Chapter 1

Introduction

The study of mountain ranges developed at converging plates is fundamental for understanding the processes that govern the subduction of one plate, overriding of the other and in some cases, the collision of both. Within the context of converging plates, there are two large plateau regions in the world: one is the Tibetan plateau which is associated with a collisional orogen between two continental plates (India and Asia). The other one, the Altiplano-Puna plateau, is related to subduction of an oceanic plate (Nazca) beneath a continental plate (South America) in the Central Andes. The elevation of the Altiplano-Puna plateau (~ 4 km) achieved under a subduction regime involving magmatism, shortening, deformation and mass transfer within the upper lithosphere (e.g. Coira et al., 1982; Isacks, 1988; Reutter et al., 1988, Baby et al., 1992; Gubbels et al., 1993; Scheuber et al., 1994; Allmendinger et al., 1997), shows the importance of geodynamic processes to the generation of the impressive Andes ranges and perhaps ironically, how little these generation mechanisms are understood.

The “Cordillera de los Andes” is a long mountain belt located along the western edge of the South American continent, extending for over 7000 km from north to south. It represents one of the world’s best examples of an area that has been formed under the effects of uplift and magmatism arising from the subduction of an oceanic plate (Nazca Plate) under a continental plate (South American Plate) (Figure 1.1). The Andes reach their greatest width at a region known as the Central Andes (central sector between ~14°S and ~24°S) where subduction of the Nazca plate occurs at angles near 20-30° at a rate of 65mm/yr (Angermann et al., 1999; Cahill and Isacks, 1992).

