

DEEP SEISMIC IMAGING
IN THE PRESENCE
OF A HETEROGENEOUS OVERBURDEN:
NUMERICAL MODELLING AND CASE STUDIES
FROM THE
CENTRAL ANDES AND SOUTHERN ANDES

SEISMISCHE ABBILDER
HETEROGENER MEDIEN:
NUMERISCHE MODELLIERUNGEN UND FALLBEISPIELE
AUS DEN
ZENTRALEN UND SÜDLICHEN ANDEN

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Wenn jemand sucht, dann geschieht es leicht,
dass sein Auge nur noch das Ding sieht, das er sucht,
dass er nichts zu finden, nichts in sich einzulassen vermag,
weil er nur immer an das Gesuchte denkt,
weil er ein Ziel hat, weil er vom Ziel besessen ist.
Suchen heisst: ein Ziel haben.

Finden aber heisst: frei sein, offen stehen, kein Ziel haben.

HERMANN HESSE

SUMMARY

Heterogeneities of various sizes and different magnitude of velocity fluctuations are distributed within the subsurface. The amplitude and phase fluctuations due to scattering of the wave field severely influence the reflectivity and the coherency of reflections. In this thesis prestack depth migrated images of synthetic and real data sets were analysed to provide an improved understanding of reflection images from complex media. Also, the Reflection Image Spectroscopy method RIS was invented to extract structural details from seismic reflection images of strongly heterogeneous media.

Three numerical experiments were carried out to investigate: the image distortion due to scattering in the heterogeneous layer, the reflection images containing narrow-frequency-bands (RIS method) and the influence of errors in the migration velocity on the reflectors. Three deep reflection data sets from the South American Andes were processed using Kirchhoff prestack depth migration. Furthermore, the ANCORP and the NVR-SPOC data were analysed using the RIS method.

To investigate the influence of scattering in the heterogeneous layer on seismic images synthetic depth sections were calculated using finite difference modelling and Kirchhoff depth migration. Several velocity models consisting of a deep reflector and heterogeneous layer were built. The standard deviation of the velocity fluctuations and the correlation lengths varied.

In the first experiment the influence of scattering on the reflectivity and on the coherency of the reflectors was studied. The results showed that the apparent reflectivity is not only dependent on the magnitude of the velocity fluctuation, but also on the size of the wavelength relative to the correlation length. When the correlation length and the wavelength are of similar size the reflectivity of the heterogeneous layer and of the deep reflector is significantly decreased.

The results indicated that strong scattering in heterogeneous layers might cause the abrupt change in reflectivity of the Nazca reflector in the ANCORP image. Also, the lack of deeper reflections in the eastern part of the profile was related to strong scattering. It was proposed that the QBBS and the Altiplano reflectors represent such heterogeneous layers. The correlation lengths of the heterogeneities in the QBBS are estimated to be few kilometers, and in the Altiplano region a few hundred meters.

The RIS method was applied to the synthetic data in the second experiment. The low-pass and band-pass filtered synthetic seismogram sections were migrated and analysed.

The images showed that the deep reflector appeared incoherent and disrupted in the broadband image. The image fluctuations along the deep reflector continuously decreased with continuous suppression of the high frequency contents. The real reflector shape was recovered in the low-frequency image.

The third experiment studied the influence of migration velocity errors on the shape and the coherency of a reflector below a heterogeneous layer. Mainly the depth of the reflector image was affected. The reflector was shifted linearly to smaller depth when using slower migration velocity and shifted into larger depth when using faster velocity. The shape of the reflector was not distorted by using wrong migration velocities.

