2 GEOLOGY

The 3D density model presented later in this thesis is based on constraints from geophysical data, as well as geological observations. The study area, located at latitudes between 36 and 42°S, is characterized by geological and geophysical features that are very different to those in the Central Andes (20–25°S). Therefore, before entering the subjects of the actual gravity data and gravity field analysis, existing geological knowledge is summarized.

2.1 Regional scale features of the Andes

2.1.1 Introduction and a short outline of the evolution

The Andes are a mountain belt over 8000km long (Figure 1.1), extending along the western continental margin of South America. They are the result of the convergence of the oceanic Nazca Plate toward the South American Plate (Figure 2.1). An average convergence rate of 80 mm/a for the last 3 Ma has been determined from oceanic magnetic anomalies (DeMets et al. 1994, Somoza 1998). However, GPS data show present rates of 62 mm/a (Kendrik et al. 2003), implying a decrease in the convergence rate.

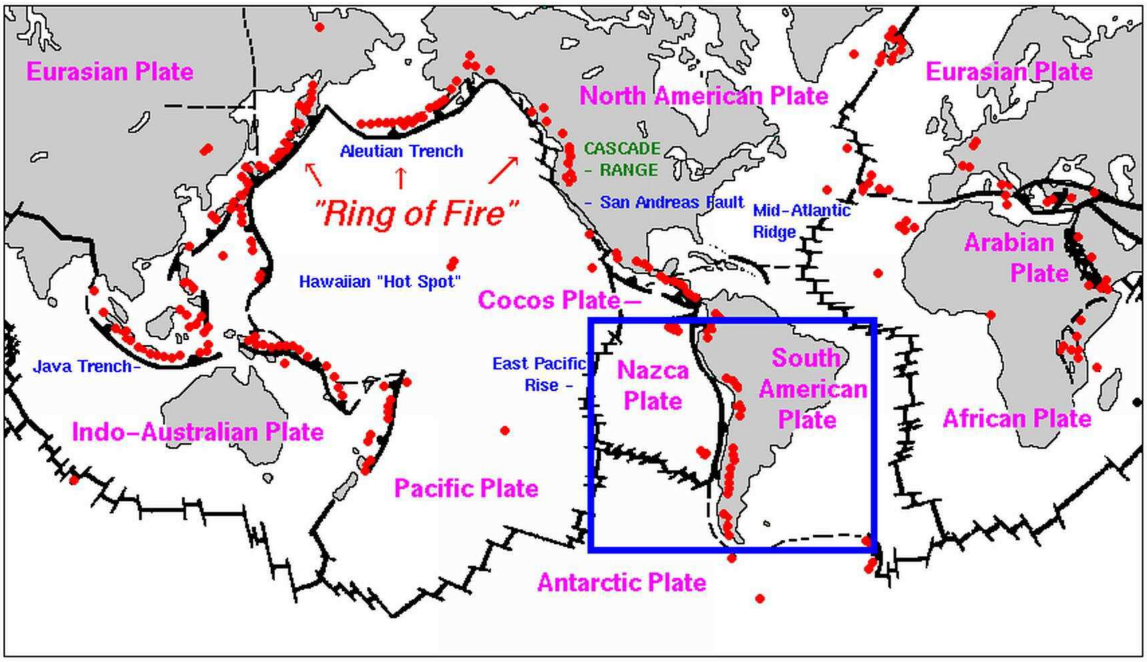

Figure 2.1
The region of interest (box) is shown in a global context. Tectonic plate boundaries are marked by black lines. Circles mark active volcanoes (after USGS, Topinka, 1997).

The following summary is based on Mpodozis & Ramos (1989), unless otherwise stated.

The Andes have a complex history that started in the Palaeozoic with the accretion of Pacific micro-continental blocks to the western margin of Gondwana. At that time, Gondwana's south-western coast was not far from the present-day Sierras Pampeanas in Argentina. The accretion of the terranes, with a new subduction zone forming along its western margin, belongs to the early Palaeozoic Famatian tectonic cycle of Andean evolution. This subduction zone left a large accretionary prism preserved along the Pacific margin of Chile south of 25°S (Hervé et al., 1981). In the second Gondwana tectonic cycle, the magmatic arc composed of granitoids and rhyolitic volcanic rocks was developed within this accretionary prism and in adjacent areas eastwards of it. The last evolutionary stage, the Andean tectonic cycle (Mesozoic to Cenozoic), is characterized by a major palaeogeographic change. The complex of backarc basins associated with the arc developed on late Palaeozoic basement during the Jurassic – Early Cretaceous. Subsequent subduction erosion removed large amounts of the accumulated Palaeozoic forearc. The Mesozoic-Cenozoic Andes, in contrast to the Palaeozoic Andes, lack evidence for the collision of major terranes and appear to be related to the tectonic erosion of the continental margin. The extraordinary feature of the Mesozoic evolution of the Andean orogen is the along-strike tectonic segmentation. There are differences in the geological evolution, structural styles and behaviour of the related magmatic arcs of various segments, as well as changes in the nature of the backarc basins (Mpodozis & Ramos, 1989 and references therein). Therefore, there must be two significant controls on the tectonic segmentation: the plate interactions and the pre-existing inhomogeneities of the South American plate (e.g. Jordan et al., 1983). Thus, the Andes offer a great opportunity to understand and study the coupling of subduction and continental orogenesis. As proposed by various authors (e.g. Barazangi & Isacks, 1976; Jordan et al., 1983; Mpodozis & Ramos, 1989; Cahill & Isacks, 1992), the Andes can be subdivided into several segments. In the following, the study area at the latitudes between 36–42°S will be referred to as a part of the Southern Andes (cf. Bohm et al., 2002; Tassara & Yáñez, 2003).

