5 Conclusions

The work presented in this dissertation should be considered as part of a way toward a better comprehension of the role that the inherited compositional-geological variability of the Andean crust exerts on the strength of the continental margin and therefore on its capability to absorb fractions of plate convergence by internal deformation. The main hypothesis explored during this study was that the spatial variation of the crustal structure controls, at least partially, the fate of the Andean margin and the maintenance of its long-term along-strike segmentation throughout the intrinsic strength of the continental lithosphere.

The development of this dissertation has been motivated by previous results, summarized in the work of Tassara and Yáñez [2003]. There it was suggested that along-strike changes of the rigidity of the Andean orogen, parameterised in variations of the estimated elastic thickness T_e from less than 10 km to more than 35 km between 33° and 38°S, might be related to changes of the bulk crustal composition and rheology from felsic-dominated and quartz-rich along the Central Andes to mafic-dominated and plagioclase-rich toward the southernmost Southern Andes. These compositional-rheological along-strike variations are fairly consistent with spatial changes of the surface geology [e.g. Mpodozis and Ramos, 1989; Schobbenhaus and Bellizzia, 2001], demonstrating that the old geological configuration of the continent is controlling the long-term mechanical behaviour of the margin. The inherited rheologic-geological structure of the margin must be considered in order to understand the causes of the Andean segmentation and the evolution of the orogenic processes responsible for the construction of the present-day cordillera.

The investigation carried out throughout this thesis attempted to extend the reach of these conclusions. This resulted in three scientific manuscripts, currently at different stages of publication by international journals (see the Preamble of this dissertation for a description). These articles deal with different aspects of the research program defined to analyse the explored working hypothesis; they use different approaches and arrive to a number of conclusions that are not always directly related to the main avenue of this work. The next section summarizes the main conclusions reached by each paper. Followingly, I try to connect these conclusions discussing their implications and limitations to the driving ideas of this dissertation. Finally, the open questions and problems that remain unresolved are analysed in a future perspective.

5.1 Summary of Chapters 2, 3 and 4

Chapter 2. Interaction between the Nazca and South American plates and formation of the Altiplano-Puna plateau: Review of a flexural analysis along the Andean margin (15°-34°S)

The elastic thickness estimates of Tassara and Yáñez [2003] for the Central Andes region are here reviewed in order to characterize spatial rigidity variations and to understand the role of the forearc in the formation of the Altiplano Plateau. Forearc rigidity decreases gradually southward of 23°S and sharply toward the orogen, which is very weak (T_e < 10 km) along the entire Central Andes.

A semi-quantitative rheological interpretation of these trends suggests that across-strike rigidity variations are dominated by the thermal structure derived from the subduction process that makes the forearc a strong, cold and rigid geotectonic element resisting the deformation of the weak orogen. Supporting a thermomechanical control of the slab in the forearc rigidity, the southward weakening of the forearc seems to be related to the decreasing thermal age of the subducted slab.

Very low rigidities along the main orogen might result from the existence of a thick, quartz-rich crust submitted to a low strain rate-to-heat flow ratio. This, combined with theoretical considerations based on the yield strength envelope concept, suggests that the strength of the plateau lithosphere is localized in an upper-crustal layer whose base, at ca. 15 km, correlates with a mechanical discontinuity imaged by geophysical experiments. The forearc-plateau rigidity boundary, which coincides at the surface with a west-verging structural system, might be considered a zone of changing thermal conditions, eastward-increasing crustal thickness and felsic component in the crust, and low strain-rate deformation.

These conclusions allow the proposition of a geotectonic model imaging the rigid forearc as a pseudo-indenter against the weak plateau that favours the accumulation below it of ductile crustal material moving westward from the actively shortened eastern foreland. This pseudo-indenter is geometrically represented by a crustal-scale triangular zone rooted at the physical discontinuity imaged below the plateau.

Chapter 3. Factors controlling the crustal density structure underneath active continental margins with implications for their evolution

In order to design, and then to interpret the three-dimensional density model developed in Chapter 4, this article analyses the effect exerted on density of continental crustal columns by its chemical composition, pressure-temperature (PT) conditions, water content and degree of partial melting. This was achieved using two independent thermodynamical approaches over 55 geochemical analyses and PT conditions characterizing calc-alkaline, subduction-related continental margins.

