Structure and Neotectonics of the Southern Chile forearc

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Jacob Matthias Geersen

Abstract

Marine forearcs are among the geologically most complex regions on Earth. They are shaped by a variety of tectonic processes that are active on a wide range of spatial and temporal scales. The aim of this PhD thesis is to characterize the active tectonic evolution of the South Chilean marine forearc by a combined investigation of surface (swath bathymetric) and subsurface (reflection seismic) data. In particular, I will analyze how geomorphologic deformation patterns connect to individual tectonic processes.

One of the major results of the study is the subdivision of the South Chilean marine forearc in the area 35°S – 40°S into four geomorphologically distinct along-slope segments. Tectonic processes such as compressional and extensional faulting as well as sediment underthrusting are identified as first order controls for this segmentation. The subdivision as well as the causal interpretation is based on a combined analysis of five reflection seismic lines and an extensive set of swath bathymetric data. Geomorphologic variations across the segment boundaries occur over remarkably short distances of some kilometres. This high level of complexity has remained unrecognized during previous studies which merely considered narrow transects normal to the plate margin along reflection seismic lines.

A second focus lies on the detailed investigation of giant submarine landslides, one of the previously identified geomorphologic features, which are observed in the area of the Arauco Peninsula. The combination of reflection seismic and swath bathymetric data reveals three slope failures that range among the largest submarine slides known from active continental margins. Slope failures are likely preconditioned by the specific tectonic regime of the Arauco area where continuous high uplift rates repeatedly cause oversteepening of the continental slope.

Finally, this thesis investigates the impact of the three outstanding slope failures on the long term seismotectonic evolution of the study area. The locations of the slope failures coincide with the location of a major earthquake segment boundary. The region to the south of the Arauco Peninsula was last ruptured during the Mw 9.5 Great Chile Earthquake on 22 May 1960, whereas the region to the north was affected by the Mw 8.8 Maule Earthquake on 27 February 2010. Seismic reflection data image an undisturbed and well layered sedimentary trench-fill and a continuous décollement in the areas where no slope failures are observed. However, at the exact locations of the slope failures, which coincide with the boundaries of the 1960 and 2010 earthquake ruptures, chaotic slide deposits compose the lower part of the trench-fill. At these locations no continuous décollement is documented. I suggest that the underthrusting of the highly inhomogeneous slide deposits prevents the development of a continuous décollement and thus the build-up of a thin slip zone that is continuous in space as necessary for earthquake rupture propagation. This is the first time that mass wasting is considered as a possible control on earthquake segmentation at active continental margins.

Kurzfassung

Die marinen Bereiche aktiver Kontinentalränder gehören zu den geologisch aktivsten Regionen der Erde. Sie werden stetig durch eine Vielzahl aktiver tektonischer Prozesse, die auf unterschiedlichen zeitlichen und räumlichen Skalen agieren, deformiert. Das Ziel dieser Doktorarbeit ist die Erforschung der geologischen und tektonischen Entwicklungsgeschichte des südchilenischen Kontinentalrandes auf der Grundlage geophysikalischer Daten. Die Kombination von Oberflächen- (Fächerecholot) mit Untergrunddaten (Reflektionsseismik) soll Aufschluss über den Zusammenhang zwischen geomorphologischen Deformationsmustern und unterliegenden tektonische Strukturen geben.

Ein wichtiges Ergebnis ist die Unterteilung des Gebietes zwischen 35°S – 40°S in vier geomorphologisch unterschiedliche Segmente. Unterschiede in der Geomorphologie werden primär bedingt durch verschiedene tektonische Prozesse wie Überschiebungen, Abschiebungen, Subduktion oder basale Akkretion von Sedimenten. Die Unterteilung in individuelle Segmente sowie die Interpretation der für diese Segmentierung verantwortlichen tektonischen Prozesse basieren auf einer kombinierten Analyse von flächendeckenden Fächerecholotdaten und fünf reflektionsseismischen Profilen. Die Struktur des Kontinentalrandes variiert über kurze Distanzen von wenigen Kilometern. Diese räumliche Komplexität wurde in vorherigen Studien nicht erkannt, da diese oft auf wenigen seismischen Profilen beruhen und die Bereiche zwischen diesen Profilen nicht berücksichtigt wurden.

Die Arbeit beschäftigt sich desweiteren mit der detaillierten Untersuchung von großen submarinen Hangrutschungen, die als besonders auffällige geomorphologische Erscheinungen im Gebiet der Arauco Halbinsel in einem der zuvor definierten Segmente auftreten. Die Kombination von Fächerecholot- und reflektionsseismischen Messungen zeigt, dass die drei untersuchten Hangrutschungen zu den größten weltweit bekannten submarinen Hangrutschungen an aktiven Kontinentalrändern gehören. Die Instabilität des Kontinentalhanges in dieser Region ist vermutlich direkt verknüpft mit der besonderen tektonischen Struktur des Gebietes um die Arauco Halbinsel, welches durch sehr hohe Hebungsraten gekennzeichnet ist. Konstante Hebung führt zu einer Übersteilung des Kontinentalhanges und somit zu den beobachteten Hangrutschungen.

Der letzte Teil der Doktorarbeit untersucht die Auswirkung der zuvor analysierten großen submarinen Hangrutschungen auf die seismotektonische Entwicklung des südchilenischen Kontinentalrandes. In dem Gebiet, in dem die großen Hangrutschungen auftreten, liegt auch die Grenze zweier bedeutender Erdbebensegmente. Die Region südlich der Arauco Halbinsel wurde zuletzt im Jahr 1960 von dem großen Chile Erdbeben (Mw 9.5) getroffen, während in dem Gebiet nördlich der Halbinsel am 27. Februar 2010 das Maule Erdbeben (Mw 8.8) stattfand. Reflektionsseismische Messungen zeigen eine ungestörte und horizontal geschichtete sedimentäre Füllung des Tiefseegrabens sowie eine kontinuierliche Plattengrenzfläche dort wo keine Hangrutschungen beobachtet werden. An der Erdbebensegmentgrenze, die mit der Position der größten submarinen Hangrutschung übereinstimmt, ist der Tiefseegraben primär mit chaotischen Ablagerungen dieser Hangrutschung gefüllt und die Plattengrenzfläche ist nicht kontinuierlich ausgebildet. Vermutlich verhindert die Subduktion des von der Oberplatte abgerutschten Materials die Ausbildung einer kontinuierlichen und wenige Millimeter mächtigen potentiellen Bruchzone, wie sie für die Ausbreitung von seismischen Brüchen über große Distanzen notwendig ist. Zum ersten Mal wird somit ein direkter Zusammenhang zwischen gravitativen Massenumlagerungsprozessen und Erdbebensegmentierung an aktiven Kontinentalrändern hergestellt.

Contents

1 Introduction

1.1 Convergent Plate Margins

Located directly in the collision zones of tectonic plates, convergent plate margins are among the geologically most active regions on Earth. More than 90% of the global earthquake activity and almost all explosive volcanism concentrate in these regions. The collision of continental plates produces the Earth's largest mountain chains such as the Alps and the Himalaya (Figure 1.1A). If an oceanic plate is involved, the colder and denser oceanic plate subducts below the less dense continental or oceanic plate (Figures 1.1B and 1.1C). In such a case, collision causes the subduction and recycling of lithosphere. The temperature difference between the cold and dense subducting plate and the warm and less dense asthenosphere and the resulting negative buoyancy is the main driver for plate tectonics.

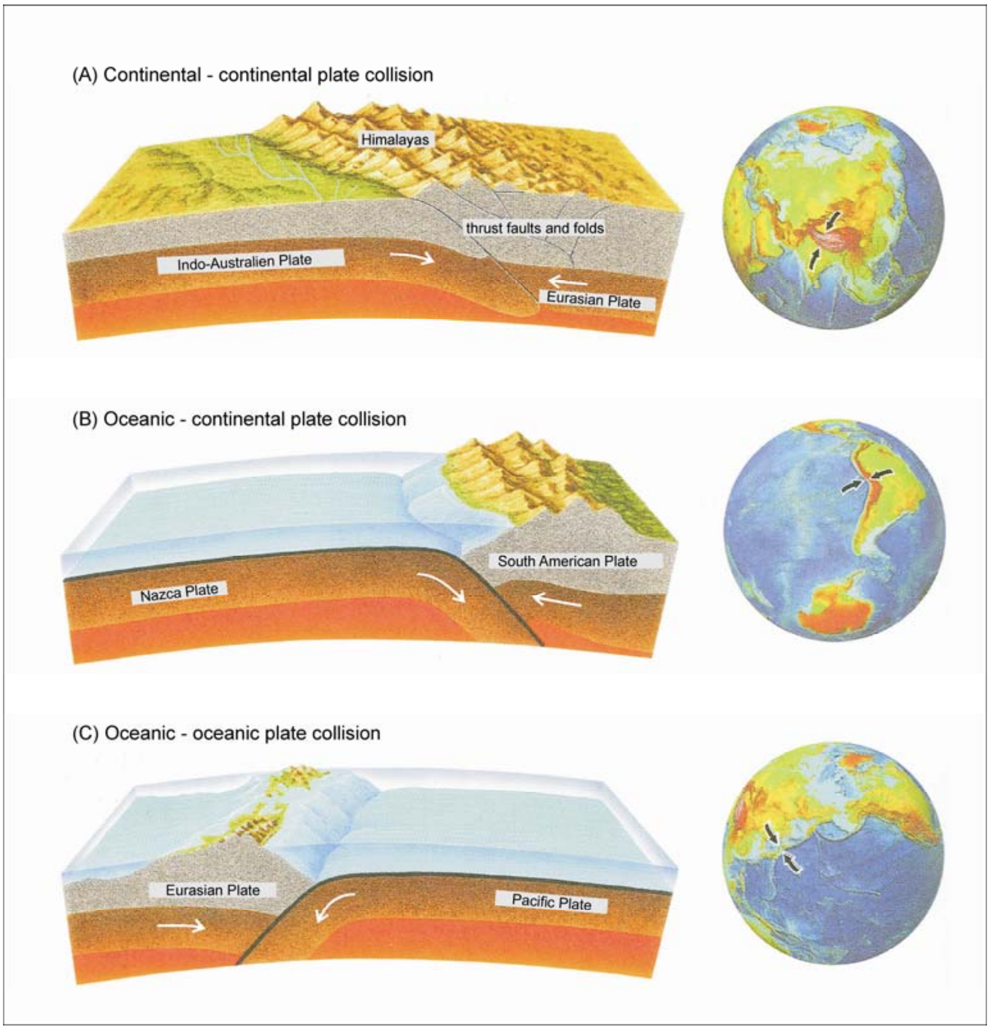

Figure 1.1: (A) *The collision of two continental plates results in large scale thrust faulting and folding. This process causes significant thickening of the continental crust and can produce enormous mountain chains such as the Himalayas.* ***(B)*** *The collision of an oceanic plate with a continental plate causes the subduction of the oceanic plate and the recycling of lithosphere.* ***(C)*** *If two oceanic plates collide the older and denser one will be subducted below the younger one. Modified from Press and Siever (2003).*

1.1.1 Structural Elements of a Convergent Plate Margin

The processes of plate collision and subduction control the structural evolution of a convergent plate margin. This chapter summarizes the main structural elements that characterize a subduction zone with an oceanic plate subducting below a continental plate, such as for example off Chile. If not cited elsewise, information given in the introduction is taken from Moore and Twiss (1995), Kearey et al. (1999) and Twiss and Moore (2006). Main structural elements (from the ocean towards the continent) are: (I) the outer swell, (II) the trench, (III) the marine forearc, (IV) the terrestrial forearc, (V) the magmatic arc and (VI) the backarc (Figure 1.2).