2.1.2 Segmentation/variations along the margin

Offshore

The oceanic Nazca Plate is being subducted under the South American continental plate along the Peru-Chile Trench, an 8000 km long feature offshore from western South America (Figure 1.1). The continental tectonical segments are mostly coincident with changes in the subducting Nazca Plate. Along-strike variations in the geometry of the slab from north to south are observed in the subduction angle, the Wadati-Benioff-Zone seismicity, which reaches depths > 525 km in the north, whereas in the south only ~200km (e.g. Barazangi & Isacks, 1976; Cahill & Isacks, 1992; Figure 2.2), and the depth of the coupling zone (36–41km in the north and 48–53 km in the south, Tichelaar & Ruff, 1991). Also, the eastern limit of the Wadati-Benioff-Zone corresponds to the eastern deformation limit of the overriding South American Plate (Jordan et al., 1983). Additionally, the sides of the subduction of oceanic ridges (Juan Fernández Ridge at 33.5°S and the Chile Ridge at 46°S) marks major tectonic boundaries, as described above and further in this chapter. Based on these observations it has been proposed by various authors (e.g.Barazangi & Isacks, 1976; Jordan et al., 1983) that the incoming lower plate has a major control on the upper plate and its segmentation.

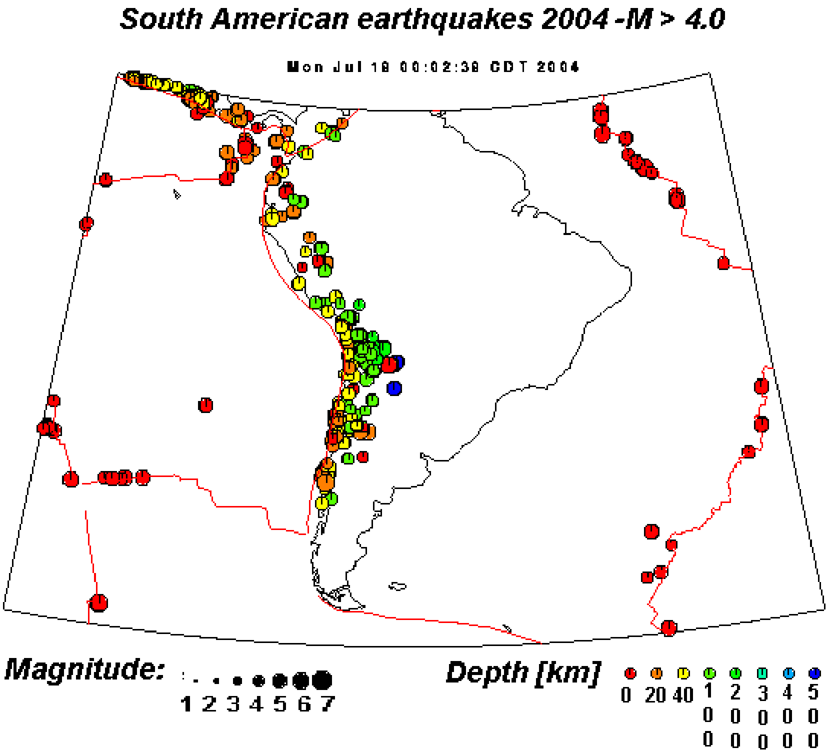

Figure 2.2
Recent seismicity at the boundary of the Nazca and South American plates showing a gradual decrease in seismic events below the Andes in depth and width towards the south. Image from USGS National Earthquake Information Center. (http://www.eas.slu.edu/Earthquake_Center/FQHTML/sa04.html).

Segmentation is also recognized within the trench (e.g. Schweller et al., 1981; Díaz-Naveas, 1999 and references therein). It is generally shallow and partially sediment-filled at its northern and southern ends, but it is deeper and almost empty in the central region. The depth of the oceanic basement reaches a maximum of 8 km at ~23°S (Schweller et al., 1981) and decreases to ~4 km off Peru and Southern Chile (Scholl et al., 1970). The area at latitudes between 28°S–33°S is a transition zone between the deep, empty and narrow (north of 28°S only 10 km wide) trench to a large asymmetrical wedge-shaped deposit of sediment up to 2 km thick, that broadens from 30 km south of 33°S, reaching almost 150 km at 42°S (Schweller et al., 1981; Reichert & Schreckenberger, 2002). South of 37°S the trench, because of its sediment infill, disappears as a bathymetrical feature (Figure 1.1).

