Chapter 4

Seismic imaging in heterogeneous media - Case studies from the South American Andes

4.1 Introduction

In the previous chapter the influence of heterogeneous media on the seismic image of deeper structures was investigated using numerical modelling studies. The RIS method was introduced and first applications to synthetic data were presented. This method extracts additional structural information about the reflectors by frequency-selective processing of the reflection data. In the following the RIS method will be applied to deep reflection seismic data sets from the South American Andes.

The investigation areas are located in the Central Andes and in the Southern Andes (Fig. 4.1). The subduction of the oceanic Nazca plate below the South American continent led to the development of the Andean mountain belt along the western margin of South America. With its highest elevations over 6000 m it represents the second largest orogen after the Himalaya. The development of both, the Central Andes and the Southern Andes, is related to the same subduction process. However, both systems show significant differences regarding their structure and their dynamics. The Central Andes are regarded as an erosive subduction system (Clift and Vannucchi, 2001). Here, the bottom of the upper plate is being eroded by the rough surface of the subducting lower plate. The eroded material is being transported along the plate boundaries down to greater depths. The

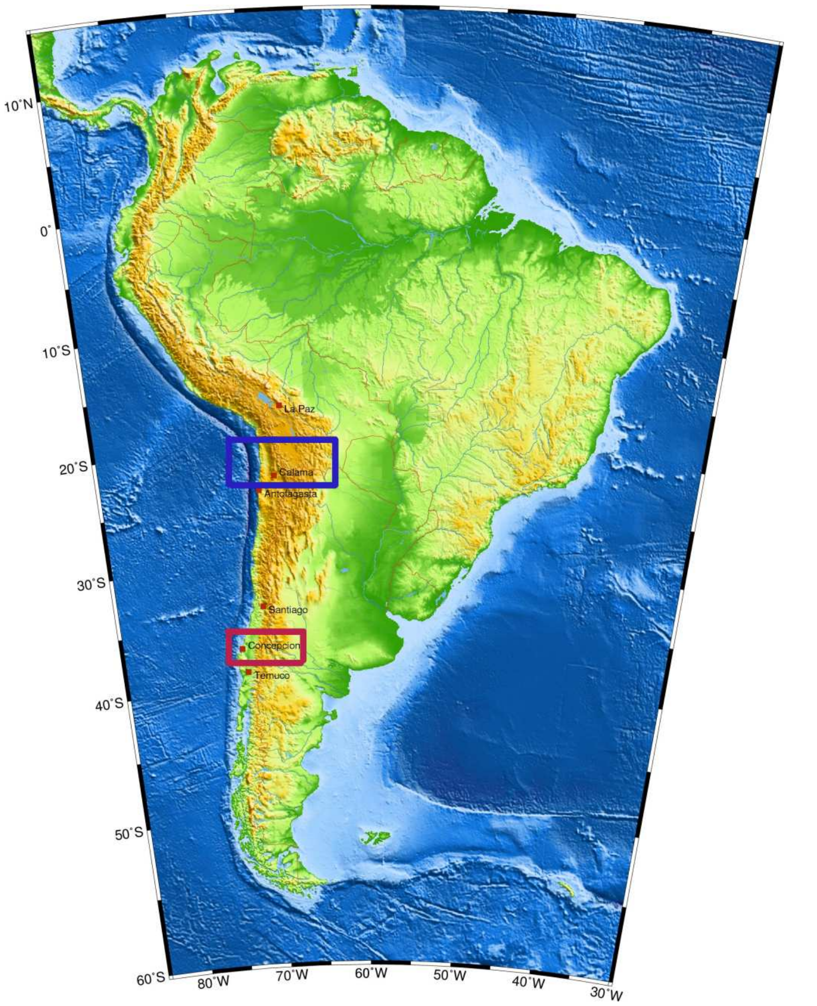

Figure 4.1: The investigation areas in the Central Andes and Southern Andes are marked by a blue and red box, respectively.

Southern Andes are regarded as an accretionary margin. Erosion plays a minor role, but trench sediments are frontally accreted. During the ongoing subduction process the trench material is underplated below the overriding plate.