(I) The outer swell is a topographic high formed by the bending of the subducting oceanic plate on its way into the mantle. Plate bending often causes the generation of trench parallel normal faults which can cut deep into the mantle and is accompanied by outer rise seismicity. Normal faulting in these areas has been proposed to support hydration of the cold crust and upper mantle (e.g. Ranero et al., 2003).

(II) Between the outer swell and the marine forearc, the trench forms a structural depression with maximum water depths of up to 8 km. If two oceanic plates collide, water depth in the trench can reach more than 11 km in places. In many subduction zones, the trench depression is filled with sediments, predominantly turbidites, that mainly originate from the continental shelf and slope. However, in areas where the terrigenous input is low, e.g. due to arid conditions in the hinterland, a sedimentary trench-fill can be totally absent. This is e.g. the case off Northern Chile.

(III) The boundary between the trench and the marine forearc is marked by the deformation front. Here, sediments in the trench are incorporated into the accretionary prism which marks the lowermost part of the marine forearc. In regions where a sedimentary trench-fill is absent, the prism is predominantly formed of slope debris and is termed frontal prism (e.g. von Huene et al., 2000). The continental slope landward of the accretionary prism can be deformed in a number of ways by extensional and compressional tectonics. In many areas, the slope hosts forearc basins filled with sediments originating from the upper slope and shelf. The continental shelf describes the seaward (submerged) extension of the continent. It has a gentle slope and extends from the shoreline down to a few hundred meters of water depths. Most shelves were exposed during the last glacial periods when the sea level was lower.

(IV) The terrestrial forearc describes the area landward of the coast and seaward of the magmatic arc. It can have a number of structural elements and features. In Southern Chile the terrestrial forearc is composed of a coastal cordillera with medium elevations (around 1000 m), a flat central valley and the westernmost part of the Andean mountain chain.

(V) The magmatic arc is the area where active and explosive volcanism occurs. It is formed of young volcanoes built on top of continental basement rocks which are often highly metamorphosed.

(VI) Backarc regions can host the same metamorphosed basement rocks as the magmatic arcs. Such areas are often characterized by extensional tectonics and subsidence relative to the magmatic arc. However, the central Andes are a prominent exception as compression resulting in crustal shortening is also observed in the backarc.

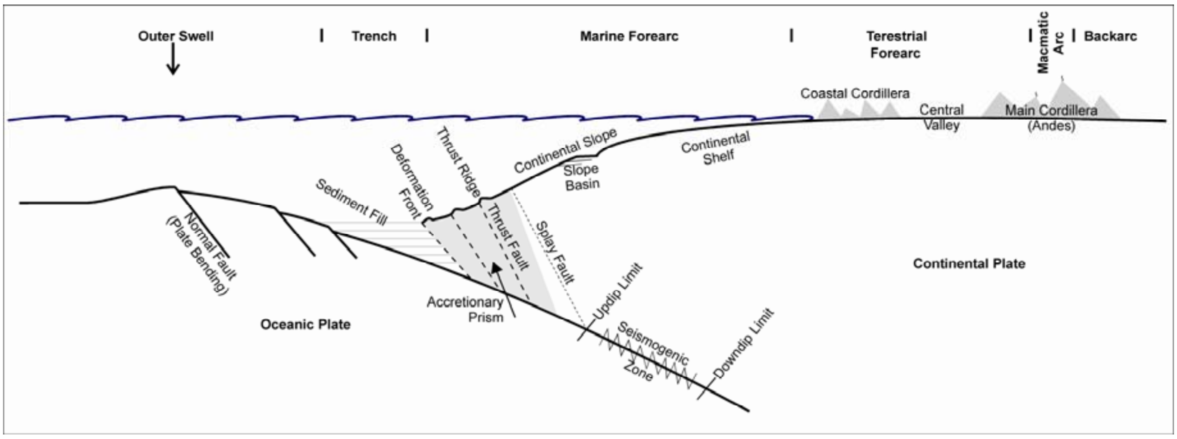

Figure 1.2: Sketch of the main structural elements of a subduction zone with an oceanic plate subducting below a continental plate.

1.1.2 Subduction Related Earthquakes at Convergent Plate Margins

The described structural elements mainly develop as the result of tectonic processes that shape a convergent margin on timescales of millions of years. In contrast, earthquakes related to the subduction process cause active deformation within seconds to minutes. These events recur within centuries to decades. The most powerful earthquakes occur in the seismogenic zone (Figure 1.2) at the interface of the subducting and overriding plate. These earthquakes rupture the plate interface at a convergent continental margin over areas of hundreds to thousand kilometres along the arc with coseismic slip up to some tens of meters.

During recent years, a number of powerful subduction earthquakes occurred at active continental margins throughout the world and caused several hundred thousand fatalities and billions of Euros of economic damage. The latest examples are the Mw 9.2 (December 2004) and the Mw 8.7 (March 2005) Sumatran Earthquakes, the Mw 8.8 Maule Earthquake in Chile (February 2010) and the Mw 9.0 Tohoku Earthquake in Japan (March 2011). During the last 50 years, the area of Southern-Central Chile (Figures 1.3 and 1.4), that is investigated in this PhD thesis, was not only affected by the Maule Earthquake but also by the Mw 9.5 Great Chile Earthquake in 1960. Until today, the Great Chile Earthquake represents the largest ever instrumentally recorded earthquake in the world.

The very recent events are by far the best monitored plate-boundary earthquakes to date and the first of their kind since a series of M>9 earthquakes in the 1950's-60's. Therefore, they offer a challenging ground from which a lot can be learned about processes associated to the rupture of such powerful earthquakes. Moreover, the area of Southern-Central Chile has a long history of geological and geophysical research and the good instrumentation available makes the Maule Earthquake one of the best investigated plate-boundary earthquakes in the world.

The seismogenic zone (Figure 1.2) defines the part of the dipping plate interface where overriding and subducting plate shear against each other resulting in temporal locking and the build-up of elastic strain, which is suddenly released during an earthquake when a critical state is exceeded. Plate interfaces are generally aseismic in their shallowest part (above the so called updip limit of the seismogenic zone) and below a certain depth, i.e. below the downdip limit of the seismogenic zone (e.g. Hyndman et al., 1997). Upper and lower ends of the seismogenic zone are predominately controlled by temperature, with the updip limit at depths of 5 – 15 km (100 – 150°C) where the transition from smectite, which supports aseismic sliding, to illite occurs. Nevertheless, during the Mw 9.2 Sumatra earthquake on 26 December 2004 rupture extended beneath the accretionary prism (Ammon et al., 2005) contributing to the destructive Indian Ocean tsunami. Thus, in addition to the smectite – illite transition, other parameters seem to play a role for the (updip) extend of the seismogenic zone. The downdip limit of the seismogenic zone is situated between depths of 10 – 100 km depending on the age and thus the temperature of the subducting lithosphere. It is either controlled by the transition from velocity weakening to velocity strengthening rheology around 350°C or by the brittle to ductile deformation of crustal rocks at about 450°C. Alternatively, the contact of the subducting plate with the continental mantle can also define the downdip limit of the seismogenic zone (Oleskevich et al., 1999). Earthquakes have also been recorded at depths down to 700 km. However, these deep events are not produced by interplate coupling because the warm asthenosphere is too weak to support the buildup of sufficient stress. Instead, deep events occur within the descending oceanic plate and are likely controlled by the dehydration of serpentinite formed at shallow depth (until about 300 km) and by the phase change from olivine to spinell (below 300 km). The latter transformation is completed around 700 km, where seismicity terminates.

1.1.3 Seismotectonic Segmentation of Convergent Plate Margins

Great subduction earthquakes rupture areas of up to several thousand square kilometres along a continental margin. This rupture is, however, typically arrested and stopped within a short distance at geographically well defined regions (barriers). As the spatial extent of the rupture area controls the magnitude of the earthquake and thus its destructiveness, these barriers and the segmentation that they impose seem to set limits to the total earthquake magnitude at a given forearc. The recent destructive megathrust earthquakes in Sumatra (2004, 2005), Chile (2010) and Japan (2011) showed that the factors that control extent and limitations of rupture during such earthquakes are more complex than previously thought and thus only poorly understood. This holds true although the phenomenon of earthquake segmentation has been observed for decades and in spite of the socio-economic impact of this type of earthquake and their associated tsunamis.

In general, the pattern of coseismic rupture during powerful plate-boundary earthquakes is controlled by the physical state of the interface between the upper overriding and lower subducting plate (e.g. Kelleher and Cann, 1976). Variations in physical properties at the subduction interface modify the degree of coupling between both plates and are known as seismic asperities and