The wide range in axial sediment thickness along the entire trench reflects climatic influences. Extremely wet climates near the equator and south of 40°S cause large amounts of sediment to be transported to the continental shelf and slope, and eventually to the trench via turbidity flows and hemipelagic sedimentation (Schweller et al., 1981). The distribution of the axial sediments can be attributed to the northward transport of the turbidites along the axis from the high-input region south of 40°S. The intersection of the Juan Fernández Ridge with the trench may be related to the restriction of this transport north of 33°S. Therefore, the forearc in Southern Chile, with a well-developed accretionary prism, is characterized by frontal/basal accretion and sediment subduction (Bangs & Cande, 1997; Díaz-Naveas, 1999; Lohrman et al., 2001); whereas along the Central Andes, where the climate is more arid, the trench is deep and empty and the forearc, lacking the accretionary wedge, undergoes tectonic erosion (von Huene & Ranero, 2003).

Onshore

The Andes are highest north of 33°S, where the elevation rises to ~6800 m, and include the second largest continental plateau on Earth, the Altiplano-Puna Plateau located between 15 and 28°S. South of 33°S the mean elevation decreases gradually to less than 2000 m (for the Andean topography see Figure 1.1). The width of the orogen varies from ~450 km in the Central Andes (~18°–20°S) to ~200 km north and south of it. The volcanic arc south of ~41.5°S is narrowing to 40 km (López-Escobar et al., 1995). The crustal thickness, as inferred from seismic data, decreases from 70 km in the Central Andes (e.g. Wigger et al., 1994; Yuan et al., 2002) to ~35–40 km in the southern Andes (Hildreth & Moorbath, 1988; Bohm et al., 2002; Lüth et al., 2003; Tassara & Yáñez, 2003). The southern Andean magmatic arc (~35°S–40°S) has been stationary relative to the South American continent since the Jurassic. Due to subduction erosion, the magmatic arc of the Central Andes migrated progressively eastward during the Meso-Cenozoic from its initial Jurassic position near the present day coastline (e.g. Mpodozis & Ramos, 1989; Scheuber & Reutter, 1992; Hervé, 1994).

2.2 Local features of the study area (36°–42°S)

As it will be shown later, the local-scale segmentation that is recognizable within the gravity field correlates with geological observations, and is therefore significant for the density model. The model is described in detail in Chapter 5, whereas the geological observations are presented in the following section.

2.2.1 Offshore

The situation in the study region off southern Chile appears to be also complex. Subduction of the Chile Ridge at ~46°S results in distinction of the downgoing slab along the margin at these latitudes. The oceanic plate subducting under this point of the margin originates at two different spreading centres (Figure 2.3). North of 38°S, the trench is subducting crust formed at the East-Pacific Rise at least 35 Ma ago. Between 40°S and the Chile Margin triple junction at 46°S, the Peru-Chile Trench is subducting oceanic crust that was generated within the past 20 Ma at the Chile Ridge (Herron, 1981). This causes a southwards' decrease in the age of the oceanic lithosphere, as well as other features such as buoyancy forces acting within the subduction zone. The old and denser oceanic lithosphere sinks more easily, resulting in steep subduction zones. The young and buoyant lithosphere resists subduction, causing strong coupling between the plates (Stern, 2002). The northern limit of the crust generated at the Chile Ridge axis is defined by the Agassiz Fracture Zone (Figure 2.3), an extension of the Valdivia Fracture Zone (FZ) (Herron, 1981; Tebbens & Cande, 1997). The age offset is also pronounced across the Mocha FZ north of the Valdivia FZ at ~39°S (Figure 2.3). These two fracture zones form a triangular area between the latitudes of 39°S and 40°S. This zone, being the boundary between oceanic crust of different age and structural grains, should be related to the geological processes onshore in its vicinity (Herron, 1981). The triangular area corresponds to the northern limit of the rupture zone of the moment magnitude, M_w, 9.5 Valdivia earthquake of May 22, 1960. Only the area south of the Mocha FZ was involved in the rupture zone, causing the area of the Chilean margin between 37°S–46°S to rupture. That would indicate that the young and warm oceanic plate controls the deformation associated with the earthquake sequence (Herron, 1981).

