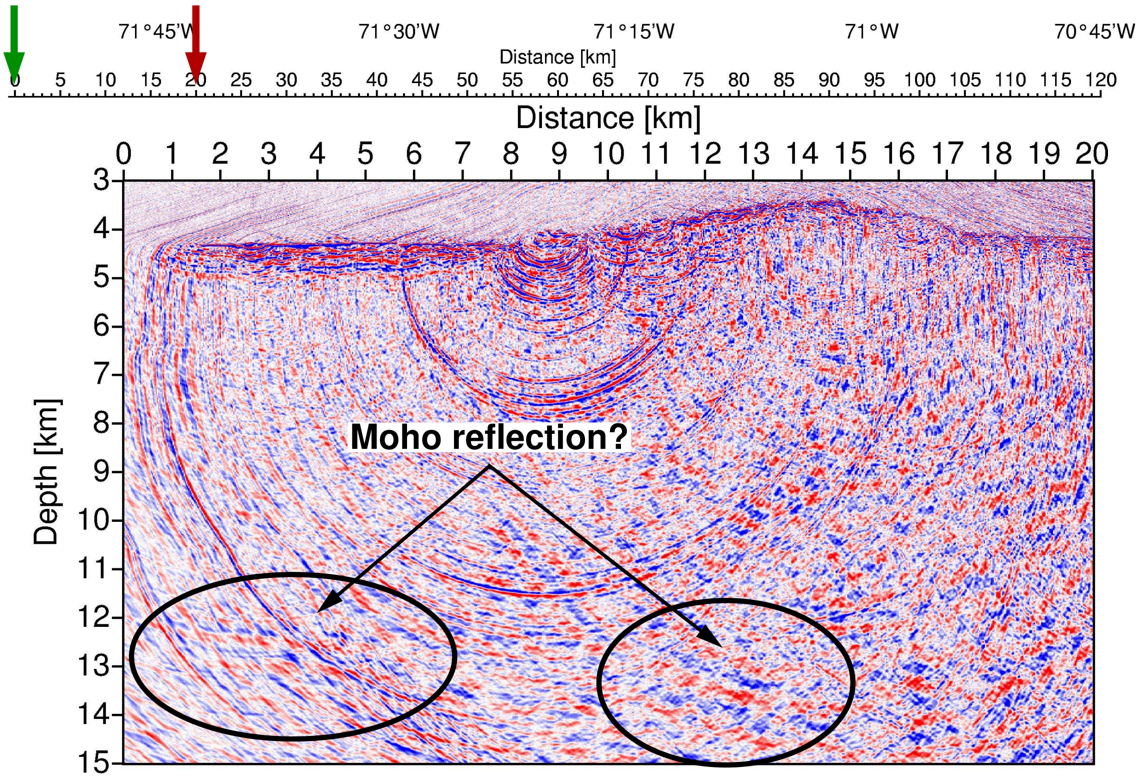


Figure 5.13: Depth section of the beginning of the profile migrated with the wide-angle model. A horizontal reflection occurs at a depth of about 7 km - 8 km beneath the seafloor. This event might be from the oceanic Moho which is expected in such a depth range.

5.4 Fresnel Volume Migration of line SO104-13

In this section only the Fresnel images are presented since they contain more structural details of the regarded area. A comparison of the depth sections resulting from both methods can be found in appendix A.

5.4.1 The ocean bottom and near-surface structures west of the trench

At the very beginning of line SO104-13 between 5 km and 8 km along the profile, a bundle of steep reflection events appear (surrounded by the black circle in Figure 5.14). They are, in fact, hard to distinguish from migration smiles which are visible in the Kirchhoff results (see Figure A.1 in appendix A). However, some of these reflections are oriented in the contrary direction as the artifacts within the Kirchhoff image indicating steeply dipping faults.

