Anomalous Crust of the Bolivian Altiplano, Central Andes: Constraints from Broadband Regional Seismic Waveforms


Abstract. A one-year deployment of broadband seismographs in the Bolivian Altiplano recorded numerous intermediate-depth earthquakes at near-regional distances. We modeled the associated broadband waveforms of two earthquakes to estimate an average crustal structure for the Altiplano. The resulting model is characterized by an anomalously low mean P velocity of 6.0 km/s, a low Poisson's ratio of 0.25, and a crustal thickness of 65 km. The combination of the low mean velocity and low Poisson's ratio can be explained only by a predominantly quartz-rich, felsic bulk composition. This constraint precludes significant volumes of magmatic addition from the mantle contributing to the great thickness of the Altiplano crust, but is consistent with thickening by compressive shortening concentrated in a weak felsic layer.

Introduction

The rugged topography of the central Andes (Figure 1) and the development of the high plateaus—the Altiplano and Puna—are attributed to crustal thickening since the late Oligocene early Miocene, when both magmatism and compressional shortening have accelerated during a period of fast Nazca–South American plate convergence (Sacks, 1988). James (1971) measured surface wave dispersion to establish the great thickness (~70 km) of the Altiplano crust. A seismic refraction experiment along an east-west traverse at ~21°S found that the Andean crust thickens from ~40 km to ~70 km and declines in average velocity from 6.5 to 6.0 km/s from the coast to the western Cordillera (Wigger et al., 1994). However, this experiment could not establish the crustal thickness or deep crustal velocity of the Altiplano–Puna region because of severe attenuation of the surface explosions.

To further investigate the structure of the central Andean lithosphere, two lines of broadband seismic stations were deployed within and across the central Andes for 1 to 1-1/2 years during 1994–1995. The passive seismic experiments consisted of a 16-station, 1000-km-long, east-west transect called the BANJO (Broadband ANdean JOint) experiment and a 7-station, 350-km-long, north-south transect called the SEDA (Seismic Exploration of the Deep Altiplano) experiment (Beck et al., 1994, 1996). A combination of 11 SEDA and BANJO stations on the Altiplano between 17°S and 20.5°S provided, for the first time, excellent broadband seismic coverage of the central Altiplano region (Figure 1).

Near-Regional Shear-Coupled P Waves

Many of the larger local and regional data recorded by SEDA and BANJO stations are intermediate-depth earthquakes in the subducting Nazca plate. At near regional distances (<1000 km) these seismograms display a large-amplitude arrival following the P wave that appears to be an S wave at first glance but which we identified as a shear-coupled P wave by its particle motion and apparent velocity. These waves are clearly visible in the seismograms (Figure 2) for the June 27, 1994 (Julian day 178, hereafter event 178) earthquake near the Bolivia–Chile border. A large-amplitude phase with P wave (in-phase) particle motion is observed about 30 s after the direct P wave (Figure 2A). An examination of a distance profile of the data revealed that these large arrivals have P wave apparent velocities. Filtering shows this wave group is characterized at long periods by a prograde (vertical motion leading

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Figure 1. Topography of the central Andes represented by thin, solid elevation contours (in kilometers). Shaded area highlights the Altiplano, the plateau bounded by higher mountain ranges and approximately enclosed by the 4-km contour. The straight, thick, solid lines represent the raypaths between two intermediate-depth earthquakes and seismic stations of the SEDA and BANJO experiments.
investigated the sensitivity of the waveforms to a simple layer-over-halfspace model with perturbations to crustal thickness, mean crustal $V_p$, mean crustal $V_p/V_s$ (related to Poisson’s ratio $\sigma$), $Pn$ velocity, and upper mantle gradients. Waveforms at distances of up to -2 focal depths are relatively insensitive to structural parameters, which makes these waveforms ideal for source studies. Beyond ranges of 2-3 focal depths, both the $PSV$ and $SH$ waveforms are sensitive to structure. The $sPn$ waveform is most sensitive to the mean crustal $P$ velocity, while the timing of $P$ with respect to $SH$ and $sPn$ with respect to Rayleigh waves is most sensitive to mean crustal $V_p/V_s$. The timing of both $sPn$ and Rayleigh waves is also sensitive to crustal thickness, although to a lesser degree than to crustal velocity. With a distance profile of data, we can resolve the velocity-thickness tradeoff. For the distance range investigated we found only subtle variations in the timing and amplitudes of $sPn$ for upper mantle velocity variations of ±0.2 km/s and mantle velocity gradients between zero and 0.0006 s⁻¹.

Modeling Altiplano Near-Regional Waveforms

A well-constrained location and focal mechanism are crucial for an unbiased use of these regional waveforms for structure studies. Using $S$–$P$ differential traveltimes, we first eliminated the origin time and located the epicenter. For event 178, the epicenter located by this procedure (20.93°S, 68.87°W) is ~17 km west of the NEIC relocated epicenter (R. Engdahl, personal communication, 1995). We next used the waveforms (filtered from 50 to 15 s) to estimate the moment tensor and depth using the full waveform inversion technique of Randall et al. [1995]. The long-period waveforms are relatively insensitive to the crustal structure, especially at close ranges, but the $sPn$ waveform is sensitive to the focal depth and mechanism. The resultant focal mechanism (strike = 341.5°, dip = 46.6°, rake = -63.4°) is within 10° in strike, 1° in dip, and 13° in rake of the Harvard CMT solution. A depth search yielded a focal depth of 100 ± 5 km. A second event on December 12, 1994 (Julian day 346) was located near the northern end of the SEDA line (17.27°S, 69.65°W) and was inverted for source parameters and depth (strike = 206.4°, dip = 32.7°, rake = -60.2°, depth = 145 km).

