Deep crustal structure of the sheared South African continental margin: first results of the Agulhas-Karoo Geoscience Transect

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ABSTRACT

The southern margin of South Africa developed as a consequence of shear motion between the African and South American plates along the Agulhas-Falkland Transform Fault during the Early Cretaceous break-up of Gondwana. The Agulhas-Karoo Geoscience Transect crosses this continental margin, and includes two combined offshore-onshore seismic reflection/refraction profiles. We present results from the western offshore profile. Using ocean-bottom seismometers and a dense airgun shot pattern, a detailed image of the velocity – depth structure of the margin from the Agulhas Passage to the Agulhas Bank was derived. Modelling reveals crustal thicknesses of between 7 km and 30 km along the profile. The upper crust has P-wave velocities of between 5.6 and 6.6 km/s and the lower crust has velocities that lie between 6.4 and 7.1 km/s. Uppermost mantle velocities range from 7.8 to 8.0 km/s. The 52 km wide continent-ocean-transition zone, where the Moho rises steeply, occurs at the Agulhas-Falkland Fracture Zone.

Beneath the Southern Outeniqua Basin and the Diaz Marginal Ridge, a zone of relatively low velocities (~5 km/s) with a thickness of up to 3 km, can be discerned in the upper crust. We interpret this zone as an old basin filled with pre-break-up metasediments, which may be related to the Cape Fold Belt. We suggest that the origin of the Diaz Marginal Ridge is bound up with the tectonic history of this basin as it exhibits a similar velocity structure. Almost no stratified sediment cover exists in the Agulhas Passage because of strong erosion due to ocean currents. The velocity structure and seismic reflection results indicate the presence of alternating layers of volcanic flows and sediments, with a mean velocity of about 4 km/s. We suggest these volcanic flows were an accompaniment of possible re-activation events of parts of the Agulhas-Falkland Fracture Zone. Tectonic motion seems to be sub vertical instead of strike-slip along the re-activated part of the fracture zone. Therefore, a relation to the uplift of the South African crust may be possible.

Introduction

Continental accretion and break-up processes can be traced back over more than 3.5 billion years in southern Africa and along its margins. The Agulhas-Karoo Geoscience Transect is part of the Inkaba ye Africa framework project (de Wit and Horsfield, 2006) and is an onshore-offshore transect crossing the southern continental margin of South Africa starting in the Karoo Province, passing through the Cape Fold Belt (CFB), the Agulhas Bank, the Agulhas-Falkland Fracture Zone (AFFZ) and the Agulhas Plateau (Figure 1). This transect offers an unprecedented opportunity to address many different objectives concerning South Africa and its southern continental margin, applying seismic reflection and refraction, magneto-telluric, petrological, geological and geochemical methods. The main objectives of the onshore part of the survey are the identification of the sources of the Beattie Magnetic Anomaly and the Southern Cape Conductivity Belt, (Weckmann *et al.*, this issue) and an explanation of the history of the CFB (Stankiewicz *et al.*, this issue). Offshore, the structure and formation of the AFFZ and adjacent basins, and the evolution of the Agulhas Plateau and its crustal structure including its volume, age and magmatic source are addressed. The entire transect is a unique opportunity to use multidisciplinary data to create an overarching model of the architecture and dynamics of this margin. This model supplies new insights into the break-up of Gondwana in this region, the possible causes of the epeirogenic uplift of southern Africa, and the geodynamic processes that shaped the sheared continental margin.

Using seismic refraction and reflection data from the western of two offshore seismic lines (Figure 1), this contribution provides new detailed information on the crustal structure of the sheared South African continental margin. We discuss results with reference to the deep structure of the Outeniqua Basin, the composition of the Diaz Marginal Ridge, and the tectonomagmatic evolution of the AFFZ.

Tectonic framework

The South Atlantic formed due to rifting and seafloor spreading during the break-up of Gondwana in the Early Cretaceous (*e.g.* Barker, 1979, Ben-Avraham *et al.*, 1997). At the same time, shear processes along the Agulhas – Falkland Transform (AFT) caused the development of the southern margin of South Africa. Right-lateral strike-slip motion separated the African from the South American continent along this transform, which had a maximum ridge-ridge offset of 1200 km (Ben-Avraham *et al.*, 1997). Due to a series of ridge jumps (Barker,

doi:10.2113/gssajg.110.2/3.393

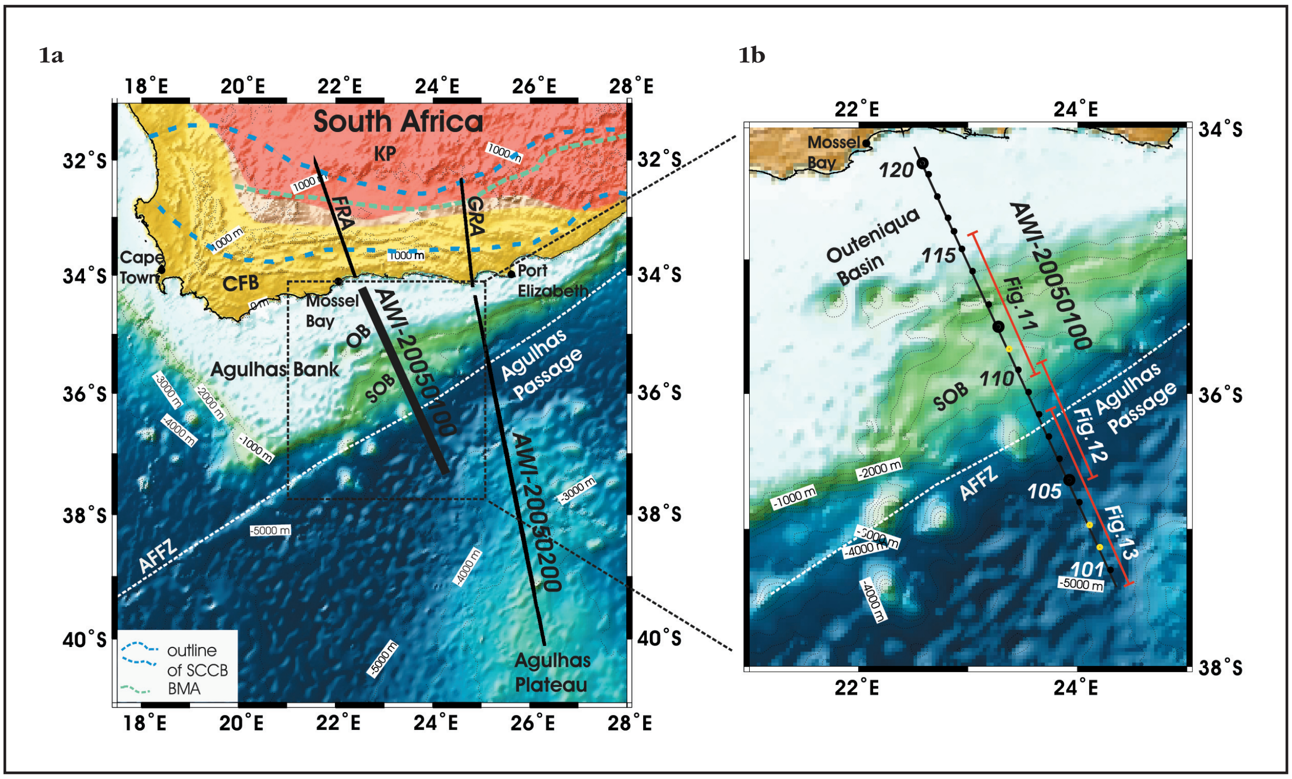

Figure 1. (**a**) In the overview map (left) the satellite derived topography (Sandwell and Smith, 1997) of the area of investigation is shown. Offshore (*AWI-20050100*, *AWI-20050200*) and onshore (*FRA*, *GRA*) seismic lines of the Agulhas-Karoo Geoscience Transect are plotted as black lines. The Agulhas-Falkland Fracture Zone (AFFZ) is marked with a white dashed line. The Cape Fold Belt (CFB) is drawn as a yellow area and the Karoo Province (KP) in light red on the map. The position of the Southern Cape Conductivity Belt (SCCB) is outlined by a blue dashed line and the location of the Beattie Magnetic Anomaly (BMA) is sketched by a green line (positions after de Beer *et al.*, 1982). Abbreviations are OB=Outeniqua Basin, SOB=Southern Outeniqua Basin, which is part of the OB. (**b**) In the enlargement (right) the shot profile *AWI-20050100* is shown as black line and positions of ocean-bottom seismometers (OBS) on the profile are marked with points. Thick points mark OBS whose data are shown in Figures 4, 5, and 6. Yellow points mark OBS which did not record data. Red bars illustrate the positions of coincident seismic reflection sections on the OBS profile, which are shown in Figures 11, 12, and 13.

1979; Tucholke *et al.,* 1981) the offset has been reduced to about 290 km at the present day (Figure 2). The present Agulhas-Falkland Transform is an intraoceanic feature located between 46.3°S, 10.0°W and 46.9°S, 13.3°W (Figure 2) that separates the South American and African arms of the Agulhas-Falkland Fracture Zone from each other. South of the African continent, the AFFZ can be divided into four parts, from southwest to northeast: the Mallory Trough segment, Diaz Ridge segment, East London segment and Durban segment (Ben-Avraham *et al.* 1997) (Figure 2). Ben-Avraham *et al.* (1995) interpreted disturbed seafloor in the eastern part of the Diaz Ridge segment as evidence for a renewal of tectonic activity in the Quaternary. The causes of the initial development of such a long offset transform boundary are still poorly understood.