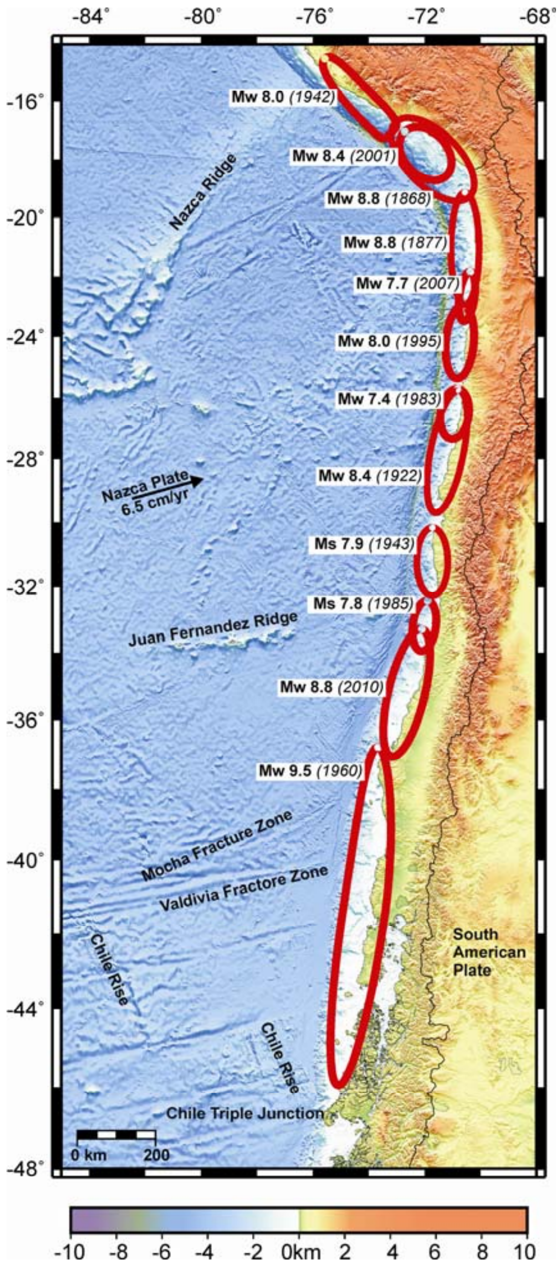

Figure 1.3: *Earthquake segmentation (including year and magnitude of single events) for South America dating back to the 19th century. Modified from Contreras-Reyes and Carrizo (2011).*

barriers (Aki, 1979; Kanamori, 1994). Asperities develop in regions where plate coupling is consistently high. High plate coupling results in the build-up of high stress levels during the interseismic period. Once the critical stress required for failure is overcome, these regions concentrate coseismic slip during an earthquake. In contrast, seismic barriers develop in regions where the degree of plate coupling changes over short distances. These regions do not slip during large earthquakes and thus limit the extent and the magnitude of an earthquake (Aki, 1979). In the case of extremely high plate coupling the dynamic stress during coseismic rupture is too small to overcome the critical stress required for failure. However, if upper and lower plates are not coupled no stress will be accumulated during the interseismic period. During an earthquake such regions will not absorb and transport coseismic rupture and thus prevent further propagation of the event. There is evidence that seismic barriers, and the segmentation they impose can be stable over multiple earthquake cycles (e.g. Melnick et al., 2009). Figure 1.3 illustrates earthquake segmentation of Chile based on records dating back to the 19th century.

A number of processes and features have been proposed to modify the physical properties at the plate interface and thus to control earthquake segmentation. A key parameter is the morphology and topography of the subducting oceanic plate (Bilek et al., 2003; Bangs et al., 2006) which is spatially modified by seamounts, fracture zones or basement ridges. On the one hand, these features modify the thickness and composition of the oceanic crust; i.e. seamounts are composed of magmatic material whereas fracture zones are characterized by hydrated mantle rocks and commonly comprise bodies of serpentinite (e.g. Contreras-Reyes et al., 2008). On the other hand, plate coupling is affected and in many cases increased by the excess buoyancy of such features. For example the northern limit of the Mw 8.8 Maule Earthquake that ruptured Southern Chile in February 2010 is located where a prominent hotspot track, the Juan Fernandez Ridge, subducts (Sparkes et al., 2010; Contreras-Reyes and Carrizo, 2011). During the 1946 earthquake in the Nankai trough co-seismic rupture was deflected around a subducting seamount (Kodaira et al., 2002).

Another key parameter for earthquake segmentation is the composition of the subducted sediments. Variations occur in the amount, structure and composition of sediments that cover the oceanic plate and fill the trench. The deeper sections of the trench sediments are commonly transported along the plate interface in the subduction channel and may thus impact on earthquake segmentation in a number of ways. Variations in sediment properties that result in different rupture behaviours have been inferred on either side of the segment boundary between the Mw 9.2 (2004) and the Mw 8.7 (2005) Sumatran earthquakes (Dean et al., 2010). Also, the amount of sediment incorporated into the subduction channel may impact on plate coupling through smoothing of the subduction interface; i.e. where a thick sedimentary sequence is subducted, a homogeneous coupled plate-boundary is expected that allows rupture propagation over long distances (e.g. Contreras-Reyes et al., 2010).

Earthquake segments are also often correlated with structural variations in the upper plate. Song and Simons (2003) and Wells et al. (2003) identified negative forearc gravity anomalies for some seismotectonic segments, whereas Ranero and von Huene (2000) found similarities between rupture zones and forearc basins. Their results indicate that structures that separate forearc basins along the margin may control earthquake segment boundaries. However, for these examples the causality is difficult to obtain. Forearc structures can either be the result of earthquake segmentation or control earthquake segmentation – or a combination of both.

Nevertheless, for many seismotectonic segments the controlling factors for seismic barriers that limit rupture propagation at certain locations are poorly understood. This includes, among others, the southern boundary of the 2010 Maule Earthquake and the coincident northern boundary of the Mw 9.5 Great Chile Earthquake (1960). No significant topography is observed on the subducting plate in front of the subduction zone and no indications for the presence of subducted relief are found in geophysical data.

1.2 Active Deformation of the Marine Forearc

All structural elements of a convergent margin are directly coupled to and shaped by the subduction process. However, in this dynamic environment the marine forearc is possibly the region that responds most sensitive to changes in tectonic parameters. The marine forearc is located directly above the deformation front, the only place where subducting and overriding plate are in direct contact at the surface of the solid Earth.

1.2.1 Accretionary and Erosive Forearcs

In the marine forearc, material is transferred from the oceanic to the continental plate by frontal or basal accretion. However, material can also be offscraped from the continental plate by subduction of slope sediment and tectonic erosion (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). Depending on whether these processes lead to a net growth or loss in the volume of the continental plate, a convergent margin is either termed “accretionary margin” or “erosive margin”. According to Clift and Vannucchi (2004) erosive margins usually occur where the plate convergence rate exceeds 6 +/-0.1 cm/yr and where the sedimentary trench-fill is thinner than 1 km. Accretion is favoured in regions that are characterized by a low convergence rate (<7.6 cm/yr) and by a sedimentary trench-fill that exceeds 1 km. The South Chilean margin investigated in this PhD thesis is currently in an accretionary mode. Therefore, the last section of this chapter concentrates on deformation processes related to accretionary margins, although some of these processes also occur in erosive settings.

1.2.2 The Accretionary Prism

The accretionary prism is the seaward-most part of a marine forearc. It develops by accumulation of trench sediments to the overriding plate as the result of plate collision. In a cross section, accretionary prisms are generally characterized by thrust ridges at the seafloor which are underlain by landward dipping thrust faults that separate individual thrust sheets (Figure 1.2). However, along several active margins, such as off Sumatra, evidences for seaward dipping faults have been found in this part of the marine forearc (Henstock et al., 2006). Although accretionary prisms along individual subduction zones often appear similar in cross-sections, they show differences in the slope angle of the marine forearc as well as in the subduction angle of the oceanic plate. As accretionary prisms can be treated as critical Coulomb wedges (e.g. Davis et al., 1983), the slope angles can be used to investigate changes in mechanical parameters such as friction along the plate-boundary, internal strength or pore fluid pressure.

1.2.3 Active Faults in the Marine Forearc

Depending on the active tectonic processes, marine forearcs can be affected by a number of compressional, extensional as well as transpressional faults. Compressional faults in the accretionary prism have been mentioned in the previous section. However, thrust faulting which leads to active shortening of the marine forearc is not limited to the accretionary prism but can occur along and across the entire marine forearc. In many places, i.e. off Ecuador and Japan, splay faults have been observed (e.g. Collot et al., 2008; Strasser et al., 2009). Splay faults are long thrust faults that rise from the subduction plate-boundary megathrust and intersect the seafloor (Figure 1.2) (Moore et al., 2007). Off Ecuador and Japan, the position of splay faults seems to correlate with the updip limit of the seismogenic zone. Splay faults are potential candidates for accommodating portions of co-seismic slip and may contribute to the generation of destructive tsunamis (e.g. Moore et al., 2007).

Apart from compressional faulting, a number of marine forearcs host extensional faults. Large scale normal faults are known e.g. from the Cascadian (McNeill et al., 1997) and the Northern Chilean (von Huene and Ranero, 2003) continental margins. They are a result of oversteepening and gravitational collapse of the marine forearc, caused by shortening and uplift across upper plate compressional faults, subduction of major topographic features such as seamounts or basement ridges (Lallemand et al., 1994; Hampel et al., 2004), steepening of the margin due to progressive subduction erosion (von Huene and Ranero, 2003; Sallarès and Ranero, 2005; Ranero et al., 2006) or basal underplating of trench sediments (Kopp et al., 2000; Kukowski et al., 2001). In the Oregon subduction zone normal faulting is supported by unstable underlying sediment packages. Wang and Hu (2006) further showed that extensional faulting in the region landward of the accretionary prism is possible during the coseismic period.

Where plate convergence is not normal to the continental margin, upper plate transpressional faults which originate at or close to the plate-boundary and reach the seafloor (thus have bathymetric expression) have been observed. Such structures are generally reported as steeply dipping faults which are difficult to identify in reflection seismic data. However, as they produce distinct seafloor expressions, swath bathymetric data can help to identify them. They occur at the rims of isolated blocks or forearc slivers that accommodate components of margin-parallel deformation (i.e. oblique convergence). Good examples can be found at the South Chilean (Melnick et al., 2009), Ecuador (Collot et al., 2008) and Cascadia (Goldfinger et al., 1997) continental margins. By connecting the plate interface with the seafloor these faults may accommodate co-seismic slip of the plate interface during great subduction earthquakes and thus may limit further along-strike spatial evolution of co-seismic rupture. If slip is transported to the surface across such structures this will result in distinct morphologic seafloor expressions and may have significant impact on tsunami generation if rupturing coseismically and generating significant vertical deformation

1.2.4 Sediment Subduction

Sediments in the trench which are transported towards the deformation front and collide with the lower forearc, are either frontally accreted and therewith contribute to the buildup of an accretionary prism, or subducted below the marine forearc. In the latter case, these sediments are transported between the subducting and the overriding plate forming a subduction channel. Depending on their physical properties and the geometry of the overriding continental and the subducting oceanic plate, subducting sediments can influence the subduction process and the tectonic evolution of a convergent plate margin in a number of ways.

Sediments transported into the subduction zone impact on the strength and frictional behaviour of the plate interface and thus influence the rupture of great subduction zone earthquakes and their potential to generate destructive tsunamis (e.g. Ruff, 1989; Tichelaar and Ruff, 1991). Variations in the rupture patterns of the two giant Sumatran earthquakes (Mw 9.2 in 2004 and Mw 8.7 in 2005) have been attributed to variations in the physical properties of subducted sediments on either side of the earthquake barrier (Dean et al., 2010; Gulick et al., 2011). The subduction of a thick sedimentary sequence may smooth the subduction interface allowing coseismic rupture to overcome potential physical barriers (e.g. Contreras-Reyes et al., 2010). Subducting sediments can also be accreted to the overriding plate. In this case they may cause localized uplift of the forearc (Kopp et al., 2000; Kukowski et al., 2001).