The first pronounced ocean bottom structure along the profile can be observed between 7 km and 15 km (Figure 5.15). The Fresnel image of this area provides

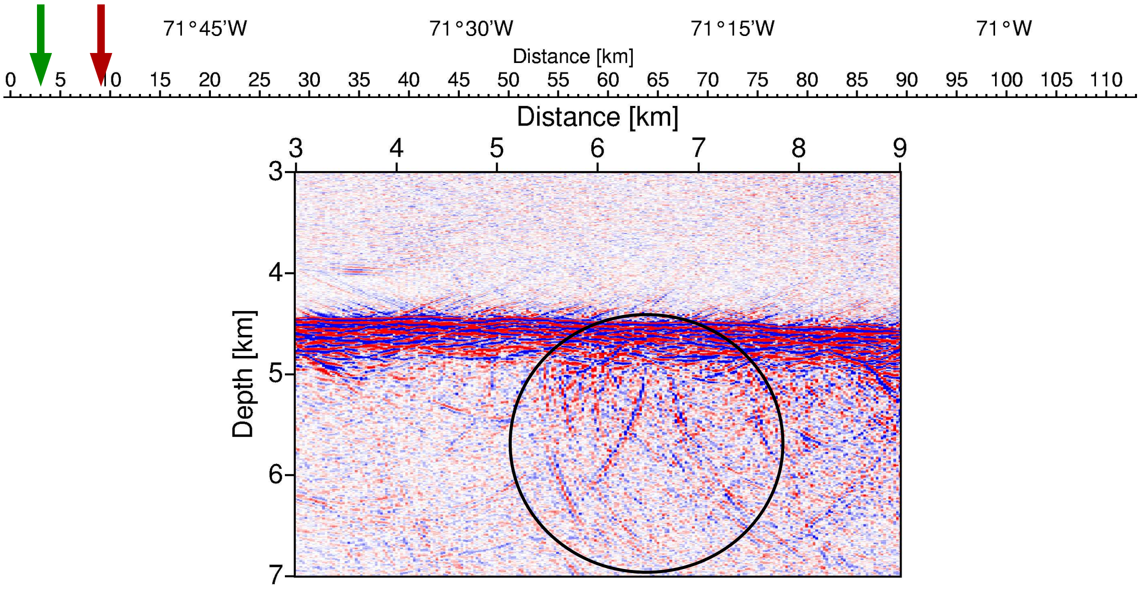


Figure 5.14: Reflection events indicating steeply dipping faults between 5 km and 8 km.

an insight into the subsurface underneath this feature. Besides the possible normal faults, marked by black arrows, some structures appear between approximately 7 km and 11 km (yellow circles) which are oriented nearly parallel to the overlying normal