Complex basins and marginal ridges are typical features of sheared margins (Bird, 2001). North of the AFFZ the Outeniqua Basin is a complex network of sub-basins (Figure 3). From west to east, the northern part of the Outeniqua Basin comprises the Bredasdorp, Infanta, Pletmos, Gamtoos and Algoa sub-basins (Figure 3). These basins are separated from each other by basement arches and faults (McMillan *et al.*, 1997) (Figure 3). The margin-parallel Southern Outeniqua Basin (SOB) lies between these sub-basins and the Diaz Marginal Ridge (DMR) (Figure 3). From the observation of great depths to acoustic basement (Figure 3), Ben-Avraham *et al.* (1997) concluded that the Outeniqua Basin is either underlain by oceanic or highly stretched continental crust. Reconstructions of the Falkland Plateau to its former position at the South African margin show that the Southern Outeniqua Basin and the Falkland Plateau Basin between Maurice Ewing Bank and the Falkland Island platform (Figure 2) were originally juxtaposed across the AFFZ (Martin *et al.* 1981; Ben-Avraham *et al.*, 1997).

The DMR, which borders the Outeniqua Basin to the south, is usually described as a basement ridge (*e.g.* Scrutton, 1979) although it has no strong magnetic intensity field signature (Ben-Avraham *et al.*, 1993). Ben-Avraham *et al.* (1993) discuss three possible compositions of the DMR; upward faulted continental basement, sedimentary rocks deformed during movement along the AFFZ, and extruded volcanic rocks. Ben-Avraham *et al.* (1993) prefer the second explanation, based on interpretation of seismic reflection results.

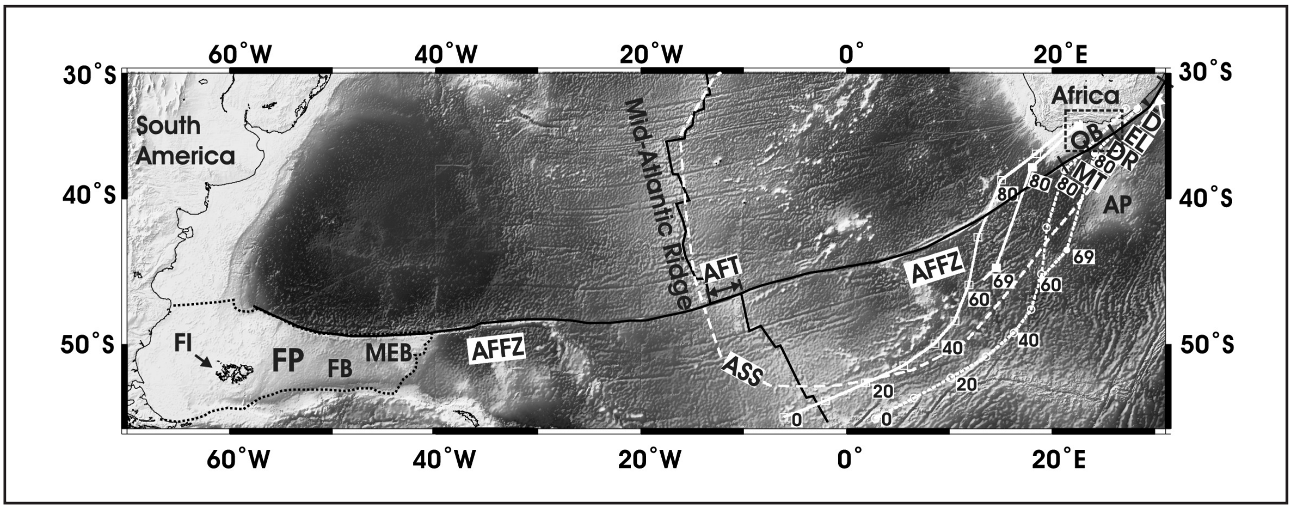

Figure 2. Satellite derived topography map (Sandwell and Smith, 1997) illustrating the tectonic setting. The white dashed line encircles the African Superswell (ASS). Tracks of the Shona hotspot (filled squares with solid lines according to Martin, 1987; open squares with solid lines according to Hartnady and le Roex, 1985) and the Bouvet hotspot (filled circles with dashed lines according to Martin, 1987; open circles with dashed lines according to Hartnady and le Roex, 1985) are shown and numbers refer the time in Ma when the hotspot is assumed to have reached that position. Abbreviations are FP=Falkland Plateau, FB=Falkland Basin, FI=Falkland Islands, MEB=Maurice Ewing Bank, AFT=Agulhas-Falkland Transform, MT=Mallory Trough segment, DR=Diaz Ridge segment, EL=East London segment, D=Durban segment. A detailed view of the Outeniqua Basin, as outlined in the dashed square, is shown in Figure 3.

Seismic data acquisition

In April-May 2005, the Alfred Wegener Institute of Polar and Marine Research (AWI) together with the Geoforschungszentrum Potsdam (GFZ) conducted a combined land-sea seismic experiment in southern Africa (Figure 1). During RV Sonne cruise SO-182, *AWI* acquired marine seismic reflection and refraction/wide-angle reflection data (Uenzelmann-Neben, 2005) along two sub-parallel profiles (*AWI-20050100* and *AWI-20050200*) across the southern continental margin of South Africa. Eight G.Guns™ and one Bolt airgun, with a total volume of 96 litres, were fired every 60 seconds, corresponding to a shot spacing of approximately 150 meters. The seismic reflection equipment consisted of a 180-channel streamer of 2250 m active length. The 457 km long western profile, *AWI-20050100,* starts in the Agulhas Passage, crosses the Agulhas-Falkland Fracture Zone, and carries on across the Outeniqua Basin and the Agulhas Bank (Figure 1). Along this profile, *AWI* deployed twenty ocean-bottom seismometers (OBS) with an average spacing of 20 km (Figure 1). The profile was extended landward by the

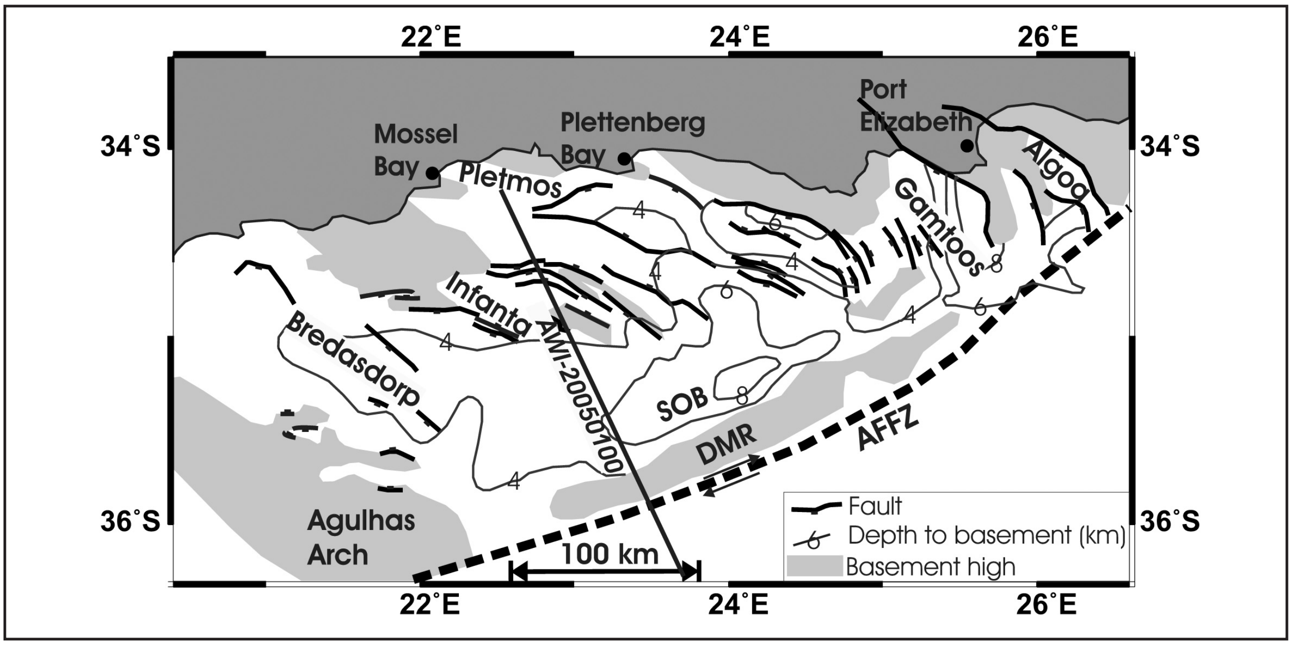

Figure 3. Map of the Outeniqua Basin adapted from Petroleum Agency SA (2003) showing its subbasins (Bredasdorp, Infanta, Pletmos, Gamtoos, Algoa, and Southern Outeniqua Basin), dominant faults, and basement heights.

