Impact of the lateral variability of the incoming ocean plate in South Chile on the structure of the marine forearc and the generation of mega thrust earthquakes

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1. Introduction

South Central Chile is among the areas of the world with the highest levels of tectonic erosion, producing several kilometres of subsidence to the south of the city of Valdivia. This fact is perhaps best documented by the Golfo Ancud separating the Isla Chiloe from the mainland. The Gulf has been formed by subsidence of the continent and represents the southward continuation of the Valley Central. Further to the south, however, there is evidence for focused local uplift and a gap in arc magmatism. Such prominent changes in the structure of the forearc and continent are governed by the properties of the subducting ocean plate.

At 46°S the Chile Ridge – an active spreading centre – is currently subducted. The Chile Ridge is offset by several left stepping transform faults, resulting in 50 to 300 km long spreading segments. These fracture zone offsets have created a situation in which neighbouring sections of oceanic lithosphere created at the same spreading axis are subducted under Chile at ages ranging from zero age at 46°S to 25 Mio. years near Valdivia at 40°S. In this context slab-age-dependent effects affect the tectonics and volcanism of the overriding South American plate. Anomalously high regional forearc subsidence caused by tectonic erosion strongly correlates with younging ages of the subducting plate producing up to several kilometres of along-forearc subsidence in the region just north of the subducting ridge. Where the ridge itself is actively subducting, there is a focussed pulse of local forearc uplift and subsidence. Furthermore, a gap in arc magmatism exists just to the south of the region of active ridge subduction, in the region between 47°-49° S, where the subducted slab of age <~10 Ma is underlying the 'normal location' for arc magmatism.

This area of strong lateral change in the structure and properties of the incoming ocean plate and margin tectonics was affected by the world's largest earthquake ever recorded instrumentelly: the great Chile earthquake and tsunami of 1960.

The major goal of the GEOTECHNOLOGIEN programme **TIPTEQ** – from **T**he **I**ncoming **P**late to mega **T**hrust **E**arth**Q**uake processes - is to evaluate the controlling factors of great subduction zone earthquakes and to understand the interrelation between earthquake nucleation, tectonic erosion and the properties of the incoming ocean plate. The aims and first results described here are from the *Themenbereich A* and focus on the *»Lateral variability of the incoming ocean plate and of the marine forearc«*. During a major sea going programme aboard the German research vessel SONNE geophysical data have been collected from December 6, 2004 to February 24, 2005. Two networks of Ocean Bottom Seismometers offshore Isla Chiloe and Isla Mocha are in operation until October 2005 to record the natural seismicity from the plate interface where mega thrust earthquakes nucleate.

2. Objectives and data collection during RV SONNE cruise SO181

A long-term goal of continental margin research is to study the processes by which oceanic plate subduction drives arc magmatism, continental accretion or erosion, and earthquake processes. One key first-order parameter shaping a subduction zone is the thermal structure (i.e. age) of the downgoing plate. RV SONNE cruise SO181 as part of the TIPTEQ initiative studied a roughly 1000 km long region along the Chile trench surrounding the Chile Triple Junction at 46°S. This area represents a natural laboratory to study subduction zone processes at various ages and hence thermal regimes.

The TIPTEQ project is a multidisciplinary study that aims at the quantification of

1) Material fluxes (mass and fluids) along and across the forearc area,
2) Thermal structure of the oceanic plate and subduction zone,
3) Rheological behaviour of the subducting sediment along the interplate megathrust,
4) Seismic activity and generation of large subduction-related earthquakes, and
5) Relationship between material fluxes and volcanic arc products, including thermal modelling of the entire subduction zone system.

The results to these goals will yield a detailed view of the entire subduction system. A comprehensive data set has been collected along five corridors with geophysical data at key locations during SO181 (Figure 1). Each corridor provides wide-angle seismic data, multichannel seismic data (either existing or new high-resolution data), heat flow measurements, multibeam bathymetry and magnetic field data. The corridors were complemented by mapping with multibeam bathymetry and magnetic field data. Additionally, two short-term (1 month) and two long-term (9 months) marine seismological networks were deployed to obtain a comprehensive data set in the survey area.