The prestack migrated images of the ANCORP and the PRECORP data from the Central Andes and the SPOC-NVR data from the Southern Andes provided a detailed structural image of the subduction zone. In the ANCORP image the Nazca reflector is visible over a distance of about 110 km in E-W direction. The compiled image of the depth section with local earthquake data shows a good spatial correlation between the hypocenters and the upper boundary of the oceanic crust at the beginning of the profile. At greater depths an offset between the hypocenters and the Nazca reflector is visible. A slightly smaller offset is observed in the PRECORP image between the Nazca reflector and the local hypocenters. The ANCORP data were recalculated using two alternative velocity models from tomographic inversion to study whether the observed offset is a result of using wrong migration velocities or whether it is related to the subsurface structure. The comparison of the three depth sections showed that the refraction model provides an accurate image of the reflections from the oceanic crust in the beginning of the profile as well as of the deeper Nazca reflector. The compilation of the depth sections with the hypocenters showed that the apparent offset remains in both recalculated images. It was concluded that the offset is independent from the used migration velocity model, but related to the subsurface structure.

The application of the RIS method to the ANCORP data revealed additional structural details of the Nazca reflector. The data were band-pass filtered in three frequency ranges and migrated. In all of the narrow-band-frequency images distinct reflections from the top and bottom of the oceanic crust were observed along the first 110 km. In the middle of the profile the high-frequency image revealed thin east dipping reflections that were not visible in the broadband depth image. These reflections were located near the lower boundary of the Nazca reflector and were interpreted as the top of the oceanic crust. The high-frequency image also showed thin horizontal reflections at a depth of 80 km interpreted as the top of the reflective continental mantle wedge. The PRECORP section was reinterpreted. The

horizontal reflections visible at a depth of 80 km were interpreted as the highly reflective continental mantle wedge. The thin east dipping reflectors at depths larger than 80 km were interpreted as the oceanic crust. The continuation of the top of the oceanic crust indicated that the local seismicity is limited to the oceanic crust and to the upper mantle. The RIS method provided a well resolved image of the internal structure of the Nazca reflector and provided new insights improving the knowledge and the understanding of the deeper subduction zone and the processes therein.

In the SPOC-NVR section reflections from the permo-triassic accretionary wedge were revealed. Mainly east dipping reflections were observed. A band of horizontal reflections at a depth around 23 km showed good correlation with a wide-angle reflector from the continental crust. By enhanced amplitude stacking and trace normalisation reflections from the top and the bottom of the oceanic crust were revealed. Furthermore, the RIS method revealed a strong reflection from the oceanic Moho at depths between 35 - 40 km. Additional details of the structures within the continental crust were not obtained.

The RIS method application provided first meaningful results. The focus of the application was mainly set on the analysis of the reflector image and the uncovering of reflectors masked in the broadband images. The relation between the spatial parameters of the heterogeneities and the apparent reflectivity in different frequency bands was not sufficiently investigated. Further numerical modelling studies are still necessary for an improved understanding of the RIS method and its benefits.

ZUSAMMENFASSUNG

Im Untergrund sind Heterogenitäten unterschiedlicher Grösse und mit unterschiedlicher Stärke der Geschwindigkeitsfluktuationen verteilt. Die durch Streuung des Wellenfeldes verursachten Amplituden- und Phasenfluktuationen beeinflussen dabei die Stärke und die Kohärenz seismischer Reflexionen. In dieser Arbeit wurden synthetische und reale Datensätze Prestack-Tiefen migriert und analysiert, um zu einem besseren Verständnis von seismischen Abbildern komplexer Medien beizutragen. Ausserdem wurde die Reflection-Image-Spectroscopy Methode (RIS) eingeführt, welche strukturelle Details aus seismischen Abbildern heterogener Medien extrahiert.

Es wurden drei numerische Experimente durchgeführt. Dabei wurde die Zerstörung des seismischen Abbildes durch eine heterogene Schicht untersucht. Seismische Sektionen, die nur ein schmales Frequenzband der Daten abbilden, wurden miteinander verglichen und ausgewertet (RIS Methode). Ferner wurde der Einfluss von Fehlern in der Migrationsgeschwindigkeit auf das seismische Abbild der Reflektoren analysiert. Mittels der Kirchhoff Migration wurden drei reflexionsseismische Datensätze aus den südamerikanischen Anden bearbeitet. Zwei dieser Datensätze wurden mit der RIS Methode bearbeitet und interpretiert.