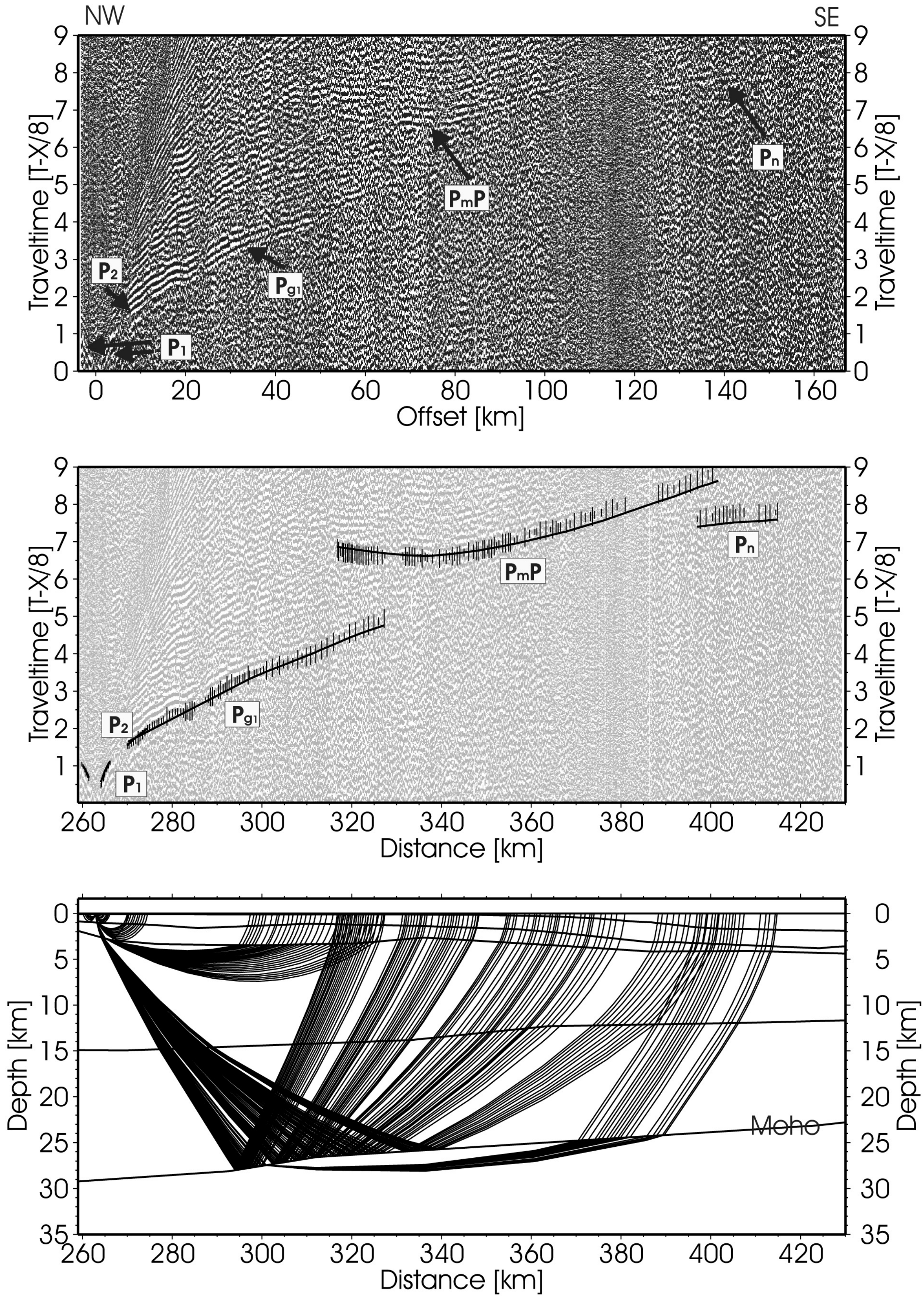

Figure 4. Seismic refraction data of OBS site 120. From top to bottom, the seismogram, picks and modelled travel time curves, and raypaths are shown.

Table 1. Phase indexes used in text and figures.

Phase index	Type	Layer
P_1	refracted wave	1st model layer (sediments and sedimentary rocks)
P_2	refracted wave	2nd model layer (sedimentary rocks, metasediments)
$P_{c1}P$	reflected wave	top of 3rd model layer (upper crust)
Pg_1	refracted wave	3rd model layer (upper crust)
$P_{c2}P$	reflected wave	top of 4th model layer (middle and lower crust)
P_{g2}	refracted wave	4th model layer (middle and lower crust)
PmP	reflected wave	top of 5th model layer (mantle)
Pn	refracted wave	5th model layer (mantle)

GFZ (Stankiewicz *et al.*, this issue), using 48 seismic stations spaced over a distance of 240 km. Most of the OBS records produced good to very good data quality. P-wave arrivals with maximum offsets of up to 200 km can be traced on the vertical component sections.

Multibeam bathymetry and sub-bottom profile data were recorded by SIMRAD and Parasound systems onboard RV Sonne.

Data processing

All OBS data were corrected for clock drift and converted into SEG-Y format. The data were corrected for discrepancies between the surface deployment positions and the final OBS location on the seafloor using the direct water arrivals at the OBS stations. The offset corrections were small on the continental shelf, only a few tens of meters, but significantly higher (a few hundreds of meters) in the Agulhas Passage due to strong currents. No deconvolution processing was applied as tests suggested there was no obvious improvement to the signal-to-noise ratio. During P-wave travel time picking, a bandpass filter (4 to 17 Hz) and automatic gain control with a 0.5 seconds window were applied. We picked the travel times of refracted and wide-angle reflected phases as parameters for a velocity-depth model.

Seismic reflection data were processed to depth-migrated sections. The acoustic basement was picked from the depth-migrated reflection section and used to constrain the velocity-depth model of the refraction data.

Data and modelling

Data from 17 of the 20 stations of profile *AWI-20050100* were used for modelling (Figure 1). These data show refracted and reflected P-wave arrivals from the crust and upper mantle (Table 1).

Phases refracted in the uppermost layer (P_1; Figure 4) are not found on all records because they were often masked by direct water arrivals. Reflection phases from the acoustic basement in the seismic reflection sections provided additional constraints for this layer. The model layer below is defined by refracted arrivals (P_2; Figures 4; 5) at almost all stations, with the exception of stations 101 and 104 in the southern part of the profile. Wide-angle reflections from the top of the upper crustal layer ($P_{c1}P$) define the downward extent of the second layer. These arrivals are often of low amplitude and hence were picked at just five stations. All stations show refracted arrivals from the upper crust (P_{g1}; Figures 4 to 6). Reflections ($P_{c2}P$; Figures 5; 6) recorded at five stations define the boundary between the upper crust and the lower crust. Refractions from the lower crust (P_{g2}; Figure 5; 6) are sparse in the northern part of the profile, due to their long offsets. On the southern part of the profile, all data show arrivals from the lower crust. Locally it is difficult to distinguish P-wave arrivals from the upper crust from those of the lower crust because of changes in the gradient of the travel time branch due to topography. Upper mantle refraction phases (P_n; Figures 4, 5) are identifiable at seven stations and wide-angle reflections from the Moho (P_mP; Figures 4 to 6) with strong amplitudes are observed at 14 stations.

Modelling of the seismic refraction data was performed using the 2-D traveltime inversion routine of Zelt and Smith (1992). Their algorithm was applied assuming a sub-horizontal, laterally-continuous layering using velocity and depth nodes for parameterisation of these layers. Station and shot locations were projected onto a line fitted through the OBS positions starting at the first land station and ending at the last shot point. This leads to a total onshore-offshore profile length of 660 km, of which the offshore part is considered here. Pick uncertainties in the range from 40 ms to 125 ms were assigned to the picked arrival times, depending on the signal-to-noise ratio. These values were higher than the true pick uncertainty, but encompass the additional uncertainties in the discrimination of different phases with similar travel times.