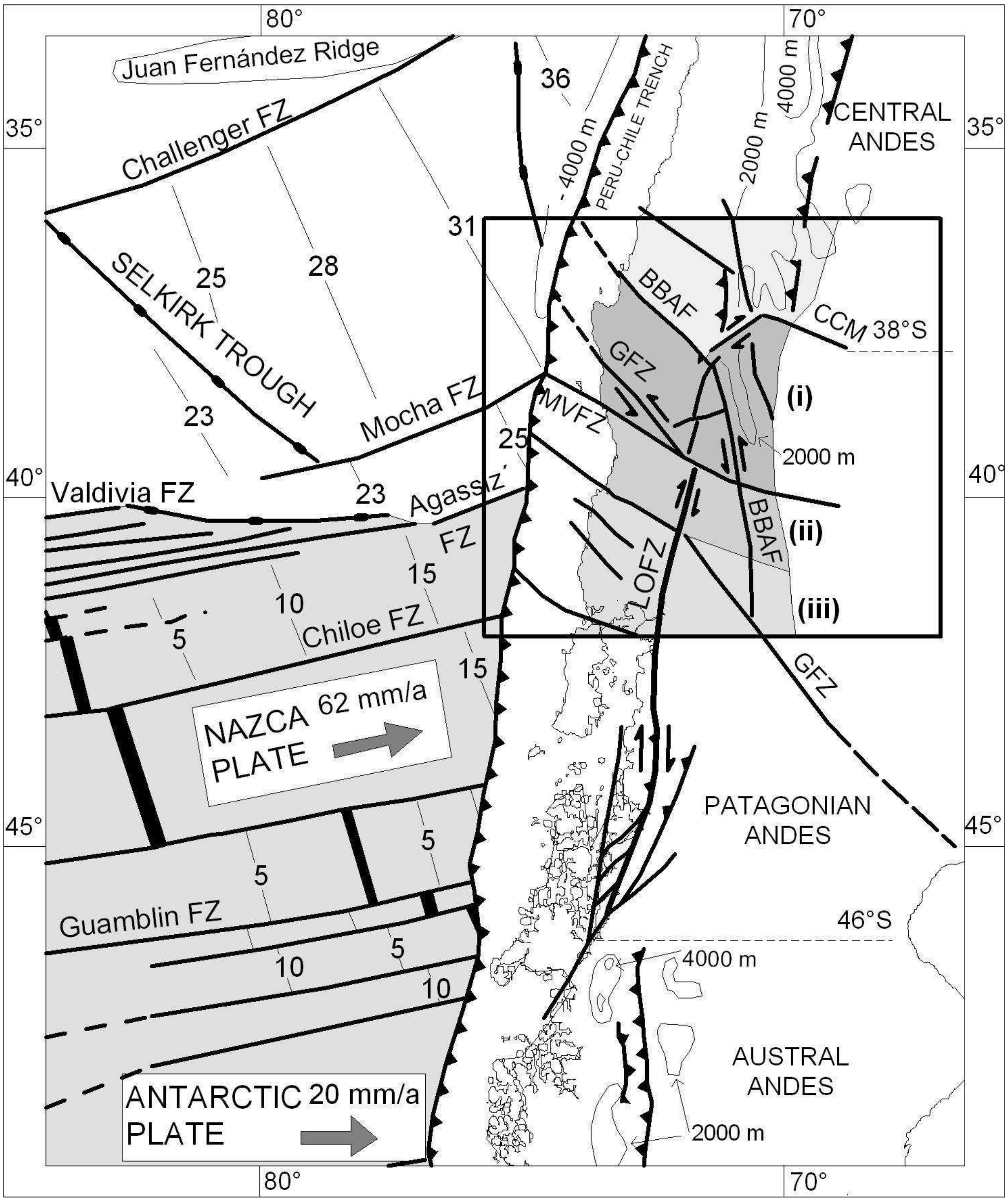

Figure 2.3

Regional tectonic setting and segmentation, with the study area shown by the black box (Melnick, pers. comm., 2003). Nazca Plate: after Tebbens & Cande (1997) indicating ages in Ma (the numbers in black); dark gray marks the oceanic crust produced by the Chile ridge. The Peru-Chile Trench is marked by the black line with triangles.
South American Plate: the division of the study area into three segments (dark, medium and light gray colours), described in the text, is based on geological observations and the gravity field (Chapters 3 and 5).

abbreviations:
BBAF/BAF: Bío-Bío fault
GFZ: Gastre Fault Zone (also referred to as Lahnaluhe Fault Zone)
LOFZ: Liquiñe-Ofqui Fault Zone
MVFZ: Mocha-Villarica Fault Zone
the contour lines of 2000 and 4000 m elevation are based on GTOPO30, USGS .