The history of seismic measurements across the Andes started in 1957, the International Geophysical Year (Tatel and Tuve, 1958), where the Carnegie Group carried out refraction seismics using blasts from copper mines. Since 1993 the Collaborative Research Center 267 - Deformation Processes in the Andes - investigated the geodynamics of the Central Andes between 18° and 24° S. In this frame a number of geological and geophysical surveys were carried out. The seismic measurements included active and passive experiments, onshore and offshore surveys, and reflection and refraction seismic acquisition. The following projects were carried out: PISCO (seismological network), OLIVINO and PRECORP (reflection data), ANCORP (refraction, reflection and passive seismic data), and CINCA (combined onshore and offshore wide-angle seismics, and marine reflection seismics). In recent years the scientific focus moved to the subduction system of the Southern Andes between 34° - 42° S. In the frame of the SPOC project - Subduction Processes off Chile - a large number of marine reflection and refraction profiles, combined onshore and offshore seismic profiles, onshore wide-angle profiles and a near-vertical-reflection profile (SPOC-NVR) were acquired.

In this thesis the results of a prestack depth processing of the PRECORP and ANCORP reflection data will be presented. Recalculated ANCORP depth sections using different velocity models from tomographic inversion as well as the results from RIS application to the data will be shown. Also, results from prestack depth processing of the SPOC-NVR profile and the application of RIS to this data set will be presented.

The layout of this chapter is the following: The northern and the southern investigation areas and the corresponding data will be presented separately. Each part will provide a short introduction to the geology and to the technical parameters of the reflection data sets. A description of the prestack depth processing scheme and the application of RIS to the data will follow. A discussion and interpretation of the obtained results closes each part. Finally, a summary and concluding remarks are given.

4.2 The Central Andes

4.2.1 The morphostructural units and the Precordilleran Faults System

This section provides an introduction to the morphostructural units of the Central Andes, that are crossed by the ANCORP profile. According to Reutter et al. (1988) these units are the Coastal Cordillera, the Longitudinal Valley, the Precordillera, the Preandean Depression, the Western Cordillera, and the Altiplano (Fig. 4.2).

The Fore-arc region

The Coastal Cordillera, the Longitudinal Valley, the Precordillera and the Preandean Depression form the fore-arc region. The **Coastal Cordillera** strikes north-south, parallel to the coast. It is a mountain range which extends from Arica in the north to Central

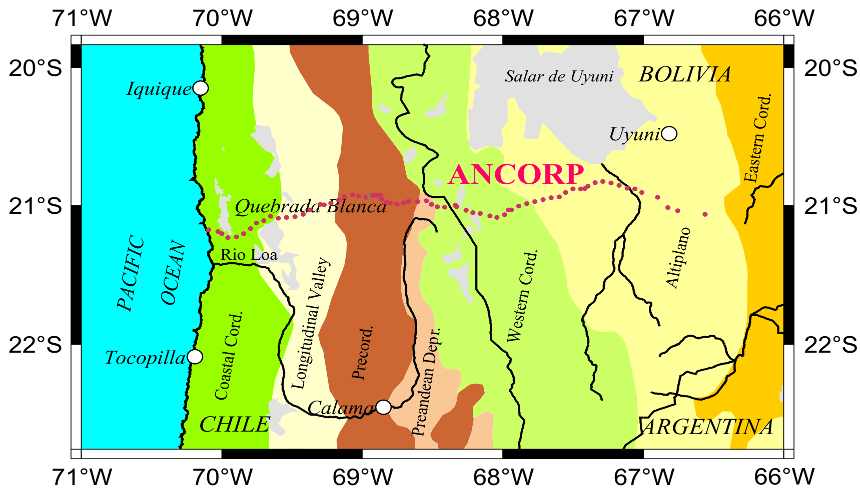

Figure 4.2: Map of the Central Andes with the morphostructural units and the location of the ANCORP reflection profile (red dots).