Growing evidence indicates that the oceanic lithosphere undergoes profound changes as it flexes at the outer rise and plunges into the trench. Multibeam bathymetry at different margins shows that the ocean plate can be pervasively broken by flexural normal faults. In addition, some large outer rise earthquakes (M=6-8) document that normal faults can in some cases cut to > 20 km depth. The consequence is that water may penetrate along permeable faults to mantle depths so that the oceanic mantle is serpentinised and the ocean lithosphere may be dramatically cooled by water circulation along the faults. Recent modelling and geochemical studies suggest that water circulation and serpentinisation of the ocean mantle may play a major role in the thermal structure of the plates and in magma generation at volcanic arcs. In addition, deserpentinisation may control intraslab earthquakes. Therefore, a major goal was to collect a comprehensive data set from the ocean plate immediately seaward of the trench in order to understand the input of water into the subduction system. Multibeam bathymetry will show the response of the different oceanic crust segments to flexure and the variations in normal faulting. Magnetic data will provide detailed information on lithospheric age and the nature of tectonic boundaries. Wide-angle seismic data (P and S waves) will map the changes in crustal and/or mantle velocities and Poisson ratios along and across the ocean plate yielding an estimate of the amount of serpentinisation and thus on the amount of water added to the ocean plate. Heat flow measurements will show the changes in thermal structure related to age and to water circulation.

The subduction of laterally heterogeneous ocean plate segments influences the evolution of the arc-forearc system. The processes, however, can only be understood by collecting data that yield information on the entire thikkness of the overriding plate and on volumes of different types of rocks along and across the forearc area. The geophysical corridors collected across the ocean plate were extended into the margin to evaluate the material flux variation related to changes in structure of the subducting ocean plate and trench sediment supply. Such data allow to quantitatively estimate material fluxes of accreted sediment and continental framework rock. Detailed velocities from prestack depth migrated seismic reflection profiles will yield information on the location and amount of fluid flow at the front of the margin. Geotechnical testing of the trench sediment, heat flow measurements and thermal modelling of the subduction system constrain the depths of metamorphic reactions and dehydration. Heat flow data also provide the observations necessary to estimate the temperature at the plate boundary at depth.

Seismological observations are crucial to relate long term deformation observed to other methods and to the short term response of the structures. Earthquake depths, distribution and focal mechanisms determine the depth of faulting in the ocean lithosphere at the outer rise. Furthermore they inform on the evolution of subducted structures of the ocean plate showing whether structures like fracture zones and normal faults formed at the spreading centre are reactivated. It is of particular interest to find out if the subducted part of the Chile Ridge still is expressed in the seismicity pattern beneath the forearc and volcanic arc. This is crucial for the attempt to locate the subducted ridge and understand the relationship between spreading centre subduction, the gap in arc volcanism and slab window processes. The combination of seismicity, heat flow measurement and data from frictional properties of the subducting sediment helps to understand the controls on the updip and downdip limits of the interplate zone of seismic rupture (seismogenic zone). For example, we can test the hypothesis that the updip limit occurs at the 100-150°C isotherm and is related to the illite - smectite phase change, or whether other processes and other temperatures are important.

