CHAPTER 1
THE SOUTHERN ANDES

The Andes of South America are a natural laboratory for the study of the processes of subduction and mountain building under a variety of tectonic and climatic settings. This study focuses on the Southern Andes (also termed the North Patagonian Andes) between latitudes 38°S and 42°S. They are compared with the high and broad Central Andean plateau and Bolivian orocline a relatively narrow and low-relief mountain belt where deformation has been localized within the intra-arc zone for at least 180 Ma. Potential factors controlling the difference in topography and deformation along the South American margin are: (1) plate kinematic parameters, (2) interplate coupling, (3) the physical properties of the overriding plate, and (4) climatic parameters. Prerequisite for the geodynamic discussion of those steering factors are quantitative kinematic constraints of intra-overriding plate deformation. Whereas the tectonic evolution of the Central Andes is very well constraint meanwhile, analogous kinematic constraints are still short of in the Southern Andes, preventing a meaningful discussion. It is the aim of this study to contribute to this discussion by providing first quantitative constraints on the tectonics of the Southern Andes.

To reveal the relative importance of climatic and tectonic control on the Southern Andean topography, morphometric analysis and isostatic modeling has been performed (Ch. 3). Based on structural mapping of key-areas and petrologic studies (Ch. 4) combined with isotopic dating of magmatic and metamorphic mineral assemblages (Ch. 8), and morphostructural interpretation of digital imagery (Ch. 5) combined with fault kinematic analysis (Ch. 6), the tectonic evolution of the intra-arc zone between latitudes 38°S and 42°S has been reconstructed. Finally, deformation associated with the most prominent tectonic feature of the Southern Andes, the Liquiñe-Ofqui Fault Zone, has been quantified (Ch. 7).

1.1 Climatic setting

The study area is located between the arid to temperate climate of Central Chile and the glacial climate of Southern Chile and is characterized by a moderate oceanic/humid climate. Whereas the northern part of the study area is influenced by the south-easterly Tradewinds, the southern part is influenced by the strong and moist Westerlies focusing erosion on the seaward side of the Andes. The mean annual temperatures are between 10 - 13°C, frost is seldom at lower altitudes and there is no vegetative pause (Hueck, 1966).

Climatic parameters and indicators vary both across and along strike of the Southern Andes: The annual rainfall decreases eastward across the Southern Andean cordillera and northward along the margin from more than 300 cm/a at Isla Chiloé (42°S, 74°E) to less than 50 cm/a in the Argentine Pampa at 38°S/70°E (Ziegler et al., 1981). Accordingly, the vegetation changes from the Valdivian evergreen forest dominated by Tique (*Aextoxicon punctatum*), Alerce (*Fitzroya patagonica*), and Arranyanales (*Luma apiculata*) typical of a high-moisture, moderate temperature climate south of ca. 40°S to the summergreen Nothofagus woods dominated by Roble (*Nothofagus oblique*), Rauli (*Nothofagus procera*), and Araucaria (*Araukaria araucana*) characteristic for the dry and temperate climate north of 40°S (Hueck, 1966).

Since 7 Ma, several glacial events occurred in the Southern Andes (Mercer and Sutter, 1982, Rabassa and Clapperton, 1990, Lliboutry 1956, 1999), the latest of which is the Llanquihue event 13.9 - 33.5 ka ago (Mercer, 1976, Lowell et al., 1995). During the Llanquihue event, glaciers occupied almost the entire continental margin south of 40°S, where the ice front reached the coast. North of 40°S, glaciers occupied only the higher parts of the Southern Andean Main Cordillera. Mean annual temperatures were probably 4 – 6°C lower than today (Mercer, 1976). Until 11 ka b.p., the ice cap shrinked to leave glaciers principally of the same extent as today. Ice-melting induced global Holocene sea level rise may have been about 110 m (e.g. Haq et al., 1988), roughly the same order of magnitude as post-glacial rebound (Ivins and James, 1998, James and Ivins, 1999). Rates of erosion dropt from up to 8 mm/a during the glacials to ca. 1 mm/a (Scholl et al., 1970).