This petrophysical modelling technique was used to calculate density values under anhydrous conditions for the whole dataset at critical PT conditions down to a 70 km thick crust and to regress these values against silica. The resulting regressions have correlation factors greater than 0.9, which indicate that densities in a dry crustal column are inversely correlated with wt% SiO_2 for all depth levels. These regression lines constitute empirical relationships that are useful for constraining the density range of anhydrous crustal rocks. It was also established that the effect on density of water-saturation and retained melt is minimal for intermediate to acidic compositions and therefore the empirical density-SiO_2 relationships obtained under anhydrous conditions could also be applied to a wet, melt-containing crust with bulk silica content higher than 55-60 wt%. That is not the case for rocks formed from (ultra)basic compositions, which absorb large amounts of water via the formation of amphiboles, notably reducing their density with respect to the garnet-pyroxene assemblages formed under dry conditions.

These results were used to infer that lower crustal zones of (picro)basalt bulk composition at the base of hydrated, partially molten subduction-related arcs of normal crustal thickness (<50 km), could be positively buoyant with respect to the mantle. These amphibole-rich, melt-retaining zones should have seismic velocities typical of anhydrous rocks of basaltic andesite composition, and hence it is speculated that estimates of crustal composition based on seismic models could underestimate the basicity of the continental crust. The results also suggest restricted thermal, compositional and tectonic conditions for the removal of lower crust into the mantle.

Chapter 4. Three-dimensional density model of the Nazca plate and the Andean continental margin

This work presented a 3D density model covering the Nazca plate (85°W) and the Andean continental margin (60°W) between Northern Peru (5°S) and Patagonia (45°S). This is an idealized and simple representation of the Earth density structure down to 410 km depth that results from a forward modelling of the Bouguer anomaly. This structure matches the observed and calculated anomalies with an average misfit of 15.05 mGal. The modelling was constrained by a compilation of independent (mostly seismic) data in order to fix the geometry of the subducted Nazca slab, locally the Moho of the oceanic and continental crusts, and indirectly the lithosphere-asthenosphere boundary (LAB) underneath the continental plate. Density values for the bodies forming the model were allocated after a quantitative analysis that considers this parameter to be a function of several thermodynamic factors. This analysis is based on the conclusions reached in Chapter 3 for the continental crust and was extended to the mantle and slab. A sensitivity study allows a quantification of the uncertainties associated with the modelling and together with the results of Chapter 3 conforms a tool to interpret the meaning of density discontinuities that were not constrained by independent information. The final density structure resulting after the modelling suggests some significant conclusions on the geometry, composition, thermal regime and geodynamic evolution of the Andean convergence system.

Less than 55% of the oceanic Nazca plate in the study area has crustal thickness lying in the worldwide average range of 7±1 km. The spatial distribution of oceanic crustal material seems to be correlated with significant water-depth anomalies with respect to the plate-cooling model. They could be further related with thermal and/or compositional anomalies in the mantle lithosphere. The Nazca ridge has a continuous and thick crustal root (>25 km) compared with the thin (<15 km) and discontinuous Iquique and Juan Fernández ridges.

The morphology revealed by the model for the southern Peruvian flat-slab (south of 12°S) is clearly associated with the subduction of the huge Nazca ridge. However, this segment is shallower and less flat than the northern Peruvian and Argentinean flat-slab segments. The morphology of these two latter segments shows a notable parallel with the upper plate morphostructure. These observations and the fact that the Iquique ridge, being similarly sized than the Juan Fernández ridge, is not associated with a flat-slab segment, allow to suggest that subduction of buoyant oceanic ridges might be necessary but perhaps insufficient to produce the flattening of the slab. Another factor to be considered is the dynamic coupling of the slab with a westward-advancing and mechanically heterogeneous continental plate that absorbs part of the convergence by decreasing amounts of crustal shortening away from the Altiplano region.