3. Summary of first results

From December 2004 to February 2005 the RV SONNE cruise SO181 took place as part of the TIPTEQ project in southern Chile to acquire various geophysical and geological datasets across the subduction zone between 35° S and 48° S. Here, the oceanic Nazca plate, the oceanic Antarctic plate and the continental South American plate join at the Chile Triple Junction, south of which the active spreading centre is subducting. To the north of the triple junction, the Nazca plate is segmented by several fracture zones across our survey area, allowing us to study subduction of differently aged oceanic crust and thus different thermal regimes. In addition, a simple plate motion environment exists with a constant convergence rate between the Nazca and the South American plate, constant spreading rates at the spreading centres, and a homogeneous motion vector, turning this area into a favourable natural laboratory for subduction zone process studies. We have chosen five major east-west oriented corridors as transects for the data acquisition, with crustal ages ranging from 25 Ma down to 3 Ma, four of the lines north and one line south of the triple junction. All transects were covered with seismic wide-angle refraction and vertical incidence reflection data, and the northern four transects also with heat flow either on or near the transects. Furthermore, two short-term and two long-term seismological networks of ocean bottom seismometers and hydrophones were deployed. The short-term arrays were located on top of the outer rise and recorded for about six weeks, and four short streamer profiles were shot across them, firstly to re-locate the ocean bottom receivers and secondly to obtain structural images. The long-term seismological arrays were deployed towards the end of this cruise to be recovered in October 2005. During the entire survey bathymetric profiling took place and several long magnetic profiles were collected. In total, 260 ocean bottom seismometer and hydrophone stations were deployed, with 30 instruments remaining on the seafloor for the long-term seismological networks, one instrument being lost, and 229 successful recoveries. The data quality overall is good to excellent, with only few components being weak or without data. Three types of airguns were used for shooting the seismic lines; for wide-angle refraction shooting these were two simultaneous bolt guns of 32 l each, and a cluster of 8 G-guns of 8 l each, i.e. nominally 64 l capacity for each wide-angle shot; for shallow reflection shooting into a seismic streamer only, we used two 1.72 l GI-guns. A total number of 45180 shots were fired during this cruise at an overall excellent performance rate.

Initial results from onboard data analyses exhibited a high data quality, and superb results are to be expected. For example, the outer rise networks recorded several thousand earthquakes, almost 600 of which have been located during the cruise, and it appears that this pilot study exhibits a clear potential for analysing plate-bending related earthquakes at outer rise areas. Furthermore, the combined 1440 km of seismic wide-angle coverage along the five TIPTEQ corridors illuminate well the different stages of the subduction. Strong seismic anisotropy of about 7% was detected in the upper mantle, with the fast orientation matching the direction of spreading. Seismic reflection profiling produced clear images of the sedimentary cover. Remarkably, only small differences exist in the sedimentary thicknesses between the lines, despite the difference in ages of the oceanic crust. The sedimentation rate appears high except around 41° S. The reflection data also confirm the existence of a bottom simulating reflector, indicating gas hydrates, and this reflector will allow heat flow estimates. However, from our in-situ heat flow measurements, we directly measured values in the trench, on the outer bulge, and landwards of the trench. Heat flow values near the deformation front are highest on the youngest crust (150-200 mW/m^2) and very low on the oldest crust (20 mW/m^2). However, anomalously low heat flow values around 20 mW/m^2 in the trench seem to be influenced strongly by sedimentation effects, and extremely low values of 7 mW/m^2 in the outer rise area offshore Isla Chiloe correlate with apparent sea-water inflow into the oceanic crust. Due to advection of heat into the subduction zone by the downgoing lithosphere, heat flow values decrease landwards of the deformation front to values of 35-70 mW/m^2. High resolution bathymetry data were collected along about 17600 km of ship track, complementing existing multibeam data. These bathymetric images show a well developed sedimentary cover, however no surface-cutting faults from plate bending were identified in the new areas, though high resolution seismic reflection data indicate that basement faults continue in the sedimentary blanket. Finally, the magnetic field measurements successfully detected the magnetic field reversals imprinted in the oceanic crust and allow an accurate age determination of the incoming plate. Profiles along these anomalies, roughly north-south oriented, did not detect possible magnetite from serpentinisation, however anomalies from fracture zones could be measured.