1.2 Plate tectonic setting

The present day plate tectonic setting of the Southern Andes is illustrated in Fig. 1.1. North of the Chile Triple Junction (CTJ), where the Chile Ridge, an active spreading center (Tebbens et al., 1997), is currently colliding with the active margin, the Nazca Plate subducts at an dip angle of ca. 25 - 30° (Barazangi and Isacks, 1976, Bohm et al., 2002) beneath the South American Plate in a northeasterly (ca. N80°E) direction at a rate of ca. 66 mm/a (Angermann et al., 1999). This dextral oblique subduction geometry has existed basically throughout the Cenozoic interrupted by a short period of orthogonal convergence between 20 – 26 Ma (Cande and Leslie, 1986, Pardo-Casas and Molnar, 1987, De Mets, 1990, 1994, Somoza, 1998). South of the CTJ, the Antarctic Plate is subducted almost orthogonal to the trench (to the east) at a rate of ca. 20 mm/a (DeMets et al., 1994). Subduction of the Chile Ridge started ca. 14 Ma ago at the southern tip of South America and has migrated northward along the trench since then (Cande and Leslie, 1986, Ramos and Kay, 1992, Gorring et al., 1997).

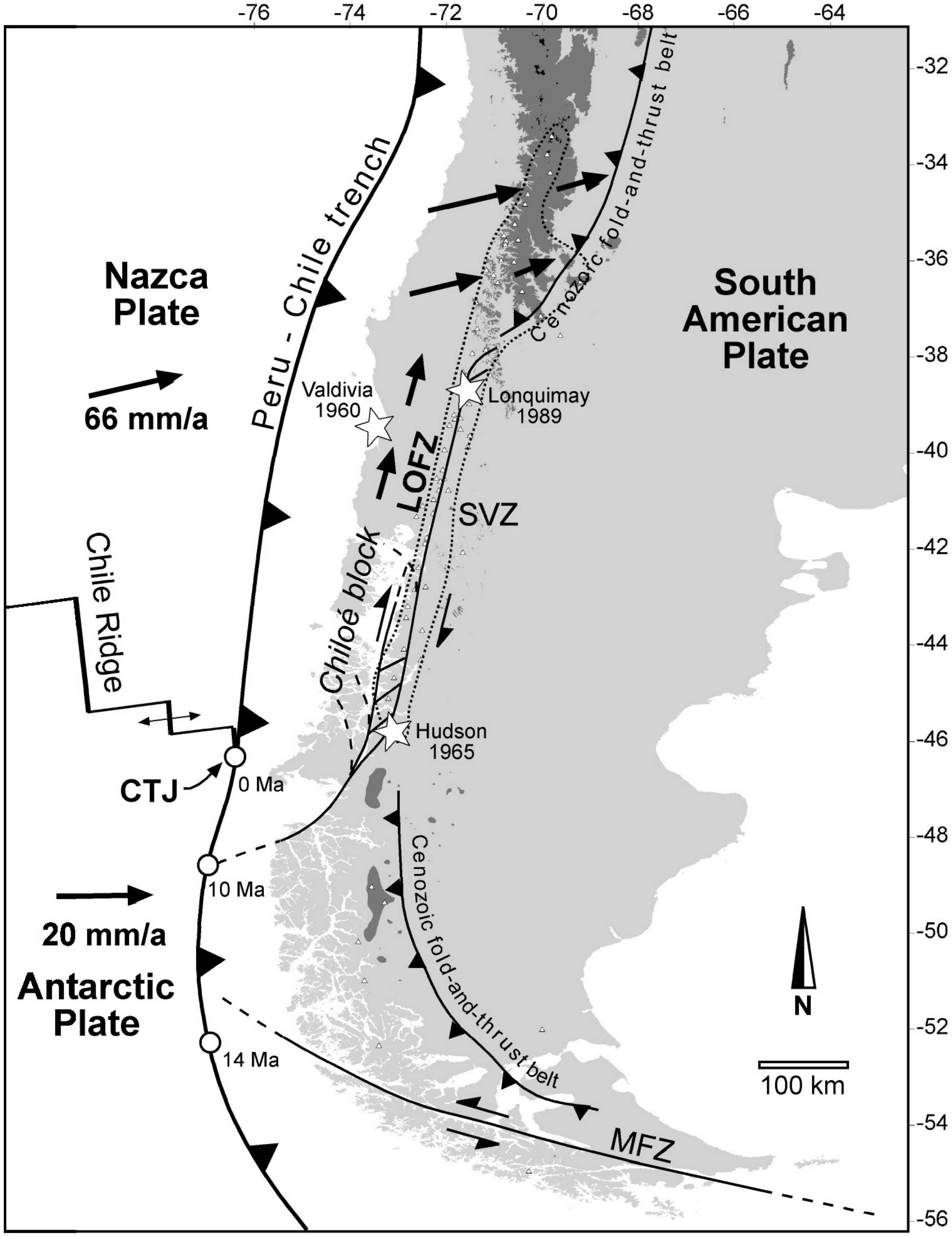

Fig. 1.1: *Plate tectonic setting of the Southern Andes. Abbreviations: LOFZ = Liquiñe-Ofqui Fault Zone, MFZ = Magellanes Fault Zone, CTJ = Chile Triple Junction (dots indicate the northward migration of the CTJ during the Neogene), SVZ = Southern Volcanic Zone of the Andes. Stars mark the locations of historic earthquakes (associated with volcanic eruptions in the SVZ). Arrows indicate horizontal displacements. Dark shaded continental areas are higher than 2000 m.*

An active volcanic arc (the Southern Volcanic Zone of the Andes, SVZ, Lara et al., 2001, Lopéz-Escobar and Vergara, 1997, Stern and Skewes, 1995, Lopéz-Escobar et al., 1995, Stern, 1989, Muñoz and Stern, 1988) is developed 250 - 300 km east of the trench. The depth of the subducted slab beneath the SVZ is ca. 90 km (Stern, 1989), substantially less than beneath the Central Volcanic Zone of the Andes (ca. 130 km, Barazangi and Isacks, 1976).

