1 Introduction

1.1 Andean segmentation: Facts and open questions

Since the beginnings of plate tectonic theory, the Andes have been cited as the best example of an active orogen formed by the subduction of oceanic lithosphere underneath a continental margin [Hamilton, 1969; James, 1970]. Despite of the spatial continuity of the cordillera for more than 7.000 km along the western edge of South America and the uniqueness of the process responsible for its formation, the Andean margin is notably marked by a strong along-strike segmentation. 200 My of uninterrupted ocean-continent convergence and particularly the very compressive Late Cenozoic orogenic process [e.g. Mpodozis and Ramos, 1989; Sobolev and Babeyko, 2005] have produced a highly segmented margin, characterized by systematic and coupled along-strike variations in topography, morphostructure, tectonics, basin distribution, volcanism, subduction geometry, deep lithospheric structure and geologic history [e.g. Gansser, 1973; Jordan et al., 1983; Isacks, 1988; Mpodozis & Ramos, 1989; Cahill & Isacks, 1992; Dewey and Lamb, 1992; Kley et al., 1999; Gutscher, 2002; Jacques, 2003; Stern, 2004; Yáñez and Cembrano, 2004].

Owing to these along-strike changes, the Andean margin can be divided into several first-order segments. However, different authors studying distinct aspects of the margin have proposed different definitions for them. In order to build a primary and adequate framework for this thesis, I found it necessary to use an ad-hoc definition of the Andean segmentation, which is based on a modification of those proposed by Gansser [1973], Jordan et al. [1983], Mpodozis and Ramos [1989], Kley et al. [1999] and Stern [2004]. Fig. 1.1 shows the suggested boundaries and nomenclature for continental-scale segments as follows: Northern (10°N-3°S), Central (3°S-33.5°S), Southern (33.5°-46.5°S) and Austral (46.5°-56°S) Andes.

The morphology of the Andean margin is dominated by the huge topography of the Altiplano-Puna, which is the Earth’s biggest continental plateau after the Tibet. In contrast to the Tibetan plateau that resulted from collision between two continental masses during the last ~50 My [e.g. Tapponnier et al., 1986], the Altiplano-Puna has been constructed in a relatively short time span (last ~25 My) and by the convergence of South America with the oceanic Nazca plate [e.g. Isacks, 1988; Allmendinger et al., 1997; Lamb and Hoke, 1997; McQuarie, 2002]. The mechanisms responsible for the construction of such a huge orogenic plateau in a non-collisional geotectonic setting have faced the geoscientific community since decades.