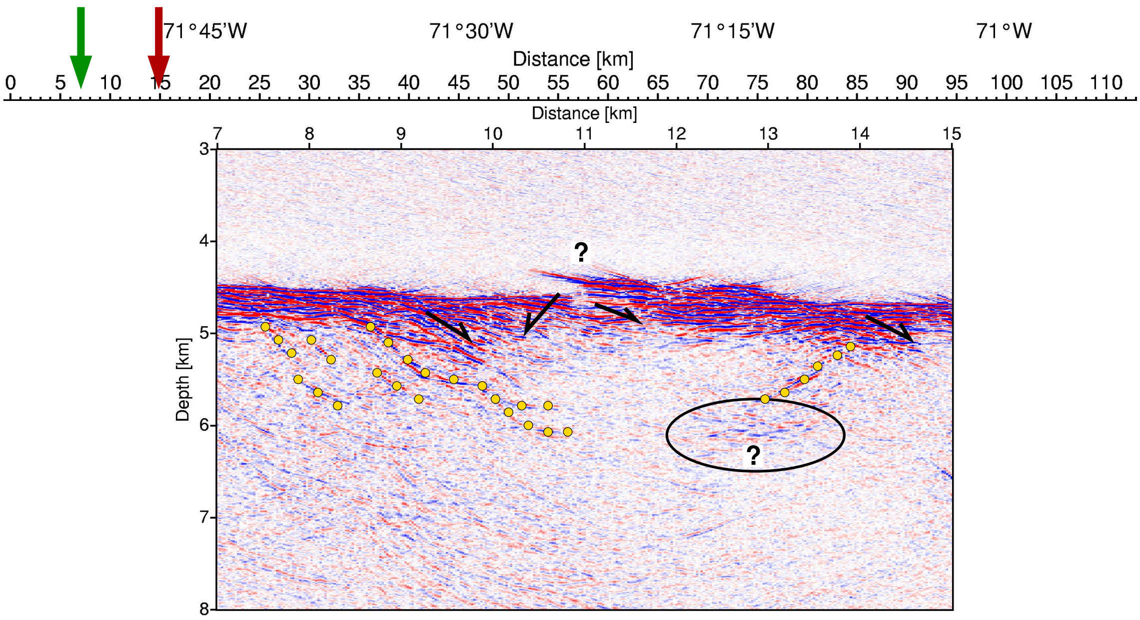
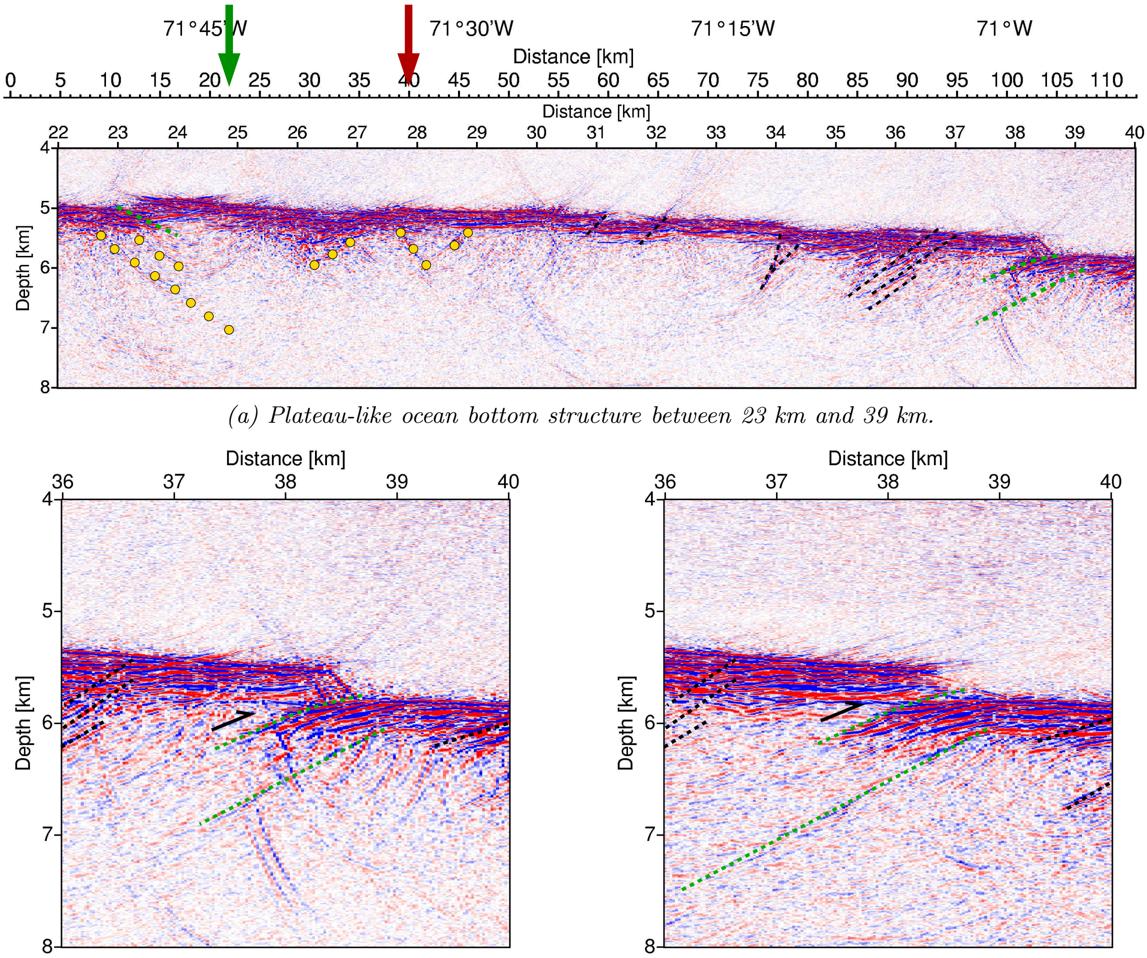