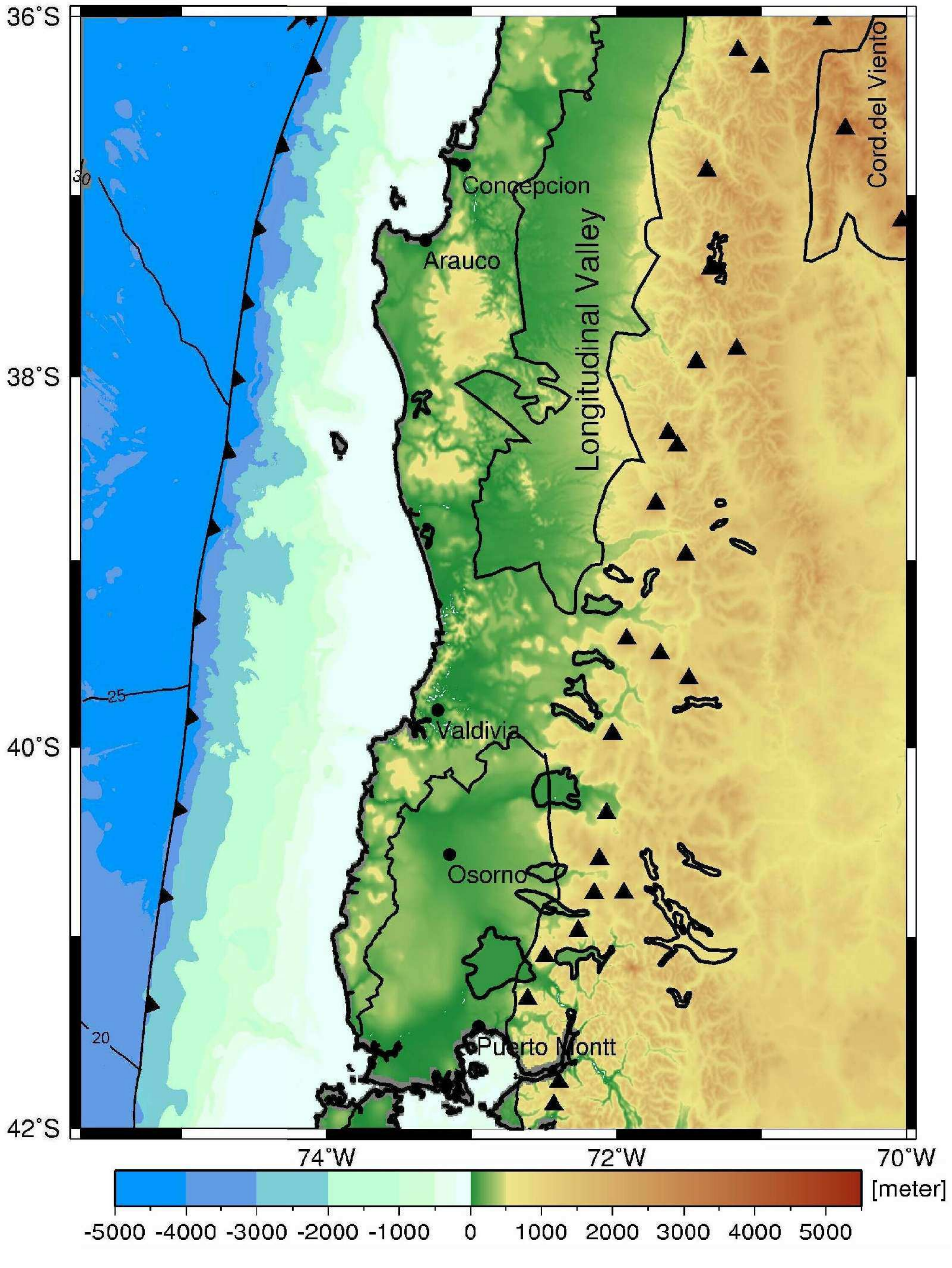

Figure 2.4
Bathymetry and topography in the study area (from the GLOBE DEM). The trench axis is indicated by a black line with triangles, and the lines with numbers offshore indicate the age of the oceanic plate. The black lines onshore mark lakes and the position of the Longitudinal Valley, which is in the Valdivia region absent, but continues south of 40°S in the area of Osorno. The Cordillera del Viento massif, having the highest elevation within the study area, and corresponding to the most pronounced gravity anomaly minimum (Figure 3.8), is also marked. The main volcanic arc is denoted by black triangles.

2.2.2 Onshore

The segmentation within the study region is observable not only within the oceanic plate, but also within the upper plate. The Main Cordillera of the Southern Andes shows significant transitions with respect to surface expression and geology. From the broad and topographically high (>4000m) northern mountains including the Cordillera del Viento massif (36°–37°S), it significantly narrows and descends to mean altitudes of around 1000 m towards the south (42°S). The Coastal Range has a maximum elevation of ~1500 m at latitudes between 36°S–38°S (in the Nahuelbuta Range), decreasing to only a few hundred meters south of 39°S (Figure 2.4).

In order to construct the most realistic 3D density model, the modelled structures should represent real geological features. Thus, one important aspect of the modelling procedure is to link the modelled upper-crustal structures to the real surface observations in terms of geometry (location of certain bodies) and composition (characteristic density values). Using this approach, a real situation can be better simulated by a model. Careful analysis of a study area is therefore necessary.

2.2.3 Volcanic arc

The volcanoes of the study area belong to the Southern Volcanic Zone (SVZ) (López-Escobar et al., 1995), extending from 33°S to 46°S, making up the western-central part of the Principal and Patagonian Cordillera. This Quaternary volcanic arc is divided into four provinces (López-Escobar et al., 1995 and references therein): Northern (NSVZ, 33–34.5°S), Transitional (TSVZ 34.5°–37°S), Central (CSVZ, 37°–41.5°S) and Southern (SSVZ 41.5°–46°S). The northern boundary at 33°S is defined by the absence of active Quaternary volcanoes for 650 km further north, coinciding with the impingement of the Juan Fernandez Ridge on the Chile Trench. The southern boundary is marked at 46°S by the Chile Rise Triple Junction (Tormey et al., 1991), and is Late Pleistocene-Holocene in age. The arc is formed by numerous stratovolcanoes and hundreds of minor eruptive centres. It displays a general NNE-trend (~N10°E) and contains basaltic rocks, as well as andesites, dacites and rhyolites. Quaternary centres on the volcanic front north of 37°S consist predominantly of andesite to dacite. The CSVZ (south of 37°S) consists of basalts and rhyolites, with a predominance of basalts and basaltic andesite (López-Escobar et al., 1995). These volcanic centres contain a high proportion of andesite and basalt that are mafic in composition (Hildreth & Moorbath, 1988 and references therein). Other authors (e.g. Tormey et al., 1991) discuss a north to south increase in the degree of mantle melting, controlled by variable fluxing from the slab or variations in the thickness of the mantle column that undergoes melting. Thicker crust in the north leads to a thinner mantle column and a lower degree of melting. The lavas south of 37°S incorporate insignificant amounts of continental crust (Tormey et al., 1991).

