Chapter 4

The Altiplano Plateau

4.1. The Central Andes at 21°S and the Altiplano plateau

4.1.1. Geotectonic setting of the Altiplano

As mentioned in the Introduction, the Andes mountain belt represent an area that has been formed as a result of convergence and subduction of an oceanic plate (Nazca Plate) under a continental plate (South American Plate). The Central Andes (between ~14°S and ~24°S) are located where the subduction of the Nazca Plate occurs at angles near 20-30°, at a rate of 65mm/yr (e.g. Cahill and Isacks, 1992, Angermann et al., 1999) and are the widest segment of the mountain range (Figure 1.1).

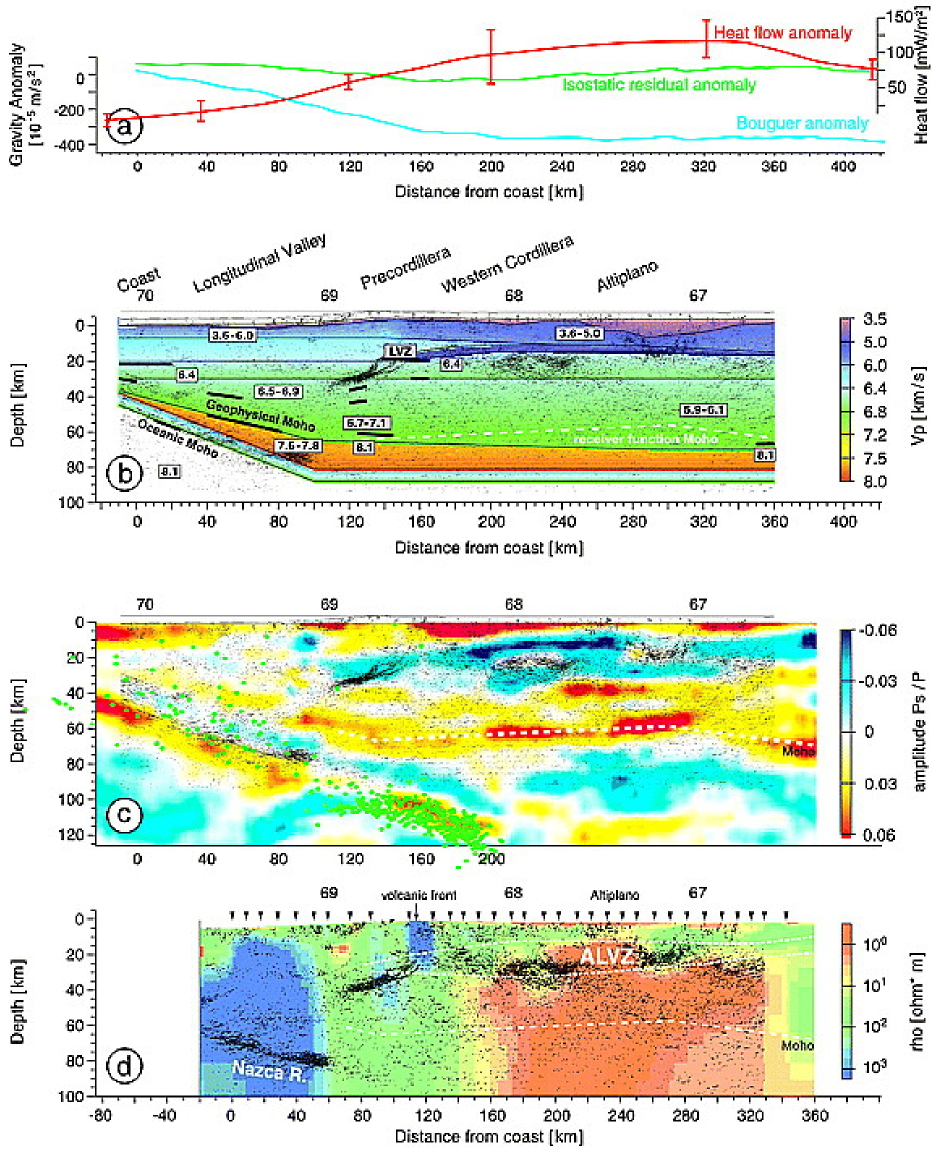
The variable thickness of the crust and the different dipping angles of the subducting plate along strike have created an elevated plateau in the central segment of the Andean orogeny with geological, morphological and magmatic characteristics that enable a differentiation of the plateau between the Altiplano in the north (Bolivia and Peru) and the Puna in the south (north-western Argentina) (e.g. Allmendinger et al., 1997).