Figure 5.15: The first horst-like structure between 7 km an 15 km along profile. Yellow circles: faults transecting the oceanic crust. Arrows: location of possible normal faults.

fault. A similar feature is located between 13 km and 14 km along profile but this fault dips, in contrast to the above mentioned structures, to the west. Directly below this reflector some weak events are visible (surrounded by the black ellipse in Figure 5.15).

Between 23 km and 39 km along profile, a plateau-like surface structure is located (Figure 5.16). Underneath this topographic formation several reflectors are visible, where structures which transect the sedimentary layers are marked by dashed lines and those located within the oceanic crust are depicted by yellow circles in Figure



(a) Plateau-like ocean bottom structure between 23 km and 39 km.

(b) Enlargement of the region between 36 km and 40 km.

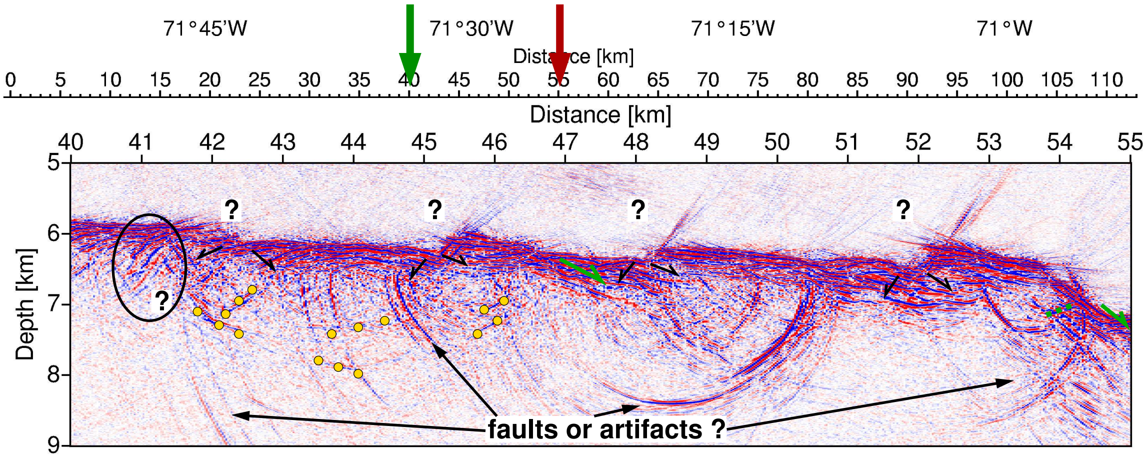
(c) Fresnel Volume Migration of the f-k filtered data set.

Figure 5.16: (a) The plateau-like ocean bottom structure between 23 km and 39 km along profile. (b) Enlargement of the region between 36 km and 40 km. (c) Enlargement of the same region as shown in (b). Here the f-k filtered data set was used for Fresnel Volume Migration. Dashed lines: fault structures crossing the sedimentary layers. Yellow circles: reflection events within the oceanic crust.

