Chapter 3

Geological Background

The Andes belong to an active continental margin comprising the western margin of South America. The name is attributed to the mountain chain, which stretches over 5000 km from the Caribbean to Tierra del Fuego. Their relief rises east of the 8000 m deep sea trench reaching heights up to 7000 m above sea level, ones of the highest peaks on earth. The oceanic Nazca plate moves to the east subsiding beneath South America, with a relative velocity with respect to each other of 8.5 cm/yr (fig.3.1). The convergence between the two plates has a slight ENE obliqueness.

The Andes are divided into three distinct active volcanic zones of different subduction geometries: Northern, Central and Southern Andes (fig.3.1). The Central Andes stretch in between latitudes 16°S and 28°S. In this thesis, the study area is located in the southern part of Southern Central Andes (20-21°S).

Overview of the Central Andes

As in all subduction zones, the Andes is segmented in forearc, magmatic (or volcanic) arc and backarc regions. The volcanic arc has shifted eastwards since Jurasic times (280 Ma). The recent volcanic arc from the last 25 Ma is the Western Cordillera (fig.3.2). Thus the actual **forearc** is located west of it, consisting from the coast line to the east of the following geomorphological units: *Coastal Cordillera*, *Longitudinal Valley*, *Precordillera* and Preandean Depression (fig.3.2; inset). In the backarc region the Subandean ranges mark the eastern limit of the Andean tectonic deformation, rising up to 6000 m high to the west, at the Eastern Cordillera. In between both structures are located the *Altiplano* and Puna (fig.3.2). They constitute the high-plateau of the Andean system, in which the greatest regional tectonic uplift since around 25 Ma ago have developed, associated in general with horizontal shortening, crustal thickening and magmatic intrusion processes (e.g., Allmendinger et al. [1997]).

The Coastal Cordillera, Longitudinal Valley, Precordillera and Western Cordillera comprise the region of the study area (fig.3.2). These geomorphological units belong to the evolution of the magmatic arc since the Jura until Recent times, where the volcanic activity has drifted from west to east over time.

The geomorphological units mentioned above develop according to other terms of tectonic

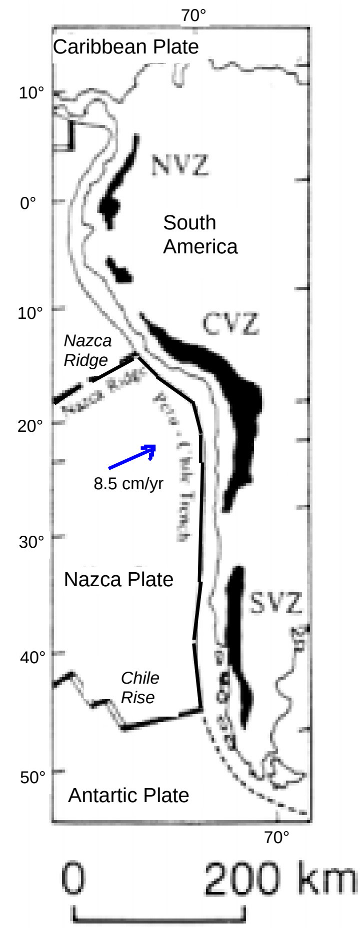

Figure 3.1:
Subduction geometry of the South American plate. The oceanic Nazca plate subsides with a slight ENE obliqueness beneath the South American continent. The Central Andes comprises the Central Volcanic Zone (CVZ). NVZ and SVZ are Northern and Southern Volcanic zones of Andes. Modified picture after de Silva [1989].

and magmatic evolution, such as the convergence rate and geometry of the subduction. An important controlling factor for the deformation in the magmatic arc is the angle of convergence obliqueness, which has led to the deployment of two mega strike-slip faults of approximately N-S trend (Scheuber and Reutter [1992]). One is the so called **Atacama fault** (AF) originally formed in the past jurassic magmatic arc (the actual Coastal Cordillera; fig.3.2). The other mega fault system is the **West Fissure** located in the Precordillera, the former Late Cretaceous-Paleogene arc (fig.3.2; WF). More information will be given with respect to these tectonic features since they are the important conductivity structures identified in the regional 3-D modeling (Chapter 10).