Die synthetischen Tiefensektionen wurden mittels Finite-Differenzen Modellierung und Kirchhoff Prestack-Tiefen Migration für unterschiedliche Geschwindigkeitsmodelle erzeugt. Die Modelle bestanden aus einem ebenen Reflektor unterhalb einer heterogenen Schicht mit variierenden Geschwindigkeitsfluktuationen und Korrelationslängen der Heterogenitäten.

Die Ergebnisse der numerischen Modellierungen zeigten, dass die Reflektivität einer heterogenen Schicht nicht nur von der Stärke der Geschwindigkeitsfluktuationen, sondern auch von dem Verhältnis der Wellenlänge zur horizontalen Korrelationslänge der Heterogenitäten beeinflusst wird. Die Reflektivität nimmt dabei deutlich ab, wenn die Wellenlänge und die Korrelationslänge in einer Grössenordnung liegen. Die Anwendung der RIS Methode zeigte, dass die Fluktuationen des seismischen Abbildes in unterschiedlichen Frequenzbereichen unterschiedlich stark zu beobachten sind. Bildete man ein schmales Frequenzband ab, in dem die Fluktuationen geringer waren als in anderen einem Frequenzband, so konnte z.B. das von Fluktuationen unbeeinflusste wahre Reflektorabbild gewonnen werden. Bei der Migration von reflexionsseismischen Daten in heterogenen Medien mit falschen Geschwindigkeiten wurde hauptsächlich die Tiefe des abgebildeten Reflektors beeinflusst. Die Reflektivität und die Kohärenz des Reflektors wurden nicht verändert.

Die Kirchhoff Prestack-Tiefen Migration der reflexionsseismischen Datensätze ANCORP

und PRECORP aus den zentralen Anden und das SPOC-NVR Profil aus den südlichen Anden erbrachte ein detailliertes strukturelles Abbild der Subduktionszone. So wurde im ANCORP Profil der Nazca Reflektor über eine Länge von 110 km in ost-westlicher Richtung abgebildet. Dieser markiert die subduzierende ozeanische Kruste. Am Anfang des Profils konnte eine gute Übereinstimmung des Reflektors und der Bebenlokationen beobachtet werden. Dahingegen wurde zur Mitte des Profils hin ein Versatz in der Tiefe zwischen dem Reflektor und den Bebenlokationen festgestellt. Ein ähnlicher Offset wurde auch in dem PRECORP Profil beobachtet. Der ANCORP Datensatz wurde mit zwei Geschwindigkeitsmodellen aus der Tomographie neumigriert, um zu klären, ob der beobachtete Offset durch falsche Migrationsgeschwindigkeiten verursacht wurde, oder ob der Offset im Zusammenhang mit den Untergrundstrukturen zu sehen ist. Der Vergleich der alten und der neugewonnenen Sektionen zeigte, dass das Weitwinkel-Geschwindigkeitsmodell ein optimales Abbild der ozeanischen Kruste und des Nazca Reflektors erbrachte. Der beobachtete Offset zwischen dem Nazca Reflektor und den Bebenlokationen war auch in den Neuberechneten Sektionen zu beobachten. Daraus wurde geschlussfolgert, dass der Offset struktureller Natur ist.

Durch die Anwendung der RIS Methode auf die ANCORP Daten konnten weitere strukturelle Details des Nazca Reflektors gewonnen werden. Die Daten wurden dabei in drei verschiedenen Frequenzbereichen Bandpass gefiltert und migriert. Die Hochfrequenzsektion zeigte schmale nach Osten einfallenden Reflexionen, die in der Breitbandfrequenzsektion nicht zu erkennen waren. Die Reflexionen im unteren Bereich des Nazca Reflektors wurden als Oberkante der ozeanischen Kruste interpretiert. Desweiteren waren in der Hochfrequenzsektion horizontale Reflektoren in einer Tiefe von 80 km sichtbar, die als die Oberkante des hydratisierten Mantelkeils in der kontinentalen Platte interpretiert wurden. Die in der PRECORP Sektion beobachteten nach Osten einfallenden Reflexionen in einer Tiefe von über 80 km wurden ebenfalls als ozeanische Kruste, die darüber abgebildeten horizontalen Reflektoren als hydratisierter kontinentaler Mantelkeil interpretiert.