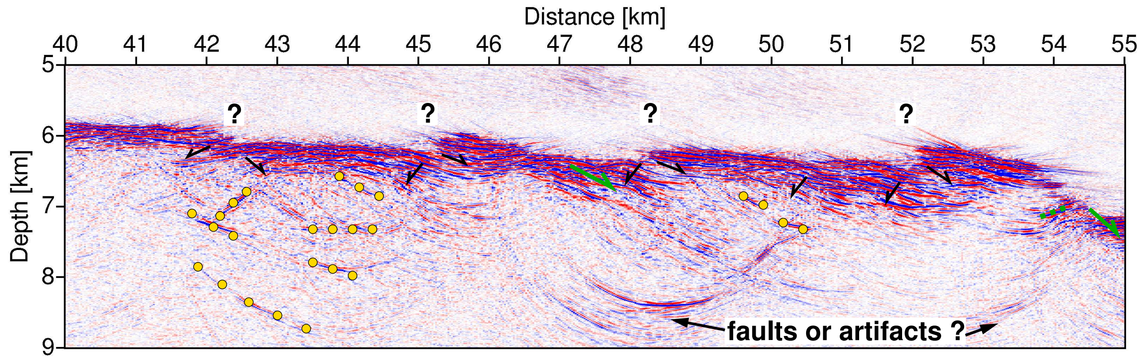
5.16. At 24 km and 38 km along profile faults can be observed (dashed green lines) which suggest thrust faults. Beneath the westernmost thrust fault between 22 km and 25 km two parallel, eastward dipping reflectors can be found in the oceanic crust (yellow circles). Also marked by yellow circles are the intra-crustal faults between 26 km and 29 km. Seaward dipping structures cross the sediments (31 km - 37 km) which reach down to a depth of approximately 1.5 km underneath the seafloor at 36 km along profile. The enlargements (Figures 5.16(b) and (c)) of the region between 36 km and 40 km confirm the interpretation of the observable features as thrust faults (dashed green lines). The dip of these faults as well as the reflections from the sedimentary layers at 38 km suggest overthrusting. While in Figure 5.16(b), which represents the result of migration with the unfiltered data set, some remaining artifacts are visible between 6 km and 8 km depth, the result of migration with the f-k filtered data set Figure 5.16(c) shows that these features are suppressed due to filtering. However, Figure 5.16(c) clearly images the thrust fault between 36 km and 39 km down to a depth of about 7.5 km.

In Figure 5.17, the region between 40 km and 55 km along profile is illustrated. Due to the rough ocean bottom topography near the trench some strong migration artifacts appear in the upper plot (Figure 5.17(a)). Some of them might also be generated by structures located in the northern or southern vicinity of this region (3D effects). Again, a few faults can be found in the oceanic crust between 41 km - 46 km along profile (yellow circles). Only two normal faults can clearly be identified (green arrows): the first one is located between 46 km and 50 km with an eastward dip, extending down to a depth of 8 km; the second one at about 54 km also dipping to the east. The latter is connected to a small fault, cross-cutting the eastern flank of the ocean bottom structure at 54 km along profile (dashed green line). Black arrows in Figure 5.17(a) depict features which can neither clearly be identified as normal faults nor as thrust faults. The appearance of reflectors below the corresponding flanks (at 42 km, 45.5 km, 48.5 km and 52 km), especially in Figure 5.17(b), indicate thrust faults rather than normal faults.

The additional use of an f-k filter prior to migration Figure 5.17(b) suppress that portion of the artifacts in Figure 5.17(a) arriving with particular angles (i.e. similar to the apparent velocity) at the receivers. A disadvantage of the f-k filter is that other events with nearly the same apparent velocity might also be attenuated. This effect is obvious at the flanks of the surface structures which are not as clearly imaged after f-k filtering (Figure 5.17(b)). Nevertheless, the strong artifacts in this region necessitated the use of a f-k filter to obtain a more detailed image of the subsurface as shown in Figure 5.17(b). Here, a few more structures (yellow circles) can be found between 42 km and 44 km at a depth of approximately 8.5 km and



(a) Fresnel Volume Migration result using the unfiltered data set.



(b) Fresnel Volume Migration result using the f-k filtered data set.

Figure 5.17: The region between 40 km and 55 km along profile. (a) Unfiltered data set. (b) F-k filtered data set. The arrows mark possible thrust or normal faults. Structures within the oceanic crust are marked by yellow circles.

between 49 and 50 km directly below the seafloor. A comparison of Figure 5.17(b) with the corresponding Kirchhoff image can be found in appendix A (Figure A.3).

Between 63 km and 65 km along profile, within a graben, a small sedimentary basin is located (Figure 5.18). This basin might be built up from material which stems from the neighbouring horst.

