# Chapter 1

# Introduction and motivation

The earth's interior has been the target for seismic imaging over at least the last five decades. Seismological investigations of the crust and the mantle revealed them as heterogeneous fabrics containing heterogeneities over all scales. Seismic scattering occurs due to the interaction between elastic waves propagating through the earth and these heterogeneities within. Depending on the scattering strength the reflections from structures below heterogeneous regions suffer from signal distortion and amplitude loss. The reflections become complex or apparently disappear completely such that imaging of deeper structures becomes difficult. This issue plays an important role for the structural and geodynamic interpretation of seismic images of complex and strongly scattering regions, for example when imaging sub-basalt or sub-salt targets. Thus, the understanding of scattering phenomena and their impact on the seismic image is of ongoing interest, not only in exploration seismic surveys, but also for deep seismic reflection projects focusing on crustal and mantle structures.

Studies extracting the statistical parameters of heterogeneous media, i.e. the standard variation of the velocity fluctuation and correlation lengths of the heterogeneities, provided structural information about the heterogeneities within the earth. A number of borehole data analyses revealed that the magnitude of velocity fluctuations shows significant variation with the locality (Holliger and Levander, 1994) and with increasing depth (Frenje and Juhlin, 1998). A typical average value for the standard deviation of velocity fluctuations in the crust is about 4 % (Martini et al., 2001), while measures of exposed lower crustal rocks showed that the standard deviation can be about 1.5 % (Bean, 1996). Correlation-spectra analysis of neighbouring wells and other case studies showed that the correlation lengths of the heterogeneities in the upper crust range between hundreds of meters up to few kilometers (Dolan et al., 1998; Wu et al., 1994; Levander and Holliger, 1992). Pullammanappallil et al. (1997) showed that the spatial properties of the acoustic impedance field are related to the spatial properties of the backscattered wavefield, but the accuracy of the extraction methods and the reliability of the extracted values are still rather questionable. They appear to be strongly dependent on the data type, e.g. zero offset data, CMP stacked data, CMP migrated data etc. and on the frequency content of the analysed data (Pullammanappallil et al., 1997; Bean et al., 1999). Another numerical modelling study revealed that the presence of strong scattering components biases correlation lengths obtained from analysis of the backscattered field towards shorter values (Hurich, 1996).

Numerical modelling studies of wave propagation in heterogeneous media were carried out since the early eighties by Frankel and Clayton (1984, 1986) and Raynaud (1988). Later studies investigated seismic scattering in the context of seismic imaging, i.e. reflection and refraction data analysis (Gibson and Levander, 1988; Levander and Gibson, 1991; Levander and Holliger, 1992). For example Emmerich et al. (1993) investigated the signatures of scatterers in the subsurface. In these studies scatterers with predominantly horizontal or vertical orientation as well as scatterers without preferred orientations, i.e. isotropic, were studied. The results from migration of synthetic seismograms revealed that the determination of scatterer orientations is less reliable than commonly assumed, such that interpretation of scatterer orientation should be handled with care. Other studies showed that complex reflection patterns are not only caused by the complex reflector itself, but also by scattering in the heterogeneous layer above (Henstock and Levander, 2000). Thereby, laterally discontinuous reflectors located below heterogeneous layers cause complex incoherent reflections of mixed polarities. An excellent velocity control and prestack migration techniques are required to obtain sufficient signal-to-ratio levels on reflections from strongly scattering areas (Martini et al., 2001).

The ANCORP data is one example of a deep reflection seismic data providing an image of a strongly heterogeneous environment of 400 km lateral extent and 100 km depth (Yoon, 2001). The data set was acquired to investigate the geodynamic processes in the Central Andes at 21° S (North Chile and Bolivia). It yielded a detailed seismic image of a convergent continental margin, where the oceanic Nazca plate is being subducted below the South American continent (Fig. 1.1). The seismic image revealed an east dipping Nazca reflector at depths between 40 - 90 km and bright reflective structures in the continental crust. At the beginning of the profile a very thin reflection is visible at a depth of 35 km. This is interpreted as the reflection from the continental Moho. Below, two distinct parallel reflectors were visible and interpreted as the top and the bottom of the oceanic crust.