1.2.5 Submarine Landslides

Gravitational driven mass transport processes can have an enormous impact on the morphology of continental slopes. The most potent of these processes are submarine landslides which can involve several thousand cubic-kilometres of sediments, thereby exceeding the volume of the largest subaerial landslides by two to three orders of magnitude (Masson et al., 2006). They occur at active as well as passive continental margins worldwide, encompassing a wide size spectrum (e.g. McAdoo et al., 2000; Collot et al., 2001; Mitchell, 2005; Masson et al., 2006). The largest landslides at active continental margins have been found off New Zealand. The Ruatoria Debris Avalanche reaches a volume of 1958 km^3 (Collot et al., 2001) and the Matakaoa Submarine Instability Complex comprises a compacted volume around 2000 km^3 but has been generated by three individual events (Lamarche et al., 2008). Other huge landslides that affect the full width of the continental slope from the shelf break to the trench have been reported from the Oregon and the Peru continental margins (Duperret et al., 1995; Goldfinger et al., 2000). Apart from the mentioned large landslides, a huge number of smaller slides are known from active continental margins throughout the world. Off Sunda Brune et al. (2009) reported six landslides with a mean volume of 10 km^3 whereas McAdoo et al. (2000) investigated 45 slides from the Oregon and Californian continental margins with mean volumes of 2.5 km^3 and 3.5 km^3.

Submarine landslides can be caused by different mechanisms. On continental margins sediments and rocks are influenced by gravitational forces that are balanced by cohesive or frictional forces within the soil. In a fully drained case, the latter forces determine how steep a continental slope can become before it fails and re-establishes a lower slope angle. Processes that increase the angle of the continental slope such as tectonic uplift or undercutting by subduction erosion or submarine canyons thus bring the slope closer to a critical state. In addition, processes that decrease the frictional or cohesive forces acting on the subsoil, i.e. the dissociation of gas hydrates, as well as processes causing pore pressure above hydrostatic, i.e. rapid deposition on low permeability sediment, make a continental slope prone to failure. Along active continental margins large magnitude earthquakes related to the subduction process can serve as triggers for sediment failure, either by increasing the pore pressure or through reducing the sediment strength (e.g. Sultan et al., 2004). However, recent investigations of slope failure related to the Mw 8.8 Maule Earthquake (2010) showed that the impact of a seismic trigger is further limited by factors such as sediment supply, distribution and rheology (Völker et al., in press).

1.3 Geological Setting of the South Chilean Forearc

The geologic framework of the continental margin of Southern Chile is shaped by the subduction of the oceanic Nazca Plate below the South American Plate (Figure 1.4). The present convergence rate is approximately 6.6 cm/yr but has decreased ~40% over the last 20 Ma (Pardo-Casas and

Molnar, 1987; Angermann et al., 1999; Oncken et al., 2006). Today, plate convergence is slightly oblique at a direction of 80.1° (Angermann et al., 1999). The age of the oceanic Nazca Plate increases along the trench from 0 Ma at the Chile Triple Junction where the Chile Ridge subducts (46°S) northwards to about 35 Ma at 33°S (Tebbens et al., 1997). A prominent offset in the Nazca Plate age occurs between 37°S and 40°S where the Valdivia and the Mocha Fracture Zones separate young (0 – 25 Ma) oceanic crust in the south from older (30 – 35 Ma) crust in the north (Figure 1.4).

1.3.1 Sediment Accretion vs. Subduction Erosion over Time

At present, the South Chilean forearc between the Juan Fernandez Ridge and the Chile Triple Junction is in an accretionary mode. In this area, the Chile Trench is filled with 1.5 - 2 km of sediment (Diaz-Naveas, 1999; Ranero et al., 2006; Völker et al., 2006), resulting in the build-up of a young accretionary prism at the lower continental slope that is 15 – 20 km wide (Bangs and Cande, 1997). As an exception, the direct area around the Chile Triple Junction is currently not accreting (Behrmann and Kopf, 2001). Here, the trench is devoid of sediment, but accretion continues south of the Chile Triple Junction where the Antarctic Plate subducts (Ranero et al., 2006) at a comparably slow rate of 1-2 cm/yr (deMets et al., 1990). However, the present volume of sediments in the Central and South Chilean Trench (north of the Chile Triple Junction) that is incorporated into the accretionary prism is incompatible with a continuous history of accretion. This mismatch indicates that on longer timescales episodic phases of tectonic accretion, non-accretion and erosion occurred. Subduction erosion was likely dominant until the switch to accretion occurred in the middle Miocene (Kukowski and Oncken, 2006), or possibly as late as in the Pliocene (Melnick and Echtler, 2006a). The change from subduction erosion to accretion was likely caused by glaciation in the Patagonian Andes, resulting in an increased sediment flux to the trench (e.g. Bangs and Cande, 1997; Melnick and Echtler, 2006a). However, remnants of a Mesozoic or Palaeozoic accretionary prism that abuts against the presently active accretionary prism to the west and the crystalline rock of the continental platform to the east indicate that accretion was already active before subduction erosion became the dominant mode in the Miocene.

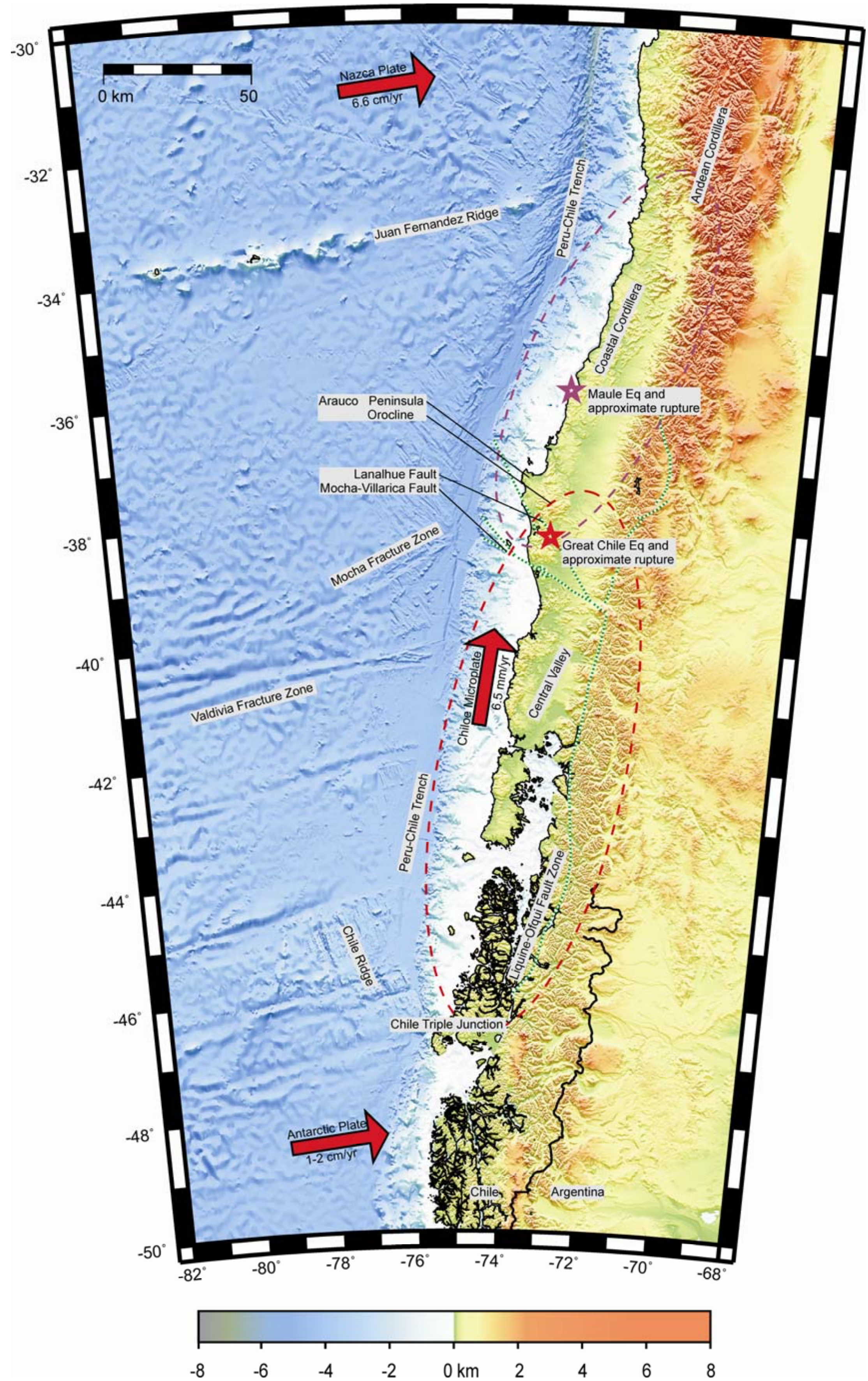
0 km 50
Nazca Plate
6.6 cm/yr
Juan Fernandez Ridge
Peru-Chile Trench
Andean Cordillera
Coastal Cordillera
Maule Eq and approximate rupture
Arauco Peninsula Orocline
Lanalhue Fault
Mocha-Villarica Fault
Great Chile Eq and approximate rupture
Mocha Fracture Zone
Chiloe Microplate
6.5 mm/yr
Central Valley
Valdivia Fracture Zone
Peru-Chile Trench
Liquine-Ofqui Fault Zone
Chile Ridge
Chile Triple Junction
Antarctic Plate
1-2 cm/yr
Chile
Argentina
-30˚
-32˚
-34˚
-36˚
-38˚
-40˚
-42˚
-44˚
-46˚
-48˚
-50˚
-82˚
-80˚
-78˚
-76˚
-74˚
-72˚
-70˚
-68˚
-8
-6
-4
-2
0 km
2
4
6
8

Figure 1.4: *(previous page) Overview map of Southern-Central Chile and Western Argentina (data from GEBCO_08 Grid; version 20091120, http://www.gebco.net). Positions of major upper plate faults (dotted green and white lines) are redrawn from Melnick and Echtler (2006b) and Melnick et al. (2009). The convergence directions of the Chiloe Microplate, the Antarctic Plate and the Nazca Plate are indicated by red arrows. Red and purple stars mark the epicentre locations of the 1960 Mw 9.5 Great Chile and the 2010 Mw 8.8 Maule earthquakes. Approximate rupture areas of the two earthquakes are given by dashed red and purple ellipses.*

1.3.2 Liquine-Ofqui Fault Zone and Chiloe Microplate

Oblique subduction is a likely cause for the existence of the longitudinal deep rooted Liquine-Ofqui Fault Zone (LOFZ) which is a prominent feature in the Main Cordillera of the Andes between 37°S - 46°S. Similar margin parallel fault systems have been found at other convergent plate margins around the world where plate convergence is not normal to the margin, i.e. off Oregon (Goldfinger et al., 1997) or Sumatra (Sieh and Natawidjaja, 2000). The LOFZ has been active in transpressional dextral mode since the Pliocene (Hervé, 1994; Cembrano et al., 2000; Thomson, 2002; Rosenau et al., 2006) with a long-term (6 Ma) shear rate of 32 ± 6 mm/yr in the southern domain (42°S – 46°S) and 13 ± 3 mm/yr in the northern domain (38°S – 42°S) (Rosenau et al., 2006). Similar to the decrease in plate convergence rate, the strike-slip rate of the LOFZ has decreased to a present value of 6.5 mm/yr according to GPS data (Wang et al., 2007). In Southern Chile, the LOFZ decouples the Chiloe Microplate, a northward translating crustal sliver from the rest of the South American Plate (Figure 1.4). The northward motion of the Chiloe Microplate and its collision with the South American Plate around 37°S is a likely cause for transpressional upper plate faults (e.g. Lanalhue Fault, Mocha-Villarica Fault Zone) that dissect the continental forearc in southeast–northwest direction (Figure 1.4) (Melnick and Echtler, 2006b; Melnick et al., 2009). Active shortening across these faults may be primarily responsible for the high elevations found in the continental forearc between 35°S - 37°S, with the Arauco Orocline locally exceeding 1500 m, and for the existence of the two islands of Santa Maria and Mocha rising up to 350 m above sea-level. Uplift rates up to 5.5 mm/yr have been inferred from inversion of fore-arc basins (Melnick and Echtler, 2006a), reorganization of river networks (Rehak et al., 2008) and uplifted and tilted marine terraces (Kaizuka et al., 1973; Melnick et al., 2006).