With an average elevation of ~4 km and a width of ~400 km, the Andean plateau is limited to the west by an active volcanic arc (Western Cordillera) and to the east by an active westward verging thin-skinned foreland thrust belt (Eastern Cordillera) (e.g. Whitman et al, 1996). To the east, the topography descends by steps at the Interandean Zone, the currently active Subandean fold-thrust Belt and the Chaco Plain that progressively overlaps with the Precambrian Brazilian shield (also called Guaporé Shield) (Figure 3.1B).

4.1.2. Geophysical investigations in the Central Andes

A series of projects have integrated geophysical methods and geological observations to investigate subduction related features. Steep-angle and wide-angle reflection surveys (Wigger et al., 1994; Ancorp Working Group, 1999 and 2003; Haberland and Rietbrock, 2001; Lueth, 2000) and PISCO 94 (Schmitz et al., 1999; Graeber and Asch, 1999), CINCA 95 (Husen et al., 1999; Patzig, 2000), ANCORP 96 (Haberland and Rietbrock, 2001; Ancorp Working Group, 2003), PUNA97 (Schurr et al., 1999 and 2003; Schurr, 2000; Schurr and Rietbrock, 2004) passive seismological networks were operated to obtain receiver function and local tomography images.

The ANCORP project integrated steep angle reflection and refraction at 21°S with a network of passive seismic stations to image the subduction zone and related volcanism, crustal thickness and other subduction related structures. The first results presented by the Ancorp Working Group (1999) imaged the subduction and extension of the Benioff zone (Nazca reflector down to 100 km depth) and detected the presence of another reflector at a depth of 20 to 30 km (~68.5°W) that was given the name of Quebrada Blanca Bright Spot reflector anomaly (QBBS, also in Ancorp Working Group, 2003). The origin and composition of the QBBS in not clear but it has been suggested to be caused by the presence of fluids (results of ANCORP are summarized in Figure 4.1). Although magneto-telluric soundings have not detected the QBBS anomaly, an important conductivity anomaly (Altiplano Conductivity Anomaly) below the Altiplano has been detected while the presence of free fluids is proposed due to high electrical conductivity values (up to 1 S/m) (Brasse et al., 2002; Haberland et al., 2003). At the same time this high reflective anomaly (QBBS) has not been observed in gravity data (Götze and Kirchner, 1997). To the east, a reflector was also detected coinciding with the approximately position of the Altiplano Low-Velocity Zone (e.g. Wigger et al 1994; Yuan et al., 2000).



ANCORP Working Group, 2003

Figure 4.1: The main results for the central Andes transect at 21° S as presented by the ANCORP Working Group (2003) a): gravity data - Bouguer anomaly ~ -400 mGal. and heat flow data (from Goetze and Kirchner, 1997 and others); b): wide angle results from ANCORP data; c): receiver function results from Yuan et al., 2000; d) electrical resistivity model (Brasse et al., 2002). Note the position of the ALVZ in figures c) and d). The ANCORP line extended from the coast in Chile at ~70.3°W to 66.5°W in Bolivia. Our Refuca profile extended the ANCORP line ~200 km to the east.

At a depth of 80 km, a reflector above the oceanic slab has been interpreted as the serpentinization front that delivers rising fluids (Ancorp Working Group, 1999; Schilling et al., 1997 and 2000). Beneath the Altiplano-Puna region, a crustal low-velocity layer has been detected by receiver functions and magneto-telluric studies and is explained as being related to the presence of partially melted material (Wigger et al., 1994; Yuan et al., 2000; Brasse et al., 2002; Chmielowski et al., 1999; Zandt et al., 2003).