A simple starting model was developed incorporating one water layer, two layers with velocities typical for sedimentary rocks, two crustal layers and the mantle. Picks from the acoustic basement in our seismic reflection sections and information from onboard bathymetry measurements were included in the layer parameterisation. Using a forward modelling technique, the initial model was improved, layer by layer, from top to bottom. The resulting model was input into travel time inversion code (Zelt and Smith, 1992), in which the differences between the observed and calculated travel times are iteratively minimised by adjustment of the velocity and depth parameters. A layer stripping approach, in which we invert for velocity and depth nodes of the first layer until a satisfactory fit is obtained,

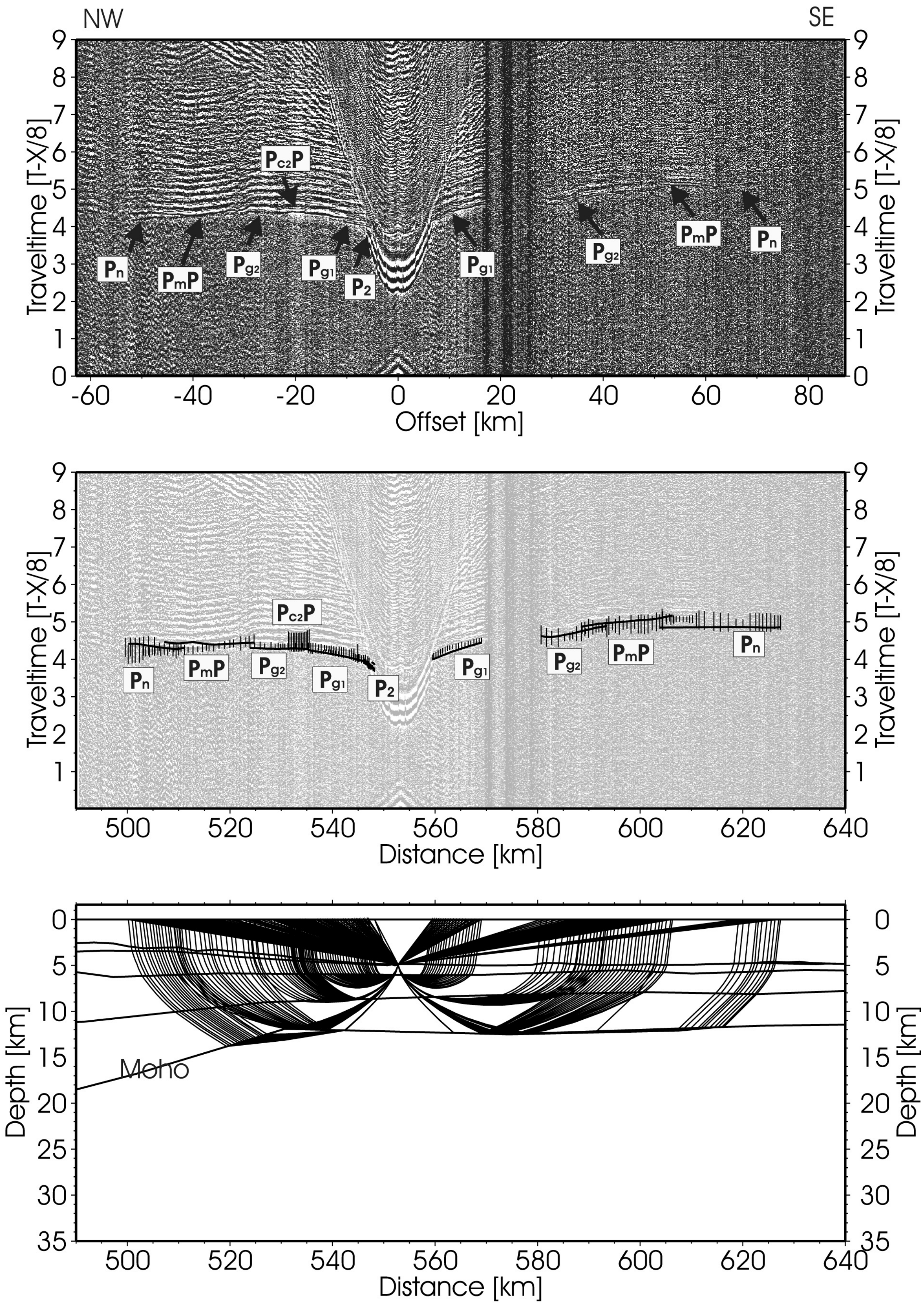

Figure 5. As Figure 4, with seismic refraction data of OBS site 105.

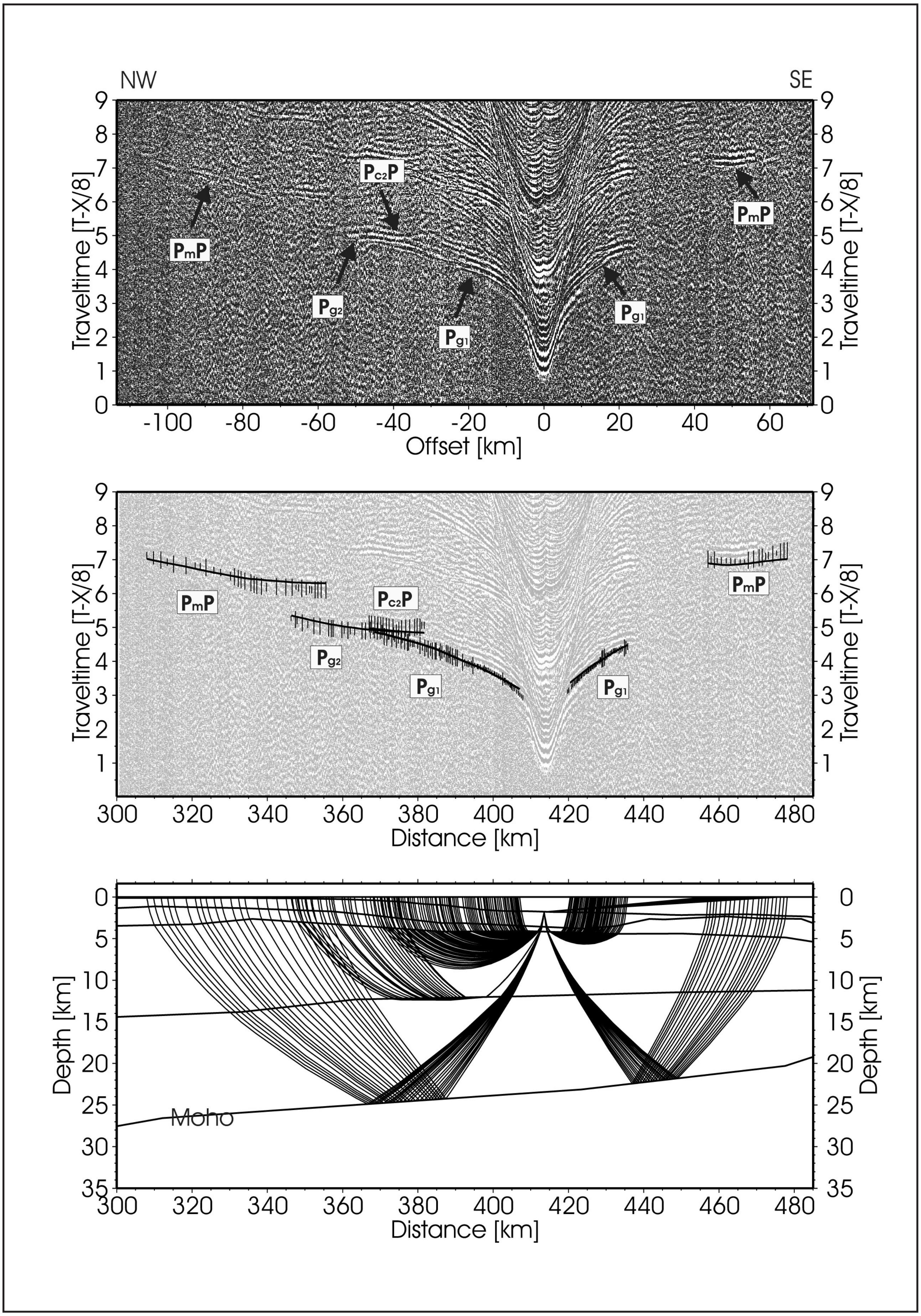

Figure 6. As Figure 4, with seismic refraction data of OBS site 112.