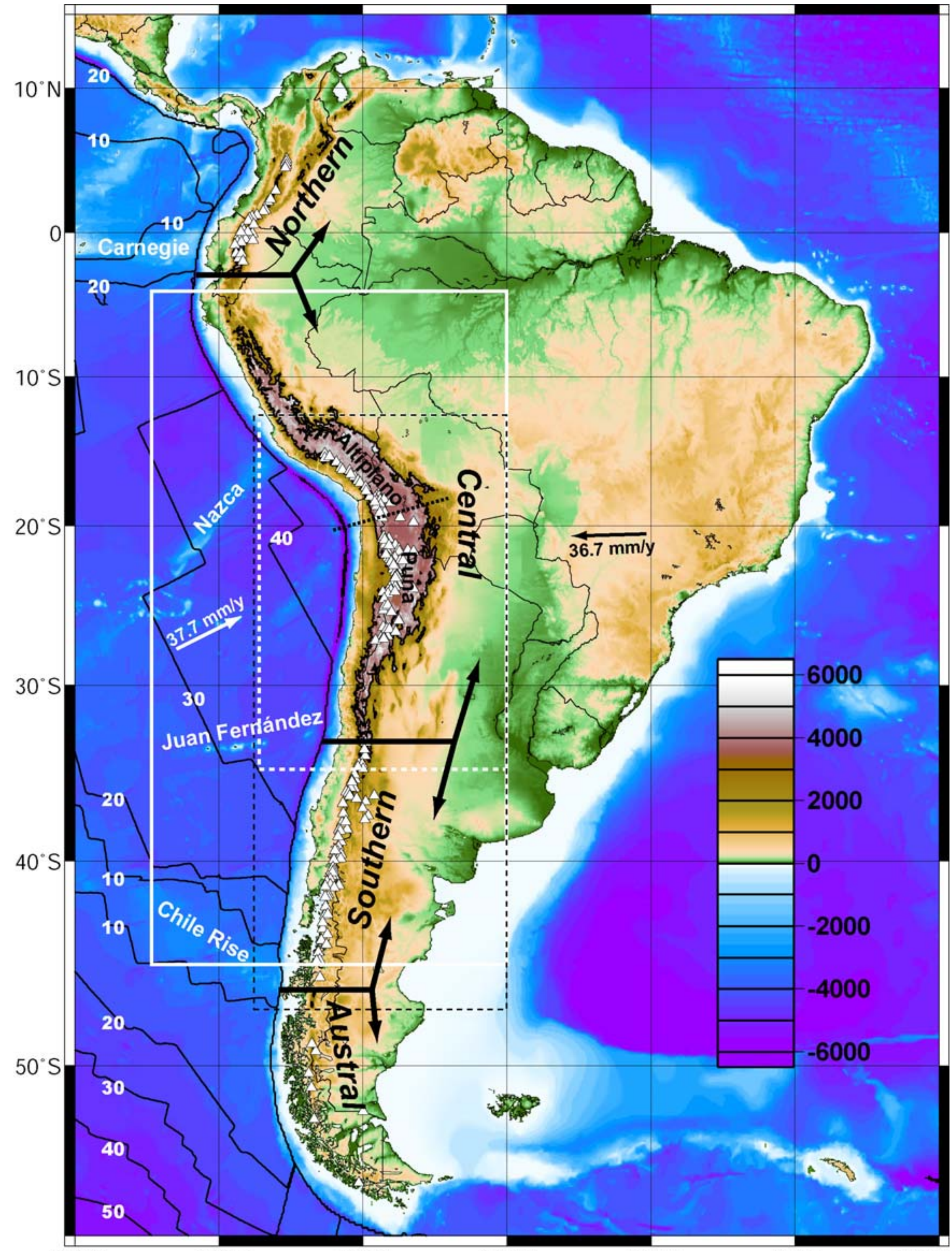

Fig. 1.1. Main geotectonic framework of the Andean continental margin. Digital topography and bathymetry from http://www.ngdc.noaa.gov/mgg/gebco. Black lines with numbers mark isochrones of the Nazca plate [Müller et al., 1997] and white names depict the location of oceanic ridges and Chile Rise active spreading centre. White triangles are Holocene volcanoes from http://www.volcano.si.edu/gvp/world, black line is the 3500 m elevation contour, dotted line is the symmetry axis defined by Gephard [1994] for the Altiplano-Puna plateau, bold lines with diverging arrows mark the proposed boundaries of first-order Andean segments that are labelled with bold-italics characters. Arrows with magnitudes in mm/y are vectors of Nazca and South America movement with respect to the hotspot reference frame after Marrett and Strecker [2000]. Boxes show the working areas of studies referred in the text; black segmented line for Tassara and Yáñez [2003], white segmented line for Chapter 2 [Tassara, 2005a] and white bold line for Chapter 4 [Tassara et al., under review in JGR].

The Altiplano-Puna plateau is located in the central part of the Andean margin, has elevations higher than 3500 m and is wider than 400 km along a symmetry axis that parallels the convergence direction [Gephard, 1994] (Fig. 1.1). Compared to the Central Andes, the Northern, Southern and Austral Andes show a subdued orogenic topography characterized by narrow (<150 km width) and shallow (<2500 m high) mountain belts.

The causes of this segmentation are not yet completely understood. The obvious correspondence between boundaries of Andean segments with subduction of oceanic ridges and along-strike variations of the shape of the subducted slab, together with the significant correlation between the age of the Nazca plate at the trench and the morphology of the orogen (Fig. 1.1), have motivated the generally accepted thought that the segmentation is primarily controlled by the current configuration of the subducting Nazca plate [e.g. Jordan et al., 1983; Pilger, 1984; Pardo Casas y Molnar, 1987; Gutscher et al., 2000; Ramos et al., 2002; Yáñez et al., 2001, 2002; Lamb and Davies, 2003; Yáñez and Cembrano, 2004].

