1. Introduction

1.1. Overview

This introductory chapter aims to present the motivations and objectives for the here presented thesis, and to give a guide post through the different chapters. In addition, both natural laboratories are shortly introduced.

The here presented project is a PhD thesis supported by the German National Merit Foundation, together with the GeoResearchCentre Potsdam (GFZ).

Chapter 2 (**"Methods"**) gives an overview over the methods used in this study, which encompasses the analyses of structural data, estimation of PT conditions, image analyses for clast scaling, microscopic scale investigations using petrographical and binocular microscopes and SEM, structural restoration of a cross section, provenance analyses, analyses of Sr isotope signatures, and Rb/Sr as well as Ar/Ar geochronology.

Chapter 3 (**"Anatomy of recently active plate interfaces"**) gives an overview about the "state-of-the-art" knowledge of structures and processes obtained from recently active convergent plate margins. This includes hypotheses about the subduction channel, a database of geophysical investigations, and the distribution of interface earthquakes in the depth range of the seismogenic coupling zone.

Chapter 4 (**"Anatomy of a fossil subduction channel – a quantitative view on changing structures along the plate interface"**) concentrates on the analysis of the fossil subduction mélange and its upper plate in the European Alps. Therein, a coarse overview about the Alpine evolution and the geology of the working area are given. In addition, basic concepts of subduction channels and of coseismic and interseismic deformation are reviewed. The temporal framework of deformation within the study area is mentioned on the base of published data. This chapter provides information about the distribution of different key features along the ancient plate interface, which was restored into its former subduction geometry on the base of published and own geothermobarometric data. Finally, we discussed our field data in terms of post-accretion changes, long-term kinematics, short-term kinematics, and fluid flow.

Chapter 5 (**"Temporal constraints for unstable slip – ^{40}Ar/^{39}Ar geochronology applied to pseudotachylytes"**) concentrates on Ar/Ar age dating of pseudotachylytes sampled at the northwestern rim of the Engadine window immediately above the base of the upper plate. Pseudotachylytes are unambiguous evidence for fossil seismicity. Despite of analytical limitations and constraints by recrystallization of the pseudotachylyte groundmass since the time of melt generation, ^{40}Ar/^{39}Ar geochronology provides an approximation about the time frame of occurrence of unstable slip.

Chapter 6 (**"Abandonment of the South Penninic-Austroalpine paleosubduction interface zone, Central Alps: constraints from Rb/Sr geochronology"**) deals with Rb/Sr isotopic data in order to constrain the termination of subduction related deformation in the study area. In addition, Sr isotope signatures of marine (meta-) carbonates are used to define the influence and nature of fluids circulating through the subduction mélange. We used our isotopic data as hints for the mass transfer mode along the fossil plate interface zone. Tectonic erosion as the prevailing mass transfer mode is referred to the geological evolution of the Gosau group depocenters, which represents slope basins formed onto the upper plate during the time of subduction. Finally, isotopic dating yielded information about the pre-Alpine history of the study area as well.

Chapter 7 (**“Final discussion and conclusions”**) summarizes the results of the different subchapters and aims to integrate them into a model of structures and processes along the seismogenic zone of convergent plate interfaces with special emphasize on the spatiotemporal subduction history of the European Alps.

Additionally, microprobe analyses, $^{40}Ar/^{39}Ar$ analytical data, and sample locations are given in the **“Appendix A, B and C”**.

1.2 Objectives and motivation

Convergent plate margins generate most of the world’s seismicity, and nearly all of the earthquakes with magnitudes >8. They initiate within the seismogenic coupling zone, which marks the transient, seismically active part of the subduction channel developed between the two converging plates. Despite the enormous social, economic and scientific importance associated with seismogenic zones of convergent plate interfaces (e.g. destructive earthquakes, tsunamis), processes occurring in the intervening subduction channels are poorly understood. To date, the plate interface of convergent plate boundaries (i.e. subduction channels) cannot be directly accessed by drilling nor through surface observations, but has been intensely studied with geophysical methods, numerical modeling, and sandbox simulations. These, however, either have only poor resolution, or are strongly dependent on a number of poorly constrained assumptions. In consequence, direct investigations of exhumed ancient convergent plate boundaries are requested to achieve insights into deformation processes, which occurred along the plate interface despite multiple overprinting during exhumation. No continuous exposure exhibiting the complete seismogenic part of a subduction channel has been analyzed as yet. However, outcrops of rocks, which suffered subduction and subsequent exhumation, exist e.g. in the European Alps or Southern Chile.

The here presented study contributes to the understanding of convergent plate boundaries in the depth range of their former seismogenic zone aiming at testing inferences and hypotheses of the various kinematic and mechanical concepts presented for the seismogenic zone. Therefore, we use the complete exposure of this part of a former plate interface in the European Alps, one of the best-studied mountain belts that has resulted from successive subduction, accretion and collision, where we analyzed a mélange zone tracing the plate interface zone of the fossil convergent plate margin. Additionally, we included information from Southern Chile, where material, which formerly underwent deformation along the plate interface, was exhumed to the surface by large scale basal accretion at a certain depth to the base of the upper plate. This part of the study provided additive hints for structures and processes occurring along the plate interface zone of convergent plate margins (i.e. within the subduction channel), at least for a restricted PT domain.