2.2.4 The Morphotectonic Units

The continental plate in the study region may be divided into three morphotectonic units: the forearc, main arc and backarc. The forearc consists of the Coastal Cordillera and the Longitudinal Valley, also called the Central Valley or Central Depression. The Main Arc is a chain of basaltic Quaternary stratovolcanoes and the basement of Meso-Cenozoic intrusive rocks. The Neuquén Basin, North Patagonian Massif, Cordillera del Viento and the foreland basins constitute the backarc region (Figure 2.5).

The Coastal Cordillera consists mainly of a low-grade late Palaeozoic accretionary complex represented by the metamorphic rocks of the two parallel belts called 'Western Series' and 'Eastern Series', intruded in the northern part of the region by the synmetamorphic granitoids of 'Nahuelbuta Mountains' (Cingolani et al., 1991). The Nahuelbuta Mountains represent a well-exposed part of the Upper Palaeozoic basement of felsic composition, mostly granitoids that extends from the latitudes of Santiago down to Chiloé Island (Creixell, 2001). Triassic continental and Late Cretaceous to Quaternary marine and continental sedimentary sequences were deposited in independent offshore forearc basins (Itata, Arauco, Valdivia) (Mordojovic, 1982; Pineda, 1986). These basins are interpreted to be controlled by the major repeatedly reactivated faults, the Bío-Bío-Aluminé Fault (BAF, 36°40’-38° S) and Gastre Fault Zone (GFZ, 37°40'–39°20', which has been recently renamed to Lahnaluhe FZ) (Echtler, per.comm., 2003).

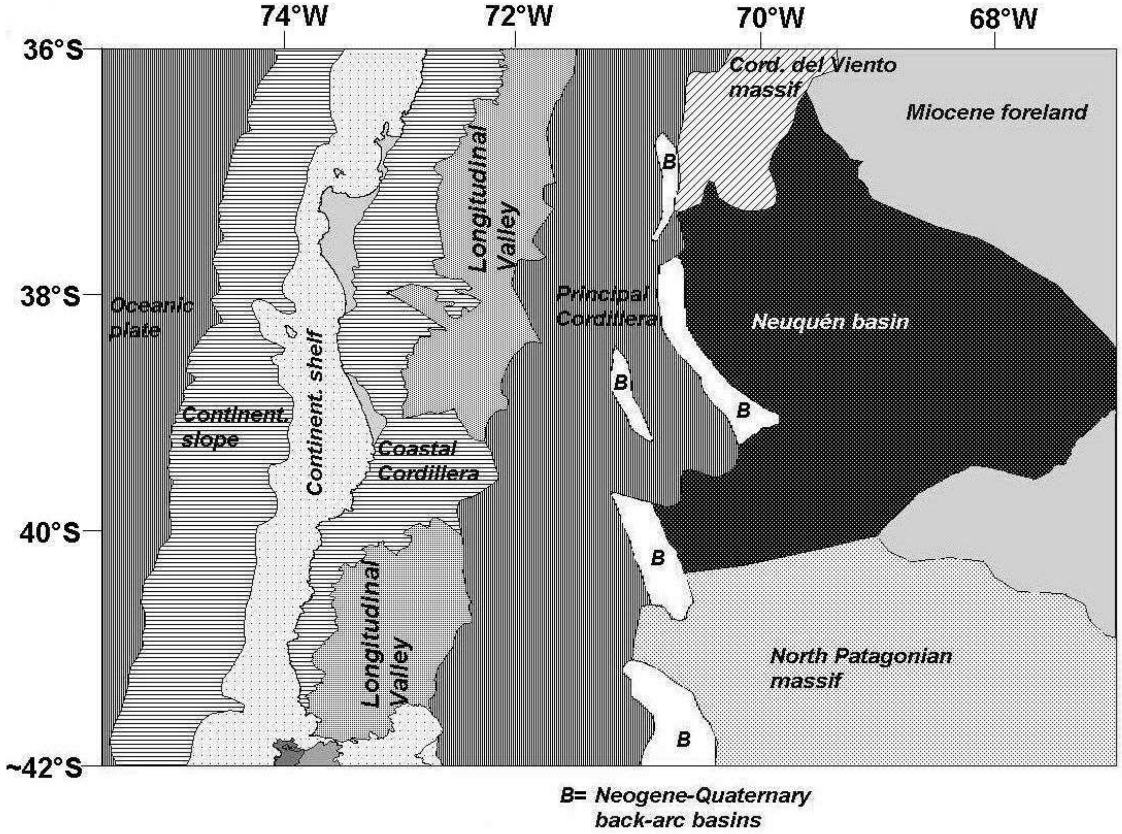

Figure 2.5
The main morphotectonic units in the study area, modified after Melnick (2003, pers. comm.). The displayed units are reproduced in the density model, where they construct upper-crustal layers (Figure 5.16).