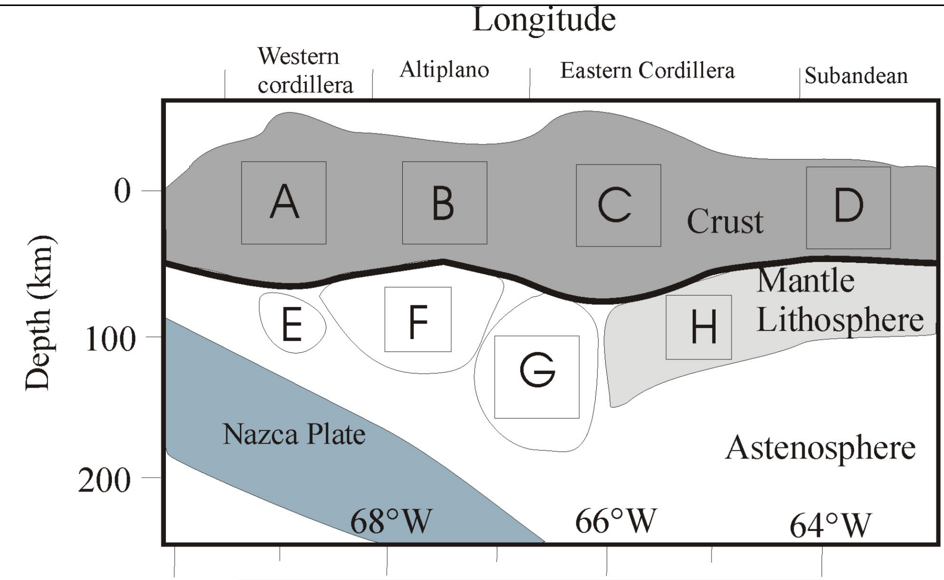
Related to the subduction zone, teleseismic receiver function analysis imaged the oceanic Moho down to a depth of 120 km (Yuan et al., 2000) which coincides with a reduction in seismicity in the slab. Short-period conversions from local earthquakes extend these observations to depths of 160 km (Bock et al., 2000). Guided wave studies (Martin et al., 2003) trace a thin wave guide channel above the subducted slab down to a depth of at least 160 km.

Other projects carried out in the region provided important results about the lithospheric structure and crustal-thickness variations. The Broadband Andean Joint (BANJO) and Seismic Exploration of the Deep Andes (SEDA) experiments operated broadband seismometers to record local and teleseismic earthquakes. BANJO was a west-east oriented array of 16 stations from Chile to Bolivia between 19° and 20°S. The SEDA array was oriented mainly north-south through the transition region between Altiplano and the Eastern Cordillera from 17° to 20°S. The results obtained provided information about travel-times and attenuation of P- and S- waves for regional mantle earthquakes and greatly improved the knowledge of the Central Andean crust and mantle lithosphere (Beck et al., 1996; Myers et al., 1998; Dorbath and Mason, 2000; Beck and Zandt, 2002).

A map of the Altiplano lithosphere obtained from attenuation tomography inferred from regional mantle earthquakes shows variations in the thickness of mantle lithosphere interpreted as a reaction to lithospheric thinning and shortening (Figure 4.2), (Myers et al., 1998).

Other authors (e.g. Beck and Zandt 2002) combined teleseismic and deep regional events for receiver function analysis and suggested that the thick crust supporting the high elevations should be of felsic to intermediate composition. They support the results of Wigger et al. (1994) and also suggest that the Brazilian lithosphere is underthrusting part of the western side of the

Eastern Cordillera. According to their results, basal parts of the lithosphere could be delaminating at the Altiplano-Eastern Cordillera boundary area.



	A	B	C	D
Vp	~6.5	~6.2	~6.2	~6.4
Vs	~3.6	~3.6	~3.5	~3.6
Qp	~500	~500	~200	~1500
Qs	~300	~100	~80	~900
	E	**F**	**G**	**H**
Vp	~7.8	~8.3	~7.8	~8.1
Vs	~4.3	~4.6	~4.45	~4.6
Qp	~200	~500	~300	~1200
Qs	~100	~200	~100	~900

Vp and Vs in km/s

Figure 4.2: A map of the Altiplano lithosphere inferred from a tomographic inversion and evaluated seismic attenuation based on data recorded by the BANJO and SEDA arrays. Note the low Vp and Vs and low Qp-Qs for G at 100 km depth (Modified from Myers et al., 1998).

Data integrating some of the before mentioned temporary broadband networks (BANJO, SEDA, PISCO) recorded teleseismic and local waves, providing information from above and below the subducted slab. Shear wave splitting analysis shows fast polarization velocities from north to south (trench parallel). A change of anisotropy to fast velocities from west to east at ~65°W (Polet, 2000) has been related to the old and cold Brazilian lithosphere.

Results from global teleseismic inversions have provided a clear image of the subduction zone for the Altiplano plateau area along ~21°S (Figure 4.3) and show low-velocities in the area of the continental crust and relatively high velocities for the subducted slab (Bijwaard et al., 1998). However, global tomographic images lack the resolution necessary to investigate the upper portions of the asthenosphere-lithosphere region.