1.3. Working areas

1.3.1. Alps

A detailed discussion about the working area in the European Alps, comprising their geological, structural, metamorphical and geochronological framework, as well as the general Alpine evolution as far as interesting for our purpose, can be found in Chapters 4, 5 and 6. Here, we only present a brief overview about the location of the

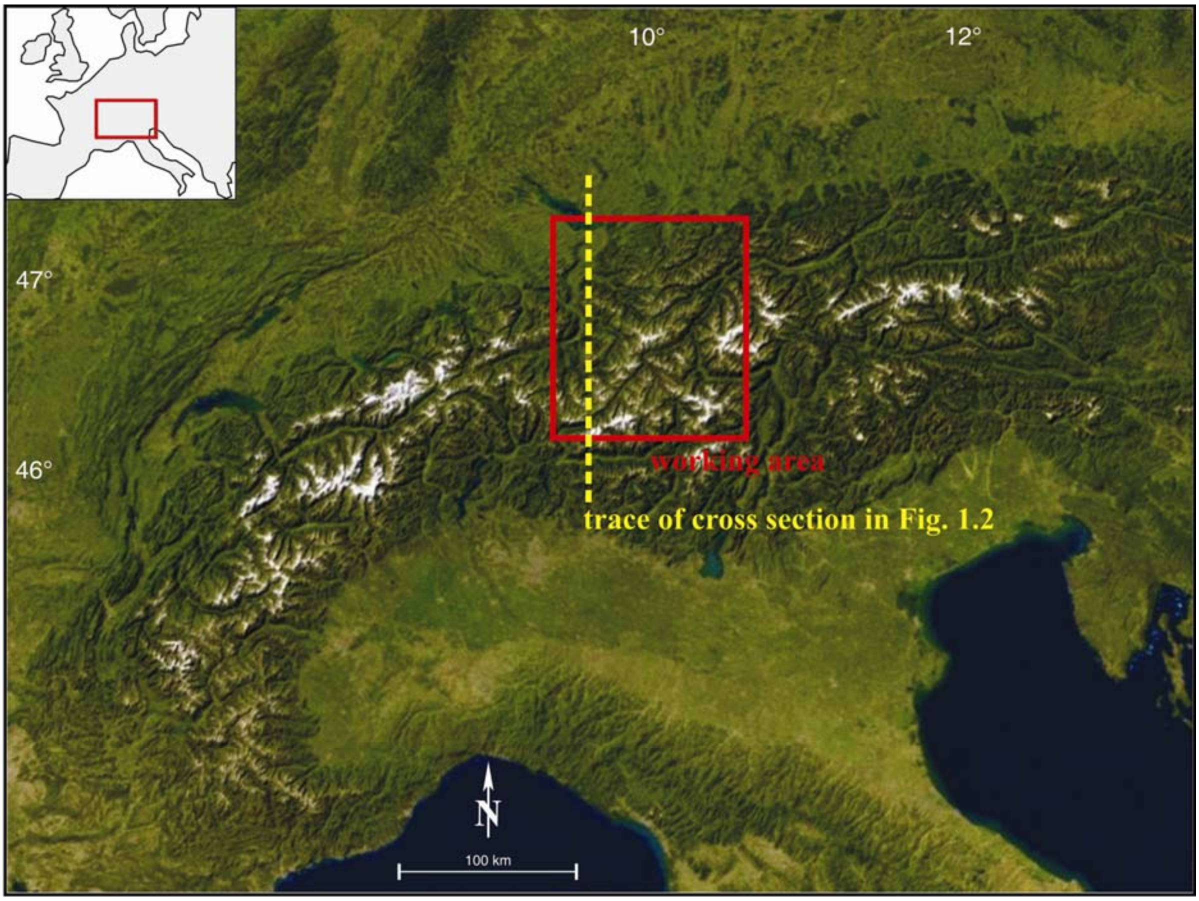

Figure 1.1: Satellite image of the European Alps. The shown section is comparable to the geological maps presented in Chapters 4 and 6. Red rectangle outlines the working area, yellow line represents the trace of the cross section of Figure 1.2. Source: www.worldwind.arc.nasa.gov.

study area, the main geological units, and their evolution in time and space.

The working area for the main part of this study is located in the central part of the European Alps along the transition from the Western to the Eastern Alps (Fig. 1.1). It extends from the Swiss-Austrian border in the north to the Swiss-Italian border in the south.

The European Alps are the result of continent-continent collision between the European plate and the Adriatic plate following the subduction and accretion of intervening oceanic domains (Penninic units) during the Mesozoic and Tertiary times. Most models differentiate two orogenic cycles during Alpine evolution: A Cretaceous orogenic cycle (referred to as Eoalpine, e.g. Wagreich 1995) is defined by an east to southeast dipping subduction zone related with the closure of the Meliata ocean leaving signatures of subduction-related deformation within the Austroalpine nappes (Adriatic plate, e.g. Schmid et al. 2004). Stacking within the Austroalpine is associated with top-W, locally top-SW and top-NW thrusting (Froitzheim et al. 1994, Handy 1996). The direction of convergence changed to north – south during the Tertiary orogenic cycle (referred to as Mesoalpine to Neoalpine, e.g. Wagreich 1995) with top-N thrusting and closure of the Alpine Tethys in-between the European and Adriatic plate (Froitzheim et al. 1994, Handy 1996, Schmid et al. 2004). According to Froitzheim et al. (1994) the transition between top-W thrusting and top-N thrusting is marked by a Late Cretaceous extensional phase with top-SE directed