The LAB underneath the continental margin is shallower than 80 km along active volcanic zones and deeper than 100 km for volcanic gaps associated with flat-slab subduction. The thickest lithosphere (>160 km) is observed underneath the eastern Brazilian shield. An ENE-oriented zone of deep LAB (>120 km) in western Argentina seems to correlates with the limit between the Rio de la Plata craton and the suspected Pampia terrain. Similarly, a gradual decrease of the lithospheric thickness from the Pampean region toward the south supports a difference in the nature of the Patagonian terrain with respect to the continental blocks to the north. The extremely thin lithosphere observed in this region (<80 km) could be associated with the thermal anomaly probably related to the Cenozoic alkaline volcanism characteristic of Patagonia.

A crust thicker than 60 km underlies most of the Central Andean cordillera. The Moho reaches maximum depths of ~75 km along the eastern-central part of the Altiplano plateau. A region of crustal thickness less than 55 km underneath the Puna can be correlated with a proposed recent lower-crustal delamination event. Variations in the morphology and thickness of crustal roots and their relation with topography and amounts of crustal shortening suggest large- and small-scale variations in the isostatic mechanisms compensating the mountain chain.

The intracrustal density discontinuity (ICD), separating felsic upper crust from intermediate to mafic lower crust, is a proxy to the three-dimensional mass distribution resulting from changing upper-crustal geology together with compositional and thermal variations in the lower crust. A surface density map, obtained from a digital geology database, helped to isolate the effect of near-surface density variations in the geometry of the ICD.

An analysis of this geometry indicates that dense Meso-Cenozoic magmatic rocks exposed at the surface along the Central Andean forearc are also likely forming the offshore forearc and could be spatially connected to similar rocks along the axis of the southernmost Southern Andean orogen. A zone of shallow ICD in western Argentina –suggesting the dominance of high density, mafic rocks in the crust– correlates with the location of suspected terrains, supporting their alloctonous origin with respect to the more felsic autochthonous Andean basement. The Central Andean Plateau is dominated by an ICD significantly deeper (> 20 km) than along the Southern Andean Cordilleras (< 10 km). Expecting similar crustal temperatures, hydration and partial melting degrees, because of similar positions along active volcanic arcs, this observation suggests a first-order difference in the crustal composition associated with the old geological structure of the continent. This pre-existing difference probably controls to some extend the integrated strength of the margin, which in turn can help to explain the long-term Andean segmentation.

5.2 Implications and limitations of this work for understanding the Andean segmentation issue

The results of Chapter 2 show that the age-dependent thermal structure of the subducted slab exerts a primary thermomechanic control on the rigidity of the forearc region.

Something similar has been proposed by Yáñez and Cembrano [2004] on the basis of a thermomechanical model. The subducting Nazca plate is oldest in front of the Altiplano-Puna plateau (Fig. 1.1 and 4.1), suggesting that the high rigidity of the forearc along this region is a consequence of the comparatively cold and strong nature of the shallow slab there and that this mechanical behaviour favours the generation of a high continental plateau. However, this study suggested that the construction of the huge Altiplano-Puna plateau is also a likely consequence of the intrinsically weak nature of the orogenic crust, which seems to be dominated by a felsic composition and quartz-rich rheology favouring the absorption of convergence via crustal shortening and thickening. Variations in the width of the inherited felsic-dominated crust, which can be delineated from correlated variations of surface geology and spatial distribution of elastic thickness, could explain in this scenario why the plateau develops in the central part of the Central Andes and why the width of the orogen decreases toward its northern and southern extremes. In addition, Tassara and Yáñez [2003] concluded that, in order to explain the increase of elastic thickness and decrease of orogenic mass along the Southern Andes, it might be necessary to advocate a southward-increasing mafic and strong plagioclase-rich component in the crust that precludes the absorption of convergence by internal crustal deformation.

The reach of these conclusions are limited by two main facts: 1) the elastic thickness estimates of Tassara and Yáñez [2003] reviewed in Chapter 2 only softly constrain the along-strike variations in rigidity, because their derive from a 1D-forward modelling performed along trench-perpendicular profiles; 2) most importantly, the suggested control of crustal composition and rheology on the strength and overall tectonic segmentation of the margin came from a qualitative rheological interpretation of elastic thickness data into the context of the yield strength envelope and cannot be used to quantitatively asses the mechanical relationship between crustal compositional structure, the strength of the continental margin and its deformation mechanisms. Nevertheless, the ideas emanating from these conclusions do contribute significantly to a better comprehension of the factors controlling the geotectonic segmentation of the Andean margin.