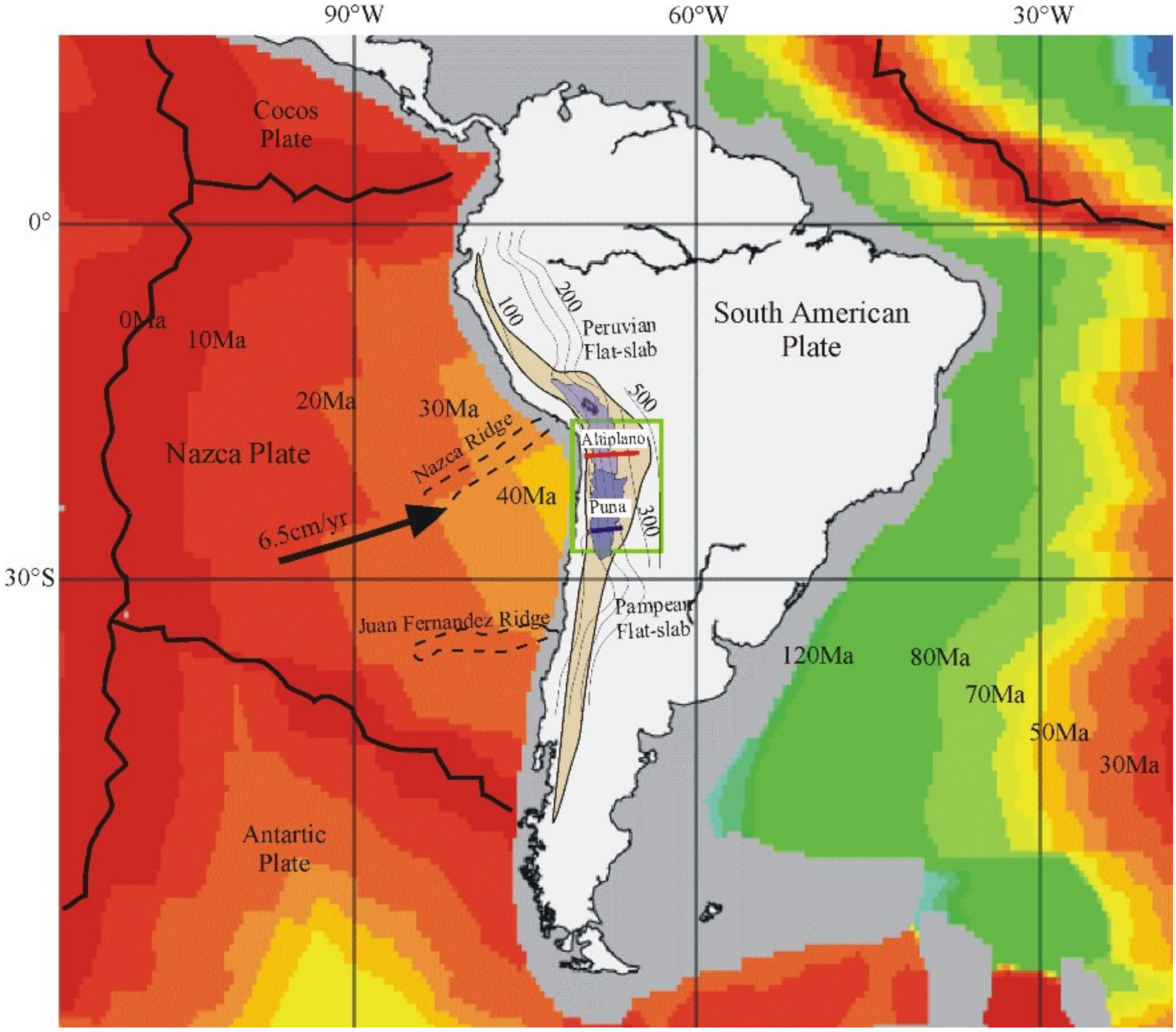

Figure 1.1: The South American continent and the associated tectonic plates. Different colours represent sea-floor age in million of years; bold lines: limit between oceanic plates (spreading centers); Arrow: Nazca/South American plates convergence rate (Angermann et al., 1999). Brown shaded area shows the extent of the Andes from ~5°S to~ 47°S. Thin lines are depth contours of the Wadati-Benioff zone in km (Cahill and Isacks, 1992). Green rectangle: Altiplano-Puna study area in the Central Andes. Red line: Altiplano profile at 21°S. Blue line: Puna profile at 25.5°S. Sea-floor ages after Müller et al., 1997).

Several authors have proposed different geological classifications to describe the Andes. The most accepted approach was given by Gansser (1973) who, based on tectonic and geological differences among the segments of the orogen, proposed three main regions: Northern, Central and Southern Andes. The Northern Andes, north of ~3°S, are mainly constituted of an oceanic basement as a consequence of oceanic crust accretion during Mesozoic times (e.g. Ramos 1999).

The Southern Andes (~47°S to ~52°S) are developed south of the triple junction zone where the South American, Nazca and Antarctic plates produce ridge collision deposits without magmatic activity from the arc (e.g. Ramos, 1999).

The Central Andes extends from ~3°S to ~47°S and are flanked by flat-slab areas to the north (between ~3°S - ~14°S) and to the south (~28°S - ~32°S) where subduction is horizontal to sub-horizontal. Portions of the oceanic plate subducting the central parts of the Andes (Figure 1.1) have ages between ~40 Ma and ~47 Ma (Müller et al., 1997). The Central Andes went through various stages of extension, compression and transtension, alternating with periods of tectonic inactivity (Reutter et al., 1988; Scheuber et al., 1994; Sempere et al., 1997). During Paleogene times, the actual configuration of the central part of the Andes began to take form due to compression between the involved tectonic plates (Pilger, 1981 and 1983; Pardo Casas and Molnar, 1987).

Crustal shortening, variable thickness in the crust and different dipping angles of the subducting plate along strike have created an elevated plateau in the central part of the Andean orogen with geological, morphological and magmatic characteristics that enable a differentiation between the Altiplano in the north (Bolivia and Peru) and the Puna in the south (north-western Argentina) (e.g. Schmitz, 1994; Allmendinger et al., 1997; Kley and Monaldi, 1998, Riller et al., 2001; Riller and Oncken, 2002).

The Altiplano-Puna plateau (Figure 1.1) is the main tectonic feature of the central Andean region and stretches for about ~1700 km from north to south. The plateau has an average elevation of ~4 km and is ~400 km wide. It 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. Kley and Rheinhardt, 1994; 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 (the location of the mentioned morphological units can be seen on Figures 3.1B and 6.1) (e.g. Wigger et al., 1994).

In the Central Andes, the presence of low-velocity layers in the upper crust (Wigger et al., 1994; Yuan et al., 2000 and 2002) and the position of bright spots (ANCORP Working Group, 1999 and 2003) as well as possible delaminated portions of the lithosphere (Schurr, 2000 and Schurr et al., 2003) have been described and considered when resolving the internal structure of the Andean plateau (Haberland et al., 2001; Victor et al., 2004; Elger et al., 2005; Scheuber et al., submitted). Other processes, referring to the differences in constitution, tectonic shortening, altitude above sea level or topography, thickness of the crust, differences in volcanism and magmatism are not well understood (e.g. Allmendinger et al., 1997).