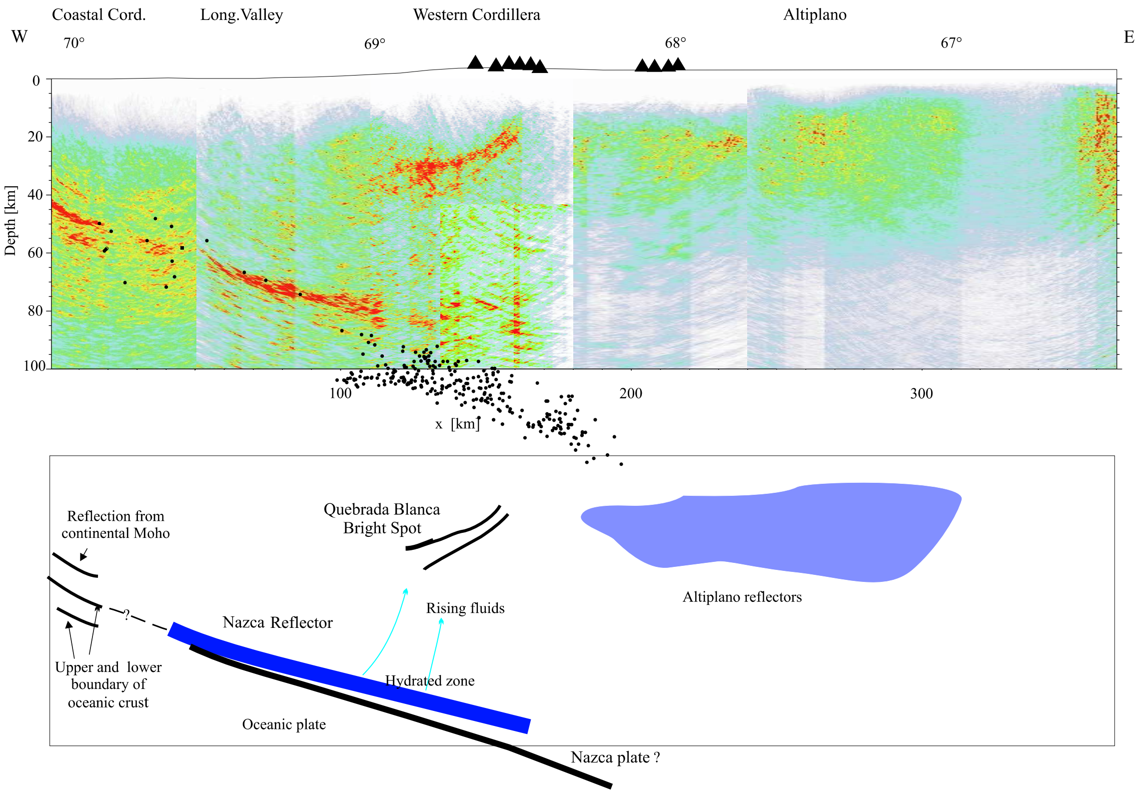


Figure 1.1: **Top:** Prestack depth section of ANCORP96 (Yoon, 2001) with black dots indicating local earthquake hypocenters (Gräber and Asch, 1999). **Bottom:** Interpretation of the seismic section adapted from the ANCORP Working Group (1999).