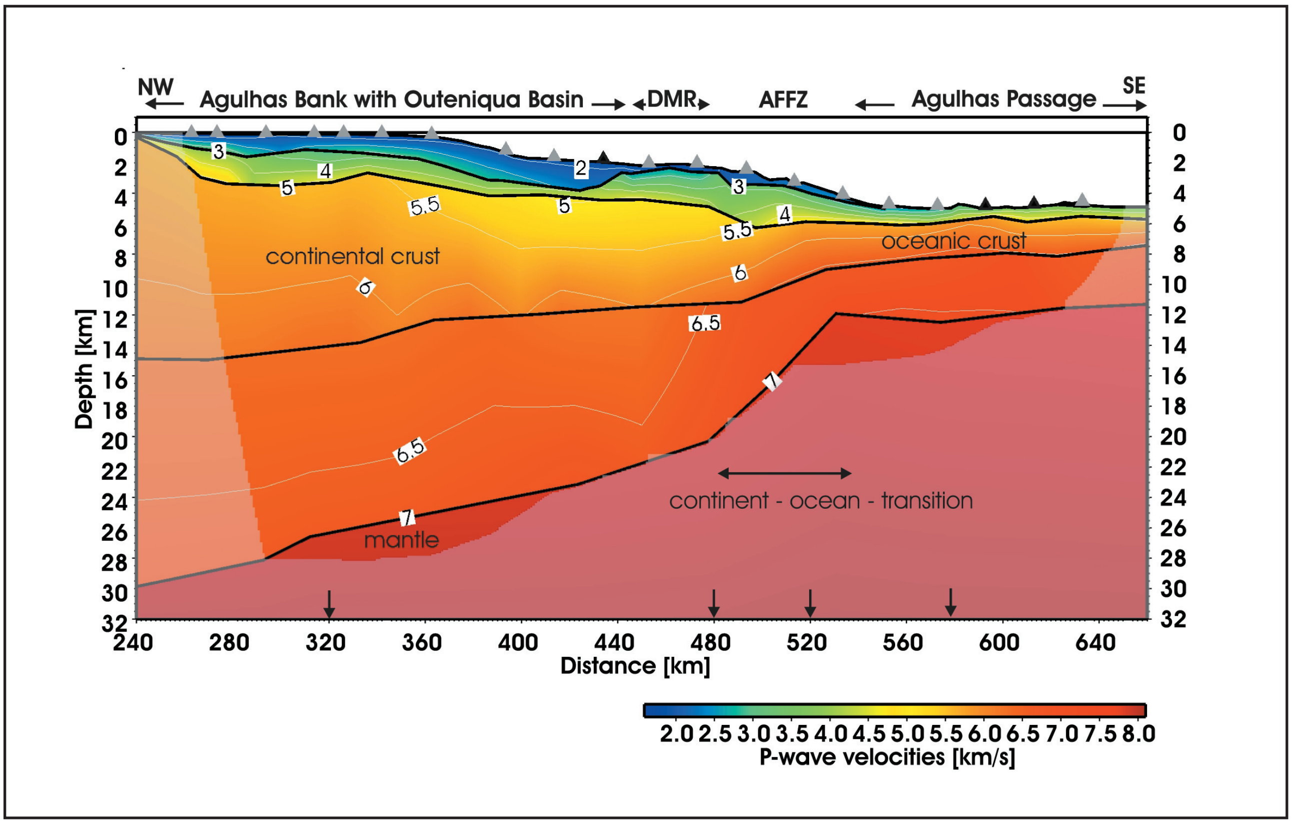

Figure 7. P-wave velocity model of profile *AWI-20050100*. Gray triangles mark positions of ocean-bottom seismometers. Arrows at base of figure show positions, where average crustal velocities (without 1st and 2nd model layer) were calculated. They are as follows v_{av} = 6.19 km/s (at 320 km model distance), 6.26 km/s (at 480 km), 6.50 km/s (at 520 km), 6.64 km/s (at 580 km). DMR is abbreviation for Diaz Marginal Ridge. Numbers on white isolines refer to seismic P-wave velocities. Black lines represent model layer boundaries.

was applied. These parameters were kept fixed when inverting for the depth and velocity of the second layer. This process is repeated until all values were adjusted in order to obtain a sufficient fit.

Velocity-depth structure from the Agulhas Bank to the Agulhas Passage

The final velocity-depth model of the profile *AWI-20050100* (Figure 7) consists of six layers. The water layer (layer 0) has a velocity of 1.5 km/s and thicknesses ranging from 0.1 to 5 km. Beneath this, layer 1 with P-wave velocities between 1.7 and 3.0 km/s, and a thickness of up to 2 km, can be observed from the continental shelf to the Southern Outeniqua Basin. These velocities suggest this layer consists of sediments. South of the Outeniqua Basin, this layer thins out and disappears in the Agulhas Passage. There, layer 2 with velocities between 3.0 to 5.0 km/s, and which can be found along the entire profile, crops out at the seafloor. Beneath this, the upper crust (layer 3) is modelled with velocities between 5.6 and 6.6 km/s. We modelled average velocities of between 6.4 and 7.1 km/s for the lower crust (layer 4), and uppermost mantle (layer 5) velocities of 7.8 to 8.0 km/s. The observed crustal thickness (including sediments) along the profile varies from 30 km on the inner continental shelf to 7 km in the Agulhas Passage.

Agulhas Bank (with Pletmos Basin)

On the Agulhas Bank, the crustal thickness ranges between 26 and 30 km (Figure 7). A layer with P-wave velocities between 1.7 and 3.0 km/s and a thickness of 1.5 km lies on top of a 0.8 to 2.5 km thick layer with velocities between 3.0 and 5.0 km/s (Figure 7). The upper crust exhibits velocities of between 5.5 and 6.3 km/s. Modelled lower crustal velocities vary between 6.3 and 6.6 km/s.

Southern Outeniqua Basin and the Diaz Marginal Ridge

The uppermost crustal layer is up to 2 km thick with velocities ranging from 1.7 to 2.9 km/s (Figure 7). These southeastward dipping, well-stratified sediments were deposited north of the Diaz Marginal Ridge, filling the Southern Outeniqua Basin (Figure 11). The oldest datable sediments drilled in the Outeniqua Basin are from the Kimmeridgian, at 151 to 154 Ma (McMillan *et al.*, 1997). A 0.5 to 1.5 km thick layer with seismic velocities averaging 4 km/s is located beneath the sediments of the Southern Outeniqua Basin. This layer continues beneath the Diaz Marginal Ridge, albeit with a broader range of velocities, from less than 3 km/s to more than 4 km/s. A sediment cover of 0.5 km thickness buries the ridge.

A broad, thick region (130 km in north-south direction and up to 3 km thick) with velocities in the

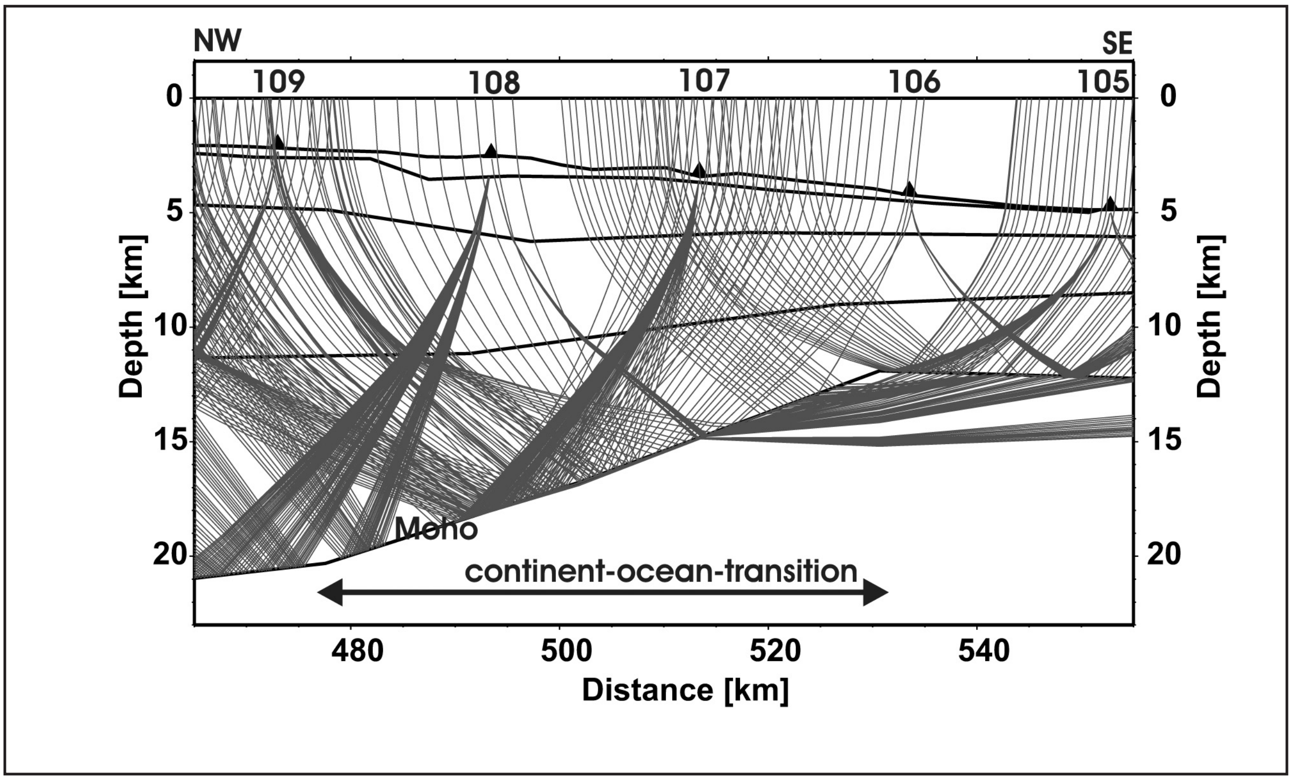

Figure 8. P_mP and P_n raypaths at continent-ocean-transition. OBS numbers are annotated on top of figure.

range of 5.0 to 5.5 km/s occurs beneath the Southern Outeniqua Basin and the Diaz Marginal Ridge in the upper crust. The lower crust is modelled with velocities between 6.2 and 6.7 km/s. The thickness of the crust underlying the Southern Outeniqua Basin declines from 25 km in the north to 22 km in the south. Beneath the Diaz Marginal Ridge, the crust thins from 22 km to 19 km thick.

Agulhas-Falkland Fracture Zone

At the Agulhas-Falkland Fracture Zone, we observe a 0.5 to 1 km thick layer with sedimentary P-wave velocities (Figure 7) lying on top of a 2 km thick layer with average velocities of 4 km/s. In the upper crust, the P-wave velocities range from 5.5 to 6.4 km/s. Velocities between 6.6 and 6.8 km/s dominate the lower crust. A north-to-south increase in seismic velocities is observed at the AFFZ. The model shows lines of equal velocity curving upwards, which means that P-waves travel faster in shallower regions than they do farther north. A distinct Moho incline of about 10° to the southeast, which is well constrained by good ray coverage (Figure 8), is observed at 476 km model distance. The Moho becomes almost horizontal again at 530 km.