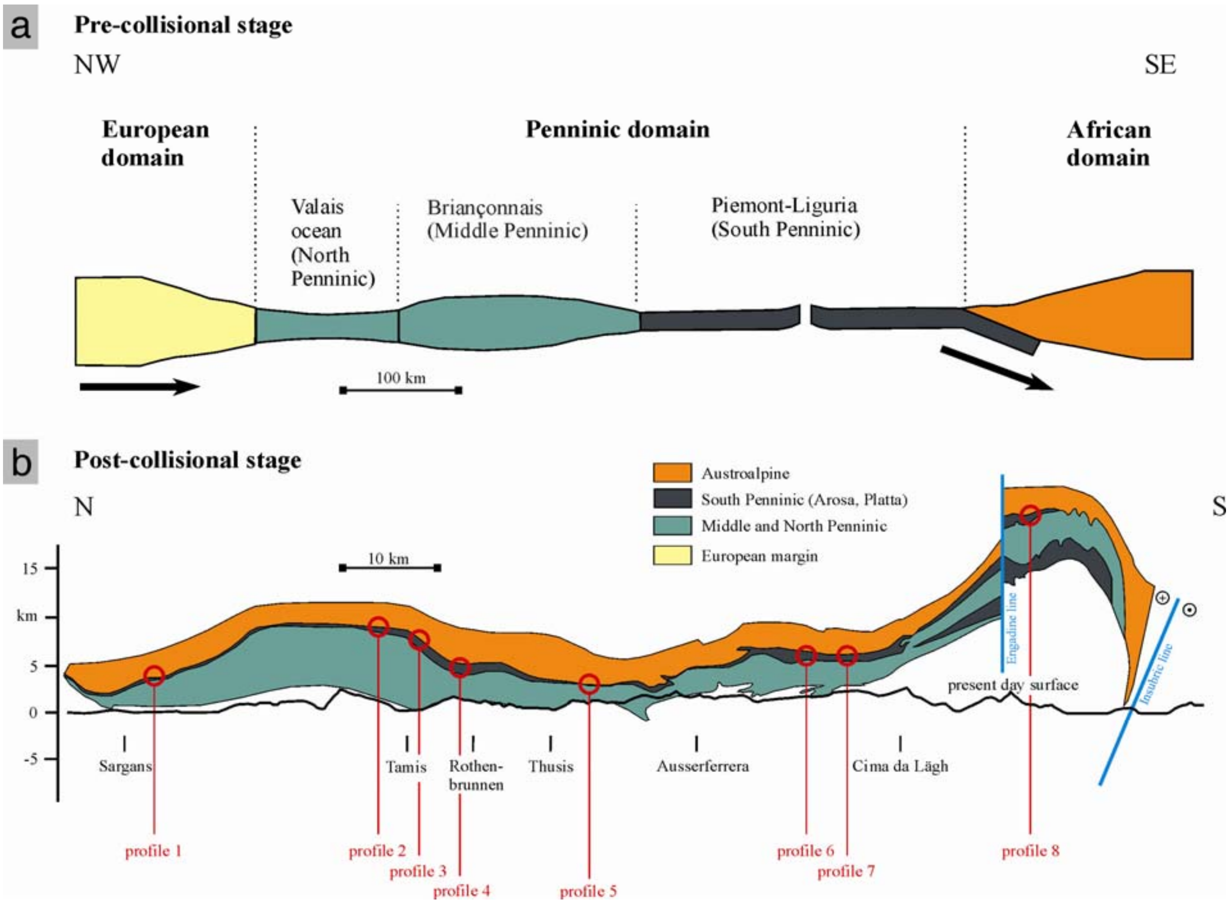

Figure 1.2: a) Schematic profile from NW towards SE illustrates the relationship between the different tectonic units. Note the subdivision of the Penninic domain into the North Penninic ocean, the Middle Penninic micro-continent, and the South Penninic ocean. The South Penninic ocean was subducted beneath parts of the African plate during Mesozoic and Tertiary times. b) N-S section of the present day situation of the tilted and exhumed South Penninic-Austroalpine plate interface zone, based on Schmid et al. (1996). The positions of the analyzed profiles are also indicated (in addition, see Chapter 4). Trace of cross section is shown in Figure 1.1.

normal faulting, which partly reactivated deformation features of the former deformational stages. This clear separation between the Cretaceous and the Tertiary orogenic cycles is only well observable in the Austroalpine nappes of the Eastern Alps (e.g. Schmid et al. 2004). However, subduction and accretion of oceanic units in the Western Alps represent a continuous process from the Late Cretaceous to the Paleogene, transforming a passive continental margin into an active one (e.g. Schmid et al. 2004).

In various paleogeographic models, the intervening oceanic Penninic units are subdivided into two oceanic basins related to the Alpine Tethys, and a micro-continent separating the oceanic sub-basins (Fig. 1.2a). The oceanic basins are termed North Penninic Valais basin and South Penninic ocean (Arosa zone and Platta nappe as local names in the study area), whereas the micro-continent is the Middle Penninic domain, respectively the Briançonnais continental swell (e.g. Florineth and Froitzheim 1994). These units were successively subducted and accreted to the Adriatic plate until the final collision of the Adriatic plate with the European plate.