Chile in the south. Its morphological structure is rough. It steeply ascends along the first kilometers at the coast, where it reaches altitudes over 2000 m. The mean altitude is about 1000 m. The overburden in this region is mainly of magmatic origin. An analysis of magmatic rocks from that area led to the conclusion that the Coastal Cordillera, as situated today, was the magmatic arc during the Jurassic and Cretacian time. The thickness of the magmatic overburden lies in the range of 3800 m - 5000 m and reaches 10 km in some regions. The **Longitudinal Valley** follows further eastward. Its average altitude is about 1000 m above sea level. This depression can be found along the entire Andean mountain chain. During the early Cretaceous the center of magmatic activity moved from the region, that is todays Coastal Cordillera, towards the corresponding former back arc basin, which is todays Longitudinal Valley. Mainly younger sedimentary overburden is found in this area. The **Precordillera** strikes NNE to SSW with altitudes around 3000 m, and highest elevation peaks of 5000 m. A huge amount of sedimentary overburden is brought in by the E-W headed crossing valleys, forming fans of detritus with large extensions in the Longitudinal Valley. The period of active magmatism in this area is restricted to the late Eocene and the early Oligocene, which is about 35 million years ago. During this time chalk-alkaline magmatic rocks with thicknesses up to 2000 m were deposited. The **Preandean Depression**, which is located east of the Precordillera, can only be found between 22°S and 25°S. The mean altitude values are around 2000 m. The Salar de Atacama and the Salar de Punta Negra are located in the southern part of this unit.

The magmatic arc

The **Western Cordillera** represents both, the continental watershed and the recent magmatic arc with a large number of volcanoes with heights that exceed 6000 m. The magmatic activity started around 25 million years ago with magmatism that temporarily covered the whole area of the Altiplano and the western edge of the Eastern Cordillera. During the Quechua period 10 million years ago a remarkable increase of magmatic activity was observed. During the Permian and the Triassic era the magmatic arc was already located here, but it moved westward to the coast until the Jurassic.

The back arc region

The **Altiplano** represents the most western part of the back arc region and presents the second largest plateau worldwide. The altitude of the plateau is around 3700 m. Some volcanoes are breaking through with heigths over 6000 m. The lift up of the Altiplano with amounts of about 3500 m to 4000 m took place after the deposition of lacustrian and marine sediments in the late Cretaceous.

The Precordilleran Fault System

The north-south striking Precordilleran Fault Systen (PFS) is the major fault zone located in the investigation area (Scheuber and Reutter, 1992). The location of the PFS is mapped in Fig. 4.3 together with the locations of the ANCORP and the PRECORP reflection profiles. South of 21.5° S the PFS locally splits up into the West Fissure (WFS) and the Sierra-de-Moreno Fault System (SMFS) (Günther et al., 1997).

4.2.2 Deep reflection seismic images - PRECORP and ANCORP

The data sets

In 1995, the PRECORP experiment was carried out as a feasibility study for a longer deep seismic reflection survey across the Central Andes. The 50 km long profile was located at 22.5°S near Calama, with shot and receiver locations between 90 and 140 km within the local coordinate system (Fig. 4.3). During the experiment 38 shot gathers were recorded using a maximum of 144 receivers with a spacing of 100 m. The maximum offset was 14.3 km. The shot point interval of the split-spread recording geometry was 2.4 km which