In der SPOC-NVR Sektion wurden die hauptsächlich nach Osten einfallenden Reflektoren des permotriassischen Akkretionskeils abgebildet. Ein Band horizontaler Reflexionen in einer Tiefe von 23 km zeigte zudem gute Übereinstimmung mit der Tiefenlage eines in den Weitwinkeldaten beobachteten Reflektors zwischen der oberen und unteren kontinentalen Kruste. Durch eine erweiterte Stapelung und Normierung der Tiefenspuren der migrierten Sektion wurden Reflexionen der ozeanischen Kruste sichtbar. Die Ergebnisse der RIS Methode zeigten dabei einen starken Reflektor der ozeanischen Moho in Tiefen zwischen 35 - 40 km.

Die Anwendung der RIS Methode auf synthetische und reale Daten zeigte erste gute Ergebnisse. Dabei wurden hauptsächlich die Fluktuationen des seismischen Abbildes analysiert. Das Verhältnis zwischen den räumlichen Parametern der Heterogenitäten und der scheinbaren Reflektivität in unterschiedlichen Frequenzbereichen wurde nicht ausreichend untersucht. Daher sind weitere numerische Modellierungen notwendig, um die RIS Methode und ihre Anwendbarkeit besser zu verstehen.

Contents

Summary	i
Zusammenfassung	v
List of figures	xiii
1 Introduction and motivation	1
2 Seismic waves in random media	7
2.1 Statistical description of random media	7
2.2 Wave phenomena in random media	10
2.2.1 Scattering regimes	10
2.2.2 Amplitude and phase in heterogeneous media	13
2.3 Factors affecting seismic images	15
3 The effects of heterogeneities on seismic images	19
3.1 Seismic modelling and imaging - The work tools	21
3.1.1 FD forward modelling using the rotated staggered grid	21
3.1.2 Imaging using Kirchhoff prestack depth migration	23
3.1.3 Travel time calculation	25
3.2 Numerical modelling studies	26

3.2.1	Image distortion due to a heterogeneous overburden	27
3.2.2	Reflection Image Spectroscopy - RIS	37
3.2.3	Impact of the velocity model on migration	43
3.3	Summary and conclusion	46
4	Seismic imaging in heterogeneous media - Case studies	49
4.1	Introduction	49
4.2	The Central Andes	51
4.2.1	The morphostructural units and the Precordilleran Faults System	51
4.2.2	Deep reflection seismic images - PRECORP and ANCORP	53
4.2.3	Migration of the ANCORP data with different velocity models	61
4.2.4	RIS applied to ANCORP	68
4.2.5	Interpretation and discussion	73
4.3	The Southern Andes	79
4.3.1	The investigation area	79
4.3.2	The SPOC-NVR profile	80
4.3.3	RIS applied to SPOC-NVR	87
4.4	Summary	91
5	Summary and outlook	95
5.1	Summary	96
5.1.1	Numerical modelling	96
5.1.2	Real data application	97
5.2	Outlook	99
	References	101

A	RIS applied to ANCORP	111
B	RIS of SPOC	114
	Danksagung	123
	Curriculum vitae	125

List of Figures

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).	3
2.1	(a) Gaussian and exponential autocorrelation functions, normalised to the lag and the variance of the medium. (b) Exponential autocorrelation functions with different correlation lengths.	9
2.2	Examples of random media realisations with (a) Gaussian, (b) exponential and (c) von-Kármán autocorrelation function (Sick, 2002).	10
2.3	The scattering regimes. The magnitude and the radiation characteristics of the scattering is controlled by the product of the wavenumber k and the radius of the scatterer a (from Pyrak-Nolte (2002)).	11
2.4	(a) Scattering regimes in the $\Lambda - \Phi$ space (after Flatté et al. (1979)). (b) Estimated scattering field for the ANCORP experiment marked by the blue box.	13
2.5	Schematic sketch showing wave propagation through random media (from Hoshihara (2000)). Rays tend to bend when facing heterogeneities in the medium, causing focusing and defocusing resulting in amplitude fluctuations.	14
3.1	Principle of diffraction stack. The summation of the amplitudes along the diffraction hyperbola in a finite-offset time section and assigning this value to the respective subsurface point yields an image of the subsurface.	24