In the following are described briefly the history and composition of the geomorphological units involved in the volcanic evolution of the Andean cycle (since the Jura; 210 Ma), documenting principally the results described by Scheuber and Reutter [1992].

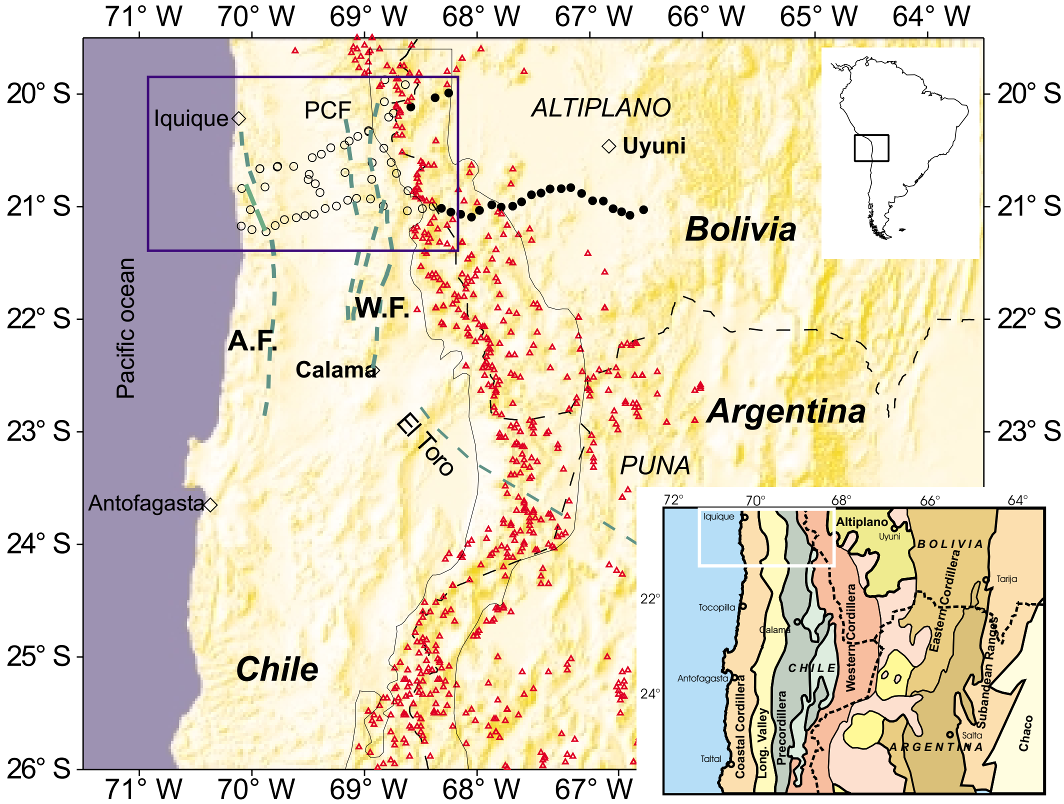

Figure 3.2: Relief geographical map of Southern Central Andes showing the modern volcanic arc (Western Cordillera; enclosed by dark lines). Open triangles indicate the volcanoes of the last 25 Ma. Thick dashed lines indicate the regional faults. In the Coastal Cordillera is located the Atacama fault (A.F), in the Precordillera the West fissure (W.F.). Both are mega strike-slip faults associated with the evolved oblique convergence of the oceanic plate beneath South America. The W.F. and the thrust fault (PCF) to the west belong to the Precordillera fault system. The rectangle marks the study area, open and dark dots are the MT sites of the Chile and Bolivia campaigns, respectively. Inset above shows the study area in South America. Inset in the bottom shows the study area (white rectangle) within the geomorphological units of Southern Central Andes (after Reutter et al. [1994]).