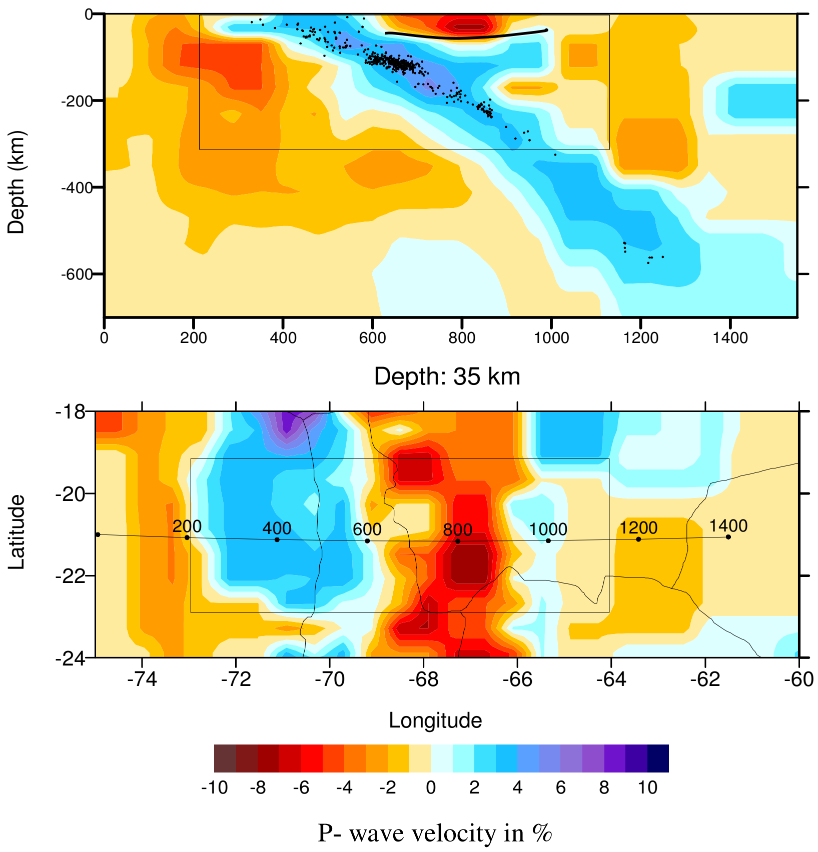


Figure 4.3: Results of the global tomography inversion after Bijwaard et al. (1998) for a vertical (top) and horizontal section (bottom). Positions of our vertical and horizontal sections shown in figures 2.1 and 3.1 are highlighted by rectangles and the line in the vertical section is the Moho topography. Colour scale is the same as in previous figures (see also Fig. 3.3 to 3.6).

4.1.3. Crustal thickness beneath Altiplano

The crustal structure of the Central Andes has usually been presented as one of the main aspects to consider when attempting to understand the evolution of the plateau. Hence, the crustal thickness has become a major subject of discussion over the last few decades (e.g. Isacks, 1988; Jordan et al, 1983; Allmendinger et al., 1997).

Among the first studies that estimated the crustal thickness of the Western Cordillera were those using surface waves (e.g. James, 1971). Later, wide angle active experiments provided results for the entire continental crust from the Pacific coast to the Chaco plain (e.g. Wigger et al., 1994; Schmitz et al., 1999).

Making use of regional gravity studies, Goetze et al. (1994) estimated the crustal depth for the entire plateau between 20°S and 26°S to be less than 70 km, while other authors obtained crustal thicknesses of ~70-75 km under the Altiplano (Wigger et al., 1994; Zandt et al., 1996; Beck et al., 1996; Scheuber and Giese, 1999; Schmitz et al., 1999; Yuan et al., 2000).

Yuan et al. (2002) produced a detailed map of the crustal thickness of the Central Andes based on receiver function analysis and showed that the depth to the Moho varies from 25-30 km at the coast, to 70-75 km beneath the volcanic arc and the Altiplano, while thining to about 30 km beneath the Subandean and Chaco plain. In comparison, the southern part of the Puna plateau has a Moho that is, on average, 10-15 km shallower and has a topographic elevation at least 500 m higher than the Altiplano. Other processes such as magmatic addition, tectonic underplating or upper mantle hydration may contribute to the thickening of the crust (Allmendinger et al., 1997).

4.1.4. Crustal shortening

Crustal shortening has been usually proposed to explain much of the thickness of the continental crust in the Central Andes (Zandt et al, 1994; Beck et al., 1996). About 250 km of crustal shortening which occurred mainly in the Eastern Cordillera (EC) and Subandean region is likely to be responsible for the thickened crust beneath the Altiplano (Baby et al., 1992; Schmitz, 1994; Allmendinger et al., 1997; Kley and Monaldi, 1998).