The crustal thickness of the South American plate in the studied segment is ca. 35 - 40 km beneath the magmatic arc (Lüth et al., 2003, Bohm et al., 2002). This rather normal crustal thickness (compared to the Central Andean 60 - 70 km thick crust, Beck et al., 1996) is reflected by the relatively low relief of the Southern Andean Main Cordillera (highest peaks around 3 km, mean elevation ca. 1 km) with respect to the high Central Andes (highest peaks around 6 km, plateau at ca. 4 km). The Southern Andes are also a relatively narrow mountain belt compared with the Central Andes (300 km versus 800 km). It is noteworthy that, although subduction may have occurred since the Jurassic, the modern Andes are a relatively young orogen mainly built during the past 25 Ma (Mpodozis and Ramos, 1989, Dewey and Lamb, 1992, Lamb et al., 1997).

Active subduction-related deformation in the Southern Andes is localized mainly at the plate interface and accommodated by mega thrust earthquakes like the hazardous magnitude 9.5 earthquake in the Valdivia area in 1960 (Plafker and Savage, 1970, Cifuentes, 1989, Beck et al., 1998). Minor intracontinental deformation is evidenced by intracrustal seismicity in the fore-arc region (Bohm et al., 2002) and in the intra-arc region (Barrientos and Acevedo, 1992, Chinn and Isacks, 1983).

1.3 The Liquiñe-Ofqui Fault Zone

The most prominent tectonic feature of the Southern Andes is the Liquiñe-Ofqui Fault Zone (LOFZ, Steffen, 1944, in Hauser, 1991, Hervé, 1976, Cembrano, 1998), a more than 1100 km long intra-arc strike-slip fault zone linking the southernmost parts of the Andean foreland fold-and-thrust belt at ca. 37°S, i.e. the Malargüe thick-skinned fold-and-thrust belt (Ramos et al., 1996), with the CTJ at ca. 47.5°S (Fig. 1.1). It has been originally described as an alignment of several margin parallel lineaments through volcanoes or along valleys and fjords. Cembrano and Hervé (1993) interpreted en échelon oriented valleys and fjords in the southern part of the LOFZ (44 – 46°S) as a crustal scale duplex structure. More recent structural (Lavenu and Cembrano, 1999, Arancibia et al., 1999, Cembrano et al., 2002) and thermochronological (Thomson, 2002) studies have demonstrated the neotectonic dextral transpressional kinematics of this duplex structure. Based on paleomagnetic data, NW-SE trending lineaments has been interpreted as dextrally reactivated, pre-Andean strike-slip faults bounding sickle shaped fore-arc blocks which rotate anticlockwise driven by oblique subduction ("buttress" model, Beck et al., 1993). The southern and northern terminations of the LOFZ are described as neotectonic transtensional horsetail structures in the literature (Potent, 2003, Diemer and Forsythe, 2000).