Agulhas Passage

Stratified sediments are only thin or absent in the Agulhas Passage (Figure 7). The second model layer, with velocities between 3.0 and almost 5.0 km/s, crops out at the seafloor. Upper crustal velocities range from 5.7 to 6.6 km/s, and lower crustal velocities range from 6.6 to 7.1 km/s. The crust in the region of the Agulhas Passage is significantly thinner at 7 km than in all other parts of the profile. The Moho is almost flat-lying, forming just a small depression between 550 and 600 km model distance, where overlying velocities of up to 7.1 km/s are modelled.

Model quality

The quality of the model (Table 2) is assessed using statistical parameters such as the normalised misfit parameter χ^2, the root-mean-squared (rms) travel time residual of the fits, and the numerical resolution of the model (Zelt and Smith 1992).

Table 2. Statistics of the velocity-depth model.

Phase	Number of picks	RMS misfit [s]	χ^2
All	3244	0.120	0.971
P_1	116	0.072	0.803
P_2	265	0.128	1.835
$P_{c1}P$	57	0.188	0.962
P_{g1}	1413	0.107	0.962
$P_{c2}P$	102	0.152	0.655
P_{g2}	438	0.119	0.790
P_mP	636	0.129	0.844
P_n	217	0.143	0.989

When $\chi^2 = 1$, the data have been fitted within their assigned uncertainties, whereas $\chi^2 < 1$ indicates that the data are overfitted, *i.e.* more tightly than warranted by the picks' uncertainties (Zelt *et al.*, 1994). $\chi^2 > 1$ indicates that small-scale features sampled by the data have probably not been resolved (Zelt and Smith, 1992). For our model, the overall average χ^2 value is 0.971, meaning that the chosen uncertainties for the picks are slightly overestimated. In the second layer (Table 2, phase P_2), χ^2 is greater than 1, which we interpret as indicating there are unresolved small-scale features and three-dimensional effects such as out-of-plane refractions. An rms-misfit value of 0.120 was obtained during modelling, which is within the assigned uncertainty bounds of the travel time picks.

We applied Zelt and Smith's (1992) travel time inversion method in order to assess the resolution of the velocity-depth model (Figure 9). This qualitative approach is based on the relative number of rays that determine the parameterisation of the model. Values greater than 0.5 are considered to be well-resolved (Zelt and Smith, 1992), which is the case for the upper sedimentary layer. Some parts of layer 2 have a resolution of less than 0.5, including two small zones north and south of the Diaz Marginal Ridge. A larger numerically unresolved zone in this second layer extends from 600 km model distance to the end of the profile. In this area only, two of four stations recorded data and these returned no refracted arrivals from layer 2. This low numerical resolution, however, is dominantly caused by the model parameterisation in this region rather than the number of rays. The numerical resolution decreases because many more nodes are needed here to parameterise the pinchout of the upper sedimentary layer. On the other hand, seismic rays that travel through layer 2 into deeper layers provide indirect information on this layer. These information are confirmed by seismic reflection data. Both layers of the crystalline crust are resolved very well, having large areas with a resolution between 0.7 and 1. Only at the borders of the model do the resolution values decrease to < 0.5. Velocities in the upper mantle are numerically well resolved, although this is mainly due to the small number of nodes rather than the large number of rays.

Discussion

Continental and oceanic crust

Continental crust, with velocities between 5.6 and 6.3 km/s in the upper crystalline crust and 6.4 and 6.7 km/s in the lower crust (Figure 7), is located from the Agulhas Bank to the Agulhas-Falkland Fracture Zone (model distance 260 to 510 km, Figure 10). Beneath the Agulhas Bank, this continental crust has a thickness of between 24 and 30 km. The crust thins towards the south. This thinning can be attributed to extensional forces that acted during the Valanginian rifting phase in the Falkland Plateau (Richards *et al.*, 1996) and Outeniqua Basin (Dingle *et al.*, 1983).

The Agulhas-Falkland Fracture Zone separates the continental side of the South African continental margin with its Agulhas Bank and Outeniqua Basin from the oceanic side with its Agulhas Passage (Figure 10). The transition zone from continental to oceanic crust is 52 km wide (profile distance 478 to 530 km), which is a typical value for sheared margins (Bird, 2001). It is characterised by a sharp decrease in crustal thickness from 30 km on the continental side to 7 km on the oceanic side (upper crust: 5.7 to 6.6 km/s, lower crust: 6.7 to 7.1 km/s) and by a southeastward increase in average crustal P-wave velocity (Figure 10). The slight increase in seismic velocity (Figure 7) in the lower crust, especially in the southern part of the continent-ocean-transition, is interpreted as indicating the presence of magmatic intrusions. Additional thinning may have

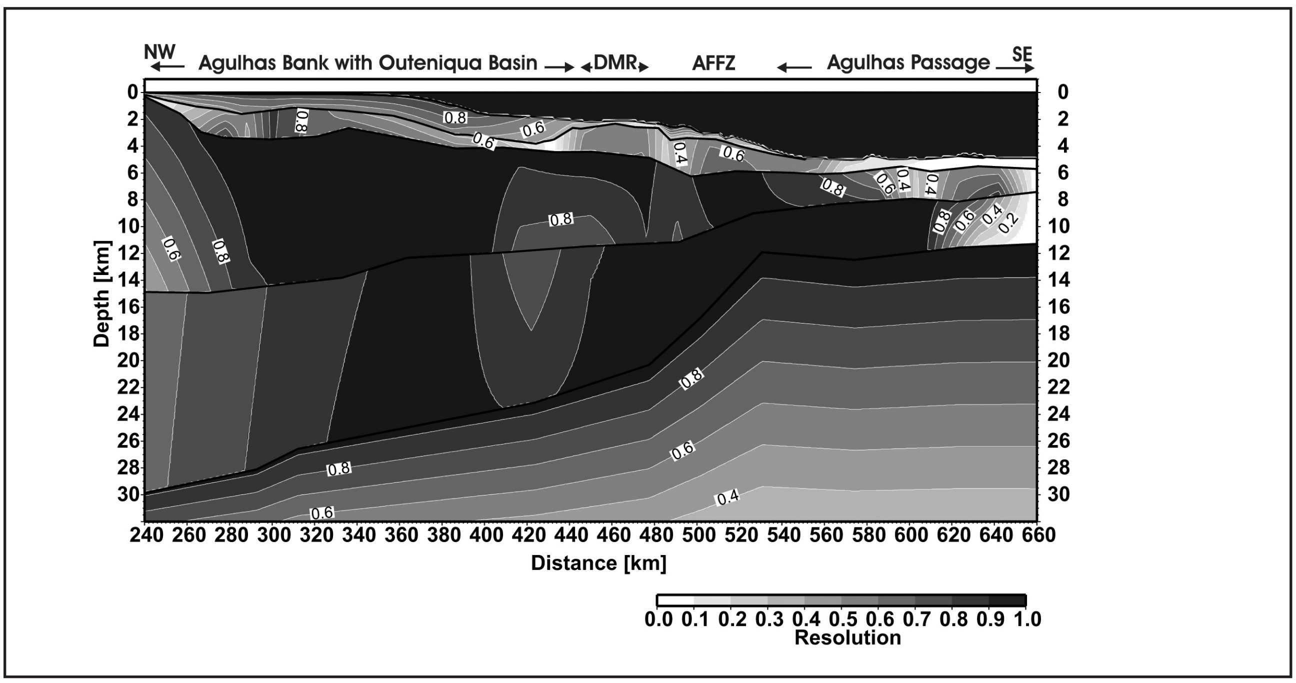

Figure 9. Numerical resolution of the P-wave velocity model of profile *AWI-20050100*.

occurred as a result of the shear process itself, where such deformation would require a ductile rather than a rigid crust. In this case it would be possible that parts of the African plate were dragged along the AFFZ and bent before frictional tension was released. Evidence of such a process seems to be preserved today in the curved strikes of the bounding faults in the northern reaches of the Outeniqua Basin (Figure 3). The Bouvet-Shona hotspot cluster (Figure 2) (Ben-Avraham *et al.*, 1997) would have produced a heat source that may have led to a more ductile rather than rigid behaviour of the plate.

A possible precursor of the Outeniqua Basin and the origin of the Diaz Marginal Ridge

The Outeniqua Basin is a complex basin, which consists of shallow basins in the north with horst, graben and half graben structures, separated from each other by basement ridges and faults, and the deep Southern Outeniqua Basin (McMillan *et al.*, 1997) (Figure 3). The Diaz Marginal Ridge blocks southward sediment transport so that sediments are trapped north of it and fill the Outeniqua Basin. The OBS profile crosses the Pletmos and Southern Outeniqua basins (Figure 3). The geometry of fault strikes (Figure 3), especially in the northern parts of the Outeniqua Basin, has been ascribed to the influence of pre-existing structures of the Cape Fold Belt (*e.g.* McMillan, 1997), whereas other authors have attributed the fault pattern to the strike-slip motion along the AFT (Ben-Avraham *et al.*, 1993; Thomson, 1999). We suggest a combined explanation. Some structures are possibly inherited zones of weakness, *i.e.* old faults of the Cape Fold Belt. These faults are likely to have been re-activated due to extensional forces causing the development of horst and graben structures. Additional faults were generated during the active episodes of the AFT in the Cretaceous. During shear motion between the African and South American plates, a ductile African crust was dragged along the AFT resulting in a bending of existing and newly developed fault structures.