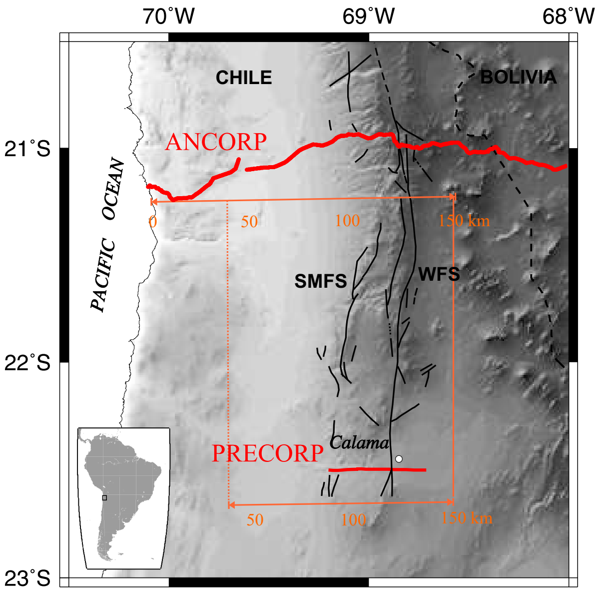

Figure 4.3: The location of the ANCORP and the PRECORP profile and the local co-ordinate system (orange) used for the prestack depth migration. The black lines mark the Precordilleran Fault System which splits up into the West Fissure (WFS) and the Sierra-de-Moreno Fault System (SMFS) south of 21.5° S.

provided a mean two-fold CMP-coverage. The recording time of each shot record was 60 s in order to gain reflections from depths down to 100 km. This was the required maximum target depth to obtain images of the subducting Nazca plate.

One year after the PRECORP experiment, the 385 km long west-east headed ANCORP profile was acquired at 21° S. It started at the Chilean coast in the west and ended in Bolivia in the east (Fig. 4.3). The number of receivers of the total 131 shot gathers was 252 with a geophone spacing of 100 m, which provided a maximum offset of 25.1 km. The shot point interval of 6.25 km yielded a data set with a mean four to six-fold CMP-coverage.

Kirchhoff prestack depth migration

The processing of both data sets was difficult, since two major problems had to be faced. First, bad receiver coupling, strong ground roll, various high frequency noise, as well as a number of seismological events occurring during the records produced a low signal-to-noise ratio. Second, a complex 3D recording geometry caused by an altitude change of more than 4000 m along the profile and a variation of the profile line in north-south direction of nearly 50 km had to be taken into account during processing. The processing of the data consisted mainly of frequency-wavenumber filtering. This was done in order to reduce the high frequency noise and low frequency signals e.g. seismological events and ground roll. Before passing the filtered data to the further processing, a top mute and an optional bottom mute had been applied. Thus, first arrivals and remaining low frequency earthquake events had been suppressed. Kirchhoff prestack depth migration has been used to image the data sets. This technique was able to handle the low coverage of the data and the crooked line geometry. The prestack depth migration was implemented in 3D from topography: The real shot and receiver locations had been taken into account during the travel time calculation and the computation of the migrated depth sections. The required 3D macro velocity model was obtained by extending a 2D model obtained from refraction data analysis (Lüth, 2000). The extension was done under the assumption that velocity variations in north-south direction are negligible. The traveltime calculation itself was performed using a finite difference eikonal solver. The migration procedure was the following: First, each shot gather was migrated separately. The grid point spacing was 100 m $\times$ 5000 m $\times$ 100 m (x = W-E, y = N-S, z = depth). Second, envelope stacking of the migrated sections yielded a 3D image with a total length of 370 km (W-E), a width of 50 km (N-S) and a depth of 100 km. The quality of the 3D depth section varies within the imaged subsurface area since the coverage is higher near the actual profile line and decreases away from it. The final imaging step was a selective stacking procedure of W-E oriented slices located near the profile line and disregarding those parts far away. This so called *offline-stacking* increased the signal to noise ratio further and provided a 2D depth image.

Compared to the 3D processing of the ANCORP data, the migration of the PRECORP data set was done only in 2D since the north-south variations of the profile line were rather small. The imaging of the PRECORP data consisted of two steps (Fig. 4.4): First, the migration was performed for early arrivals (TWT: 0 - 15 s) without any amplitude balancing. Second, later arrivals (TWT: 15 - 40 s) were migrated after correction for the geometrical spreading. The migration was performed using the ANCORP velocity model, because no other model was available. Finally, both depth sections were stacked together. This proceeding was necessary to handle the high amplitude dynamics of the records. A 100 km deep 2D seismic image with prominent features at different depths was obtained. The migration grid parameters were the same as for the ANCORP data.