The LOFZ decouples a fore-arc sliver, the Chiloé block, from the rest of the South American continent. As an effect of strain partitioning, the Chiloé block moves northward whereas the back-arc remains undeformed. This leads to a N-S segmentation of the active margin. Further north, where the LOFZ does not serve as a decoupling structure, oblique convergence is not partitioned. Instead convergence-induced compressive forces are transferred into back-arc transpressional structures (e.g., Dewey and Lamb, 1992). This is indicated by the parallelism between the Nazca-South American plate convergence vector and active shortening directions in the back-arc north of ca. 37°S (Reinecker et al., 2003, Khazaradze and Klotz, 2003, Ruegg et al., 2002, Klotz et al., 2001).

The exact nature of the transition between the southern, partitioned segment and the northern, non-partitioned segment is, however, controversial: Dewey and Lamb (1992) suggested a 500 – 600 km long transitional segment between 34 – 39°S, where the hypothetical E-W oriented dextral shear component required by differential amounts of back-arc shortening north and south of it is accommodated by diffuse deformation manifested by a dextral kink in the trench and coast line between 33 – 37°S. Potent (2003) suggested that differential movements are accommodated by a crustal scale horse tail structure at 37.5 – 38°S. Melnick et al. (in prep.) suggest that a NE-SW striking transfer fault manifested by the Callaqui-Copahue volcanic alignment at 38°S accommodates the required shear.

1.4 Morphotectonic units and geological overview

The Southern Andean continental margin shows a margin-parallel segmentation from west to east into four morphotectonic units (Fig. 1.2): (1) the offshore fore-arc/Arauco peninsula, (2) the outer fore-arc/Coastal Cordillera, (3) the inner fore-arc/Longitudinal Valley, and (4) the intra-arc/Main Cordillera. The back-arc consists of Paleozoic (or even older, Rolando et al., 2002) to Early Triassic metamorphic and magmatic rocks (Rapela and Kay, 1988, Forsythe, 1982, Caminos et al., 1988, Linares et al., 1988) of the North Patagonian Massif (or Patagonian Platform) representing the Gondwana craton. The back-arc basement is covered in places by sedimentary and volcanic rocks of Late Paleozoic to Quaternary age, for example deposits of the Late Triassic – Early Tertiary Neuquén basin in west-central Argentina (Eppinger and Rosenfeld, 1996, Vergani et al., 1995, Franzese and Spaletti, 2001, Cobbold et al., 1999) or of the Jurassic volcanic belt in southernmost Chile (Parada et al., 1997).