The main geological units within the study area are represented by remnants of the

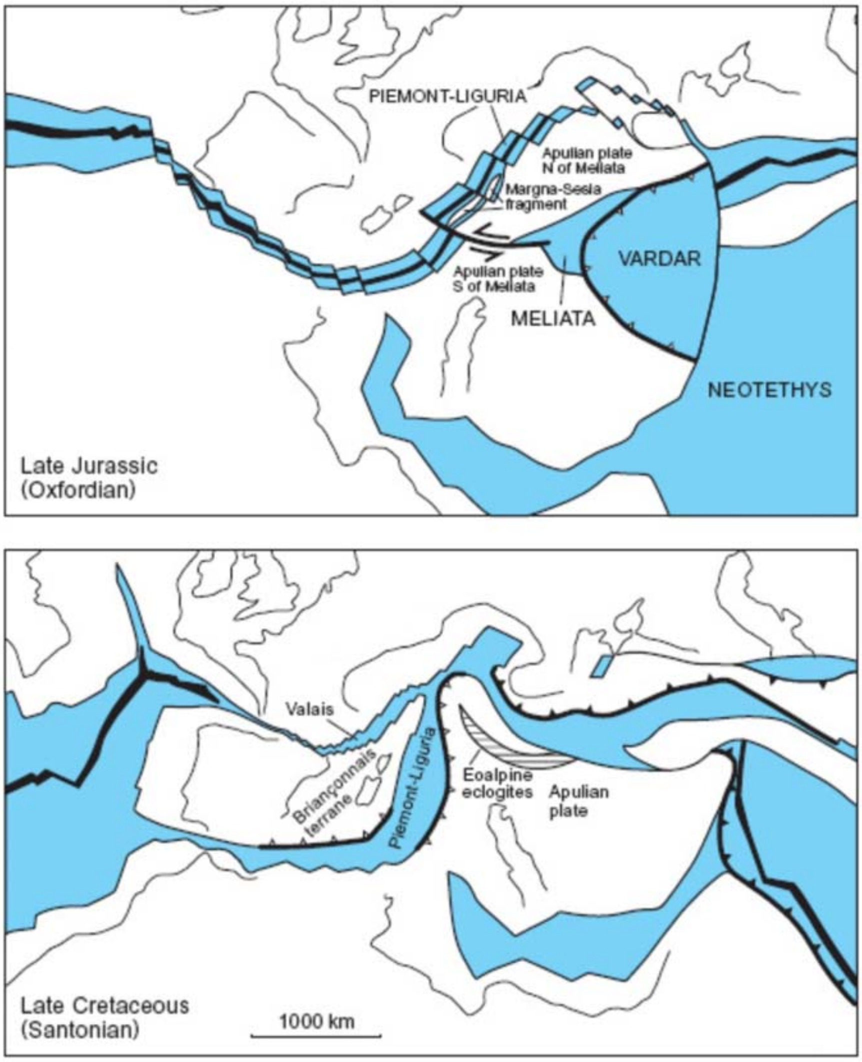

Figure 1.3: Paleogeographic map indicating the evolution of the European Alps in the Late Jurassic (upper part), and the Late Cretaceous (lower part). Modified after Schmid et al. 2004. See text for details.

South Penninic domain forming parts of the lower plate, and the Austroalpine domain as part of the Adriatic upper plate (Figs. 1.2a, b). The South Penninic domain represents a tectonic subduction mélange, which is composed of intensely deformed oceanic and continental material (Deutsch 1983, Ring et al. 1988, and references therein). It comprises Jurassic ophiolites, radiolarian chert, pelagic limestone, shale and sandstone (Ring et al. 1988). Competent blocks of Austroalpine and Penninic affinity are embedded in the incompetent shaly or serpentinized matrix (Ring et al. 1990). The apparent thickness of the South Penninic domain varies from a few tens of meters up to more than 2500 m, either reflecting their original thickness or a reduction by subsequent thinning processes. The Austroalpine upper plate consists of a suite of gneissic to amphibolitic, mainly upper crustal rocks, which experienced pre-Alpine (mainly Permo-Carboniferous) and Early (Eo-) Alpine deformation (e.g. Florineth and Froitzheim 1994, Manatschal et al. 2003, Ring et al. 1988). Metamorphic conditions of South Penninic rocks in the working area are in the range from lower greenschist facies to middle greenschist facies. The Austroalpine domain was metamorphosed to lower greenschist facies conditions during Alpine deformation (e.g. Handy and Oberhänsli 2004).

Time constraints on the evolution of the South Penninic-Austroalpine plate interface zone are sparse; a few existing data are given below. Ocean spreading, and thus opening of the South Penninic ocean, is dated to have been occurred at least since the Early to Middle Jurassic (Fig. 1.3) (186±2 Ma Ar/Ar bt, Ratschbacher et al. 2004, 165 Ma Ar/Ar phl, Gebauer 1999). Subduction of the Penninic domain underneath the Austroalpine should have been initiated during the Cretaceous (Fig. 1.3) (Wagreich 2001). This author reported the change from a passive continental margin into an active margin during the Aptian/ Albian, respectively ~110 Ma ago. Latest sedimentation within the Arosa zone (South Penninic) and the Platta nappe (South Penninic) are documented to have occurred within the Early Coniacian (Late Cretaceous, Ring 1989), or the Aptian to Albian (late Early Cretaceous; Ring 1989), respectively. Biostratigraphic ages for the flysch deposits comprising the footwall of the South Penninic mélange (derived from Middle and North Penninic units, and from the distal European margin) range between Early Cretaceous to Early/ Middle Eocene (Trautwein et al. 2001). In addition, Stampfli et al. (2002) reported distal flysch deposition until 43 Ma. Furthermore, isotopic ages point to 90 Ma - 60 Ma for a pressure-dominated metamorphism of the Lower Austroalpine units, and 60 Ma to 35 Ma for the South Penninic and European units, respectively (Handy and Oberhänsli 2004, and references therein). Schmid et al. (2004) reported HP metamorphism of South Penninic rocks during the Tertiary, at least for the Western Alps. Handy and Oberhänsli (2004, and references therein) reported thrusting and accreting under HP-greenschist facies conditions during a time span between 88 Ma and 76 Ma for the Austroalpine domain in the southern part of our study area. Additionally, Markley et al. (1995) used Ar/Ar geochronology on synkinematic white mica from Middle Penninic (Briançonnais domain) rocks. They obtained ages at around 38 Ma. Together, these data show the migration of subduction and therewith related deformation towards the foreland (respectively towards NW), which finally culminated in the collision with the European margin. The northwestward younging of flysch deposition is consistent with this migration (e.g. Handy and Oberhänsli 2004, and references therein).