Despite of the evident relevance that the incoming oceanic plate has for the geodynamics of the margin, it must be noted that these segments and their boundaries are longstanding (10^8 yr) geological features of the Andean margin [e.g. Gansser, 1973; Mpodozis and Ramos, 1989; Mégard, 1984; Kley et al., 1999]. The Andean segmentation, as a long-term attribute of the continental margin, cannot be exclusively explained in terms of the current configuration of the oceanic plate, because such configuration changes during short-term (10^6-10^7 yr) plate reorganization processes [e.g. Pardo-Casas and Molnar, 1987; Tebbens and Cande, 1997].

1.2 Working hypothesis

The main hypothesis analysed throughout this dissertation is that the Andean segmentation is, at least partially, controlled by the old geological structure of the continent that has been inherited prior to the modern orogenic process that started during the Late Cenozoic. This idea has been suggested by some previous authors [e.g. Isacks, 1988; Cahill and Isacks, 1992; Allmendinger and Gubbels, 1996; Marrett and Strecker, 2000], but never formally expressed for the entire margin nor systematically explored in terms of its causes and consequences. During this thesis I developed part of a road toward a better understanding of the role that the compositional-geological variability of the continental crust could have in controlling the strength of the margin, and hence its capability to be deformed under the effect of tectonic forces. The work I present here is by no means a conclusive final answer; it shows some relevant results of an ongoing investigation that has been motivated by previous work and that will form the precedents for further studies.

It has been established during the last decades that the strength of the continental lithosphere, being a fundamental property defining its deformation capabilities, is mainly controlled by the temperature field, the thickness of the crust and the rheological structure defined by the compositional stratification of crust and mantle [e.g. Ranalli, 1994; Burov and Diament, 1995; Lowry and Smith, 1995; Watts, 2001]. Along the active Andean margin, the thermal structure derives mostly from the geometry of the subducted slab, with high temperatures along steep-subducting segments associated with active volcanic arcs and lower ones along flat-slab segments below volcanic gaps [e.g. Hamza and Muñoz, 1996; Gutscher, 2002]. Although the formation of flat-slab segments must be related to the differential buoyancy controlled by the subduction of light aseismic ridges [Gutscher et al., 2002; Yáñez et al., 2001], some authors have argued that the shape of the slab and much of the margin's geodynamics could be partially controlled by the westward overriding of the continental plate and its intrinsically variable deformation capabilities [e.g. Cahill and Isacks, 1992; van Hunen et al., 2004; Sobolev and Babeyko, 2005; Heuret and Lallemand, 2005]. Therefore, the current thermal configuration of the convergence system could be a far-reaching consequence of the inherited rheological structure of the continental margin, the latter being in this case the most important controlling factor for the strength of the continental lithosphere, its geodynamic response to external tectonic forces and the long-term prevalence of the Andean segmentation.

1.3 Methods, previous work and study areas

The strength of the continental lithosphere can be parameterised by its rigidity or associated effective elastic thickness T_e. These parameters are normally estimated from the relationship between topographic loads and the deflexion of the lithosphere as observed through gravity anomalies, and making use of the thin elastic plate theory [e.g. Turcotte and Schubert, 2002; Watts, 2001]. The lithospheric strength can also be estimated constructing yield strength envelopes from 1) the compositional-rheological structure of crust and mantle; 2) the thermomechanical regime defined by temperature distribution with depth and strain rate of active deformation. The approach I used throughout this thesis to study spatial variations of the Andean margin strength comprises two main methodologies: Analysis of existing elastic thickness data and construction of a lithospheric-scale three-dimensional model containing a description of the compositional-rheological structure of the margin.

The first year of my doctoral work I finished a manuscript presenting and interpreting elastic thickness estimates obtained during my master thesis for the Universidad de Chile [Tassara, 1997]. This manuscript was written with the collaboration of Gonzalo Yáñez (supervisor of that master thesis) and published in Spanish in the *Revista Geológica de Chile* [Tassara and Yáñez, 2003]. It is not included in this dissertation. This paper presented estimates of the elastic thickness between 12° and 47°S along 15 cross-sections perpendicular to the margin (see study area in Fig. 1.1). Using topography-bathymetry and Bouguer anomalies as input parameters for each profile and a 1D forward modelling method [Bodine, 1981], this work showed relevant across- and along-strike variations of T_e for the continental margin. Qualitative interpretation of these results, in terms of their relationship with the rheological and thermomechanical structure of the convergence system, suggested that strong changes from very low rigidity along the Central Andes (T_e < 10 km) to comparatively high values south of 38°S (T_e > 35 km) must be related with a variation of the crustal composition from felsic-dominated north of 34°S to mafic-dominated along the southernmost Southern Andes. This conclusion motivated the development of the dissertation presented here.