With the source fixed, we forward modeled event 178 for the best fitting layer-over-halfspace model. Comparison of the broadband data fits for event 178 with the best layer-over-halfspace synthetics revealed important differences that required additional features in the velocity model. Following Saikia and Burdick [1991], we introduced complexities in the model near the crust–mantle boundary and near the free surface. The addition of a velocity gradient of 0.8 km/s over an 8-km-thick transition zone at the base of the crust and 10-km-thick surface low-velocity layer greatly improved the waveform fits. The final model and the fit between the data and synthetics (0.02 to 0.5 Hz) are illustrated in Figure 3. All three components were used in the forward modeling, although only the vertical component is shown in Figure 3. The average $P$ velocity of the model is 6.0 km/s with a $\sigma$ of 0.25 and a crustal thickness of 65 km. The crust consists of a 10-km-thick, 5-km/s layer that probably represents the sediments and metasediments of the Altiplano basins. Below is a 47-km-thick, 6.2-km/s layer that represents the bulk of the Altiplano crust. An 8-km-thick transition zone ramps the velocity up to 7.0 km/s, and the upper mantle beneath the Moho discontinuity has a velocity of 8.1 km/s ($Pn$ velocity is not well constrained).
Although the model was determined strictly by forward modeling of event 178, comparison of the synthetic seismograms of the corresponding source and distances with the recordings of event 346 shows a good overall match (Figure 3). Event 346, in effect, "reverses" the record section profile of event 178 and corroborates that the model is a reliable average for regional wave propagation within the Bolivian Altiplano.

We investigated the uniqueness of the final velocity model by perturbing the parameters until a majority of the broadband data were clearly misfit. We estimate conservative bounds on the mean crustal Vp of 5.9-6.1 km/s, on the crustal thickness of 60 to 70 km, and on the average σ of ±0.02. These stated bounds may represent actual variations within the Altiplano sampled by the different source-to-station paths (Figure 1).

Altiplano Crust: Thick, Felsic, and Weak

The thick crust, low mean crustal Vp, and the low σ confirm previous estimates of these parameters for the central Andes based on different data and analysis techniques [e.g., James, 1971; Wigger et al., 1994; Zandt et al., 1994; Schuessler, 1994]. Our data represent the best "pure" sampling of the central Altiplano (Figure 1) and constrain the P and S velocities and the thickness with common coverage. The simplicity of the average model should not be misinterpreted as indicating that the Altiplano has a simple, relatively homogeneous crust.

In fact, receiver functions reveal a complex, vertically heterogeneous crust [Beck et al., 1996]. Our data constrain the average characteristics of the crust but indirectly indicate the presence of significant lateral heterogeneity that prevents development of coherent phases from the strong intracrustal discontinuities suggested by receiver functions.

The average seismic properties of the Altiplano crust are highly anomalous compared to average continental crust. The low mean crustal Vp of 6.0 km/s and the average crustal thickness of 65 km are both in the tails of the global distribution of these parameters, with means of 6.45 km/s and 39 km, respectively [Christensen and Mooney, 1995]. Although the global distribution of Poisson’s ratio is not as well established, the Altiplano average of 0.25 is less than the global average of 0.27 estimated by Zandt and Ammon [1995]. Both the low mean Vp and relatively low σ strongly indicate a predominantly quartz-rich, felsic (granitic) bulk composition. The nearly constant velocity of 6.2 km/s of the bulk of the Altiplano crust is consistent with an entirely felsic composition with a high geotherm [Rudnick and Fountain, 1995] (Figure 3). Even with a high geotherm, which would tend to decrease the in situ seismic velocity of any rock type, a mafic composition crust would reach a minimum velocity of only 6.9 km/s at a depth of 60 km [Rudnick and Fountain, 1995] (Figure 3). We can rule out lower crustal velocities greater than 6.6 km/s, so we can eliminate the possibility of any significant
abundance of mafic materials in the Altiplano crust. Only three general rock types exhibit low Vp and σ at high confining pressures: quartzite, granite, and felsic amphibolite-facies gneiss [Holbrook et al., 1992]. However, we emphasize that our results constrain only depth-averaged bulk compositions and not specific lithologies.

A potentially important effect in quartz-rich rocks is the high-low quartz transition that can generate a pronounced decrease in Vp when temperatures approach the quartz transition temperature [Kern, 1979]. This effect has been advanced to explain unusually low σ measurements on the Tibetan plateau [Min and Wa, 1987] and in the southern Altiplano [Zandt et al., 1994]. A major uncertainty about the significance of the quartz transition is its dependence on high confining pressures, which may greatly reduce the velocity effect [Kern, 1979]. Even if it is shown to be significant at high confining pressures, it would only give further support to the preponderance of quartz-rich crust under the Altiplano.

A predominantly quartz-rich, felsic Altiplano crust has important implications for lithospheric rheology. The high heat flow (~80 mW/m²) observed on the Altiplano [Henry and Pollack, 1988] probably indicates a high geothermal gradient. The high abundance of heat-producing minerals in felsic rocks and convective fluids may partially account for the high heat flow, with a geotherm low enough to prevent complete melting [Giese, 1994]. Still, the crust is probably very weak and near its solidus through much of the lower crust. The thick, weak crust also tends to significantly lower the strength of the entire lithosphere [Kuszmir and Park, 1986]. This conclusion is consistent with the Airy-type isostatic behavior of the central Andes, as established by Beck et al. [1996]. Finally, the predominantly felsic crust eliminates magmatic addition from the mantle as a major component of the thickening of the Altiplano crust, but is consistent with an approximate doubling of an original ~23 km thick felsic layered driven primarily by crustal shortening [Isacks, 1988].

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References


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