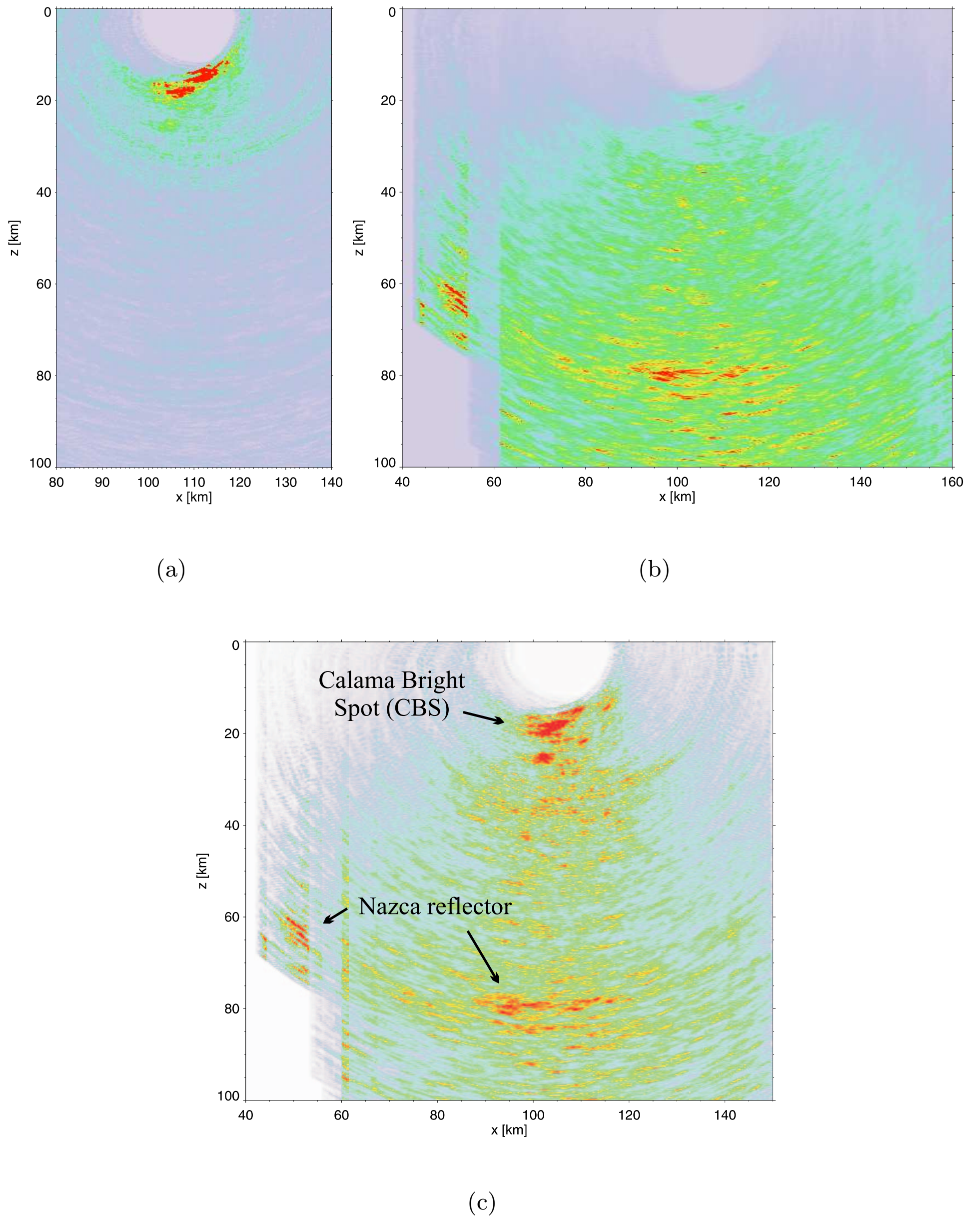

Figure 4.4: Prestack depth section of the PRECORP data. (a) The upper part of the depth section was obtained by migration of traveltimes between 0 - 15 s. It reveals the Calama Bright Spot (CBS) with an apparent west dipping component. (b) The deeper part of the depth section (15 - 40 s) shows a short Nazca reflector segment at 50 km and a deeper image of the Nazca reflector between 90 - 120 km of the profile. (c) Stacking of the upper and the lower depth section provided the final depth image.