Watts et al. (1995) analyzed the elastic thickness of the lithosphere in the Central Andes and proposed a model for explaining the large amount of shortening in the bend region at ~20°S. They suggest that where the lithosphere is flexurally strong (i.e. with a large elastic thickness) foreland deformation is concentrated on the Subandean thin skinned and fold and thrust belt that has absorbed more than 100 km of shortening. North and south of this “symmetry axis” (bend region) the flexurally weaker lithosphere has a more complex deformation that involves the basement and hence, has absorbed less shortening.

On the eastern border of the Altiplano, Wigger et al. (1994) identified west-dipping structures in the crust, also confirmed by other workers (Allmendinger et al., 1997; Watts et al., 1995; Lamb et al., 1997; Yuan et al., 2000) that are possibly related to the underthrusting of the Brazilian shield beneath the Subandean and Eastern Cordillera provinces (Figure 4.4).

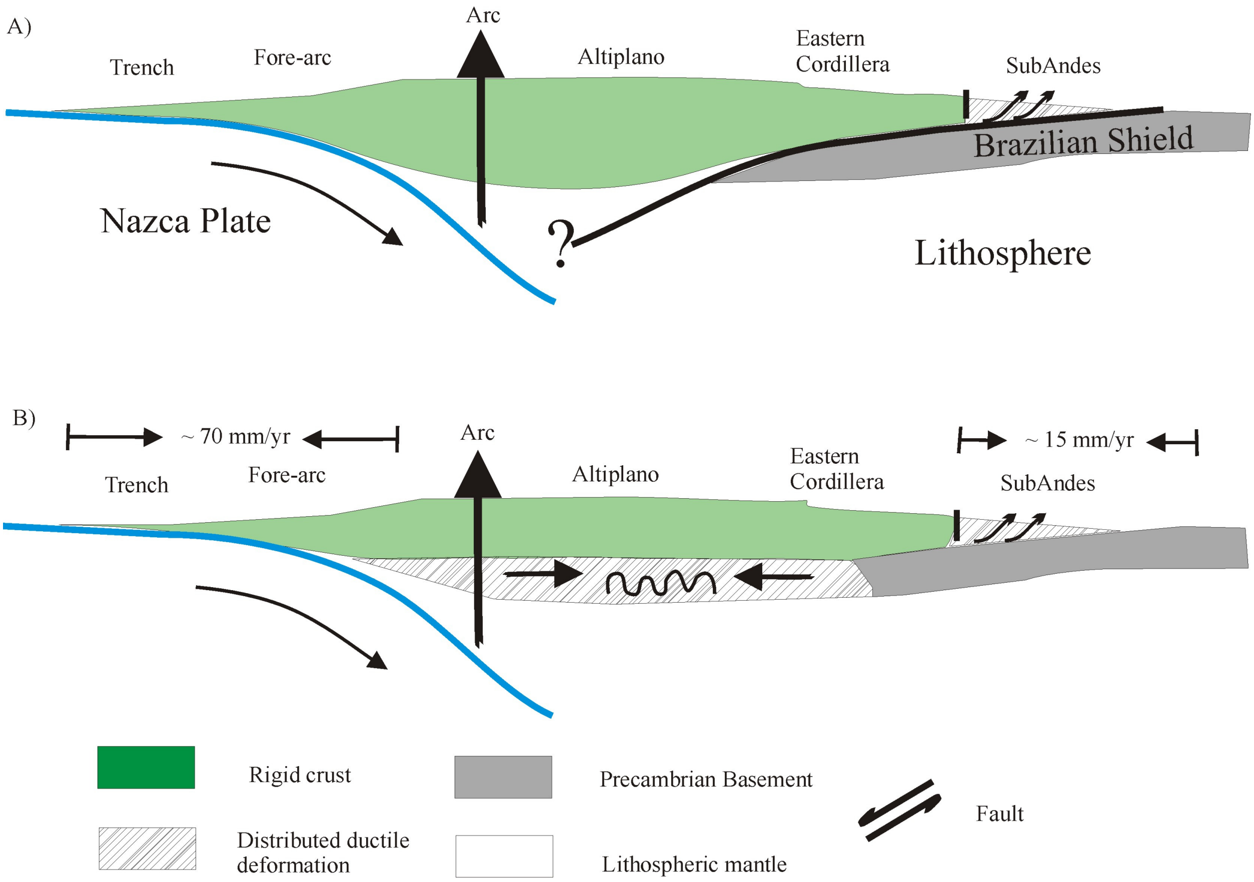


Figure 4.4: Two models for deformation at the border of Altiplano and Eastern Cordillera. The first model (top) suggests that thin-skinned deformation in the Subandean is responsible for a detachment zone that affects the entire upper crust. The second model (bottom) shows that the thermally affected lower crust is responsible for a ductile zone of deformation; in this case the Altiplano behaves like a rigid lid (after Lamb and Hoke 1997).