3.1 Coastal Cordillera and Atacama fault

The Coastal Cordillera was the Jurassic-Lower Cretaceous (210-124 Ma) volcanic arc. The ductile crust underwent into transtensional deformation due to a high convergence obliqueness, leading to N-S sinestral shear deformations −the so called Atacama fault− together with orogen-normal extensions. The mineral assemblages in metapelitic mylonites and mafic mylonites (amphibolites) indicate that high temperature/low pressure conditions were concentrated in the former magmatic arc.
The Coastal Cordillera is today conformed by 77% of mafic and felsic dykes, and by big mantle-derived batholith of gabbro- to granodioritic compositions from this time. The intrusion of the plutons reach depths of about 10 km. The mantle-derived composition of the crust and the evidence of orogen-normal extensional regime during the Jura suggest that a crustal thinning occurred, where melt intruded opening magma chambers, similar to continental rifting (Scheuber and Reutter [1992]).
The Coastal Cordillera (CC) is limited to the west with a prominent "coast scarp" and to the

east with the Longitudinal Valley, with an average E-W width and height of 70 km and 1000 m, respectively. East of the coast scarp stretches the approximately N-S trending Atacama fault zone, the "trench-linked strike slip fault" (Scheuber and Reutter [1992]) of 1000 km long from latitude 19.5°S to 29°S. The strike slip displacement (i.e, horizontal) was of about 50 km and the vertical displacement of 10 km during the Jura.
The *coast scarp* marks the highest peaks (1600 m) of the Coastal Cordillera, and is 2-5 km away from the coast line. Some authors postulate its formation as being due to orogen-normal extension, while others allude it to as resulting from marine erosion. In a recent work by Pelz [2000] is proposed that the coast scarp was originated by an isostatic flexural rebound to compensate a loss of material caused by neo-tectonic basal erosion (since 5 Ma). The eroded material is transported within the coupling zone between the continental moho and the oceanic slab (seismogenic zone; e.g., Comte et al. [1992]) and subducts further into the mantle wedge, beneath the 45 km depth where the slab and continent are decoupled. Above this decoupled zone is located the *Atacama fault* (AF), which is not considered in the isostatic modelling.
The AF has been reactivated since Holocene-Recent times in dextral orientation, under a trans-tensional deformation regime, due to the crustal stresses arisen from the modern convergence configuration.
In the Neogene the CC was an orographic barrier for the westward drainage system of the Andes, leading to the formation of several salt-lakes with lacustrine sediments. The exception is the Rio Loa, located south of Iquique (fig.3.3), which permitted an exorreic drainage system along a W-E basin of 1000 m depth.
The lithosphere in this region is cool, below the 300°C (Springer [1999]) and brittle (crustal seismicity; fig.3.4). The depth of the Moho is 40-50 km (Wigger et al. [1994], Götze et al. [1994]) and the mantle wedge begins at these depths, possibly hydrated (serpentinized; Giese et al. [1999]), considering the low seismic velocity detected at several latitudes in this zone (Wigger et al. [1994], Lüth [2000] and others). In a cold and brittle crust an active mega strike-slip fault can reach greater depths (fig.3.4) and can serve as a long path for salinary fluids if these are present (Chapter 11).

The Atacama fault in the study area

The Atacama fault (AF) stretches NNW-SSE along 50 km between Iquique and the Rio Loa (3.3). In this region underwent the strongest neotectonic reactivation of the AF. The vertical displacement since the Oligocene is of 1,1 km, and a pull-apart basin was developed that was later covered by salt-rocks, gips and anhydrits with a maximal thickness of 160 m. This is called today the "Salar Grande", a salt flat with romboidal geometry as a product of the transtensional deformation. The Atacama fault stretches over the western limit of the Salar Grande to the north and crosses it to the south (fig.3.3). The length of the Salar is as long as the AF in this sector (50 km), and it has a maximal width of 8 km (Pelz [2000]). The AF and the Salar Grande are structurally linked. North-east of the Salar predominates a N-S crustal extension regime leading to a N-S mass transport (Pelz [2000]). Several small faults extend to the east of the AF; some of them are W-E oriented (fig.3.3).