1.3.3 Across-strike Variations in the South Chilean Forearc and Magmatic Arc

The features and processes described above including the temporal interaction of accretion and erosion have caused a distinct across strike segmentation of the South Chilean Forearc. The western (seaward-most) part of the marine forearc is formed by the young (Pliocene) accretionary prism, which extends up to water depths around 2 km (Figure 1.2). In the direct vicinity of the Chile Triple Junction, a distinct accretionary prism is not observed as the trench is devoid of any sediment. On its eastern side, the accretionary prism abuts against an old (Mesozoic / Palaeozoic) backstop that represents an ancient accretionary prism (e.g. Contreras-Reyes et al., 2010 and references therein). Landward of the backstop, the crystalline rock of the continental platform is present. The width of the continental shelf is highly variable throughout the South Chilean forearc. In some areas where the coastline swings to the east it has a width of up to 100 km, whereas in the south around the Chile Triple Junction the shelf is as narrow as 5 km (Figure 1.4). The narrow width in this area is a result of erosion of slope sediments due to the collision of the Chile Ridge with the lower forearc. The continental slope and some shelf basins are covered with up to 2 km of sediment (Mordojovich, 1981; González, 1989). The continental forearc and the magmatic arc are divided into three geomorphologic and tectonic provinces; the Coastal Cordillera, the Central Valley, and the Main Cordillera of the Andes (Figures 1.2 and 1.4). The main structural element in the magmatic arc is the above described LOFZ, which decouples the Chiloe Microplate to the west from the stable South American Plate to the east.

1.3.4 Along-strike Variations in the South Chilean Forearc

Southern Chile is an interesting area to study along-strike forearc segmentation owing to the fact that it shows a broad variability of tectonic and climatic processes; from the area influenced by the extremely dry Atacama Desert in the north to a glacially influenced humid climate in the Patagonian Andes in the south. From north to south the marine forearc is incised by a number of submarine canyon systems (e.g. San Antonio Canyon, Maulle Canyon, Itata Canyon, BioBio Canyon, Paleo-Pellahuen Canyon, Tolten/Imperial Canyon, CalleCalle Canyon, Chacao Canyon and Cucao Canyon) among other smaller less well documented canyons and channels (Thornburg and Kulm, 1987; Völker et al., 2006, Heberer et al., 2010). Most of the canyons cut deep into the continental shelf and slope and are interpreted as active and long-living sediment feeders to the trench (Rehak et al., 2008). Their activity is evident from their sizes (cutting up to 1000 m into the sediments) and from the fact that most canyons are directly connected to major river systems, which drain parts of the Main Andean Cordillera and the Coastal Cordillera. On land, along-strike segmentation has been described in the rear part of the South Chilean forearc. It is reflected by (1) topographic variations; i.e. the Arauco Orocline around 38°S represents the highest elevation (>1500 m) along the Coastal Cordillera (Figure 1.4), (2) the distribution of shelf basins (Mordojovich, 1981; González, 1989), (3) gravity anomalies (Hackney et al., 2006, Tašárová, 2007), (4) seismicity (Bohm et al., 2002; Haberland et al., 2006) and (5) uplift rates. Highest uplift rates (0.8 – 5.5 mm/yr) are observed in the region of the Arauco Peninsula and Orocline (Kaizuka et al., 1973; Melnick et al., 2006). Distinct seismotectonic segments, including those ruptured during the Mw 9.5 Great Chile Earthquake in 1960 and the Mw 8.8 Maule Earthquake in 2010, are located in the South Chilean Forearc (Lomnitz, 1970, 2004; Kelleher, 1972; Comte et al., 1986; Campos et al., 2002; Ruegg et al., 2009). Some of the seismotectonic segment boundaries coincide with boundaries of earthquake rupture zones (Melnick et al., 2009).

1.4 Thesis Outline

Chapters 2, 3 and 4 represent stand-alone articles published or submitted for publication. They focus on individual aspects related to the structure and active tectonics of the South Chilean marine forearc. Chapter 5 summarizes the results of the three stand-alone articles and evaluates the main results in the greater context of active continental margin research.

In Chapter 2, bathymetric and reflection seismic data are used to analyze along-strike variations in the marine part of the South Chilean Forearc in the region 35°S - 40°S. The novel approach here is the use of surface (bathymetric) data to extrapolate results from 2D reflection seismic lines oriented normal to the plate margin into a greater area. This approach allows documentation of an along-strike segmentation which had escaped attention in previous studies that only considered narrow transects normal to the plate margin.

Chapter 3 concentrates on the analysis of giant submarine slope failures that were identified offshore the Arauco Peninsula in one of the margin segments investigated in the study described in chapter 2. The slope failures range among the largest submarine landslides detected at active continental margins so far and they were investigated in terms of morphology, volume and age. A conceptual model was developed which relates the slope failures to the active tectonic evolution of the particular margin stretch.

Inspired by the novel results of chapter 3, **Chapter 4** analyses the role of the giant submarine slope failures for earthquake segmentation of Southern Chile. The southern boundary of the 2010 Maule Earthquake and the northern boundary of the Mw 9.5 Great Chile Earthquake (1960) are located in the area of the Arauco Peninsula. Previous studies failed in explaining these boundaries as there is no significant relief observed on the oceanic Nazca Plate in this area. This study shows that upper plate mass wasting, if it impacts on the composition and nature of the sediments and rocks in the subduction channel, can control earthquake segmentation at convergent plate margins.

1.5 Additional contributions to peer-reviewed articles

In addition to the three articles presented in this PhD thesis, I contributed to the following complementary peer-reviewed articles during my PhD studies:

Analysis of submarine landsliding in the rupture area of the 27 February 2010 Maule Earthquake, Central Chile

Authors: *David Völker, Florian Scholz, **Jacob Geersen***

Journal: *Marine Geology*

Status: *in press*

Sediment transport and turbidite architecture in the submarine Dakar Canyon off Senegal, NW-Africa

Authors: *Roberto Pierau, Rüdiger Henrich, Inga Preiß-Daimler, Sebastian Krastel,* ***Jacob Geersen***

Journal: *Journal of African Earth Sciences, 60 (3), pp. 196-208*

Status: *published*

Submarine mass wasting off Southern Central Chile: Distribution and possible mechanisms of Pleistocene to recent slope failure

Authors: *David Völker,* ***Jacob Geersen****, Wilhelm Weinrebe, Jan Behrmann*

Book: *Submarine Mass Movements and their Consequences V. Advances in Natural and Technological Hazards Series, Springer*

Editors: *Yasuhiro Yamada, Kiichiro Kawamura, Ken Ikehara, Yujiro Ogawa, Roger Urgeles, David Mosher, Jason Chaytor, Michael Strasser*

Status: *in press*

Large scale mass wasting at the NW-African Continental Margin: some general implications for mass wasting at passive continental margins

Authors: *Sebastian Krastel, Russell B. Wynn,* ***Jacob Geersen****, Rüdiger Henrich, Aggeliki Georgiopoulou, Mathias Meyer, Till Hanebuth, Tilmann Schwenk*

Book: *Submarine Mass Movements and their Consequences V. Advances in Natural and Technological Hazards Series, Springer*

Editors: *Yasuhiro Yamada, Kiichiro Kawamura, Ken Ikehara, Yujiro Ogawa, Roger Urgeles, David Mosher, Jason Chaytor, Michael Strasser*

Status: *in press*

Dakar Slide offshore Senegal, NW-Africa: Interaction of stacked giant mass-wasting events and canyon evolution

Authors: *Mathias Meyer,* ***Jacob Geersen****, Sebastian Krastel, Tilmann Schwenk, Daniel Winkelmann*

Book: *Submarine Mass Movements and their Consequences V. Advances in Natural and Technological Hazards Series, Springer*

Editors: *Yasuhiro Yamada, Kiichiro Kawamura, Ken Ikehara, Yujiro Ogawa, Roger Urgeles, David Mosher, Jason Chaytor, Michael Strasser*

Status: *in press*

1.6 References from Introduction

Aki, K., 1979, Characterization of Barriers on an Earthquake Fault: Journal of Geophysical Research, v. 84, p. 6140-6148.

Ammon, C.J., Ji, C., Thio, H.-K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., and Wald, D., 2005, Rupture Process of the 2004 Sumatra-Andaman Earthquake: Science, v. 308, p. 1133-1139.

Angermann, D., Klotz, J., and Reigber, C., 1999, Space-geodetic estimation of the Nazca-South America Euler vector: Earth and Planetary Science Letters, v. 171, p. 329-334.

Bangs, N.L., and Cande, S.C., 1997, Episodic development of a convergent margin inferred from structures and processes along the southern Chilean margin: Tectonics, v. 16, p. 489-503.

Bangs, N.L.B., Gulick, S.P.S., and Shipley, T.H., 2006, Seamount subduction erosion in the Nankai Trough and its potential impact on the seismogenic zone: Geology, v. 34, p. 701-704.

Behrmann, J., and Kopf, A., 2001, Balance of tectonically accreted and subducted sediment at the Chile Triple Junction: International Journal of Earth Sciences, v. 90, p. 753-768.

Bilek, S.L., Schwartz, S.Y., and DeShon, H.R., 2003, Control of seafloor roughness on earthquake rupture behavior: Geology, v. 31, p. 455-458.

Bohm, M., Luth, S., Echtler, H., Asch, G., Bataille, K., Bruhn, C., Rietbrock, A., and Wigger, P., 2002, The Southern Andes between 36 degrees and 40 degrees S latitude: seismicity and average seismic velocities: Tectonophysics, v. 356, p. 275-289.