Identification of the fault systems or thrusts that penetrate the entire crust is still needed to image the distribution of crustal shortening along the eastern part of the Andes. Until now, there were no geophysical data available that could help us image this area over crustal scales. Geological and structural models based on kinematic studies suggest that the main thrusts could penetrate as far as the western part of the Eastern Cordillera (Kley and Monaldi, 2002).

4.1.5. Fluids and thermal structure of the plateau.

The presence of fluids and melts is assumed beneath the active volcanic front and the Altiplano-Puna plateau. Their possible pathways in the lithosphere have been traced by different authors (e.g. Ancorp Working Group, 1999; Schurr et al., 2003). Model calculations based on heat-flow density are the only type of investigation that can provide a realistic image of the Central Andes thermal state. Some authors have presented models based on surface heat-flow density data at lithospheric scales that show little thermal variation along strike and larger variations across the orogen. Local heat sources in the volcanic arc and the background heat-flow effect of the subduction process are both explained by the presence of asthenospheric mantle at shallow depths. These temperature variations would be responsible for geophysical anomalies beneath the volcanoes (local magma chambers - on a local scale) and beneath the Altiplano region on a large scale (Springer and Förster, 1998; Springer, 1999).

4.2. Results and Observations

Tomographic images for both P- and S- waves are shown in vertical and horizontal sections in the Appendix at the end of this work. The morphological units and their geodynamic relevant locations are displayed on a schematic cartoon along with the interpreted anomalies at depth, where the present results are discussed (Figure 6.1, chapter 6). As explained in chapter 3, the limitations imposed by the resolution of horizontal structures along a profile of stations do not provide adequate constraints to determine the extension of the anomalies on plan view. We will concentrate therefore mainly on the following vertical anomalies due to their position and importance (Figure. 4.5). They are described from west to east as follows.

1- The region west of the Precordillera is characterized by the presence of a pronounced high velocity anomaly seen by both P- and S- waves, to a depth of 60 km, representing the Chilean Coastal Cordillera and is part of the Longitudinal Valley. This anomaly could be related to the presence of the Jurassic arc which developed on Precambrian-Paleozoic crust (Troeng et al., 1994; Lamb and Hoke, 1997).

2- The limit between high-velocity anomalies to the west and low-velocities towards the east, at approximately 69°W, corresponds with the location of the West Fissure (WF) on the surface, representing the western limit of the Precordillera. The change in relative velocities west and east of the West Fissure indicates variations in the composition and state of the rocks along this fault. To the east of the West Fissure the presence of an anomalous reflective body has been described at a depth of 15 and 25 km and interpreted as the Quebrada Blanca Bright Spot (e.g. QBBS in Ancorp Working Group, 1999). We also interpret the position of this low-velocity anomaly as the QBBS at approximately ~68°W probably indicating the presence of fluids or magmatic bodies related to the volcanic front (Central Volcanic Zone, CVZ). Underneath the receiver function Moho (Yuan et al., 2000) we detected what we interpret to be magmatic additions at the base of the continental crust. These additions should play, in combination with other geological and geotectonic processes, an important role in crustal growth. Although the Moho topography supports this idea, it has long been estimated that magmatic addition from arc production represents ~1 % of the crustal thickness (Trumbull, pers. comm.)