The boundary between the South Penninic mélange in the footwall and the Austroalpine plate in the hanging wall represents the major large scale thrust zone in the working area, where Austroalpine rocks were thrust onto the South Penninic mélange. In a modern geodynamic context, this zone represents a fossil convergent plate interface with an associated subduction channel, along which subduction of the South Penninic ocean underneath the Austroalpine upper plate occurred. Large-scale tilting during exhumation of the fossil plate interface provides access to various paleodepths and metamorphic conditions. We analysed transects crossing the former plate interface (Fig. 1.2b) in order to identify downdip variation of key features along the former plate interface. Each transect covers a profile from the basal parts of the Austroalpine upper plate into rocks of the South Penninic subduction mélange, and in some cases even to the upper parts of the Middle Penninic domain, which was accreted to the base of the South Penninic domain.

The exposed ancient plate interface has experienced flow and fracturing over an extended period of time, including minor overprint during collision and exhumation. Although this bears resemblance to active convergent plate margins that have been active over 10s of Myrs, our results invariably contain the effects of a multistage evolution.

It has to be pointed out that we consider only remnants of the South Penninic domain as parts of the here studied fossil subduction channel. All other domains including the Middle Penninic domain and the North Penninic domain do not belong to the here analyzed subduction channel, as they were subducted beneath and accreted to a hanging wall later in the Alpine evolution. Therefore, for subduction and accretion of these domains newly formed deformation zones developed. Deformation was transferred further into the footwall, respectively into the foreland. Consequently, deformation and metamorphism for the Middle Penninic and North Penninic domains are younger in comparison to the deformation along the South Penninic-Austroalpine boundary zone. Finally, due to the occurrence of oceanic material (pelagic cherts, metabasalts) as clasts embedded within a matrix, together forming a tectonic mélange, we treat the South Penninic domain as a subduction mélange, and consequently the material of the mélange as the material, which formerly composed the fossil subduction channel at the time of abandonment of this plate interface zone.

1.3.2. Southern Chile

Several active and passive seismic measurement campaigns cover the active convergent plate margin in South-Central

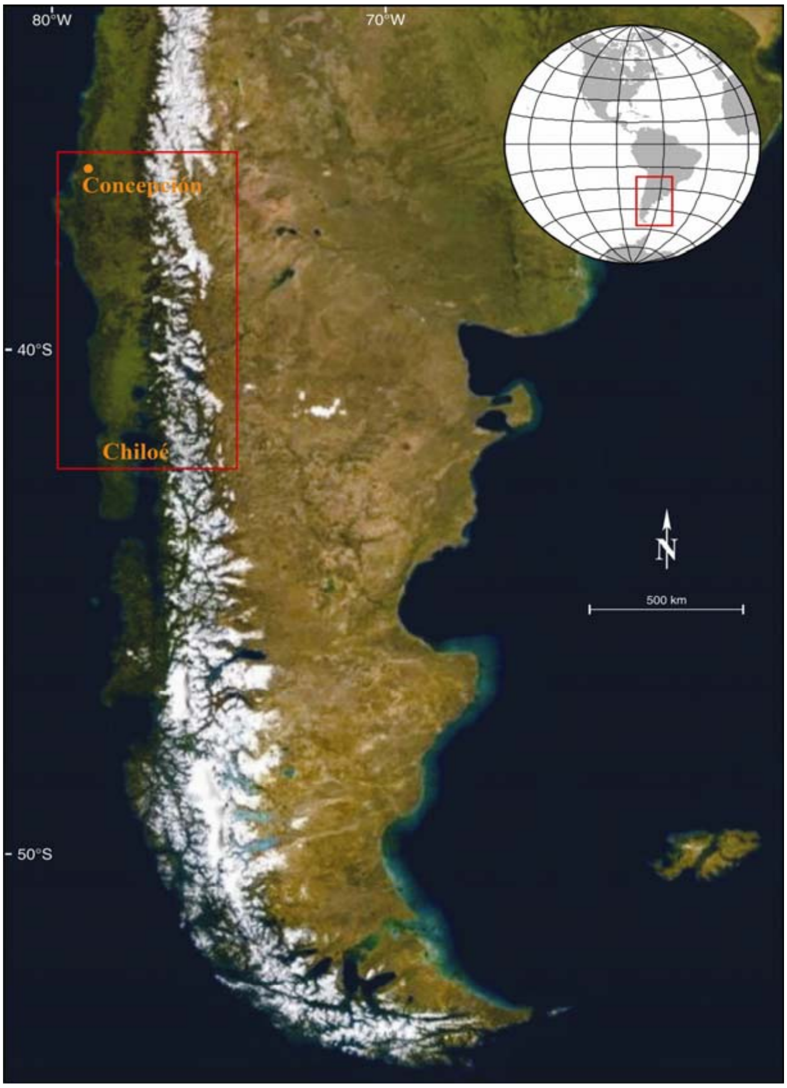

Figure 1.4: Satellite image of the southern part of South America. The study area (see also Fig. 1.5) is located along the coast between 37°S and 42°S (red rectangle). Source: www.worldwind.arc.nasa.gov.