Brune, S., Ladage, S., Babeyko, A., Müller, C., Kopp, H., and Sobolev, S., 2009, Submarine landslides at the eastern Sunda margin: observations and tsunami impact assessment: Natural Hazards, v. 54, p. 547-562.

Campos, J., Hatzfeld, D., Madariaga, R., Lopez, G., Kausel, E., Zollo, A., Iannacone, G., Fromm, R., Barrientos, S., and Lyon-Caen, H., 2002, A seismological study of the 1835 seismic gap in south-central Chile: Physics of the Earth and Planetary Interiors, v. 132, p. 177-195.

Cembrano, J., Schermer, E., Lavenu, A., and Sanhueza, A., 2000, Contrasting nature of deformation along an intra-arc shear zone, the Liquiñe-Ofqui fault zone, southern Chilean Andes: Tectonophysics, v. 319, p. 129-149.

Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust: Review of Geophysics, v. 42, p. RG2001.

Collot, J.Y., Agudelo, W., Ribodetti, A., and Marcaillou, B., 2008, Origin of a crustal splay fault and its relation to the seismogenic zone and underplating at the erosional north Ecuador-south Colombia oceanic margin: Journal of Geophysical Research, v. 113, p. B12102.

Collot, J.-Y., Lewis, K., Lamarche, G., and Lallemand, S., 2001, The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: Result of oblique seamount subduction: Journal of Geophysical Research, v. 106, p. 19271-19297.

Comte, D., Eisenberg, A., Lorca, E., Pardo, M., Ponce, L., Saragoni, R., Singh, S.K., and Suarez, G., 1986, The 1985 Central Chile Earthquake: A Repeat of Previous Great Earthquakes in the Region?: Science, v. 233, p. 449-453.

Contreras-Reyes, E., and Carrizo, D., 2011, Control of high oceanic features and subduction channel on earthquake ruptures along the Chile-Peru subduction zone: Physics of the Earth and Planetary Interiors, v. 186, p. 49-58.

Contreras-Reyes, E., Flueh, E.R., and Grevemeyer, I., 2010, Tectonic control on sediment accretion and subduction off south central Chile: Implications for coseismic rupture processes of the 1960 and 2010 megathrust earthquakes: Tectonics, v. 29.

Contreras-Reyes, E., Grevemeyer, I., Flueh, E.R., and Reichert, C., 2008, Upper lithospheric structure of the subduction zone offshore of southern Arauco peninsula, Chile, at ~38°S: Journal of Geophysical Research, v. 113.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of Fold-and-Thrust Belts and Accretionary Wedges: Journal of Geophysical Research v. 88, p. 1153-1172.

Dean, S.M., McNeill, L.C., Henstock, T.J., Bull, J.M., Gulick, S.P.S., Austin, J.A., Bangs, N.L.B., Djajadihardja, Y.S., and Permana, H., 2010, Contrasting Décollement and Prism Properties over the Sumatra 2004-2005 Earthquake Rupture Boundary: Science, v. 329, p. 207-210.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425-478.

Diaz-Naveas, J.L., 1999, Sediment subduction and accretion at the Chilean convergent margin between 35° and 40°S: Kiel / Germany, Ph.D. Thesis - University of Kiel.

Duperret, A., Bourgois, J., Lagabrielle, Y., and Suess, E., 1995, Slope instabilities at an active continental margin: large-scale polyphase submarine slides along the northern Peruvian margin, between 5 °S and 6 °S: Marine Geology, v. 122, p. 303-328.

Goldfinger, C., Kulm, L.D., McNeill, L.C., and Watts, P., 2000, Super-scale Failure of the Southern Oregon Cascadia Margin: Pure and Applied Geophysics, v. 157, p. 1189-1226.

Goldfinger, C., Kulm, L.D., Yeats, R.S., McNeill, L., and Hummon, C., 1997, Oblique strike-slip faulting of the central Cascadia submarine forearc: Journal of Geophysical Research, v. 102, p. 8217-8243.

González, E., 1989, Hydrocarbon resources in the coastal zone of Chile, in Ericksen, G., ed., Geology of the Andes and its relation to hydrocarbon and mineral resources: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources, p. 383-404.

Gulick, S.P.S., Austin, J.A., McNeill, L.C., Bangs, N.L.B., Martin, K.M., Henstock, T.J., Bull, J.M., Dean, S., Djajadihardja, Y.S., and Permana, H., 2011, Updip rupture of the 2004 Sumatra earthquake extended by thick indurated sediments: Nature Geoscience, v. 4, p. 453-456.

Haberland, C., Rietbrock, A., Lange, D., Bataille, K., and Hofmann, S., 2006, Interaction between forearc and oceanic plate at the South-Central Chilean margin as seen in local seismic data: Geophysical Research Letters, v. 33.

Hackney, R.I., Echtler, H.P., Franz, G., Götze, H.-J., Lucassen, F., Marchenko, D., Melnick, D., Meyer, U., Schmidt, S., Tašárová, Z., Tassara, A., and Wienecke, S., 2006, The Segmented Overriding Plate and Coupling at the South-Central Chilean Margin (36–42°S), in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes – active subduction orogeny: Berlin, Springer, p. 355-374.

Hampel, A., Kukowski, N., Bialas, J., Huebscher, C., and Heinbockel, R., 2004, Ridge subduction at an erosive margin: The collision zone of the Nazca Ridge in southern Peru: Journal of Geophysical Research, v. 109, p. B02101.

Heberer, B., Roser, G., Behrmann, J.H., Rahn, M., and Kopf, A., 2010, Holocene sediments from the Southern Chile Trench: a record of active margin magmatism, tectonics and palaeoseismicity: Journal of the Geological Society, London, v. 167, p. 539-553.

Henstock, T.J., McNeill, L.C., and Tappin, D.R., 2006, Seafloor morphology of the Sumatran subduction zone: Surface rupture during megathrust earthquakes?: Geology, v. 34, p. 485-488.

Hervé, F., 1994, The southern Andes between 39° and 44°S latitude: The geological signature of a transpressive tectonic regime related to a magmatic arc, in Reuter, K.J., Scheuber, E., and Wigger, P.J., eds., Tectonics of the Southern Central Andes: Berlin, Springer, p. 243-248.

Hyndman, R.D., Yamano, M., and Oleskevich, D.A., 1997, The seismogenic zone of subduction thrust faults: Island Arc, v. 6, p. 244-260.

Kaizuka, S., Matsuda, T., Nogami, M., and Yonekura, N., 1973, Quaternary tectonic and recent seismic crustal movements in the Arauco peninsula and its environs, central Chile: Geographical reports of Tokyo Metropolitan University, v. 8, p. 1-49.

Kearey, P., Klepeis, K.A., and Vine, F.J., 1999, Global Tectonics, Wiley-Blackwell, 333 p.

Kelleher, J., and McCann, W., 1976, Buoyant Zones, Great Earthquakes, and Unstable Boundaries of Subduction: Journal of Geophysical Research, v. 81, p. 4885-4896.

Kelleher, J.A., 1972, Rupture Zones of Large South American Earthquakes and Some Predictions: Journal of Geophysical Research, v. 77, p. 2087-2103.

Kodaira, S., Kurashimo, E., Park, J.O., Takahashi, N., Nakanishi, A., Miura, S., Iwasaki, T., Hirata, N., Ito, K., and Kaneda, Y., 2002, Structural factors controlling the rupture process of a megathrust earthquake at the Nankai trough seismogenic zone: Geophysical Journal International, v. 149, p. 815-835.

Kopp, C., Fruehn, J., Flueh, E.R., Reichert, C., Kukowski, N., Bialas, J., and Klaeschen, D., 2000, Structure of the Makran subduction zone from wide-angle and reflection seismic data: Tectonophysics, v. 329, p. 171-191.

Kukowski, N., and Oncken, O., 2006, Subduction Erosion – the ”Normal” Mode of Fore-Arc Material Transfer along the Chilean Margin?, in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes – active subduction orogeny: Berlin, Springer, p. 217-236.

Kukowski, N., Schillhorn, T., Huhn, K., von Rad, U., Husen, S., and Flueh, E.R., 2001, Morphotectonics and mechanics of the central Makran accretionary wedge off Pakistan: Marine Geology, v. 173, p. 1-19.

Lallemand, S.E., Schnürle, P., and Malavieille, J., 1994, Coulomb theory applied to accretionary and nonaccretionary wedges: Possible causes for tectonic erosion and/or frontal accretion: Journal of Geophysical Research, v. 99, p. 12033-12055.

Lamarche, G., Joanne, C., and Collot, J.-Y., 2008, Successive, large mass-transport deposits in the south Kermadec fore-arc basin, New Zealand: The Matakaoa Submarine Instability Complex: Geochemistry, Geophysics, Geosystems, v. 9, p. Q04001.

Lomnitz, C., 1970, Major earthquakes and tsunamis in Chile during the period 1535 to 1955: International Journal of Earth Sciences, v. 59, p. 938-960.

Lomnitz, C., 2004, Major Earthquakes of Chile: A Historical Survey, 1535-1960: Seismological Research Letters, v. 75, p. 368-378.

Masson, D.G., Harbitz, C.B., Wynn, R.B., Pedersen, G., and LÃ¸vholt, F., 2006, Submarine landslides: processes, triggers and hazard prediction: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 364, p. 2009-2039.

McAdoo, B.G., Pratson, L.F., and Orange, D.L., 2000, Submarine landslide geomorphology, US continental slope: Marine Geology, v. 169, p. 103-136.

McNeill, L.C., Piper, K.A., Goldfinger, C., Kulm, L.D., and Yeats, R.S., 1997, Listric normal faulting on the Cascadia continental margin: Journal of Geophysical Research, v. 102, p. 12123-12138.

Melnick, D., Bookhagen, B., Echtler, H.P., and Strecker, M.R., 2006, Coastal deformation and great subduction earthquakes, Isla Santa Maria, Chile (37°S): Geological Society of America Bulletin, v. 118, p. 1463-1480.

Melnick, D., Bookhagen, B., Strecker, M.R., and Echtler, H.P., 2009, Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile: Journal of Geophysical Research, v. 114.

Melnick, D., and Echtler, H.P., 2006a, Inversion of forearc basins in south-central Chile caused by rapid glacial age trench fill: Geology, v. 34, p. 709-712.

Melnick, D., and Echtler, H.P., 2006b, Morphotectonic and geologic digital map compilations of the south-central Andes (36°–42°S), in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes: Active Subduction Orogeny: Berlin, Springer, p. 565-568.

Mitchell, N.C., 2005, Interpreting long-profiles of canyons in the USA Atlantic continental slope: Marine Geology, v. 214, p. 75-99.

Moore, E.M., and Twiss, R.J., 1995, Tectonics: New York, W. H. Freeman, 415 p.

Moore, G.F., Bangs, N.L., Taira, A., Kuramoto, S., Pangborn, E., and Tobin, H.J., 2007, Three-Dimensional Splay Fault Geometry and Implications for Tsunami Generation: Science, v. 318, p. 1128-1131.