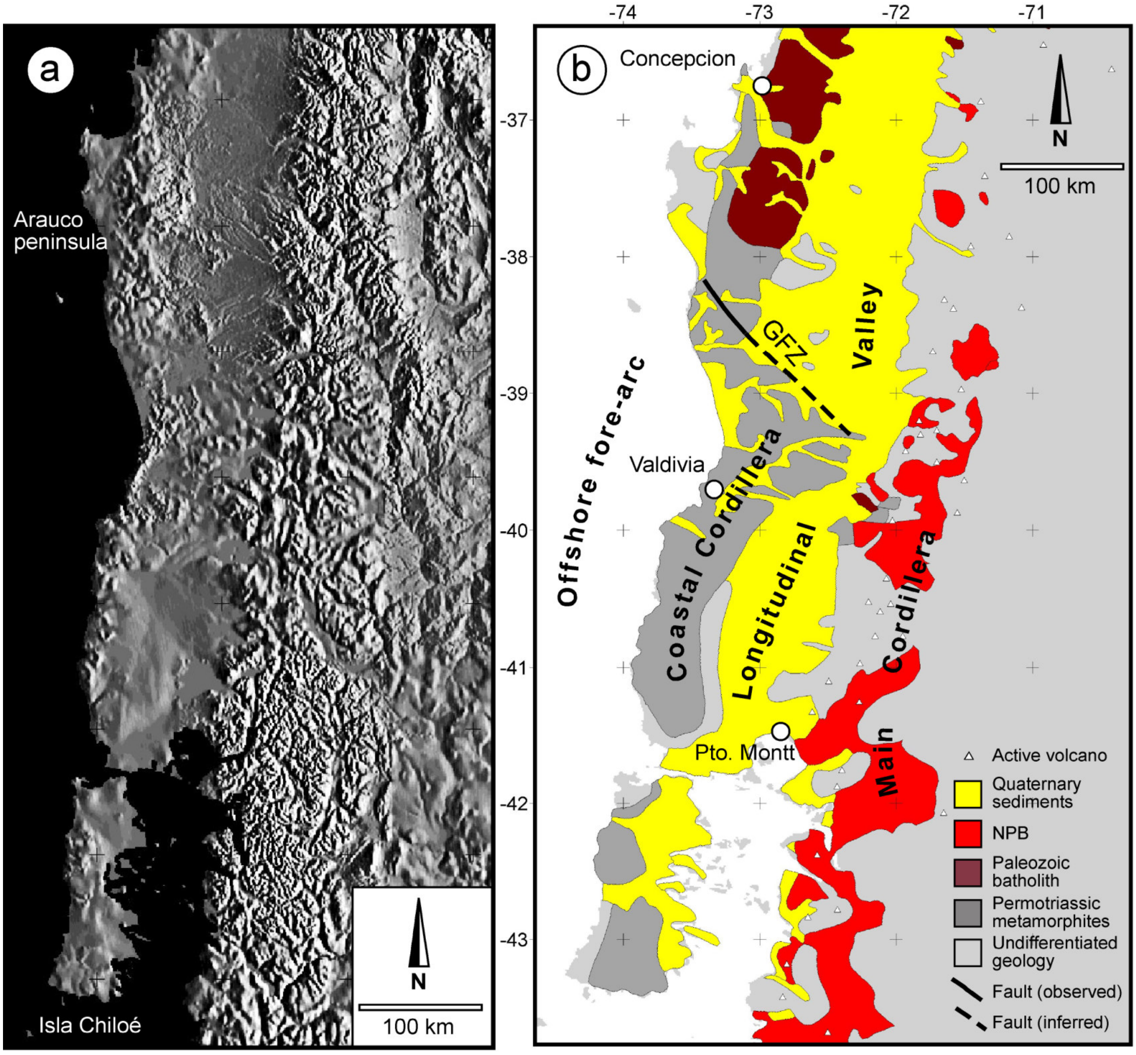

Fig. 1.2: *Morphotectonic units of the Southern Andes. a) DEM, illuminated from the E, 30° inclined, b) Tectonic units and simplified geology. Abbreviations: GFZ = Gastre Fault Zone, NPB = North Patagonian Batholith.*

1.4.1 Offshore fore-arc/Arauco peninsula

Between the 6000 – 7000 m deep trench, which is filled with 1500 - 2200 m of continent-derived sediments (Bangs and Cande, 1997, Díaz, 1999), and the Coastal Cordillera, is the ca. 100 km wide continental rise and shelf with its above sea level uplifted part, the Arauco peninsula. It consists of Upper Cretaceous to Quaternary sedimentary basins (e.g. the Itaca, Arauco, Valdivia basins, Mordojovich, 1974, 1981, Gonzales, 1989) with up to 3000 m infill on top of Paleozoic – Early Triassic metamorphic basement. These Basins are separated by actively uplifting basement highs (for example the Mocha high at 38.25°S actively uplifting at a rate of 5 – 70 mm/a, Kaizuka et al., 1973, Nelson and Manley, 1992).

The shelf topography is characterized by submarine canyons with up to 400 m high flanks (Thornburg et al., 1990). At the leading edge, the basement is truncated and a small accretionary wedge has been developed which is less than 1 – 2 Ma old (Bangs and Cande, 1997). Several NW-SE trending, active sinistral strike-slip faults cross-cut the shelf probably as a result of block-rotation due to oblique subduction (Reichert et al., 2003). Trench-normal extension indicated by active trench-parallel normal faults along with uplift of the shelf region is interpreted as a combined effect of adjustment of the accretionary wedge to the critical taper and underplating of subducted sediments (Lohrmann et al., 2000, Boettcher, 1999, Potent, 2003).

1.4.2 Outer fore-arc/Coastal Cordillera

The Coastal Cordillera represents a trench parallel basement high with maximum elevations around 1500 m (Cordillera Nahuelbuta). It is made up of two lithologic units representing a pre-Andean paired metamorphic belt: the Western and the Eastern Series (Hervé, 1977). The Western Series basement consists of a tectonic mélange of metapelites, metabasites, metacherts, metagreywakes, metapsammites, and serpentinites. This unit has indications for a high-pressure/low-temperature metamorphic history (greenschist to blueschist facies, Willner et al., 2001, 2003, Glodny et al., 2002) and is interpreted as the basal part of a Permotriassic accretionary wedge developed along the SE-margin of Gondwana (Aguirre et al., 1972). The Eastern Series rocks are metagreywakes, phyllites, hornfelses, and gneisses which show indications for a low-pressure/high temperature metamorphic history (greenschist to granulite facies) associated with the emplacement of a Carbonifereous batholith (González-Bonorino, 1970, Hervé, 1977). This unit is interpreted as a Permocarbonifereous magmatic arc (Martin et al., 1999, Willner et al., 2000). The Eastern-Western Series contact strikes generally N-S but is sinistrally offset at ca. 39°S by the NW-SE trending Gastre Fault Zone (GFZ, Rapela and Pankhurst, 1992), active during the Permo-Triassic (Glodny, pers. comm.).