- 3.2 The diffraction envelope (Yilmaz, 1987). The envelope of diffraction curves generated by a reflector consisting of several diffraction points yields the reflector itself. 24
- 3.3 Layout of the velocity model. The heterogeneous layer was generated using an exponential autocorrelation function. The standard deviation of the velocity fluctuation is 5 %. The horizontal and the vertical correlation lengths are $a_x = 1000$ m and $a_z = 200$ m. An exponential tapering function was applied to the fluctuation field in the vertical direction. The stars and black lines on top represent the source points and receiver spreads. 28
- 3.4 The 12 velocity models with varying standard deviations and horizontal correlation lengths. The vertical correlation length is constant ($a_z = 200$ m). 30
- 3.5 Synthetic seismogram section (vertical displacement) obtained from FD modelling (every 5th trace is displayed). The synthetic record shows a complex backscattered wave field between 5 – 15 s and a deep reflection hyperbola at ≈ 23.5 s with coda wavelets. Zoom of the hyperbola shows that the recorded wave field contains amplitude and phase fluctuations. . . . 31
- 3.6 The synthetic depth sections. The reflectivity in the heterogeneous layer increases for strong velocity fluctuation. The deep reflector appears weak and discontinuous for large standard deviation and short horizontal correlation length. For a standard deviation of 20 % the deep reflector nearly disappears in all images. 33
- 3.7 **Left:** The average reflectivity in the heterogeneous layer (solid: $a_x = 1000$ m; dashed dotted: $a_x = 4000$ m; dotted: $a_x = 6000$ m). For weak velocity fluctuations the average reflectivity is small for all correlation lengths. For larger standard deviation the reflectivity is strong for large correlation lengths. **Right:** The average reflectivity along the deep reflectors decreases for increasing standard deviation. The weakest reflectivity is observed for short correlation lengths. 34

3.8	Comparison of synthetic depth sections with the ANCORP image. The modelling results suggest that the apparent breakdown of the reflectivity between 110 - 160 km at depths larger than 80 km is due to scattering in the QBBS (compare left yellow box with lower left section). The synthetic results also indicate that a complex zone of heterogeneities with strong velocity fluctuations and correlation lengths in the order of few hundred meters cause the complete loss of the reflectivity of the deeper region (compare the right yellow box with lower right section). The Altiplano reflectors represent such a zone.	36
3.9	RIS applied to synthetic data. Normalised amplitude spectra of unfiltered and filtered traces. (1): Unfiltered frequency spectrum. (2) - (4): Amplitude spectra of low-pass filtered traces. (5) - (8): Amplitude spectra of band-pass filtered traces.	39
3.10	Low-pass filtered depth sections. The reflectivity in the heterogeneous layer becomes weak and smooth with continuous removal of the high frequency contents. In the unfiltered section the deep reflector appears disrupted and incoherent. The reflector becomes sharp and clear, when high frequencies are filtered from the data.	41
3.11	Band-pass filtered depth sections. The deep reflector in the high frequency image is severely affected coherency loss (15 - 20 Hz), whereas in the low frequency image the reflector is clear and undistorted (0 - 5 Hz).	42
3.12	The velocity models. (a) Velocity model with a deep horizontal reflector beneath a 10 km thick heterogeneous layer. (b) Velocity model with a dipping reflector and a 20 km thick heterogeneous layer. In both models the background velocity of the upper part is $v_P = 6000 \text{ ms}^{-1}$, the standard deviation is 15 %, and the correlation lengths are $a_z = 1000 \text{ m}$ and $a_x = 5000 \text{ m}$. The velocity fluctuations were tapered exponentially in the horizontal and vertical direction.	43
3.13	Depth sections with a horizontal reflector calculated for different migration velocities. The migration velocities were $v = 5700 \text{ ms}^{-1}$ (left), $v = 6000 \text{ ms}^{-1}$ (middle), and $v = 6300 \text{ ms}^{-1}$ (right).	45
3.14	Depth sections with a dipping reflector calculated for different migration velocities. The migration velocities were $v = 5700 \text{ ms}^{-1}$ (left), $v = 6000 \text{ ms}^{-1}$ (middle), and $v = 6300 \text{ ms}^{-1}$ (right).	45