Mordojovich, C., 1981, Sedimentary Basins of Chilean Pacific Offshore: AAPG Special Volumes, Energy Resources of the Pacific Region, p. 63-82.

Oleskevich, D., Hyndman, R., and Wang, K., 1999, The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile: Journal of Geophysical Research, v. 104(B7), p. 14965-14991.

Oncken, O., Hindle, D., Kley, J., Elger, K., Victor, P., and Schemmann, K., 2006, Deformation of the Central Andean Upper Plate System – Facts, Fiction, and Constraints for Plateau Models, in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes – active subduction orogeny: Berlin, Springer, p. 3-27.

Pardo-Casas, F., and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous Time: Tectonics, v. 6, p. 233-248.

Press, F., and Siever, R., 2003, Algemeine Geologie, Einführung in das System Erde: München, Elsevier GmbH.

Ranero, C.R., Phipps Morgan, J., McIntosh, K., and Reichert, C., 2003, Bending-related faulting and mantle serpentinization at the Middle America trench: Nature, v. 425, p. 367-373.

Ranero, C.R., and von Huene, R., 2000, Subduction erosion along the Middle America convergent margin: Nature, v. 404, p. 748-752.

Ranero, C.R., von Huene, R., Weinrebe, W., and Reichert, C., 2006, Tectonic Processes along the Chile Convergent Margin, in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes – active subduction orogeny: Berlin, Springer, p. 91-121.

Rehak, K., Strecker, M.R., and Echtler, H.P., 2008, Morphotectonic segmentation of an active forearc, 37°–41°S, Chile: Geomorphology, v. 94, p. 98-116.

Rosenau, M., Melnick, D., and Echtler, H., 2006, Kinematic constraints on intra-arc shear and strain partitioning in the southern Andes between 38°S and 42°S latitude: Tectonics, v. 25, p. TC4013.

Ruegg, J.C., Rudloff, A., Vigny, C., Madariaga, R., de Chabalier, J.B., Campos, J., Kausel, E., Barrientos, S., and Dimitrov, D., 2009, Interseismic strain accumulation measured by GPS in the seismic gap between Constitución and Concepción in Chile: Physics of the Earth and Planetary Interiors, v. 175, p. 78-85.

Ruff, L.J., 1989, Do trench sediments affect great earthquake occurrence in subduction zones?: Pure and Applied Geophysics, v. 129, p. 263-282.

Sallarès, V., and Ranero, C.R., 2005, Structure and tectonics of the erosional convergent margin off Antofagasta, north Chile (23°30´S): Journal of Geophysical Research, v. 110, p. B06101.

Sieh, K., and Natawidjaja, D., 2000, Neotectonics of the Sumatran fault, Indonesia: Journal of Geophysical Research, v. 105, p. 28295-28326.

Song, T.-R.A., and Simons, M., 2003, Large Trench-Parallel Gravity Variations Predict Seismogenic Behavior in Subduction Zones: Science, v. 301, p. 630-633.

Sparkes, R., Tilmann, F., Hovius, N., and Hillier, J., 2010, Subducted seafloor relief stops rupture in South American great earthquakes: Implications for rupture behaviour in the 2010 Maule, Chile earthquake: Earth and Planetary Science Letters, v. 298, p. 89-94.

Strasser, M., Moore, G.F., Kimura, G., Kitamura, Y., Kopf, A.J., Lallemant, S., Park, J.-O., Screaton, E.J., Su, X., Underwood, M.B., and Zhao, X., 2009, Origin and evolution of a splay fault in the Nankai accretionary wedge: Nature Geoscience, v. 2, p. 648-652.

Sultan, N., Cochonat, P., Canals, M., Cattaneo, A., Dennielou, B., Haflidason, H., Laberg, J.S., Long, D., Mienert, J., Trincardi, F., Urgeles, R., Vorren, T.O., and Wilson, C., 2004, Triggering mechanisms of slope instability processes and sediment failures on continental margins: a geotechnical approach: Marine Geology, v. 213, p. 291-321.

Tašárová, 2007, Towards understanding the lithospheric structure of the southern Chilean subduction zone (36°S–42°S) and its role in the gravity field: Geophysical Journal International, v. 170, p. 995-1014.

Tebbens, S.F., Cande, S.C., Kovacs, L., Parra, J.C., LaBrecque, J.L., and Vergara, H., 1997, The Chile ridge: A tectonic framework: Journal of Geophysical Research, v. 102, p. 12035-12059.

Thomson, S.N., 2002, Late Cenozoic geomorphic and tectonic evolution of the Patagonian Andes between latitudes 42°S and 46°S: An appraisal based on fission-track results from the transpressional intra-arc Liquine-Ofqui fault zone: Geological Society of America Bulletin, v. 114, p. 1159-1173.

Thornburg, T.M., and Kulm, L.D., 1987, Sedimentation in the Chile Trench: Depositional morphologies, lithofacies, and stratigraphy: Geological Society of America Bulletin, v. 98, p. 33-52.

Tichelaar, B.W., and Ruff, L.J., 1991, Seismic Coupling Along the Chilean Subduction Zone: Journal of Geophysical Research, v. 96, p. 11997-12022.

Twiss, R.J., and Moore, E.M., 2006, Structural Geology: New York, W. H. Freeman, 532 p.

Völker, D., Wiedicke, M., Ladage, S., Gaedicke, C., Reichert, C., Rauch, K., Kramer, W., and Heubeck, C., 2006, Latitudinal Variation in Sedimentary Processes in the Peru-Chile Trench off Central Chile, in Oncken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., eds., The Andes – active subduction orogeny: Berlin, Springer, p. 193-216.

Völker, D., Scholz, F., and Geersen, J., in press, Analysis of submarine landsliding in the rupture area of the 27 February 2010 Maule Earthquake, Central Chile: Marine Geology

von Huene, R., and Ranero, C.R., 2003, Subduction erosion and basal friction along the sediment-starved convergent margin off Antofagasta, Chile: Journal of Geophysical Research, v. 108, p. 2079.

von Huene, R., Ranero, C.R., Weinrebe, W., and Hinz, K., 2000, Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism: Tectonics, v. 19, p. 314-334.

von Huene, R., and Scholl, D.W., 1991, Observations at Convergent Margins Concerning Sediment Subduction, Subduction Erosion, and the Growth of Continental Crust: Reviews of Geophysics, v. 29, p. 279-316.

Wang, K., and Hu, Y., 2006, Accretionary prisms in subduction earthquake cycles: The theory of dynamic Coulomb wedge: Journal of Geophysical Research, v. 111, p. B06410.

Wang, K., Hu, Y., Bevis, M., Kendrick, E., Smalley, R., Jr., Vargas, R.B., and Lauría, E., 2007, Crustal motion in the zone of the 1960 Chile earthquake: Detangling earthquake-cycle deformation and forearc-sliver translation: Geochemistry, Geophysics, Geosystems, v. 8, p. Q10010.

Wells, R.E., Blakely, R.J., Sugiyama, Y., Scholl, D.W., and Dinterman, P.A., 2003, Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion?: Journal of Geophysical Research, v. 108, p. 2507.

2 Manuscript #1

Active tectonics of the South Chilean marine fore arc (35°S–40°S)

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Active tectonics of the South Chilean marine fore arc (35°S–40°S)

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[1] The South Chilean marine fore arc (35°S–40°S) is separated into four tectonic segments, Concepción North, Concepción South, Nahuelbuta, and Tolten (from north to south). These are each characterized by their individual tectonic geomorphology and reflect different ways of mechanical and kinematic interaction of the convergent Nazca and South American plates. Splay faults that cut through continental framework rock are seismically imaged in both Concepción segments and the Tolten Segment. Additionally, the Concepción South Segment exhibits prominent upper plate normal faults. Normal faults apparently relate to uplift caused by sediment underthrusting at depth. This has led to oversteepening and gravitational collapse of the marine fore arc. There is also evidence for sediment underthrusting and basal accretion to the overriding plate in the Tolten Segment. There, uplift of the continental slope has created a landward inclined seafloor over a latitudinal distance of 50 km. In the Nahuelbuta Segment transpressive upper plate faults, aligned oblique to the direction of plate motion, control the seafloor morphology. Based on a unique acoustic data set including >90% of bathymetric coverage of the continental slope we are able to reveal an along-strike heterogeneity of a complexly deformed marine fore arc which had escaped attention in previous studies that only considered the structure along transects normal to the plate margin.

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3 Manuscript #2

Pleistocene giant slope failures offshore Arauco Peninsula, Southern Chile

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Pleistocene giant slope failures offshore Arauco Peninsula, Southern Chile

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Abstract: Three Pleistocene giant slope failures are observed in high-resolution bathymetric and seismic reflection data off Southern Chile, two of which extend across the full width of the continental slope from the shelf break to the trench. With mobilized volumes between 253 km^3 and 472 km^3, these slides are among the largest submarine landslides documented at active continental margins so far. Deposits of each of the slides are imaged as chaotic sequences in seismic reflection lines buried beneath well-stratified sediments in the Chile Trench. The ages of the three slides are about 0.25, 0.41 and >0.56 Ma. The main preconditioning factor for the slope instabilities seems to be local uplift of the continental slope that results in peculiarly high slope angles of up to 30°. Uplift of the marine and continental forearc of the study area is the result of shortening across upper plate faults and therefore a long-term continuous process. Slope instability seems to be an iterative process and failure is likely to recur.

4 Manuscript #3

Segmentation of the 1960 and 2010 Chilean earthquakes controlled by a giant slope failure

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Segmentation of the 1960 and 2010 Chilean earthquakes controlled by a giant slope failure

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Introductory paragraph

Determining the factors that limit coseismic rupture during megathrust earthquakes is important for understanding seismotectonic segmentation at convergent plate margins. The boundary between the Mw=9.5 Great Chile (1960) and the Mw=8.8 Maule (2010) earthquakes in Southern Chile was the site of a giant submarine slope failure, with the chaotic debris subducted to seismogenic zone depth today, as shown by seismic reflection data. At this location a continuous décollement is absent. Away from the slope failure undisturbed trench-fill and a continuous décollement are imaged. We infer that underthrusting of inhomogeneous slide deposits prevents the development of a décollement, and thus the formation of a thin continuous slip zone necessary for earthquake rupture propagation. Thus the Great Chile – Maule earthquake rupture boundary seems to be controlled by the underthrusting of upper plate mass wasting deposits. Our results suggest that upper plate dynamics and resulting surface processes can play a key role in establishing seismotectonic segmentation at convergent plate margins.

5 Synthesis

The main aim of this PhD thesis is to improve the understanding of the active tectonic state of the complexly deformed South Chilean marine forearc. The first part focused on the documentation of the general tectonic state of the margin between 35°S – 40°S. Later work concentrated on the detailed investigation of specific tectonic features and processes that were identified in distinct regions of the overall study area. Results are based on the interpretation of surface (bathymetric) and subsurface (reflection seismic) data. Therefore, at the beginning of the PhD thesis, robust interpretation techniques had to be developed for a combined use of both types of data.