Therefore, the scientific community started to focus its attention on this region, in particular because of the well-known enigma that concerns the generation of a plateau in the absence of a collision scheme (Isacks, 1988; Reutter et al., 1988; Allmendinger and Gubbels, 1996). Hence, over the past two decades, a series of seismological projects (e.g. Wigger, 1991; Wigger et al., 1994; Patzwahl et al., 1999; Schmitz et al., 1997, ANCORP Working Group, 1999 and 2003; Graeber and Asch, 1999; CINCA Working Group, 1997; Haberland and Rietbrock, 1999; Schurr et al., 1999, Bock et al., 1998) were undertaken to bring light on understanding of the many interacting geologic-geodynamical processes in the Central Andes. These passive and active seismic experiments provided unique results that enabled, for the first time, the identification of deep structures in the crust as well as the depth and topography of the Moho- discontinuity (Beck et al., 1996, Zandt et al., 1996; Yuan et al, 2000). The Moho and implicitly the crust of the Andes mountain chain is a topic of study that has always been controversial. So far, the generation of magmas with related movement of fluids (e.g. Schilling et al., 1997) in correlation to earthquake clusters of the subducted slab has been suggested to explain melting and volcanic activity. The electrical conductivity of the Central Andes (e.g. Brasse et al., 2002) provided insight looks at units with anomalously conductive materials in the area of the plateau.

The last funding period of the Collaborative Research Center SFB-267 “Deformation Processes in the Andes” supported a two year deployment of instruments for a seismological project. Initially thought as a receiver function profile along two portions of the Central Andes, the aim was to improve the resolution of previously obtained results concerning Moho topography (e.g. Yuan et al., 2000) and collect data for applying other geophysical methods. In this study, a teleseismic tomography is performed using the collected data to analyze the different anomalies present in this area, as well as the extent to which these anomalies should reach. Previous global teleseismic tomography studies have been able to image the subduction zone on the base of P-wave analysis (Engdahl et al., 1997; Bijwaard et al., 1998). From the beginning of this project, one important issue concerned the morphological units in the subduction scheme and their relative position with respect to older structures such as the Brazilian shield, which is thought to play a key role in understanding the plateau evolution (Wigger et al., 1994; Myers et al., 1998; Polet et al., 2000, Beck and Zandt, 2002). A comparison between both Altiplano and Puna plateaus, could help us to explain the differences that are observed in the data.

The present work consists in 6 chapters and a final section with additional information (Appendix). The main structure of each chapter is described as follows:

Chapter 2 briefly addresses the field deployment of instrumentation, the characteristics of the instruments and the data acquisition. Some steps followed while installing the stations are also described.

Chapter 3 describes the data processing and the teleseismic tomography algorithm used in this study. The algorithm is then applied to both data sets (Altiplano and Puna). Synthetic tests were first carried out to evaluate vertical and horizontal resolution. Finally, the real-data inversions were performed and the results presented in vertical and horizontal sections.

In Chapters 4 and 5 an overview of the geological history of the Altiplano-Puna plateaus is given, including geodynamical environment, tectonics and magmatic characteristics. The results obtained are presented for each profile separately.

Chapter 6 includes a discussion about the obtained results and their geodynamical implications; the results are compared with those obtained from previous projects and later presented as models for both plateaus. The results from receiver function images of the Moho and other discontinuities obtained from the same data set are compared with our tomographic results. Conclusions are presented in the last part of this work.

In the Appendix, a complete list of station information and instrument characteristics is presented as well as a list of the teleseismic events from the PDE catalogue used in this study. Additional diagrams, vertical and horizontal synthetic tests and real inverted data are also shown at the end of this section.

In the case of the Altiplano profile along 21°S the intention was to improve previous geophysical results. For this reason, this project was conducted: 1) over a longer period of time (almost two years) and 2) extended from the previous experiments (e.g. ANCORP profile see ANCORP Working Group, 1999, 2003) by some 200 km to the east, reaching the Interandean zone of Bolivia (Tarija ~64.5° W). In this way, our profile covers a west-east extension of ~600 km with 59 stations. The spacing between stations (10-15 km) allows us to detect upper mantle and lower-crustal anomalies, as well as, the distribution of anomalies related to structures in the Moho and upper crust (e.g. the extension of geological units at depth or crustal lineaments delimiting them).

The other set of 19 stations along 25.5°S (~200 km long) was also run for two years and with a spacing of 10 to 15 km. The intention was to get first geophysical results for the area of Galan volcano. By applying the teleseismic tomography method, the aim was to evaluate the state of the lithosphere and asthenosphere areas below the Southern Puna were delamination was proposed to explain a series of geological and geophysical observations (e.g. Kay and Kay, 1993; Schurr et al., 2003).