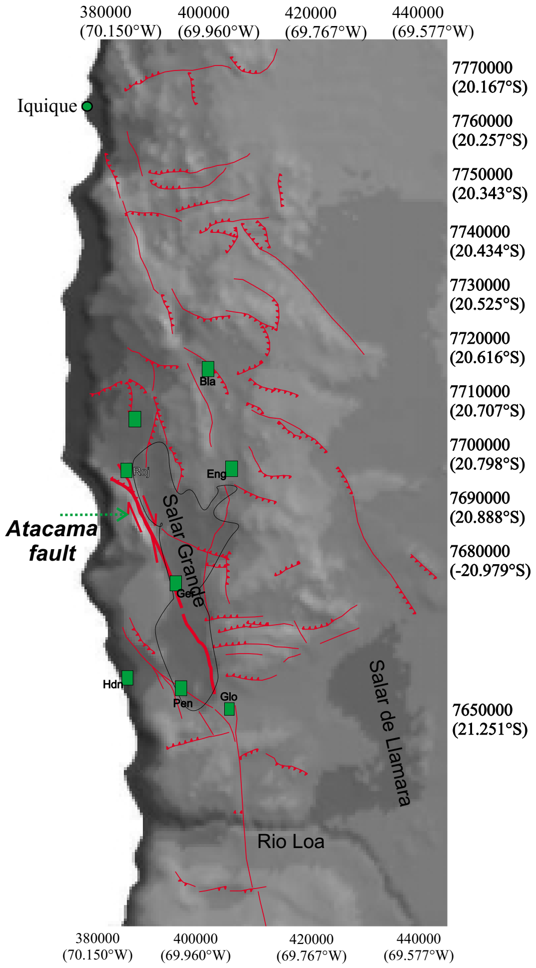

Figure 3.3: Map of the study area in the Coastal Cordillera showing diverse faults and lineaments (red lines). The *Atacama fault* is an active dextral shear zone crossing an old salt flat (Salar Grande). The deep (1000 m) drainage basin of "Rio Loa" river is in the south. The MT sites are indicated by green squares. Picture after Pelz (2000).

Longitudinal Valley

The Longitudinal Valley constituted the Mid-Createcous volcanic arc. The first stage of the magmatism developed under extensional regime (115-90 Ma) followed by a magmatic pause (90-80 Ma) associated with the oceanic ridge between the Aluk and Farallon plates. Until the Mid-Cretaceous the subduction of the Aluk plate led to extensional regime in the magmatic arc. During the Upper-Cretaceous the magmatism was reactived by the subduction of the Farallon plate (with little convergence obliqueness), leading to tectonic shortening normal to the orogen.
Most of the sediments from the Jurassic and Lower Mid-Cretaceous were folded by the crustal shortening during the Upper-Cretaceous.

3.2 Precordillera

The Precordillera (PC) was the magmatic arc of the Late-Cretaceous to Paleogene times (75-35 Ma), subjected to strong deformations due to an increase in the convergence rate.
In a first stage (∼38 Ma) it developed under compressional strengths, whereas the backarc was widened under extensional regime.

As a result of the strong orogen-normal shortening, the PC is a ∼N-S fold-thrust belt of anticlinal structure, identified as the *Precordillera fault system* (PCFS). It has a vergence to the west and east. The deformation involved older sediments, metamorphic and plutonic rocks such as granodiorites. The folds are 30 to 100 km long and $10-30$ km wide.
In a second stage the deformation became transpresional due to a higher convergence obliqueness, leading to dextral strike-slip movements of the PCFS (Reutter et al. [1995]). The deformation occurred in a weakened and heated arc's crust during a long term magmatism. Chong & Reutter (1985) proposed that the shear zone was triggered by intrusion, weakening the deeper crust levels, leading to a detachment of about 8-10 km depth.
In a third stage a reversal of the strike slip movement from dextral to sinestral occurred, when mineralization started about 32 Ma. The change of deformation is associated with a time lapse between the end of the magmatic arc in the PC and the emplacement of a new magmatic arc system in the Western Cordillera (Reutter et al. [1995]).
Along the PCFS shallow intrusive bodies subject to ductile and subsequent brittle deformations (within 650-100°C) led to an incipient mineralization manifested by copper deposits. The strongest exposure is the Chuquicamata porphyry copper deposit located in the *West Fissure*, the orogen-parallel mega strike slip fault between latitudes 20°S and 23°S (fig.3.2).
Since the Late Miocene the Recent magmatic arc is in the Western Cordillera. On that time the PC was uplifted reaching maximal elevations of 4000 m, when the Andean crust is thickened by horizontal shortening and by magmatic addition due to a higher convergence rate (e.g., Allmendinger et al. [1997]). The thrust fault of the western Precordillera (fig.3.2; PCF) could have contributed to an important tectonical shortening, where an uplift occurred through the fracture zone dipping to the east, reaching a depth of 30-35 km beneath the West Fissure, at the brittle-ductile transition zone (fig.3.4). The tectonic shortening via the thrust fault in PC (and others in the Longitudinal Valley; fig.3.4) would correspond to the west flank of the uplifting of the Altiplano, according to the isostatic model postulated by Victor [2000]. The crust in the PC should have been affected by retrograde metamorphism (Reutter, pers. comm.), as occurs after a tectonic uplift which develops rapidly in terms of geothermal relaxation (Thompson [1981]).