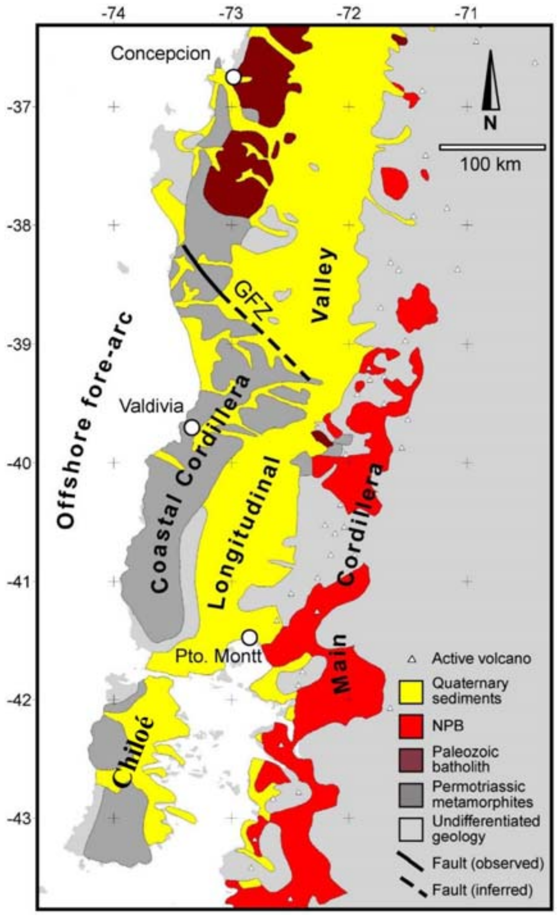

Figure 1.5: Morphotectonic units of the Southern Andes with simplified geology. GFZ = Gastre Fault Zone. The study area is located along the coastline between Concepción in the north and the island of Chiloé in the south (see also Fig. 1.4). Modified after Rosenau (2004).

Chile aiming to image structures along the plate interface (e.g. ANCORP [Oncken et al. 2003], SPOC [Krawczyk and the SPOC team 2003], TIPTEQ [Haberland et al. 2006]). In addition, we analysed outcropping rocks, which formerly underwent deformation within the subduction channel, and were brought to the present day surface by basal accretion (e.g. Glodny et al. 2005). Therefore, this particular study area favors the comparison between data about structures and processes along the plate interface (i.e. the subduction channel) gained from both recently and formerly active convergent plate margins, and we used it as our second naturally laboratory. A brief overview about the geological and structural framework of this working area is given below.

The working area for this part of the study is located in the Southern Andes, between ~37°S and ~42°S (Fig. 1.4). It extends from Concepción in the north to the island of Chiloé in the south (Figs. 1.4, 1.5). During a field campaign in 2005 we analyzed outcrops along the coast in order to compare structures within the exposed PT range with structures formed within a similar PT range studied on outcrops in the European Alps. Additionally, we used existing data from previous field studies in the same area (e.g. Rosenau 2004, Glodny et al. 2005, Melnick 2007).

The Andes formed along the active convergent plate margin of South America, and result from subduction of the Nazca and Antarctic oceanic plates underneath the South American continental upper plate. Subduction lasts at least since ~200 Ma. At present, the Nazca plate subducts with a dip angle of 25° to 30° beneath the South American plate (e.g. Barazangi and Isacks 1976). The subduction velocity is 66 mm/a, the subduction direction is oblique to the continental edge with an azimuth of 78° (Angermann et al. 1999). Due to oblique subduction, dextral strike-slip faults developed landwards, striking almost parallel to the trench (e.g. Liquiñe-Ofqui Fault Zone). To the south, the Antarctic oceanic plate subducts almost orthogonal to the trench with 20 mm/a (DeMets et al. 1994). Active subduction related deformation is mainly localized along the plate interface, and is accommodated by megathrust earthquakes (Rosenau 2004, and references therein).

According to e.g. Eppinger and Rosenfeld (1996), Forsythe (1982), Linares et al. (1988), Parada et al. (1997), and Rosenau (2004, and references therein), the continental margin of the Southern Andes shows a roughly margin-parallel segmentation into different morphotectonic