Beneath the Southern Outeniqua Basin and the Diaz Marginal Ridge, a 3 km thick and 130 km long zone of relatively low P-wave velocities (5.0 km/s to 5.5 km/s) is evident within the upper crust (Figure 7, model distance 360 to 490 km, model depth ≈ 4.5 km). This suggests the presence of either sedimentary rocks (*e.g.* sandstone, limestone, and dolomite) or metamorphic rocks (*e.g.* gneiss, marble, and schist) as these rock types have velocities in this range (Schön, 1983). Further S-wave modelling and the derivation of Poissons ratios will help to narrow down the variety of possible rocks. Dingle *et al.* (1983) reviewed the sedimentary structure of the Agulhas Bank from results of wide angle reflection and refraction studies and reported three layers with mean P-wave velocities of 2.0, 3.4 and 4.6 km/s. We suggest that the observed velocities of around 5 km/s originate from sedimentary rocks of upper Palaeozoic age, which are part of the third layer of Dingle *et al.* (1993), but which underwent further diagenesis and light metamorphism. We interpret this structure, therefore, as a precursor to the Outeniqua Basin, filled with pre-break-up metasediments (Figure 10). If this is correct, then before extensional forces formed the present Outeniqua Basin, an older basin (Pre-Outeniqua Basin) existed within the southern regions of the Permo-Triassic CFB. This basin was likely to have developed during the collision process that formed the CFB. Erosion of the CFB provided the sedimentary fill of the older basin. Our seismic reflection records show no obvious stratification of this infill (Figure 11). This

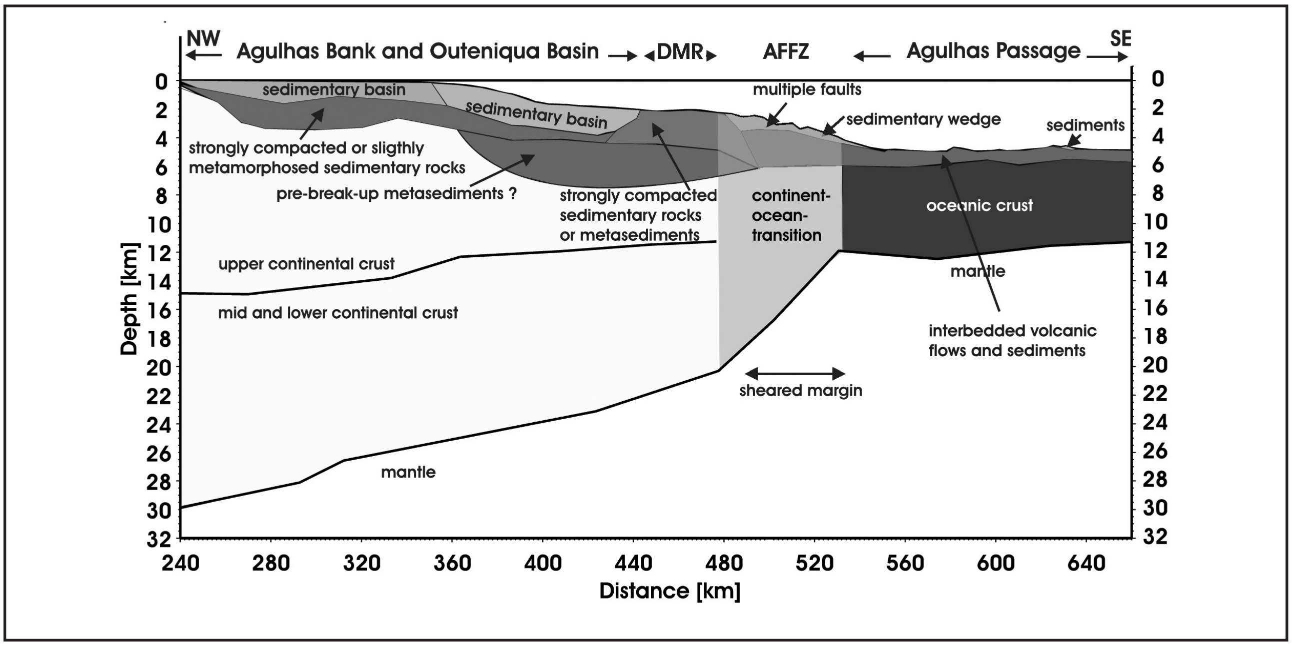

Figure 10. Interpreted structure of the sheared South African continental margin along profile *AWI-20050100* using information from the P-wave velocity model and seismic reflection sections..

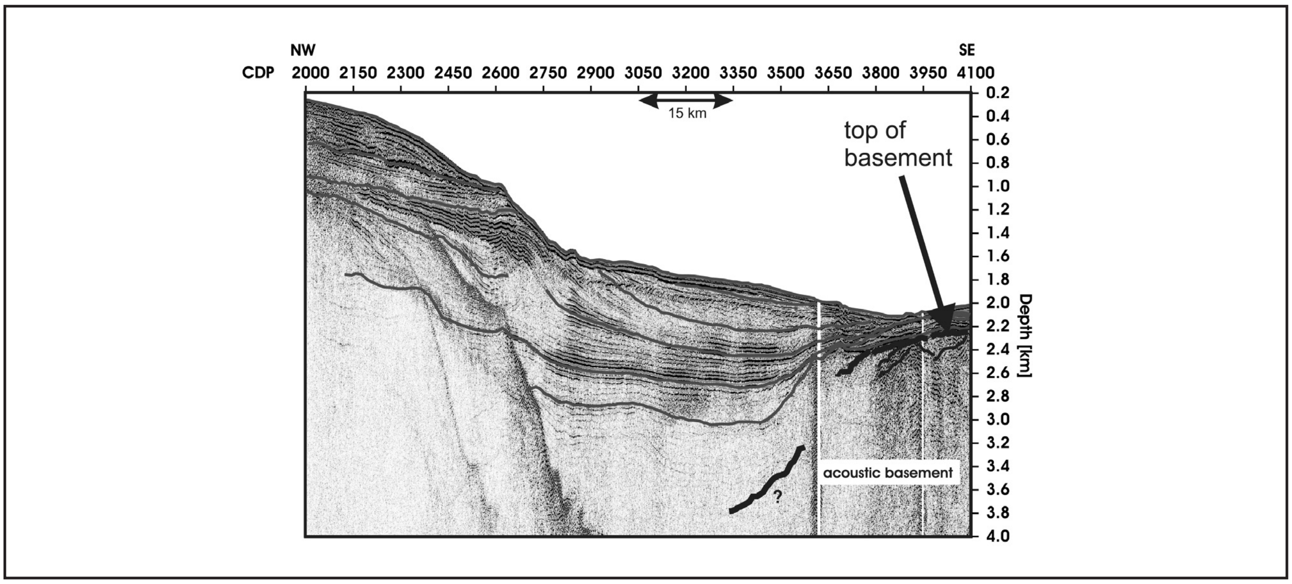

Figure 11. Part of the depth-migrated seismic reflection profile crossing the southern part of the Outeniqua Basin.

suggests that the sediments of this basin were heavily deformed during tectonic events that shaped the South African continental margin. These processes may have also been responsible for the generation of zones of crustal weakness which were (re)activated during the extensional process and caused the development of the present Outeniqua Basin. The sedimentary rocks of the older basin may have experienced metamorphism as a result of the proximity to the Bouvet-Shona hotspot cluster.

Earlier studies (Ben-Avraham *et al.*, 1993) suggest that the DMR is composed of sedimentary rocks of Jurassic to Early Cretaceous age, which were deformed due to motion along the AFFZ. Our modelling (Figure 7) leads us to a different conclusion. The DMR can be interpreted as a former part of the Pre-Outeniqua Basin (Figure 10). In addition to the strike-slip motion along the AFFZ, episodes of compression and extension are likely to have occurred. Compressional forces may have pushed parts of the metasedimentary infill of the older basin upwards to form the DMR. Thus, the metasediments underwent decompression that resulted in fracturing of the sediments which in turn caused the seismic velocities to decrease to an average of 4 km/s (Figure 7). The lack of any significant signature in the magnetic intensity field of the DMR (Ben-Avraham *et al.*, 1993) supports the theory of a metasedimentary origin.

New implications for re-activation of the AFFZ and a possible explanation

Plate-tectonic reconstructions suggest an end of the tectonic activity in this region, when the active parts of the AFFZ passed to the west at ~100 Ma (Martin and Hartnady, 1986). Ben-Avraham (1995) suggests a possible re-activation of the AFFZ occurred in the Quaternary from observations of deformed seafloor. Ben-Avraham *et al.* (1995) and Ben-Avraham (1995) noted that volcanic glasses with no significant alteration and interpretations of volcanic intrusions in seismic reflection records were consistent with the idea of neotectonic activity in this region.

A depth-migrated section of the seismic reflection line (*AWI-20050100*) illustrates the presence of several faults at the position of the AFFZ (Figure 12). These faults can be followed from the basement into the overlying sedimentary layers, suggesting re-activation of parts of the AFFZ past deposition of the sediments. This younger tectonic motion along parts of the AFFZ does not necessary have to have a strike-slip nature but may be related to vertical motions of the African Superswell (Figure 2), a zone of anomalously elevated topography and bathymetry in southern and western Africa. Nyblade and Robinson (1994) suggest the elevated topography/bathymetry is a result of heating of the lithosphere. We suggest that the AFFZ may have acted as a zone of crustal weakness to accommodate the uplift process.