I reviewed the main results of Tassara and Yáñez [2003] for the Central Andes region in a paper published in *Tectonophysics* [Tassara, 2005a] and forming the Chapter 2 of this thesis (see Fig. 1.1). Here I concentrated in a semi-quantitative interpretation of the elastic thickness results, with the aim of understanding the geotectonic interaction between the subducting Nazca plate and the continental lithosphere. This interpretation indicates that the main factor controlling the variations from high rigidity along the flanks of the orogen (forearc and foreland) to low rigidity along the center of the cordilleran system is the thermal structure exerted by the convergence process. However, crustal compositional changes from mafic in the forearc to felsic in the orogen are likely very significant. Combining this idea with existing structural and geophysical information, I proposed a geotectonic model connecting the cold and compositionally strong slab-forearc system with the warm, felsic-dominated and hence weak orogen throughout a crustal scale triangular zone rooted toward the Altiplano plateau in a subhorizontal decollement. This decouples the rigid upper crust from the ductile middle-lower crust.

In order to have an independent evaluation of the role of crustal compositional variations along the margin as a major factor controlling the deformation capabilities and the whole structure of the convergence system, a three-dimensional density model for the entire Central and Southern Andes was defined as the next task to be carried out during the doctoral work. The design and further interpretation of such a model required an adequate knowledge of the dependency of density on several potential factors controlling its expected value inside crust and mantle. After realizing that there was a lack of a generalized understanding on this topic, I performed an independent study based on existing thermodynamical tools [Sobolev and Babeyko, 1994; Connolly, 1990]. The result of this work is an article already accepted for publication in *Geochemistry, Geophysics, Geosystems (G-cubed)* that constitutes the Chapter 3 of this dissertation. In this manuscript, I analysed the role of crustal composition, pressure-temperature conditions of equilibration, water content and degree of partial melting in controlling the density structure of active continental margins.

The results of this latter work were fundamental for the development of the three-dimensional density model of the Nazca plate and the Central and Southern Andean margin that forms the Chapter 4 of this thesis, and as manuscript currently under review by the *Journal of Geophysical Research*. The working area depicted in Fig. 1.1 comprises regions of Peru, Brazil, Bolivia, Paraguay, Argentina, Chile and the Pacific Ocean. The method used is a forward modelling of the Bouguer anomaly performed with the in-house software IGMAS [e.g. Schmidt and Götze, 1998]. This software allows the definition and modification of the 3D mass distribution along vertical cross-sections and the computation of the modelled Bouguer anomaly through an optimised triangulation of the density structure between them. It also permits the visualization of independent information to constraint the main geometry of the density discontinuities forming the model. I compiled a database containing recent seismic information that was used to fix the geometry of the subducted Nazca slab, locally the Moho at the base of the oceanic and continental crust, and –together with heat flow data– also the geometry of the lithosphere-asthenosphere boundary (LAB) below the continent. This modelling produced an interesting and new view of the continental-scale structure of the Andean margin that can be used to analyse first-order variations in several parameters. That includes, but is not restricted, to the thermal regime, crustal structure and composition, hydration of crust and mantle and their degree of partial melting. Importantly, the geometry of the intracrustal density discontinuity (ICD), separating felsic upper crust from mafic lower crust into the model and that was not constrained with independent data, provides a unique perspective into the crustal compositional structure. The final geometry of this discontinuity is well correlated with the surface geology of the margin and supports the main hypothesis of this work: The Central Andes are characterized by an ICD deeper than 20 km, whereas along the southernmost Southern Andes it is shallower than 10 km. This shows that there is a significant variation in the crustal composition along the Andean margin, which, for a similar thermal state along active volcanic arcs (characterized by a similar depth to the LAB), must result in difference of the crustal strength. This crustal-controlled strength heterogeneity could help to explain differences in the deformation mechanisms responsible for the Andean segmentation. However, this work also left several open issues that should be addressed in the future throughout new studies, as proposed in the conclusions of this dissertation.