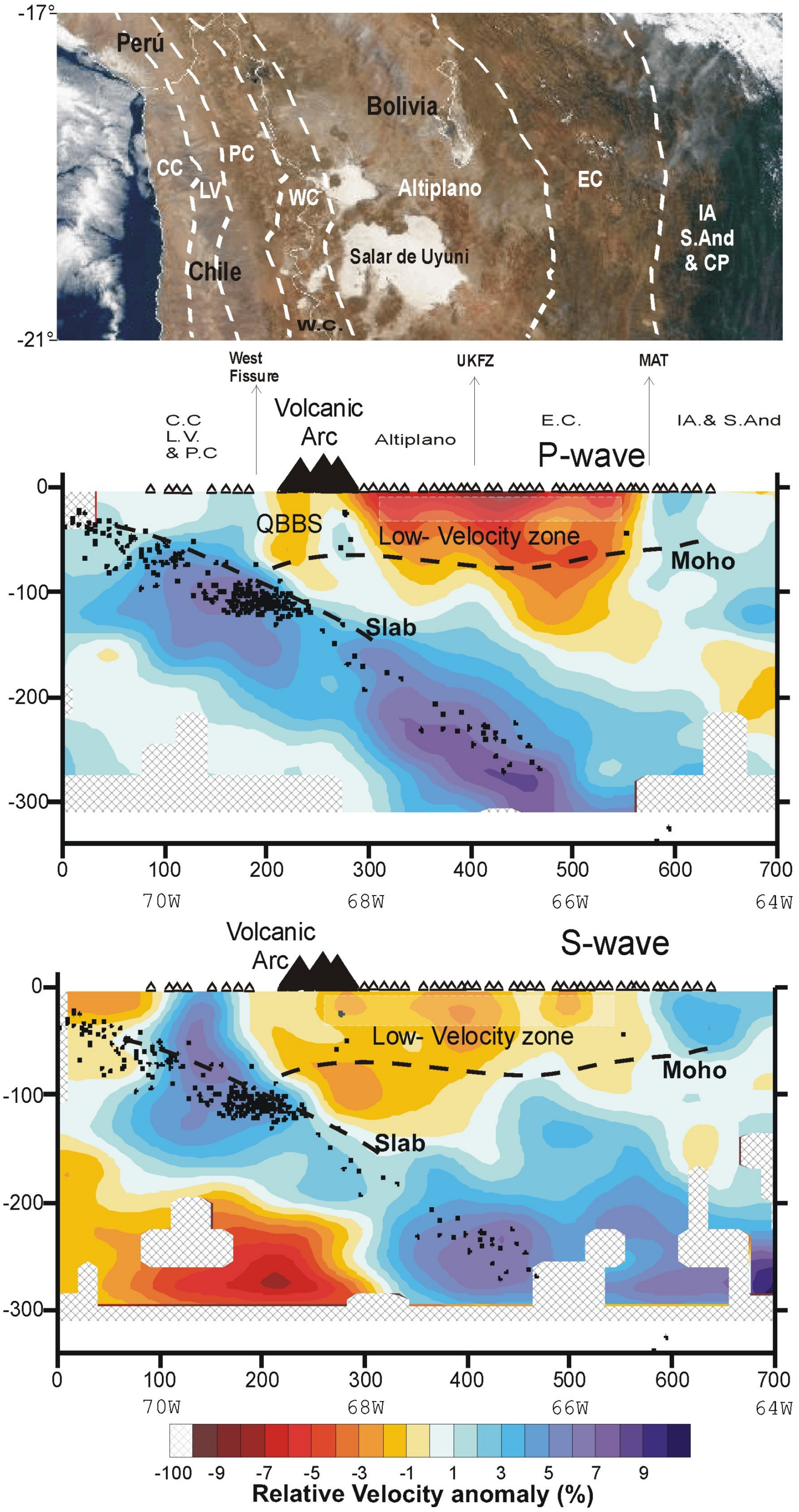


Figure 4.5: (Top) Satellite image showing morphological units along 21°S, C.C.: Coastal Cordillera; L.V.: Longitudinal Valley; PC: Precordillera; WC: Western Cordillera; EC: Eastern Cordillera; IA: Interandean; SAnd: Subandean; CP: Chaco Plain. Centre and bottom: P- and S-wave results; receiver function Moho (present data, see chapter 6); QBBS: Quebrada Blanca Bright Spot; UKFZ: Uyuni-Kenayani Fault Zone; MAT: Main Andean Trust. Low Velocity Zone is the same ALVZ Altiplano Low Velocity Zone mentioned before.

3- The Altiplano plateau is characterized by a prominent low-velocity anomaly in the east, for both P- and S-waves. The shape and position of the Altiplano anomaly seems to be strongly controlled by the presence of the Uyuni-Kenayani Fault Zone (UKFZ) at ~67°W. The presence of a low-velocity layer or Altiplano Low-Velocity Zone (ALVZ) has already been described under the Altiplano and adjacent areas (Wigger et al., 1994; Yuan et al., 2000) and is also present in our data, having a west-east extent from ~67.5°W to ~65°W. It has been generally accepted that the ALVZ represents a partially molten zone. The extension and presence of this layer of probably partially melted material may be explained in accordance with geological observations such as the Main Andean Thrust (MAT) also called Interandean Thrust (e.g. Mertmann et al., 2001; Scheuber et al., submitted). The MAT is a prominent detachment zone located at the border between EC and the Inter- Subandean units (e.g. Allmendinger et al., 1997) that could be affecting the entire portion of the upper crust (Figure 4.6). It should also be considered that such a response from the crust could be related to, at least, two possible situations:

a) Strong upper crust, strong lower crust, weak upper mantle: the first two are deformed together while the upper mantle acts as an accompanying unit where deformation is hardly recognized.

b) Strong upper crust, weak lower crust, strong upper mantle: the lower crust is deformed together with the upper crust while the upper mantle does not react and remains stable and undeformed.