The pre-Andean basement of the Coastal Cordillera had been exhumed during the Early Triassic as indicated by discordantly overlaying Middle Triassic sediments (Ferraris, 1981). Since then, renewed subsidence and exhumation did not exceed ca. 4 km (Seifert et al., in press, Gräfe, pers. comm.). The Coastal Cordillera is characterized by NE-SW and NW-SE trending lineaments related, respectively, to Triassic rifting and to Permotriassic foliation and thrusts of the paleo-accretionary wedge (Muñoz, 1997, Hervé, 1977). The drainage system reflects this orthogonal pattern which is modified by first order, E-W directed rivers cutting through the Coastal Cordillera (e.g. Río Imperial, Río Toltén). The Coastal Cordillera shows principally the same extensional tectonics during the Neogene as the Arauco peninsula (Potent, 2003)

1.4.3 Inner fore-arc/Longitudinal Valley

The Longitudinal Valley is an on average 70 km wide, Tertiary to Quaternary depocenter between the Coastal and Main Cordilleras. It parallels the margin for about 1000 km from Santiago to Puerto Montt, where it subsides below sea level. It has been tectonically active as a graben throughout the Tertiary (Lavenu and Cembrano, 1999, Jordan et al., 2001) but is uplifting at least since the Holocene (Hervé and Ota, 1993). Between 39.5 and 40°S, the Longitudinal Valley is discontinued by a basement high (Loncoche Horst). Tertiary volcano-sedimentary deposits of the Longitudinal Valley have thicknesses up to 3000 m and maximum ages dating into the Eocene (Illies, 1967, Muñoz and Araneda, 2000, Stern et al., 2000, Jordan et al., 2001). These deposits are overlayn by Pliocene-Quaternary volcanics and volcanoclastics, and fluvial and fluvio-glacial deposits. The Longitudinal Valley shows a W to NW-directed, parallel drainage which cuts deep into the oceanward dipping, uplifting surface (Endlicher and Mäckel, 1985). The internal active deformation pattern of the Longitudinal Valley suggests coeval margin-parallel extension, shortening, and block rotation (Potent, 2003, Lavenu and Cembrano, 1999).

1.4.4 Intra-arc/Main Cordillera

The Main Cordillera of the Southern Andes is an on average less than 1200 m high, ca. 200 km wide mountain belt. It consists of the Pliocene to active volcanic arc (SVZ) on top of an eroded, Late Jurassic to Miocene magmatic arc (the North Patagonian Batholith, NPB, Pankhurst et al., 1992, Mpodozis and Ramos, 1989). The age distribution within the NPB shows a longitudinal zonation with a younging towards the center of the batholith (Pankhurst et al., 1999). Geothermobarometric (Parada et al., 2000, Hervé et al., 1996, Seifert et al., in press) and thermochronologic (Thomson, 2002, Gräfe, pers. comm.) studies indicate that exhumation of the NPB increases southward (up to 25 km) and has occurred after the Miocene. North of ca. 39°S, where the NPB is less deeply eroded, Jurassic to Miocene intra-arc basin deposits are locally preserved (Jordan et al., 2001 and references therein). Mpodozis and Ramos (1989) were the first who raised the hypothesis that this exhumation gradient may be due to higher erosion in the south. It was one aim of this work to test this hypothesis.

Occurrences of pre-Andean basement are along the western foothills of the Main Cordillera in the Lake District (39.5 – 40.5°S) where they are correlated with the Eastern Series of the Coastal Cordillera (Martin et al., 1999, Munizaga et al., 1988) and along the Chile-Argentine border (Lara and Moreno, 1998, Linares et al., 1988). The age and regional relation of the latter is largely unknown and the topic of an isotope geochronological and geochemical study as a part of this work.

The Main Cordillera has been the locus of magmatic and tectonic processes throughout the Andean history including phases of extension and basin formation, compression and mountain building, and strike-slip deformation. The picture of this longlasting tectonic, metamorphic, magmatic, and morphologic evolution is still incomplete or misleading. It is the major aim of this work to complete and improve this patchwork picture.