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- 4.1 The investigation areas in the Central Andes and Southern Andes are marked by a blue and red box, respectively. 50
- 4.2 Map of the Central Andes with the morphostructural units and the location of the ANCORP reflection profile. 52
- 4.3 The locations of the ANCORP and the PRECORP profile and the local coordinate system (orange) used for the prestack depth migration. The black lines mark the Precordilleran Fault System (PFS), which splits up into the West Fissure (WFS) and the Sierra-de-Moreno Fault System (SMFS) south of 21.5° S. 54
- 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. 56
- 4.5 2D ANCORP and PRECORP depth sections. The hypocenter locations are indicated by black dots (Gräber and Asch (1999)). 58
- 4.6 Composition of the ANCORP and the PRECORP section. Two parts of the PRECORP image are pasted into the ANCORP image according to their local coordinates. The green and red horizontal arrows on top indicate the origin of the data, representing ANCORP and PRECORP, respectively. The position of the PRECORP-Nazca reflector at 50 km fits spatially well with the Nazca reflector image of the ANCORP data. The deep Nazca reflector in the PRECORP section is located less than a few kilometers deeper than the reflector in the ANCORP section. The QBBS (ANCORP) is located east of the CBS (PRECORP) and is imaged about 10 to 15 km deeper. The latter observation agrees with the hypothesis that the QBBS, which shows a north dipping component, and the CBS are related to the same structure. 60
- 4.7 Velocity models used for migration of the ANCORP data set. **Top:** Model 1 from refraction data analysis (Lüth, 2000). **Middle:** Model 2 from local earthquake tomography (Rietbrock and Haberland, 2001). **Bottom:** Model 3 from local earthquake tomography (Koulakov, pers. comm. 2004). 63

- 4.8 Travel time curves calculated for a hypocenter located at a depth of 90 km in the middle of the profile. Black - Model 1; Red - Model 2; Green - Model 3. 64
- 4.9 From top to bottom: The ANCORP sections calculated for model 1 (Lüth, 2000), for model 2 (Rietbrock and Haberland, 2001), and for model 3 (pers. comm. Koulakov, 2004). 65
- 4.10 From top to bottom: The ANCORP sections calculated for model 1, for model 2 and for model 3 with hypocenter locations (black dots). The black dashed lines indicate the prolonged reflections from the top of the oceanic crust, the pink dashed lines the top of the oceanic crust interpreted from the hypocenter locations. 67
- 4.11 The unfiltered ANCORP depth section. 69
- 4.12 RIS applied to the ANCORP data set. The recalculated ANCORP sections in narrow-frequency bands. **Top:** 5 - 10 Hz. **Middle:** 10 - 15 Hz. **Bottom:** 15 - 20 Hz. 70
- 4.13 **Top:** The high frequency ANCORP image and interpretation (see inset). The horizontal reflections are interpreted as the hydrated continental mantle wedge, the dipping reflections as the oceanic crust. The relocated hypocenter locations are indicated by black dots (Rietbrock and Waldhauser, 2004). **Bottom:** PRECORP depth section and interpretation. The horizontal reflections at depths of 80 km are interpreted as the hydrated mantle wedge, the weaker east dipping reflections at depths larger than 80 km as the oceanic crust (black lines). The black dots represent the hypocenter locations (Gräber and Asch, 1999). The pink dashed line indicates the top of the oceanic crust. 75
- 4.14 Two equivalent resistivity models derived from inversion of magnetotelluric data (pers. comm. Brasse, 2003). The first model did not consider the hydrated oceanic crust, whereas in the second starting model the oceanic crust is considered as a good conductor. Independent from the starting model a body of high resistivity is observed (blue color) between $x = 130 - 170$ km at depths between 10 - 40 km. 77