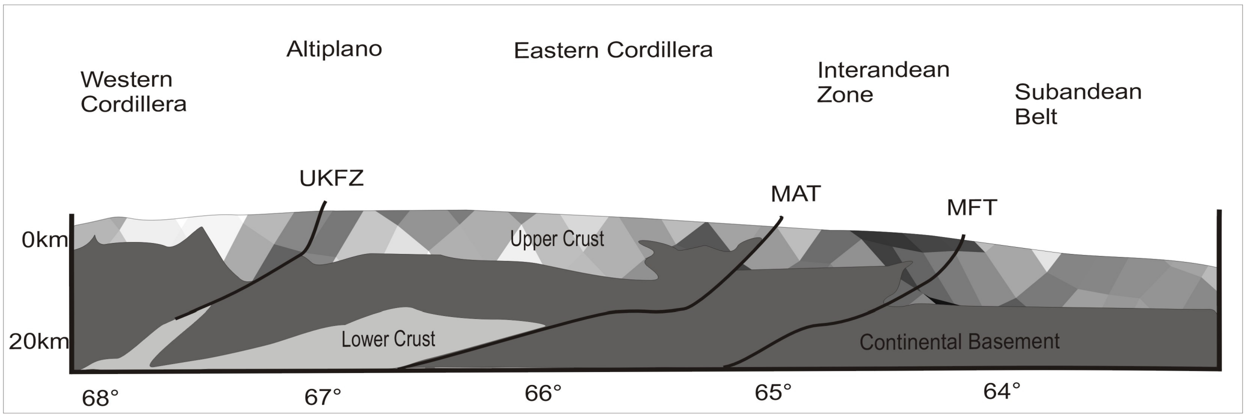


Figure 4.6: Structural cross section along 21°S. The presence of the MAT (Main Andean Trust) along the section at 21°S, affects the entire structure of the upper crust and reaches portions of the lower crust where we detect the low-velocity anomalies at the border between Altiplano and the Eastern Cordillera. Simplified after Mertmann et al.,(2001) and Scheuber et al. (Submitted).

The detachments described in this study have been clearly imaged by seismic refraction (Wigger et al., 1994) and could be responsible for zones where changes in lithostatic pressure, material state of the rocks and temperature variations affect the configuration of melts and fluids that move along these structures in the interior of the crust.

4- The Eastern Cordillera presents what we interpret as an extension of the low-velocity zone towards the east of the Altiplano (Yuan et al., 2000; Brasse at al., 2002; Haberland, et al., 2003). The anomaly is located between ~66.5°W and ~65.5°W.

At ~66°W we detect on S- wave tomographic image (see Fig. 4.5), an influx-like structure with high velocities underlain by a high-velocity body between 100 and 150 km depth that is proposed to be part of the old cold lithosphere (Lithospheric Block? in chapter 6-Figure 6.1) that might have separated from the base of the crust.

5- East of the Eastern Cordillera and the position of the Main Andean Thrust (MAT), we detect the presence of a strong, high-velocity anomaly in both P- and S-wave analyses, that we interpret as the Brazilian shield - also called the Guaporé shield covered by Neogene sediments filling the basins from the Interandean, Subandean and Chaco Plain provinces. We assume that the presence of the Brazilian shield (BS), as a cold and old unit underlying the before mentioned sediments, is responsible for the observed anomaly. Unfortunately, the resolution of the upper and deeper parts of the anomaly is not sufficient to determine if there is some type of deformation structure present. Therefore, underthrusting of the Brazilian lithosphere can not be recognized in the tomographic results. The limit between the Brazilian shield with high velocities and the Eastern Cordillera with low velocities appears to indicate that shortening occurred mainly in this region. A flexurally strong lithosphere, as suggested by Watts et al. (1995), should play a key role in the configuration of the BS anomaly and explain foreland deformation in the thin-skinned fold-and-thrust belt. The Interandean, the Subandean and Chaco morphological units could therefore be situated above a series of detachments where great amounts of shortening has taken place.