced. This resulted in the cooling and eventual dehydration of the overlying mantle material, which would then be characterized by increased P and S wave seismic velocities as seen today

in the transition zone. At approximately 10 Ma, a bend in the Juan Fernandez Ridge was subducted, bringing with it large quantities of sediments and possibly accreted forearc materials. This spatially and temporally discrete sediment load passed under the pinched out cold mantle sliver above the flat slab, releasing large quantities of silicious fluids. Because of poor resolution at the northern edge of our study area, we cannot determine whether this metasomatism extends over the entire flat slab region, or whether it is a localized feature associated solely with the subduction of the Juan Fernandez Ridge.

8. Conclusion

[39] In the southern portion of our study area, we find expected results beneath the volcanic arc above the normally dipping slab of low V_p , low V_s , and high V_p/V_s , consistent with the presence of localized pockets of melt. In the northernmost portion of our study area, we find a large volume overlying the central Chilean flat slab segment characterized by low V_p , high V_s , and low V_p/V_s . In between, we find high V_p , high V_s , and high V_p/V_s values above the transition zone. We interpret these results as reflecting the changes undergone by the mantle above the flat slab in the past 20 Myr. The transition from low V_p , low V_s , high V_p/V_s , as seen below the active arc, to high V_p , high V_s , high V_p/V_s , as seen in the transition zone, reflects the cooling of the mantle wedge above a shallowing slab as would have occurred in this region between 20 and 10 Ma, depending on the exact timing of the flattening of the Nazca plate. The transition from high V_p , high V_s , high V_p/V_s as seen in the transition zone to low V_p , high V_s , low V_p/V_s , as seen north of the Juan Fernandez Ridge track above the