- 4.15 Map of the investigation area with locations of the SPOC profiles (from Krawczyk and the SPOC Team (2003)). The blue asterisk marks the epicenter location of the 1960 Valdivia earthquake from Cifuentes (1989), the red asterisk indicates the relocated epicenter position suggested by Krawczyk and the SPOC Team (2003). The inset illustrates a schematic conceptual model of the crustal structure of the southern Chilean subduction zone at $38^{\circ} 15'S$ 79
- 4.16 Tectonic units and simplified geology of the Southern Andes (from Rosenau (2004)). GFZ = Gastre Fault Zone, NPB = North Patagonian Batholith. . . 81
- 4.17 Velocity model SPOC from refraction data analysis (Lüth et al., 2003a) with black dots indicating the hypocenter locations (Bohm et al., 2002). . . 82
- 4.18 SPOC-NVR. Schematic view of the migration geometry. **Top:** 3D view of the migration volume and the profile location (red line). The shot point locations are indicated by blue asterisks. **Bottom:** Top view of the local coordinate system. The colours indicate the shot points and the corresponding receiver arrays (Blue: FFID 01 - 05 recorded by the first array; Dark purple: FFID 06 - 09 recorded by the second array; Light purple: FFID 10 - 14 recorded by the third array). The green lines indicate the E-W depth slices that were stacked yielding the final 2D depth sections. . . 84
- 4.19 SPOC-NVR. **Top :** Depth section obtained by stacking of absolute amplitudes. **Bottom :** Depth section obtained by trace normalisation of the envelope stacked section. 86
- 4.20 SPOC-NVR. Trace normalised section of envelope stack with ISSA hypocenters between $38^{\circ} - 38^{\circ}25 S$ (after Bohm et al. (2002)). The black lines indicate prominent wide-angle reflectors derived from refraction data analysis (Lüth et al., 2003a). In the middle of the profile the east dipping reflectors at depths between 35 - 40 km correlate well with the position of the oceanic Moho. Also, the reflectors visible in the middle of the profile at depths around 23 km match well with the boundary between the upper and the lower continental crust (Conrad discontinuity). 88
- 4.21 **Top:** Low-frequency image (5 - 10 Hz). **Middle:** Intermediate-frequency image (10 - 15 Hz). **Bottom:** High-frequency image (15 - 20 Hz). 89

A.1	RIS image from ANCORP in the frequency range between 5 - 10 Hz with relocated hypocenters (Rietbrock and Waldhauser, 2004). Blue dots indicate hypocenters between 20.5° - 21.0° S	112
A.2	RIS image from ANCORP in the frequency range between 10 - 15 Hz with relocated hypocenters (Rietbrock and Waldhauser, 2004). Blue dots indicate hypocenters between 20.5° - 21.0° S, black dots the hypocenters between 21.0° - 21.5° S.	113
B.1	SPOC - Unfiltered NVR section (envelope stack)	115
B.2	SPOC - Low-frequency (5-10 Hz) image (envelope stack)	116
B.3	SPOC - Intermediate-frequency (10 - 15 Hz) image (envelope stack)	117
B.4	SPOC - High-frequency (15 - 20 Hz) image (envelope stack)	118
B.5	SPOC - Low-frequency (5 - 10 Hz) image (envelope stacking and normalisation to maximum trace amplitudes).	119
B.6	SPOC - Intermediate-frequency (10 - 15 Hz) image (obtained by envelope stacking and normalisation to maximum trace amplitudes).	120
B.7	SPOC - High-frequency (15 - 20 Hz) image (obtained by envelope stacking and normalisation to maximum trace amplitudes).	121