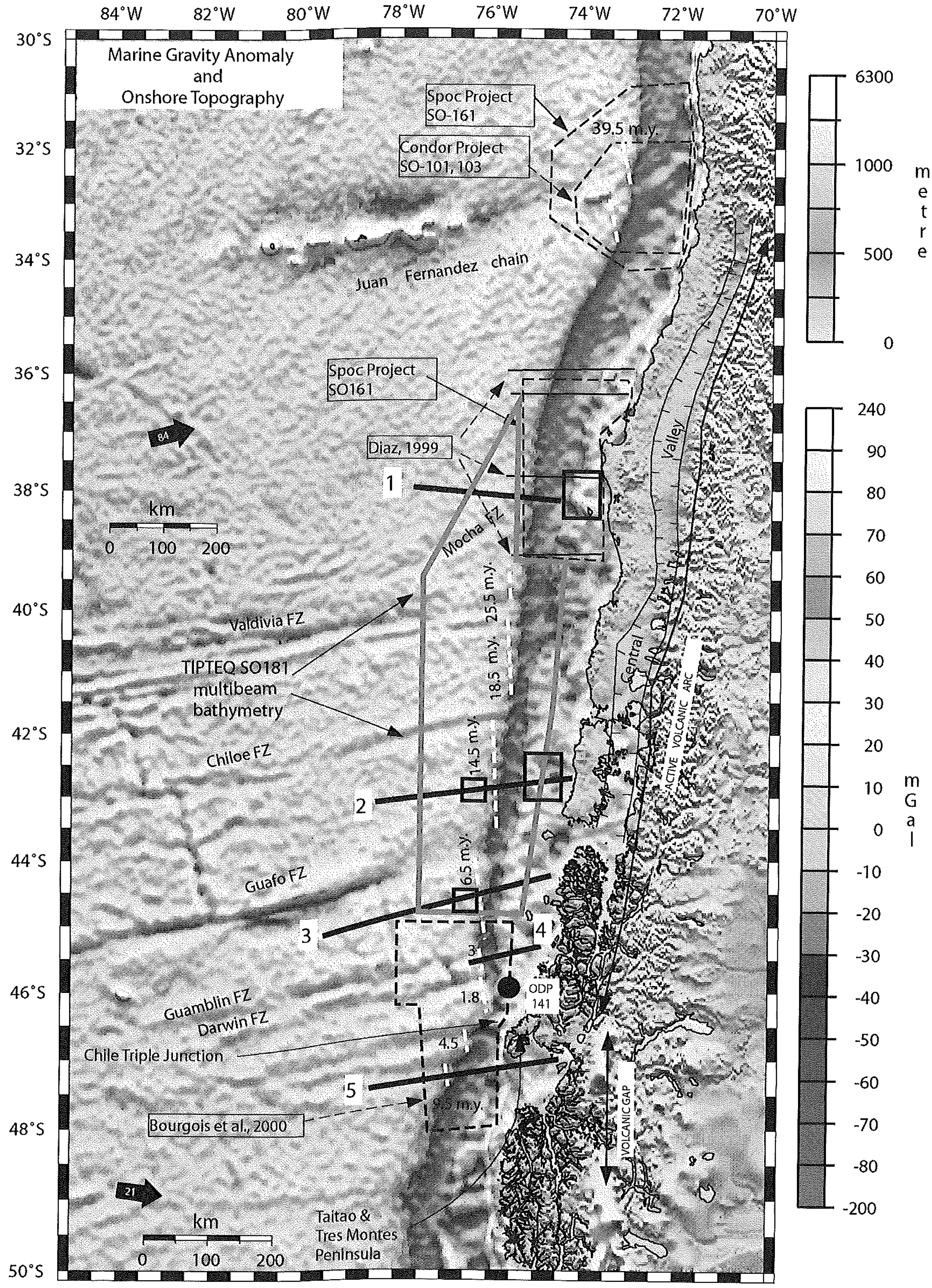

Figure 1: TIPTEQ marine corridors 1-5 (thick black lines) overlying marine gravity anomalies and land topography. They provide information on lateral changes in subduction structures of different ages. Small black rectangles indicate locations of seismological ocean bottom networks. Grey box marks area for detailed bathymetric and magnetic surveys of the TIPTEQ projects. Dashed boxes show areas of previous investigations. Thick black arrows show plate motion vectors with convergence rates in mm/a.

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