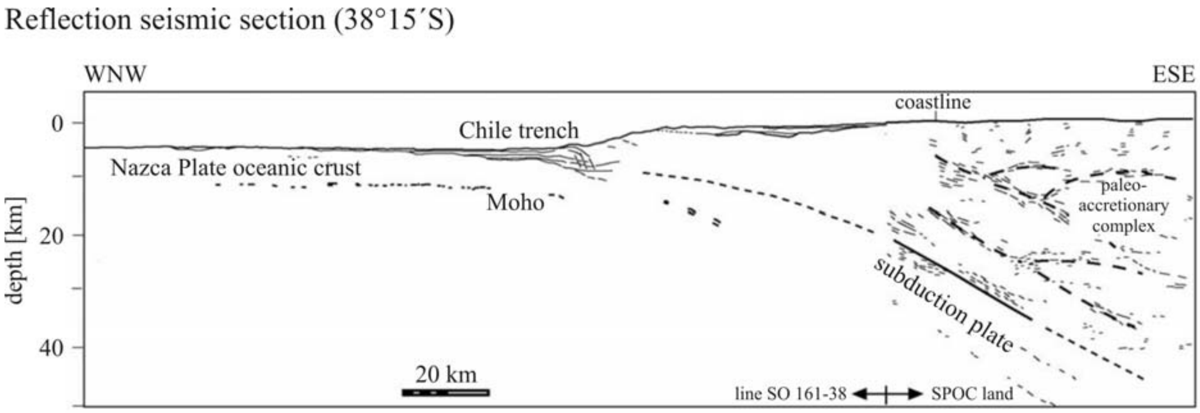

Figure 1.6: Schematic cross section through the South Central Chilean forearc at 38°15´S showing the combined reflection seismic sections from SO 161-38 and SPOC land. Note the large scale paleo-accretionary wedge with antiformal structures. Based on Krawczyk and the SPOC team (2003). Modified after Glodny et al. (2005).

units (Fig. 1.5). These are from east to west: the intra-arc (Main Cordillera), the inner forearc (Longitudinal Valley), the outer forearc (Coastal Cordillera), and the offshore forearc (e.g. Arauco peninsula). Our study area comprises the outer forearc, which is composed of a Paleozoic accretionary wedge. These rocks that formerly underwent deformation along the plate interface (i.e. within the subduction channel) were exhumed to the present-day Eastern Series and a Western Series (e.g. Glodny et al. 2005, and references therein). The Eastern Series is characterized by low P/T metamorphism and consists of metagreywackes and metapelites. In contrast, the Western Series is dominated by rocks, which suffered a high P/T metamorphism. Typical lithologies are metasediment-metabasite intercalations, which are formed by meta-turbidites, metabasites, ribbon cherts, serpentinites

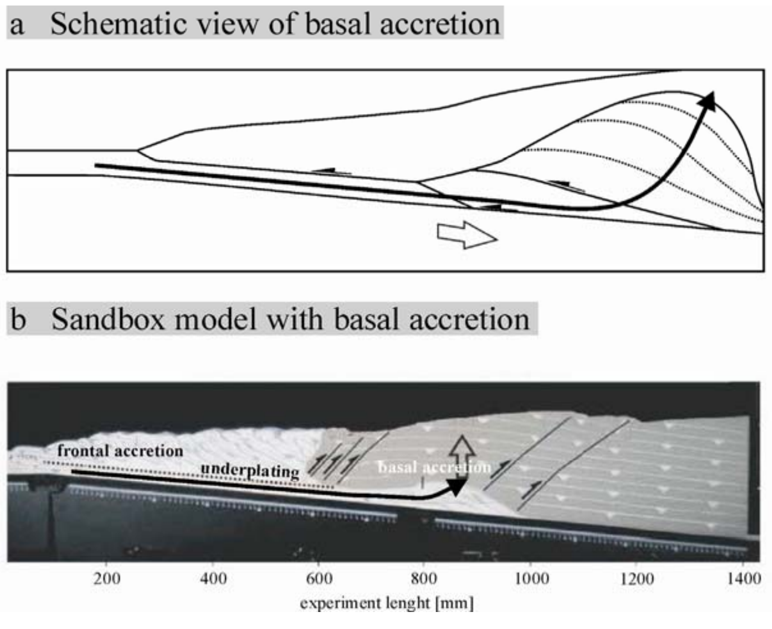

Figure 1.7: (a) Principle drawing of underplating of material to the base of the upper plate favouring exhumation, (b) Sandbox model indicating processes of frontal and basal accretion (modified after Glodny et al. 2005, Lohrmann et al. 2006).

and sulphide bodies (Glodny et al. 2005). These rocks represent the fossil sedimentary input into the subduction channel and remnants of the formerly subducted oceanic plate. Metamorphic signatures point to the transition from greenschist to blueschist facies (Glodny et al. 2005), which is indicative for subduction related metamorphism. Estimated PT conditions for outcrops of the Western Series in the study area done by Glodny et al. (2005) point to 420°C and 8-9 kbar. Therefore, this study area provides additional information about the plate interface zone in this particular PT range.

The predominant structure within the Western series is a shallow dipping, often subhorizontal foliation. Glodny et al. (2005) stated that these structures were formed during the transfer of material from the subduction channel to the base of the upper plate. Additionally, according to Martin et al. (1999), this foliation is possibly associated with low-angle recumbent nappes (see also Glodny et al. 2005). The thereby formed foliated complex is shown within reflection seismic data (e.g. Krawczyk and the SPOC team 2003), and interpreted to occur down to the plate interface (Fig. 1.6). According to e.g. Glodny et al. (2005), this complex is formed by basal accretion of material formerly transported to depth within the subduction channel. Moreover, processes of basal accretion are predicted from numerical and analogue modeling (e.g. Glodny et al. 2005, Lohrmann 2002, Lohrmann et al. 2006) (Fig. 1.7).