The Longitudinal Valley, an active extensional depocentre since the Late Oligocene, is filled with sediments up to several kilometers thick (Jordan et al., 2001). It runs through the study area with a discontinuity between 39°S and 40°S. Formation of the Central Valley basin started during a major phase of Late Oligocene to Middle Miocene extension (Muñoz et al., 2000; Jordan et al. 2001), synchronous to the start of major shortening in the Central Andes at ~20–24°S (Allmendinger, 1997).

The active volcanic arc is superimposed on igneous rocks of the Northern Patagonian Batholith (south of 38°S) that are Cretaceous-Late Tertiary in age. Together they form the Patagonian Cordillera (Tassara & Yáñez, 2003). The rocks of this part of the magmatic arc are granites, granodiorites, diorites and tonalites and they occur mainly along the western part of the cordillera south of 38°S (Cingolani et al. 1991 and references therein.) The volcanic arc is aligned along the major Liquiñe-Ofqui Fault Zone (LOFZ) that cuts the upper plate for more than

1000 km between 38°S and 46.5°S (Figure 2.3) (Hervé et al., 1994; Cembrano et al., 2000). North of 38°S the volcanic arc is part of the Principal Cordillera (Hildreth & Moorbath, 1988). The volcanic rocks (andesitic in composition) form, together with sediments, a volcano-sedimentary basin (Mpodozis & Ramos, 1989; Jordan et al., 2001). The volcanoes, situated ~270 km away from the trench and almost parallel to it, form a belt that is approximately 80 km wide (López-Escobar et al., 1995). They are closely associated, and probably also controlled by the LOFZ. Other major and minor NW-SE trending faults in this area are also related to this fault system (Figure 2.3). Along these faults, plutonic rocks probably of Tertiary age, are in contact with the volcanic rocks (Cingolani et al., 1991).

The Cordillera del Viento massif is a mountain range with altitudes reaching 4500 m at Cerro Domuyo. Palaeozoic and Triassic basement outcrops in the nucleus of a ~35 km wide, north-plunging anticline, with Mesozoic sediments and Paleocene-Eocene volcanics on the flanks. This massif experienced a first stage of uplift during the Late Cretaceous (Ramos, 1978) and reactivation and folding during the Cenozoic.

The Neuquén Basin was formed as a rift basin in the early Mesozoic and lies in north-western Patagonia, on the eastern foreland of the Andes. It is filled with several kilometers of sediments (~5 km), mainly marine, with important hydrocarbon resources (e.g. Mpodozis & Ramos, 1989; Cobbold & Rosselo, 2003).

Neogene-Quaternary backarc basins, located in the Argentinean Andean foothills in an inner backarc position, form an en-echelon arrangement up to ~40–50 km wide of elongated depressions filled with Neogene to Quaternary volcano-sedimentary sequences (Kley et al., 1999). The northern basins, Andacollo (37°S) and Loncopué (38°–39°S) are associated with extensive Quaternary monogenetic basaltic volcanism (Muñoz and Stern, 1988; Stern, 1989), related to extensional tectonics, crustal thinning, hence mantle upwelling.

The North Patagonian Massif is situated south of the Neuquén basin, between the Principal Cordillera in the west and Atlantic coast in the east. It is composed partly of Precambrian metamorphic basement, Palaeozoic-Triassic granitoids, and partly of Triassic – middle Jurassic volcanic rocks with minor local development of Cretaceous sediments and Cretaceous – recent plateau basalts (Cingolani et al., 1991).

2.3 Geological segmentation – local scale

Three domains along the Southern Andes have been defined, based mainly on differential forearc and Principal Cordillera signatures, derived from geological, geomorphological and, as will be shown later, also from gravity field observations. These are: (1) the Arauco-Lonquimay, (2) the Valdivia-Liquiñe and (3) the Bahía Mansa-Osorno segments (Fig. 2.3) (Echtler et al., 2003, Melnick et al., 2002).

The segment north of Arauco-Lonquimay is bordered by the Bío-Bío-Aluminé Fault (BBAF Figure 2.3), and characterized by active shortening and compression in the backarc, as well as by a pronounced gravity low. However, this area is out of the focus of this work, and will not be discussed in further detail.