The three-dimensional density model developed in Chapter 4, using some results produced in Chapter 3, explored an independent quantitative way to analyse the changing crustal structure along the margin and its relationship with the structure of the entire convergence system. The geometries of density discontinuities resulting after the modelling are somehow an intermediate result toward an integrated understanding of the main issue investigated in this dissertation. These geometries can be used in the future by the Andean geoscientific community to study multiple aspects of the margin's geodynamics, since they will be published in electronic format. An analysis of these geometries presented in Chapter 4 reveals some interesting observations to be taken into consideration for addressing the causes of the Andean segmentation.

The subduction of a presumably buoyant oceanic ridge is probably insufficient to flat the slab, as the Iquique ridge in front of the Puna plateau is associated with a steep subducting segment of the Nazca slab. Interestingly, the morphologies of the northern Peruvian and Argentinean flat-slab segments seem to be correlated with the morphostructural configuration of the continental plate. This suggests that the development of flat-slab segments could be partially controlled by the coupling of the slab with a westward-overriding continent (as suggested by the thermomechanical models of van Hunen et al. [2004]), especially if it is considered that the continental margin is intrinsically heterogeneous in terms of its crustal structure and therefore has a changing strength opposing the deformation driven by tectonic forces. This idea is supported by the geometry of the intracrustal density discontinuity (ICD) of the model, which indicates that the width of the domain characterized by large amounts of light, felsic and therefore weak crustal component is maximum along the Altiplano-Puna plateau and decreases toward the boundaries of the Central Andes. This means that the crust could absorb more convergence via internal compressive deformation along the plateau. This derives in turn to a limited net overriding of the continent above the slab compared to segments where the continent advance comparatively more to the west because less weak crustal material there inhibits the absorption of convergence by internal compressive deformation.

This model could help explain the current shape of the subducted slab along the Central Andes, but does not clarify why it is steep along the Southern Andes, where the geometry of the ICD suggests that the amount of felsic and weak crustal material is much lower than to the north. This challenge could be resolved considering the degree of "anchoring" of the slab into the surrounding mantle, an important parameter controlling the slab dynamics and back-arc deformation mechanisms of subduction zones worldwide, as pointed out by Heuret and Lallemand [2005]. In the global tomography model of Villaseñor et al. [2003, pers. comm.], the deep slab along the Central Andes seems to be clearly anchored at the 660 km mantle discontinuity and it could thus respond passively to the overriding of the continent [Heuret and Lallemand, 2005]. In contrast, along the Southern Andes the anchoring of the slab in the mantle is not obvious, in part due to the poor resolution of the model along this region. If these tendencies are real, they could suggest that the slab along the Southern

Andes is free to dive in the mantle driven by its own weight, rolling back away from the subduction zone. Therefore the trench would move to west in the same direction as the advancing continental plate. If the trench retreat velocity is similar to the westward velocity of the continent, no net overriding could exist in the Southern Andes, precluding any possible flattening of the slab. These ideas should be tested in the future by means of thermomechanical models.

Confirming the main conclusions of Tassara and Yáñez [2003] and those suggested in Chapter 2, the geometry of the Moho and especially of the ICD indicate that the Altiplano-Puna plateau is characterized by a thick crust containing significantly more felsic component than the thin and mafic-dominated crust of the Southern Andes. This observation constitutes independent evidence that there is a relevant along-strike variation of the bulk crustal composition along the Andean margin, which is linked with changes of the surface geology and which might be related to spatial variations in the strength of the margin. However, the depth of the ICD along the Altiplano-Puna plateau, being shallower than ~25 km, suggests that the entire middle-lower crust has an intermediate to mafic composition. That is at odds with the conclusions emanating from Chapter 2, which point toward a dominantly felsic bulk composition for the Central Andes as the cause of its low elastic thickness. A quantitative analysis on the expected strength of the lithosphere should be conducted in order to identify how this crustal structure could be related with the low rigidity of the Altiplano-Puna plateau. Preliminary results developed for a conference during 2005 [Tassara, 2005b], demonstrate that in this scenario it must be considered the existence of partial molten material reducing the strength of the lower crust. This interpretation converges with the low seismic velocities and high electrical conductivities underneath the Central Andes plateau [e.g. Schilling et al., 1997; Schmitz et al., 1999; Beck and Zandt, 2002; Brasse et al., 2002; ANCORP, 2003].