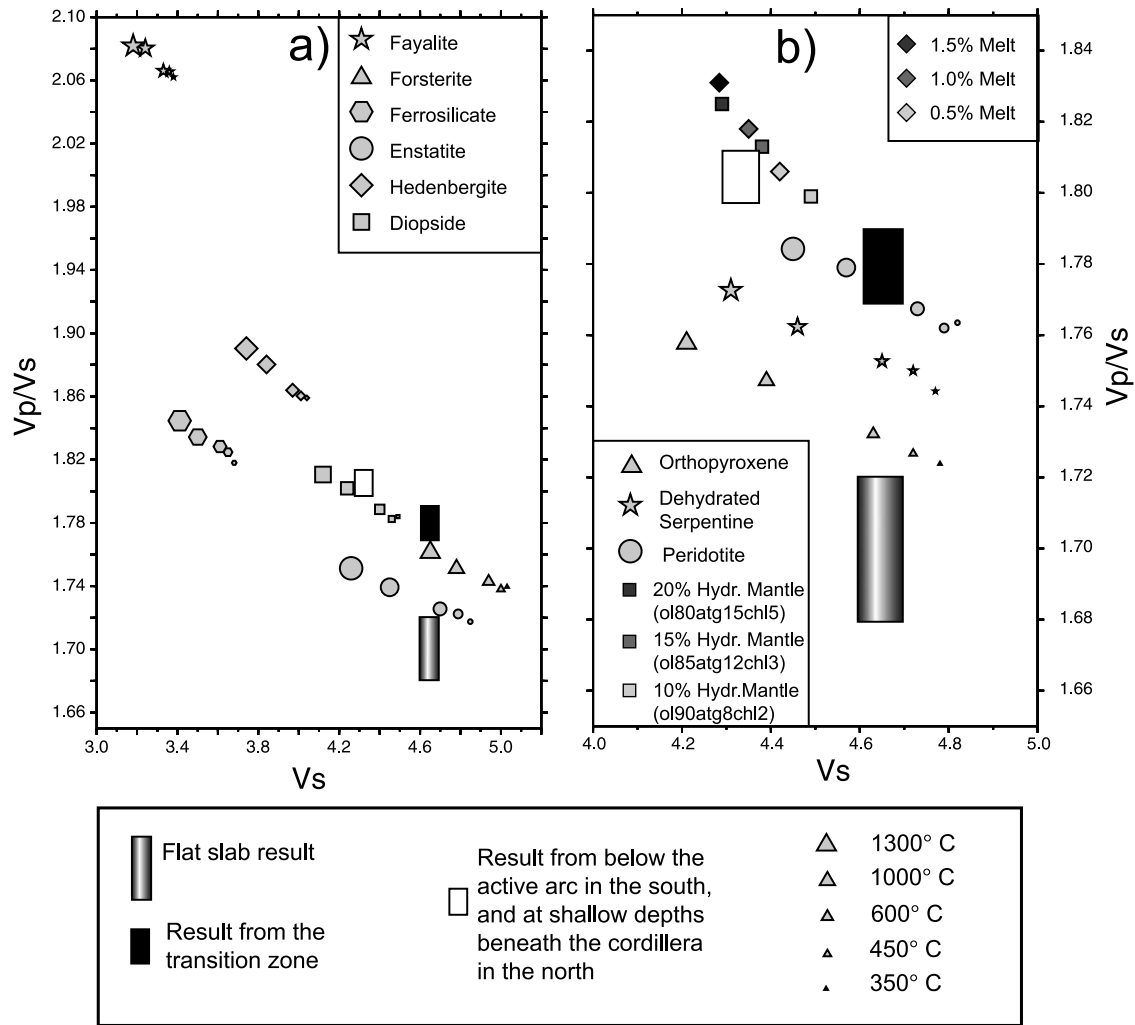


Figure 17. V_s versus V_p/V_s for a range of possible mantle mineralogies and percent melts. (a) Mg and Fe end-member compositions for olivine, orthopyroxene, and clinopyroxene. (b) Likely compositions and states for our observed anomalies. With the exception of the melts and the hydrated mineralogies, size indicates temperature, and shape indicates composition. The hydrated mineralogies shown are at 600°C. The orthopyroxene composition shown is (en95fs5). The dehydrated serpentine is (ol49opx51), and the peridotite is (ol90opx8gar2). Compositions for the hydrated mineralogies are shown in parentheses (en, enstatite; opx, orthopyroxene; gar, garnet; ol, olivine; atg, antigorite; chl, chlorite; fs, ferrosilicate). The velocity values for these compositions were determined at 3 GPa using the method of *Hacker et al.* [2003]. For the melts, velocities were calculated relative to IASPEI-91 velocities, assuming no change in temperature or pressure and assuming ellipsoidal melt geometries, according to the method of *Schmeling* [1985].

flat slab, reflects the metasomatization of these cold dry peridotites to orthopyroxenites as would have occurred here between 10 and 5 Ma. This metasomatization of the mantle would have significant effects on volcanism and tectonism should the slab resume a normal geometry, though these effects would probably be greater if the mantle were still fully hydrated [James and Sacks, 1999; Humphreys et al., 2003].

[40] The tendency of V_p/V_s ratios to decrease with decreasing temperatures may point to an especially cold lithosphere. The absence of water combined with a lack of present-day heat explains the lack of volcanism at the surface. The low V_p/V_s ratios indicate no significant quantities of serpentine are present above the flat slab to weaken

it. It is possible that a cold, unmelted, unserpentinized, high shear velocity mantle sliver could have high enough shear strength to transmit stress to the overlying crust, possibly explaining the spatial correlation between the basement cored uplifts of the Sierras Pampeanas and the presence of flat slab subduction.

Appendix A

[41] We tested the ability of two different tomography methods, one which inverts for V_p and V_s simultaneously, and the other which inverts for V_p and V_p/V_s , to recover V_p , V_s , and V_p/V_s for three different starting models. The first model had an initial anomaly only in P , resulting in an

anomaly in V_p/V_s , the second had an initial anomaly only in S , also resulting in a V_p/V_s anomaly, and the third had identical initial anomalies in both P and S resulting in no V_p/V_s anomaly.

[42] In the first case where we input only a P wave anomaly, both the P and V_p/V_s and the P and S inversions are able to recover the P wave model well, except for some vertical smearing in the easternmost regions (Figures 7 and 8). However, in the P and V_p/V_s inversion, some of the P wave anomaly apparently bleeds over to the S wave anomalies due to better resolution of V_p than V_p/V_s (Figure 7). In the P and S inversion, no anomaly is observed for V_s . V_p/V_s appears to be better recovered in the P and S inversion than in the P and V_p/V_s inversion, but this is not due to improved resolution but rather to the simplicity of our model. The P and V_p/V_s inversion shows the true extent of the resolvability of this V_p/V_s anomaly. The parts of this anomaly that are recovered in the P and S inversion that are not recovered in the P and V_p/V_s inversion do not reflect resolution of these areas but rather the bleed over of the P wave anomaly into the V_p/V_s anomaly. This is more clearly seen in the third case, to be discussed shortly.

[43] In the second case where we input only an S wave anomaly, both the P and V_p/V_s inversion and the P and S inversion recovered nearly identical results for V_p , V_s , and V_p/V_s . The P wave result shows no anomaly in either, and the V_s and V_p/V_s anomalies are equally well recovered. As with the P wave anomaly, the S wave anomaly is well recovered for the most part, except for some vertical smearing in the eastern portions above the flat slab. However, smearing is worse in this section for the S wave anomaly than for the P wave anomaly, indicating poorer coverage of S waves than P waves in the easternmost portions of the flat slab region.

[44] In the third case where we input both a P wave and an S wave anomaly, resulting in no V_p/V_s anomaly, we again find differences between the P and V_p/V_s and the P and S inversions. In the former, both P and S anomalies are recovered well, and very little V_p/V_s anomaly is observed. However, in the P and S inversion, the P wave anomaly is better recovered than the S wave anomaly, and there is a resulting V_p/V_s anomaly produced which is pronounced in the eastern flat slab region where the S wave anomaly is not well recovered. This is due to a bleed over of the P wave anomaly into the V_p/V_s anomaly. Just as the V_p/V_s ratio appears to be better recovered in the P and S inversion of the first test, the V_s anomaly appears to be better recovered in the P and V_p/V_s inversion in this case. Again, this is not due to improved resolution but rather to the same bleed over of the V_p anomaly to the V_s anomaly via the V_p/V_s ratio.

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