2.3.1 Arauco - Lonquimay (37°S–39°S)

The northern boundary of this segment is the Bío-Bío fault (BBAF) in the forearc, and the Callaqui-Copahue-Mandolegüe transfer zone (CCM) in the intra-arc zone (Figure 2.3) (Folguera and Ramos, 2000; Melnick et al., 2002). To the south it is bounded by the Mocha-Villarica Fault Zone (MVFZ; Fig.2.4), which crosses the entire active margin. The main characteristics of this segment are the Arauco peninsula, the most westward coastline (min. ~70 km distance to the trench) and the broadest on-shore forearc of the southeastern Pacific-Andean margin. The Arauco peninsula is an uplifted block of continental shelf that records temporal and spatial discontinuous marine and continental forearc basin formation (Figure 2.7) since Late Cretaceous (Pineda, 1986). Alternating episodes of uplift/erosion and subsidence/sedimentation are evident from the geological record and paleogeographic reconstructions (Pineda, 1986), possibly related to alternating cycles of tectonic accretion and erosion since the Pliocene (Bangs and Cande, 1997). Since the Early Quaternary, the active forearc deformation has been dominated by regional coastal uplift (Plafker and Savage, 1970; Kaizuka et al., 1973; Nelson and Manley, 1992). The volcanic arc is ~280 km from the coast, the largest distance of all the segments within the study area. The Arauco-Lonquimay segment includes the highest relief in the entire Coastal Cordillera, exceeding ~1500 m in the Nahuelbuta Range (Figure 2.4). The Nahuelbuta Mountains are mainly composed of intrusions of granitoids of Upper Palaeozoic age, but also include minor Upper Triassic intrusions (Creixell et al., 2002).

The granitoid intrusions, together with the metamorphic rocks of the Palaeozoic basement, form the accretionary wedge. In the Arauco-Lonquimay segment, these metamorphic rocks are dominated to 38°S by the Eastern Series low P/T rocks, mostly metapelites and metapsammites (with no mafic metavolcanics, metacherts or serpentines), (Glodny et al., 2002). South of 38°S, the high P/T metamorphic rocks of the Western Series characterize the accretionary complex. The contact between the Eastern and Western Series is present as a large-scale sinistral transform fault referred to as the Lahnaluhe Fault Zone (sometimes referred to as the Gastre Fault Zone (GFZ)).

The Central Valley of this domain shows a half-graben geometry with a significant Quaternary infill. Along the arc, the CCM transfer zone (Figure 2.3) decouples the Quaternary-to-Recent backarc shortening from LOFZ-dominant intra-arc transtension.

2.3.2 Valdivia - Liquiñe (39°S–40°S)

The Valdivia - Liquiñe segment is characterized by a relative retreat of the coastline (max. ~150 km from the trench), with volcanoes situated 250 to 270 km from the trench. The major Valdivia basin characterizes the off-shore forearc (Mordojovic, 1981). Recent minor uplift is limited to the coastal area, whereas 10–20 km coseismic subsidence may still dominant inland (Plafker and Savage, 1970). The topography of the Coastal Cordillera here does not exceed a few hundred meters (Figure 2.4). The accretionary complex is dominated by the Western Series high P/T metamorphic rocks that are considered to be the paleo-accretionary forearc complex. It is a melange of metapelites, metapsammites, and oceanic lithologies, such as metabasites with thoelitic/MORB affinity, serpentines, and the metacherts with maximum matamorphic conditions of transitional greenschist-blueschist facies (Herve, 1977; Willner et al., 2004). Internal structure suggests penetrative ductile deformation and the formation of nappe structure at near-peak metamorphic conditions (Glodny et al., 2002). The Western Series complex in the Valdivia region is believed to have been built by long term underplating (continuous basal accretion for at least 50 Ma), with long term average exhumation and corresponding erosion rates of ~0.6 mm/a (Glodny et al., 2002).

The most outstanding morphotectonic feature of this segment is the absence of a Central Valley (Figure 2.5). The low-relief Coastal Cordillera has a direct morphologic transition to the Main Cordillera. Neogene to recent deformation along the intra-arc in the Liquiñe area shows strike-slip kinematics. F-T thermochronology shows high arc exhumation rates since the Pliocene (Rosenau, 2004; Gräfe et al., 2002).

2.3.3 Bahía Mansa - Osorno (40°S–42°S)

This Bahía Mansa - Osorno segment, south of 40°S, is characterized by a trench-coastline distance of around 110 km. The topography of the narrower Coastal Cordillera is moderate, as in the Valdivia-Liquiñe segment. The accretionary complex here is also represented by the Western Series metamorphic rocks. The volcanoes are located some 220 to 250 km from the trench. The most pronounced feature of this segment is the well developed Central Valley, which is a sedimentary basin of extensional origin. N-S trending normal faults, partly inverted, along the western contact with the Coastal Cordillera, have controlled the basin formation since the late Oligocene (Muñoz et al., 2000; Jordan et al., 2001). Quaternary infill is locally up to 3000 m in thickness (McDounough et al., 1997), emphasizing the ongoing subsidence. The intra-arc zone, composed mainly of the ~10 km deep roots of the Cretaceous to Miocene volcanic arc (Seifert et al., *in press*), also has a low average topography, ~1500 m, and is dominated by dextral strike-slip deformation along the LOFZ (Lavenu and Cembrano, 1999).