5.3 Outlook for future work

Expansion of the 3D density model

Owing to the capabilities and flexibility of the modelling software IGMAS [Schmidt and Götze, 1998] and the simple initial structure of the three-dimensional density model constructed during this work, its expansion to other segments of the Andean continental margin could be a relatively easy task. The gravity database used during this modelling is part of a larger compilation that can be combined with satellite-derived gravity models (CHAMP and GRACE missions) making possible the analysis of the density structure for other regions of the South American continent. A successfully extension of the model requires, however, the use of independent information to constrain the main geometries of first-order density discontinuities. A number of geophysical experiments are being conducted along the Northern Andes [e.g. Calahorrano et al., 2005; Kellogg et al., 2005; Schmitz et al., 2005], which will produce valuable images of the subducted slab and the continental Moho that could allow to spread out the model north of 5°S with relatively good confidence. The inaccessibility of the Austral Andes makes the future expansion of the model south of 45°S a more difficult job. Due to the relatively simple lithospheric structure expected toward the interior of the continent with respect to the more complex active Andean margin and owing to the high-quality geophysical information already published for some regions of the Brazilian Shield [e.g. Assumpcao et al., 2002; Berrocal et al., 2004] one could imagine an extension of the model to most of the South American continent and their margins. The realization of such a model is a long-term challenge, but it might produce a spectacular result where most of the geoscientific information produced in the continent will be compiled in one model to generate an integrated image of the entire continental lithosphere structure.

High-resolution map of elastic thickness

One of the deficits that one can recognize in the work presented in this dissertation is the skeleton representation of the elastic thickness structure derived from the work of Tassara and Yáñez [2003] and other previous authors [e.g. Whitman et al., 1996; Steward and Watts, 1997]. All these studies are based on one-dimensional forward modelling techniques applied along selected profiles. This precludes identifying the eventually complex rigidity structure likely existing along the (very) active Andean margin. Work in progress in collaboration with Ron Hackney (CAU zu Kiel), Chris Swain and Jon Kirby (Australia) attempts to produce a high-resolution map of elastic thickness for the entire South American continent and surrounding oceans. We are using a modified, updated version of the fan wavelet method for flexural isostatic analysis developed by Kirby and Swain [2004], that is able to recover a value of T_e for each single point in a geographical grid inverting the coherence between topography and Bouguer anomaly. Due to the existence of gaps areas in the land gravity databases available for the continent, the latter has been computed from the gravity model derived from GRACE and CHAMP satellite missions. This work is going to generate a detailed map of elastic thickness for South America with an unprecedented quality and resolution.

Quantitative analysis of continental margin strength

An important shortcoming of this work is the qualitative nature of the interpretation I performed of the elastic thickness data. Other authors, some of them developing more sophisticated numerical tools, also approaches to this topic making general assessments about the relationship between elastic thickness and strength of the lithosphere or using these tools to analyse qualitatively the rigidity structure of a region in terms of its possible controlling factors [e.g. Burov and Diament, 1995; Lowry and Smith, 1995; Lavier and Steckler, 1997; Pérez-Gussinyé et al., 2004]. Such analyses demonstrate the great potential that estimates of the effective elastic thickness (ET_e) have for constraining a number of factors and processes affecting the geodynamics of the continental lithosphere (temperature, crustal and lithospheric thickness, compositional crustal structure, deformation and stress fields). During my doctoral work I have been developing (with the initial collaboration of A. Babeyko) some analytical models to compute a so-called equivalent elastic thickness (eT_e) by "intersecting" the yield strength envelope with a realistic stress tensor. This method, if supplied with a 3D model of the rheological and thermal structure of a region, has the potential to produce maps of eT_e that can be compared against those of ET_e, contributing with a powerful qualitative tool for the analysis of continental strength and its underlying causes. Such method also produces a physical 3D model showing the distribution of brittle, elastic and ductile layers inside the lithosphere that could be useful interpreting active deformation of the continent and the distribution of seismicity. In the future this method shall be completely implemented and used in conjunction with the high-resolution ET_e map and the 3D density model to quantitatively asses most of the questions remaining unresolved after this investigation.