The main outcome from the early phase of the PhD work is that the marine forearc in the area 35°S - 40°S is heavily segmented in terms of geomorphology and underlying tectonic processes. I identified four distinct tectonic segments which host different deformation structures and located the positions of the tectonic segment boundaries. Observed deformation patterns change over short distances (i.e. several kilometers). This strict segmentation, however, could only be recognized by investigating the extensive swath bathymetric dataset of the IFM-GEOMAR that covers more than 90% of the continental slope in this area. Along-slope marine forearc segmentation had escaped attention in previous studies, mainly because these studies only considered narrow transects (along reflection seismic lines) normal to the plate margin (e.g. Bangs and Cande, 1997; Diaz-Naveas, 1999). With respect to future studies on subduction zone tectonics, our results show that for a full and comprehensive understanding of the active tectonic state of a convergent margin, surface data, i.e. swath bathymetry, is fundamental.

During the remaining time of the PhD, the Nahuelbuta Segment in the area of the Arauco Peninsula (37°S – 39°S) was chosen among the four identified tectonic segments for further investigations for two reasons. First, the Nahuelbuta Segment displays a very complex geomorphology and second, it is the location of a prominent and so far not understood earthquake segment boundary. In 1960, the Mw 9.5 Great Chile Earthquake ruptured about 1000 km of the Nazca – South America plate boundary to the south of the Arauco Peninsula (Barrientos and Ward, 1990; Moreno et al., 2009). Until today this event is the largest ever instrumentally recorded earthquake in the world. About 50 years later, the immediate area to the north of the Great Chile Earthquake was ruptured on 27 February 2010 by the Mw 8.8 Maule Earthquake (e.g. Lorito et al., 2011). The detailed investigations of the Nahuelbuta Segment revealed three giant submarine slope failures, two of which affected the full width of the continental slope from the shelf break to the trench. The slope failures were analyzed regarding their volumes, ages and underlying preconditioning mechanisms. Investigations were again based on the combination of high resolution swath bathymetric data that document the slide scars at the continental slope and reflection seismic data that image the slide deposits buried beneath undisturbed sediments in the Chile trench.

Slope failure is a common process at all types of continental margins (e.g. McAdoo et al., 2000; Sultan et al., 2004; Masson et al., 2006). However, very large active margin slides with volumes comparable to giant passive margin slides such as Storegga Slide off Norway (3000 km^3; Haflidason et al., 2004) or Sahara Slide off NW Africa (600 km^3; Gee et al., 1999) are rarely documented. Our results show that the three investigated South Chilean landslides (volumes between 253 km^3 and 472 km^3) range among the largest slides ever documented at active continental margins, comparable to slope failures described off New Zealand (Collot et al., 2001; Lamarche et al., 2008), Oregon (Goldfinger et al., 2000), and Peru (Duperret et al., 1995). A question that remains open is whether giant active margin slides are globally limited to a handful of events or if they have escaped recognition so far. The three giant South Chilean slides presented in this study remained undiscovered for almost 10 years, i.e. since the seismic data was collected. A process that might contribute to overseeing submarine slides at active margins is the constant deformation, which is characteristic to this tectonic realm. Structures such as slide scars remain well preserved for a long time at passive margins, whereas similar features are rapidly overprinted by tectonic deformation at active margins. Future studies using swath bathymetric data from different active continental margins and reflection seismic data from the associated trenches may help to find the answer.

The results from this PhD thesis obtained so far were used to set up a novel model of the margin deformation that combines the tectonic segmentation results with the observed slope failures. The model explains how observed slope failures are preconditioned by the specific tectonic regime of the Nahuelbuta Segment. In that particular area, continuous and high Pleistocene and Pliocene uplift rates of up to 5.5 mm/a (Kaizuka et al. 1973; Melnick et al. 2009) have been inferred. Strong uplift likely causes repeated oversteepening of the continental slope with slope angles locally exceeding 30° resulting in the observed slope instabilities.

In addition to the observed and plausible causal relationship between tectonics and resulting mass wasting, a less obvious reverse relation was found and described for the first time. Inspired by the finding that the rupture boundary between the Mw 9.5 Great Chile (1960) and the Mw 8.8 Maule (2010) earthquakes is located in the Nahuelbuta Segment in the area of the slope failures I investigated if the three slope failures might play a role for earthquake segmentation. Until today, no convincing hypothesis was presented for the cause of this earthquake segment boundary. A major problem in explaining it consists in the fact that the rupture boundary does not correlate with any significant relief changes on the oceanic Nazca Plate (Sparks et al., 2010; Contreras-Reyes and Carrizo, 2011).

Reflection seismic data reveal that chaotic products of the slope failures are deposited in the trench in front of the slope embayments, which represent the sites of failure. In front of the largest slope failure, these deposits almost completely fill the trench down to a depth were they are underthrust beneath the marine forearc. Through being underthrust in the subduction channel, the slide deposits directly impact on the formation, character and physical state of the plate interface. I observe a well developed décollement in the areas away from the underthrust slide deposits and the absence of a décollement at the locations of the slope failures. As the position of underthrust slide deposits coincides with the earthquake rupture boundary, I speculate that coseismic rupture during the 1960 and 2010 earthquakes was arrested by the slide deposits. This leads to the conclusion that slip propagation of plate-boundary earthquakes may be defined by the dynamics of the overriding plate (i.e. forearc uplift) and resulting surface processes (i.e. catastrophic mass wasting).

The phenomenon of earthquake segmentation has been observed for decades but still many segment boundaries are not fully understood. In this context the obtained results for Southern Chile add an important piece of understanding to the complex topic as they emphasize that, while it is important to consider lower subducting plate variations, changes in the upper overriding plate might be of similar importance for the explanation of earthquake segmentation.

In summary, the results from this PhD thesis show that the active tectonic state of a convergent margin can only be fully and comprehensively understood, if different types of data are used jointly. For the South Chilean marine forearc, many deformation patterns that act on multiple spatial scales have been newly identified and investigated. The outcome that the 1960 – 2010 Earthquake boundary is likely controlled by the underthrusting of deposits of submarine slope failures forms an important contribution to the understanding of the complex topic of earthquake segmentation at convergent margins. Future studies aiming to investigate whatever aspects of the South Chilean marine forearc in the area 35°S – 40°S will profit from the detailed investigations and results of this PhD thesis. Furthermore, the combination of surface (bathymetric) and sub-surface (reflection seismic) data in this study may serve as good example how future detailed investigations on marine forearc structure and active tectonics can be realized.

5.1 References from Synthesis

Bangs, N.L., and Cande, S.C., 1997, Episodic development of a convergent margin inferred from structures and processes along the southern Chilean margin: Tectonics, v. 16, p. 489-503.

Barrientos, S.E., and Ward, S.N., 1990, The 1960 Chile earthquake: inversion for slip distribution from surface deformation: Geophysical Journal International, v. 103, p. 589-598.

Collot, J.-Y., Lewis, K., Lamarche, G., and Lallemand, S., 2001, The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: Result of oblique seamount subduction: Journal of Geophysical Research, v. 106, p. 19271-19297.

Contreras-Reyes, E., and Carrizo, D., 2011, Control of high oceanic features and subduction channel on earthquake ruptures along the Chile-Peru subduction zone: Physics of the Earth and Planetary Interiors, v. 186, p. 49-58.

Diaz-Naveas, J.L., 1999, Sediment subduction and accretion at the Chilean convergent margin between 35° and 40°S: Kiel / Germany, Ph.D. Thesis - University of Kiel.

Duperret, A., Bourgois, J., Lagabrielle, Y., and Suess, E., 1995, Slope instabilities at an active continental margin: large-scale polyphase submarine slides along the northern Peruvian margin, between 5 °S and 6 °S: Marine Geology, v. 122, p. 303-328.

Gee, M.J.R., Masson, D.G., Watts, A.B., and Allen, P.A., 1999, The Saharan debris flow: an insight into the mechanics of long runout submarine debris flows: Sedimentology, v. 46, p. 317-335.

Goldfinger, C., Kulm, L.D., McNeill, L.C., and Watts, P., 2000, Super-scale Failure of the Southern Oregon Cascadia Margin: Pure and Applied Geophysics, v. 157, p. 1189-1226.

Haflidason, H., Sejrup, H.P., Nygård, A., Mienert, J., Bryn, P., Lien, R., Forsberg, C.F., Berg, K., and Masson, D., 2004, The Storegga Slide: architecture, geometry and slide development: Marine Geology, v. 213, p. 201-234.

Kaizuka, S., Matsuda, T., Nogami, M., and Yonekura, N., 1973, Quaternary tectonic and recent seismic crustal movements in the Arauco peninsula and its environs, central Chile: Geographical reports of Tokyo Metropolitan University, v. 8, p. 1-49.

Lamarche, G., Joanne, C., and Collot, J.-Y., 2008, Successive, large mass-transport deposits in the south Kermadec fore-arc basin, New Zealand: The Matakaoa Submarine Instability Complex: Geochemistry, Geophysics, Geosystems, v. 9, p. Q04001.

Lorito, S., Romano, F., Atzori, S., Tong, X., Avallone, A., McCloskey, J., Cocco, M., Boschi, E., and Piatanesi, A., 2011, Limited overlap between the seismic gap and coseismic slip of the great 2010 Chile earthquake: Nature Geoscience, v. advance online publication.

Masson, D.G., Harbitz, C.B., Wynn, R.B., Pedersen, G., and Løvholt, F., 2006, Submarine landslides: processes, triggers and hazard prediction: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 364, p. 2009-2039.

McAdoo, B.G., Pratson, L.F., and Orange, D.L., 2000, Submarine landslide geomorphology, US continental slope: Marine Geology, v. 169, p. 103-136.

Melnick, D., Bookhagen, B., Strecker, M.R., and Echtler, H.P., 2009, Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile: Journal of Geophysical Research, v. 114.

Moreno, M.S., Bolte, J., Klotz, J., and Melnick, D., 2009, Impact of megathrust geometry on inversion of coseismic slip from geodetic data: Application to the 1960 Chile earthquake: Geophysical Research Letters, v. 36, p. L16310.

Sparkes, R., Tilmann, F., Hovius, N., and Hillier, J., 2010, Subducted seafloor relief stops rupture in South American great earthquakes: Implications for rupture behaviour in the 2010 Maule, Chile earthquake: Earth and Planetary Science Letters, v. 298, p. 89-94.

Sultan, N., Cochonat, P., Canals, M., Cattaneo, A., Dennielou, B., Haflidason, H., Laberg, J.S., Long, D., Mienert, J., Trincardi, F., Urgeles, R., Vorren, T.O., and Wilson, C., 2004, Triggering mechanisms of slope instability processes and sediment failures on continental margins: a geotechnical approach: Marine Geology, v. 213, p. 291-321.

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