We observed mineralized veins, which run

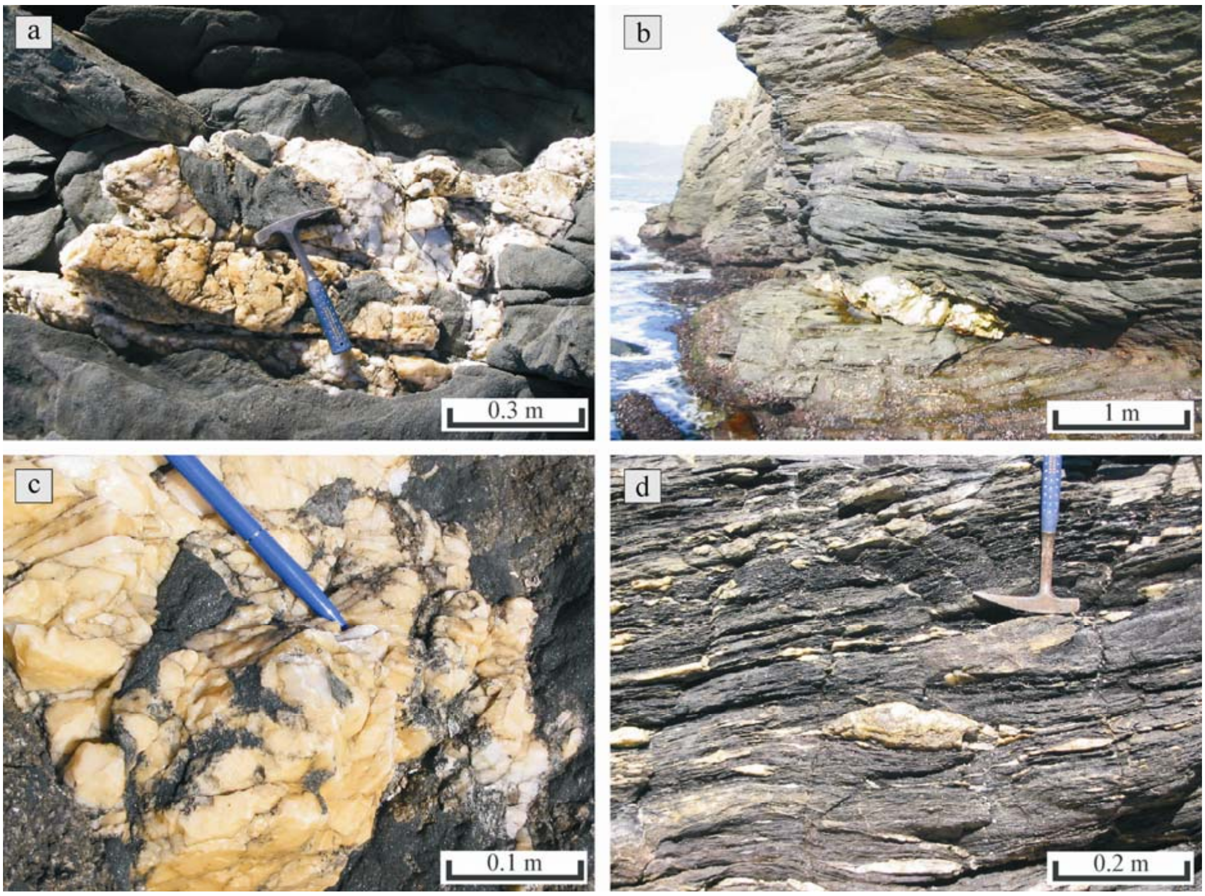

Figure 1.8: Outcrop images of mineralized veins, which run parallel or sub-parallel to the overall foliation. a) Coarse grained blocky textured mineralized vein, b) Large scale mineralized vein running sub-parallel to the tight foliation. Note the boudinaged structure of the vein, c) close-up of minerals with blocky texture comprising the vein filling, and c) smaller scale mineralized veins parallel to the foliation.

sub-parallel to the overall foliation, in both metasediments and metabasic rocks of the Coastal Cordillera within outcrops along the southern part of the Chilean coast (Figs., 1.4, 1.5, 1.8). In some cases the veins fill dilational jogs. Vein filling has a blocky texture of large minerals mostly formed by quartz and calcite, indicative for growth from a free fluid phase into a wide open cavity (Yardley, 1984; Nüchter and Stöckhert, 2007). In addition to quartz and calcite, the veins carry partly minor barroisitic amphibole, epidote, dolomite, chlorite, biotite, apatite, and white mica (Glodny et al. 2005). The incorporation of wall rock fragments within the mineralized veins with no or minor contact to the wall rock supports rapid crystallization. We propose that these veins denote prograde fluid expulsion during subduction of sedimentary material (Glodny et al. 2005). In some cases, the mineralized veins are boudinaged, which points to extensional deformation most likely during the removal of the material out of the subduction channel.

The exposed material exhumed from the plate interface has only experienced minor overprint within the brittle regime during exhumation. Therefore, it is almost undisturbed, and still contains information about structures and processes, which have occurred along the plate interface zone making this working area a suitable laboratory for the purpose of the entire study.

This second natural laboratory provided us additional hints for fluid release and formation of foliation-parallel mineralized veins deeper along the plate interface zone when compared with the Alpine example. According to Glodny et al. (2005), formation of these mineralized veins occurred at ~ 8 to 9 kbar along the Chilean subduction zone. Additionally, we prepared geochemical, fluid inclusion and isotope studies for the vein samples. Due to a shortage of time, these analyses cannot be included within this PhD thesis, and the insights from this working area remain limited to the foliation-parallel mineralized veins.