Between 20 - 50 km of the profile the reflections appear diffuse and less coherent. A band of strong reflections appears blurred with increasing thickness at larger depths towards. The reflectivity of this so called Nazca reflector decreases abruptly at 110 km of the profile. Between 110 - 160 km the reflector appears weak and its shape becomes distorted and incoherent. The reflector totally vanishes at 160 km of the profile. In the eastern part of the section at depths between 15 - 40 km the so called Altiplano reflectors are observed in a 100 km wide and ca. 20 - 30 km high zone of mainly diffuse reflectivity. The Altiplano reflectors are interpreted as a large zone of partial melts in the continental crust.

Interestingly, the abrupt reflectivity breakdown of the Nazca reflector at 110 km coincides with the location of the west dipping Quebrada Blanca Bright Spot (QBBS) above. This bright spot appears at depths between 15 - 30 km at its eastern and its western end, respectively. A detailed analysis of the QBBS revealed discontinuous reflections with changing positive and negative polarity (ANCORP Working Group, 2003). The statistical analysis of the reflection polarity distribution provided no clear results for structural interpretation. The QBBS is interpreted as reflections from a complex system of granitic intrusions or from a zone where ascending fluids are trapped and accumulated. This explanation implies the observation of a low resistivity anomaly in magnetotelluric data. However, results from magnetotelluric data inversion revealed the absence of a low resistivity anomaly at the location corresponding to the QBBS (Schwalenberg et al. (2002), Brasse pers. comm., 2003). Thus, the existence of a zone that is related to partial melts or trapped fluids could not be directly confirmed.

The Nazca reflector itself is interpreted as the image of the shear zone between the upper continental and the lower oceanic plate. According to the ANCORP Working Group (2003) the strong reflectivity and its complex image at greater depths are explained by the following processes: Fluids are supplied into the shear zone by massive dehydration of the oceanic crust. This leads to the formation of hydrous phases, e.g. serpentine and talc, in the mantle and in the shear zone. Connected to the latter process is the destruction of permeability, such that fluids are trapped at the hydration front in the continental mantle. Consequently a breakdown of the reflectivity is expected where dehydration was completed and where the temperatures become to high for serpentine stability. Also, they proposed the existence of sheared bodies in the mantle that were previously hydrated independent from the hydration process related to the ongoing subduction. In this thesis it is proposed that the weak and diffuse appearance of the Nazca reflector and its later disappearance at larger depths are not only related to petrophysical changes in the continental mantle, but also to the existence of strong scattering structures in the crust, i.e. the QBBS and the Altiplano reflectors.

The accuracy of reflector depths, reflector shapes and reflectivity in deep reflection images in the presence of heterogeneous structures will be studied. The results from numerical modelling will provide the basis for a qualitative analysis regarding the following imaging aspects: the influence of heterogeneous overburden on the reflectivity of structures below, the importance of the velocity model for reflection images and the impact of the frequency bandwidth on the seismic images. A new method will be presented which improves the interpretation of reflection images. This method is called **Reflection Image Spectroscopy (RIS)** and extracts additional structural information from the reflection data by imaging narrow-frequency bands of the data. Thereby, the frequency dependent reflection and scattering behaviour is taken into account. Especially in subsurface areas with heterogeneous overburden this method is an efficient tool to enhance reflections from deep targets.

The structure of this thesis is the following: In chapter 2 a general introduction to random media will be given. Scattering and related amplitude and phase phenomena will be discussed. In chapter 3 the numerical modelling studies will be presented. In these studies, the influence of a heterogeneous overburden on the reflection image and the effect of migration using wrong velocities will be analysed. Chapter 4 will present seismic imaging case studies from the South American Andes. In the first part the migration results obtained from two data sets (ANCORP and PRECORP) from the Central Andes will be presented. The results from recalculation of the ANCORP data using two alternative velocity models will be discussed. Also, the results from application of the RIS method to the ANCORP data will be presented and discussed in a structural context. Furthermore, depth images from the Southern Andes obtained by migration of an onshore reflection data set will be presented in this chapter. Finally, the results from RIS application and its structural interpretation will be presented. A summary of the results and a final discussion in chapter 5 will close the thesis.