The Precordillera fault system exposes continental clast-sediments intercalated by ignimbrites, reflecting the connection between tectonic shortening and the Oligocene-Miocene magmatism (Victor [2000]). The basement of the Precordillera is conformed by metamorphics and sedimentary rocks from the Early Paleozoic, volcanic rocks and widespread intrusions from the Carboniferous-Permian, and red continental sandstones of the Lower-Cretaceous (Reutter et al. [1995]).
The crust in the Precordillera does not exceed 600°C (Springer [1999]), and the Moho is at 60 km depth (Wigger et al. [1994]). There is also no evidence of seismicity in the mid-lower crust (fig.3.4). A low velocity zone at 30-40 km depth was identified from converted P-S seismic velocities (Yuan et al. [2000]), and can be interpreted as the brittle-ductile transition zone. Considering a brittle regime in the upper crust, supported also by the evidence of seismicity, the Precordillera fault system may extend to 10 km depth or even more (fig.3.4).

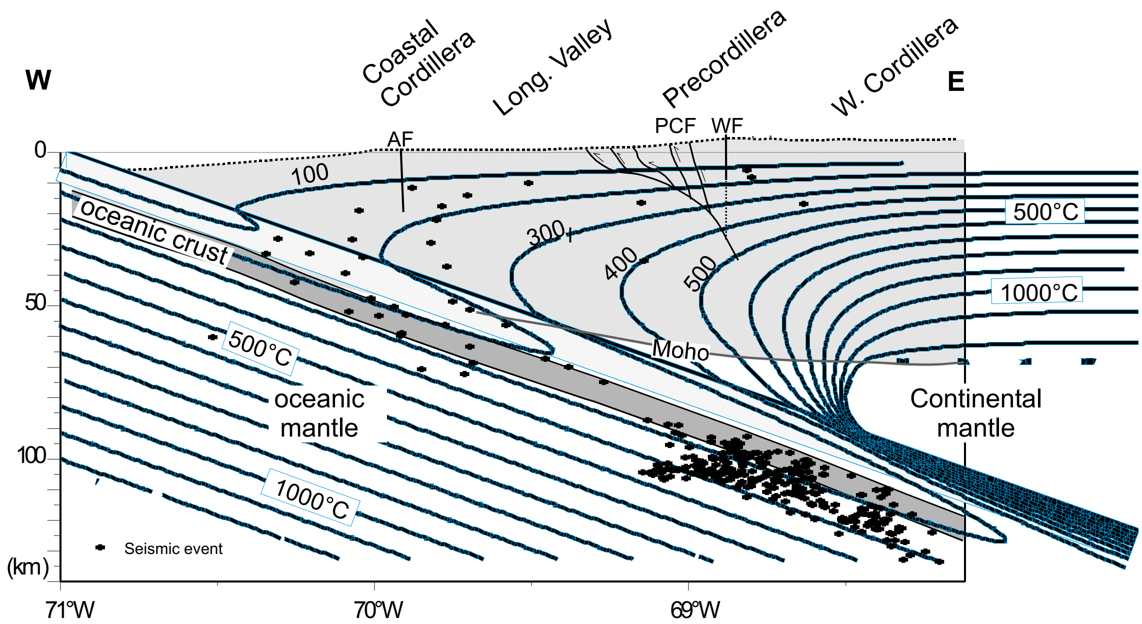

Figure 3.4: E-W profile across the Andean convergence zone at latitude 21°S. The mega strike-slip faults associated with an oblique convergence are indicated: *AF*: Atacama fault in the Coastal Cordillera (after Pelz [2000]), *WF*: West Fissure in the Precordillera. The thrust-fault system in the Precordillera (*PCF*) and Longitudinal Valley represents the west-flank of the tectonic shortening for the uplift of the Altiplano, according to the isostatic model of Victor [2000]). Dark dots show hypocenters of seismic events (Lüth [2000]), blue line represents the isothermals in °C (after Springer [1999]).