The combination of tectonic activity in the western part of the Diaz Ridge segment of the AFFZ and reported neotectonic activity on its eastern part (Ben-Avraham *et al.*, 1995) leads to the conclusion that the entire Diaz Ridge segment of the AFFZ may have experienced phases of re-activation. If the neotectonic activity, for which we observe evidence on our profile, was caused by uplift processes related to the superswell, it is possible that other sectors of the AFFZ south of the African continent were also involved.

Volcanic activity in the Agulhas Passage

Stratified sediments are absent or very thin on top of the acoustic basement of the Agulhas Passage due to erosion driven by strong ocean currents (Uenzelmann-Neben *et al.*, 2007). The uppermost kilometre exhibits P-wave velocities of between 3.5 and 4.5 km/s. Strong reflections within the acoustic basement can be clearly seen on the seismic reflection records (Figure 13). These

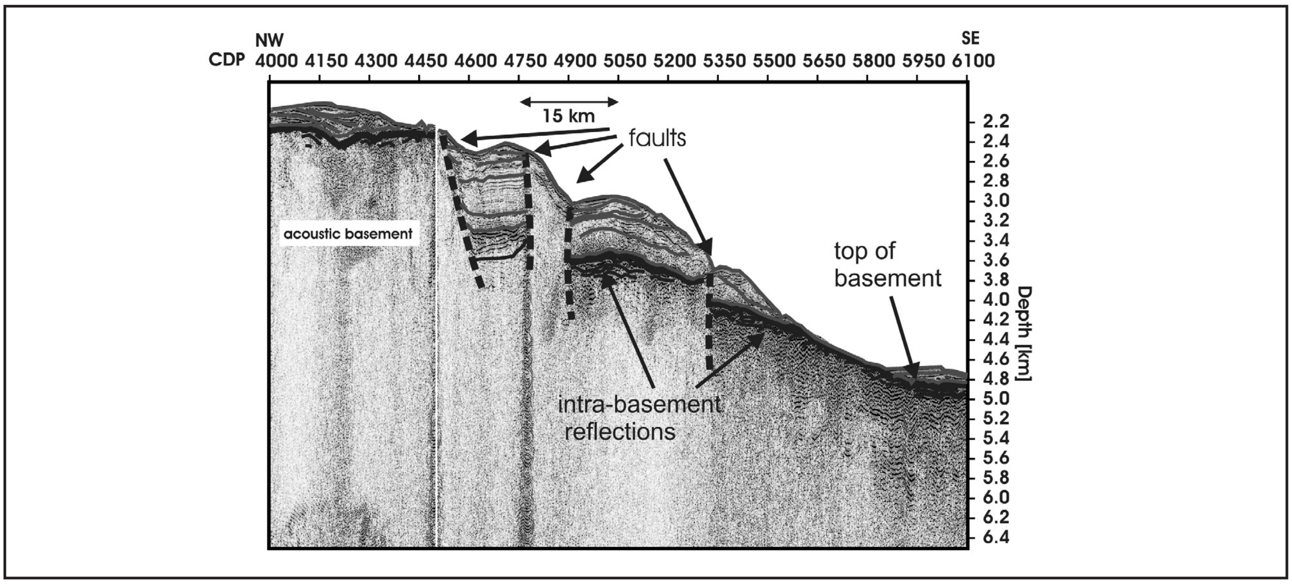

Figure 12. Part of the depth-migrated seismic reflection profile crossing the Agulhas-Falkland Fracture Zone.

reflections may be caused by interbedded strata of sediments and volcanic flows, because such alternating layers of sediments and volcanic flows could combine to explain the observed bulk velocities. Volcanic activity in the Agulhas Passage may be related to seamounts like those observed on our seismic reflection records (Figure 13). It is difficult to asses the timing of the volcanism as no dredge samples or other clues for the age of these seamounts are available, which in turn makes it difficult to identify the source of the volcanism. We speculate that this volcanism, like the re-activation of the AFFZ, might be attributable to uplift during heating of the lithosphere.

Conclusion

We obtained new insights into the structure and evolution of South African continental margin by modelling the western offshore seismic refraction profile of the Agulhas-Karoo-Geoscience Transect. The profile provides detailed information on the seismic velocity structure of this sheared margin from the Agulhas Bank to the Agulhas Passage. Coincident seismic reflection data gives a detailed view of the uppermost kilometres along the profile.

The main results and conclusions are:

1. The crust along the profile thins from 30 km beneath the continental shelf to 7 km in the deep sea.
2. The continent-ocean-transition is located at the AFFZ and extents over a ~52 km wide zone that is characterised by a Moho gradient.
3. The seismic reflection sections show faults that continue into sediments above the AFFZ. These faults

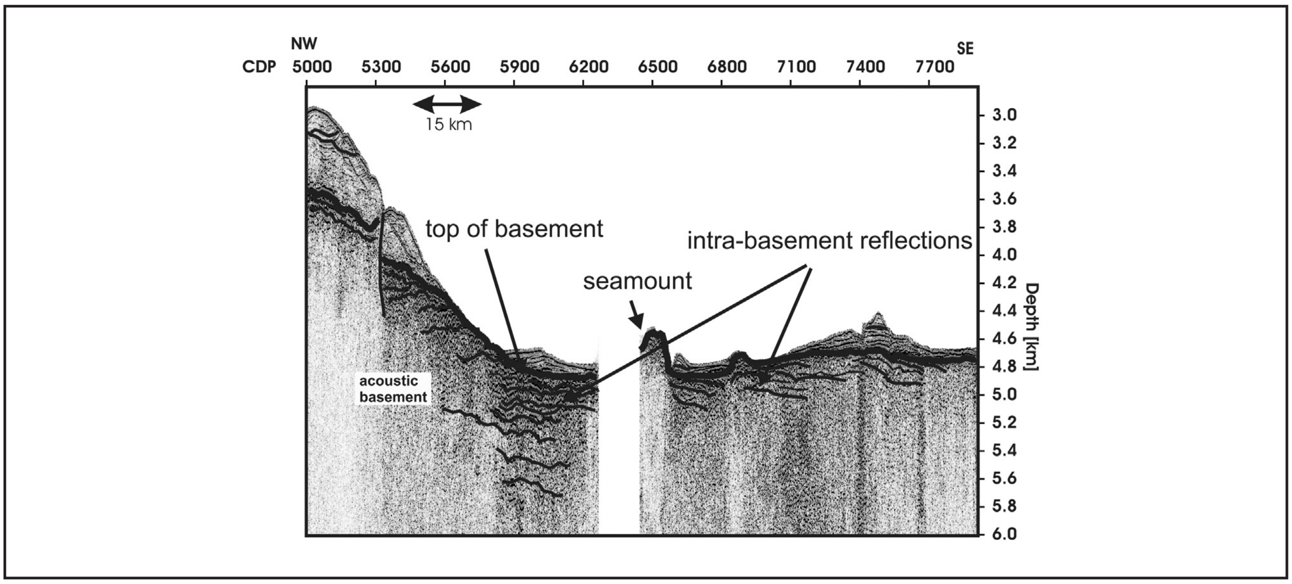

Figure 13. Part of the depth-migrated seismic reflection profile crossing the Agulhas Passage.

are probably caused by re-activation of the Diaz Ridge segment of the AFFZ and may be part of an even larger regime of re-activation related to thermal uplift of southern Africa.

4. Further indications for neotectonic and triggered volcanic activity have been identified in the Agulhas Passage. Here are indications of volcanic flows interbedded with sediments overlying basement. This volcanic activity may have accompanied the re-activation of the AFFZ.
5. In the upper crust beneath the Southern Outeniqua Basin and Diaz Marginal Ridge, a zone of about 130 km length and with a maximum thickness of 3 km has relatively low velocities (~5 km/s) compared to the adjacent basement. This region is interpreted as the metasedimentary fill of a pre-break-up basin. The basin probably formed coevally with the Cape Fold Belt and was filled with sediments shed from it, which were subsequently reworked due to magmatic and tectonic processes.
6. The Diaz Marginal Ridge is probably neither a volcanic feature nor a crystalline basement ridge, but instead may consist of metasediments. These metasediments may have been pushed upward out of the Pre-Outeniqua Basin as a result of compressional forces.

Acknowledgements

We acknowledge the cooperation of the captain and crew of RV Sonne who made it possible to collect the seismic data and thank the participants of SO-182 cruise for their support. We thank Graeme Eagles for improving the English of this manuscript and helpful discussions. We would like to thank Gesa Netzeband and an anonymous reviewer for their helpful comments. Most of the figures were generated with the Generic Mapping Tools (Wessel and Smith, 1998). The project AISTEK-I was funded by the German Bundesministerium für Bildung, Forschung und Technologie (BMBF) under contract no. 03G0182A. This is Inkaba yeAfrica contribution number 09 and AWI publication no. AWI-n 16537.

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Editorial handling: M. J. de Wit and Brian Horsfield