3.3 Western Cordillera and Altiplano

The Western Cordillera has conformed the modern magmatic arc since the Miocene (25 Ma), when the convergence rate increased and the obliqueness became smaller (<20°). Therefore the crust developed mostly in a compressional regime, leading to crustal shortening and thickening. The Western Cordillera is marked by a line of stratovolcanoes overlying older ignimbrite sheets. The Altiplano-Puna to the east stretches for 1800 km along the Central Andes with a width of 350-400 km. The plateau correlates spatially and temporally with the andean modern arc. It was uplifted primarily because of crustal thickening produced by horizontal shortening of a thermally weakened lithosphere (Allmendinger et al. [1997]).
The volcanism comprises large andesitic stratovolcanoes and great areas covered by dacitic ignimbrites, especially south of the Altiplano. The volcanic activity did not begin simultaneously along the arc, however. North of 21°S the ignimbrites date as older acitivity (>15 Ma), whereas south of 21°S the magmatism is younger (<10 Ma) and still active in some areas, expanding also to the east in the Altiplano (de Silva [1989]). The so called Altiplano-Puna Volcanic Zone (APVZ) refers to this. North of 21°S an early Paleozoic sedimentary wedge overlies an old Precambrian basement, while to the south an early paleozoic submarine arc and associated backarc sedimentary sequence were constructed upon a Precambrian basement that is younger than to the north (Allmendinger et al. [1997].
The Altiplano surface is covered by several active salars, locally recent volcanic rocks and inmense Late Miocene to Pliocene ignimbrite centers (APVZ). As supported by several geophysical models and geochemical/petrological results, there is no doubt that crustal partial

melting fed by dehydratisation process in the mantle and slab must have developed (and still present) in order to explain the huge amounts of ignimbrites formed in a relative short period of time (e.g., de Silva [1989], Giese et al. [1999], Schwarz et al. [1994], Yuan et al. [2000], Brasse et al. [2000]).

3.4 Nitrate deposits in the forearc

Nitrate deposits consist of water-soluble saline minerals that occur as cement in unconsolidated surficial material − alluvial fill in valleys, loose rocky debris on hillsides, and windblown silt and sand− and as impregnations and veins in porous and fractured bedrock (Ericksen [1983]).
The work of Chong [1994] discusses the possible origins of regional nitrate ore deposits located along a N-S trend of about 700 km long between latitudes 19.5°S and 25.5°, concentrated today in the Coastal Cordillera and Longitudinal Valley. Chong postulates that the ores were originally emplaced from magmatic fluids enriched with metallic compounds during the Lower Tertiary (66-40 Ma) volcanic arc evolution. Then in Oligocene times (36-24 Ma), in the final volcanic phase, the change of climate led to significant geothermal activity along regional faults, where meteoric water was transported. This allowed the migration of enriched brines, and were directed according to the permeability of certain sedimentary horizons. Chong presumes that the huge regional Atacama fault and West Fissure would have trapped much ore. Also related to this geothermal/tectonic process during Tertiary times was the emplacement of the biggest chilean porphyry copper deposited along the West Fissure. During the Neogene (25-5 Ma) the formation of the Altiplano began and the Longitudinal Valley became a basin with continuous lacustrine sedimentation, where nitrate ores were deposited from erosion. During the Upper Pliocene (2 Ma) more nitrate materials from the volcanic activity were introduced into the coastal basins via groundwater (Chong [1994]). In the recent geomorphology of the Coastal Cordillera great amounts of alluvial fans are located east of the Atacama Fault, and deposition of salars and mud flows are distributed in several localised areas.