5.4.2 The trench

In the Fresnel Volume Migration result of the trench region (Figure 5.19), the subducting Nazca plate appears as the strongest reflection event (grey circles). It provides a detailed image of the internal structure of the frontal prism (between about 67.5 km and 72 km) Several reflections can be observed which are marked by black dashed lines in Figure 5.19. Directly below the seafloor, which forms a ridge at

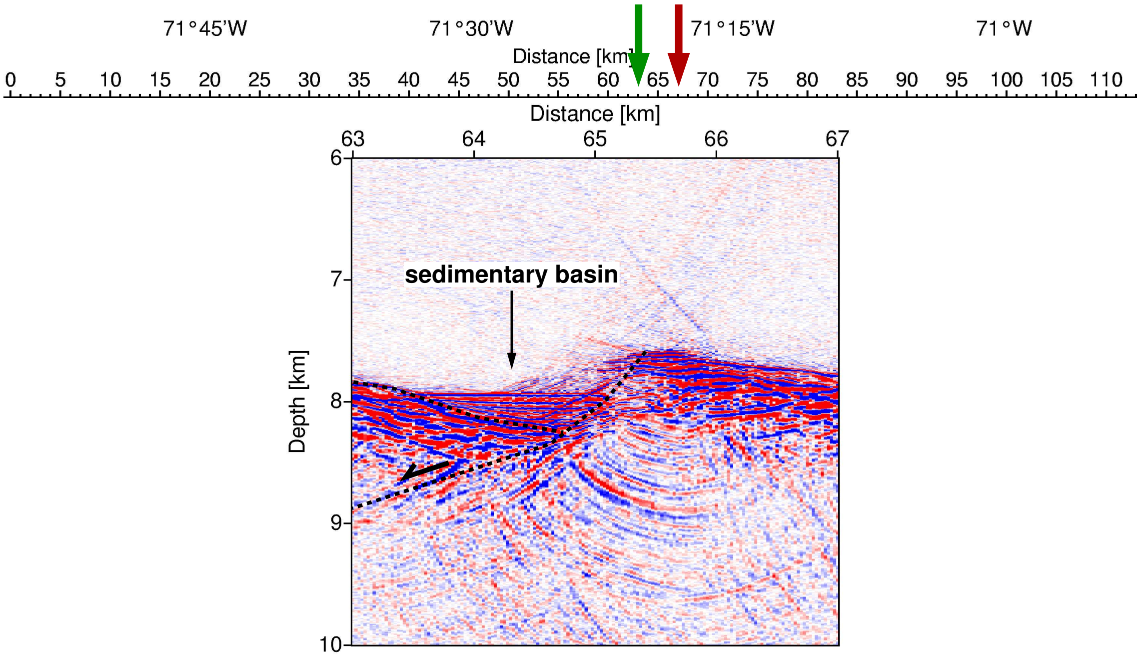


Figure 5.18: Image of a small sedimentary basin located in a graben at approximately 64 km along profile.

about 69.5 km with a height of approximately 150 m, folding can be observed. At greater depth (8 km - 9 km), the folded structure of the sediments increasingly flattens and the lowermost feature (at about 9 km depth) arises as an almost horizontal reflector. Further to the east, between 70 km and 72 km, some reflection events can be found at a depth of 8 km - 8.5 km which might be rather single fault structures than connected to the folds.

Further investigations have shown, that the frontal prism is built up of slope debris (e.g. von Huene *et al.*, 1999). The downdip graben, starting at about 68.5 km, was interpreted to be completely filled with stratified material. The small sedimentary ridge at the seafloor extends parallel along the trench axis (von Huene *et al.*, 1999, Figure 2.1) and it might be connected to the above observed ridge on line SO104-07 (Figure 5.8). It forms the deformation front along the trench axis. A non-interpreted depth section in comparison with the Kirchhoff image is shown in appendix A (Figure A.4).

5.4.3 Lower and middle continental slope

East of the trench, below the continental slope, the interface between the subducting Nazca plate and continental crust can be observed down to a depth of approximately

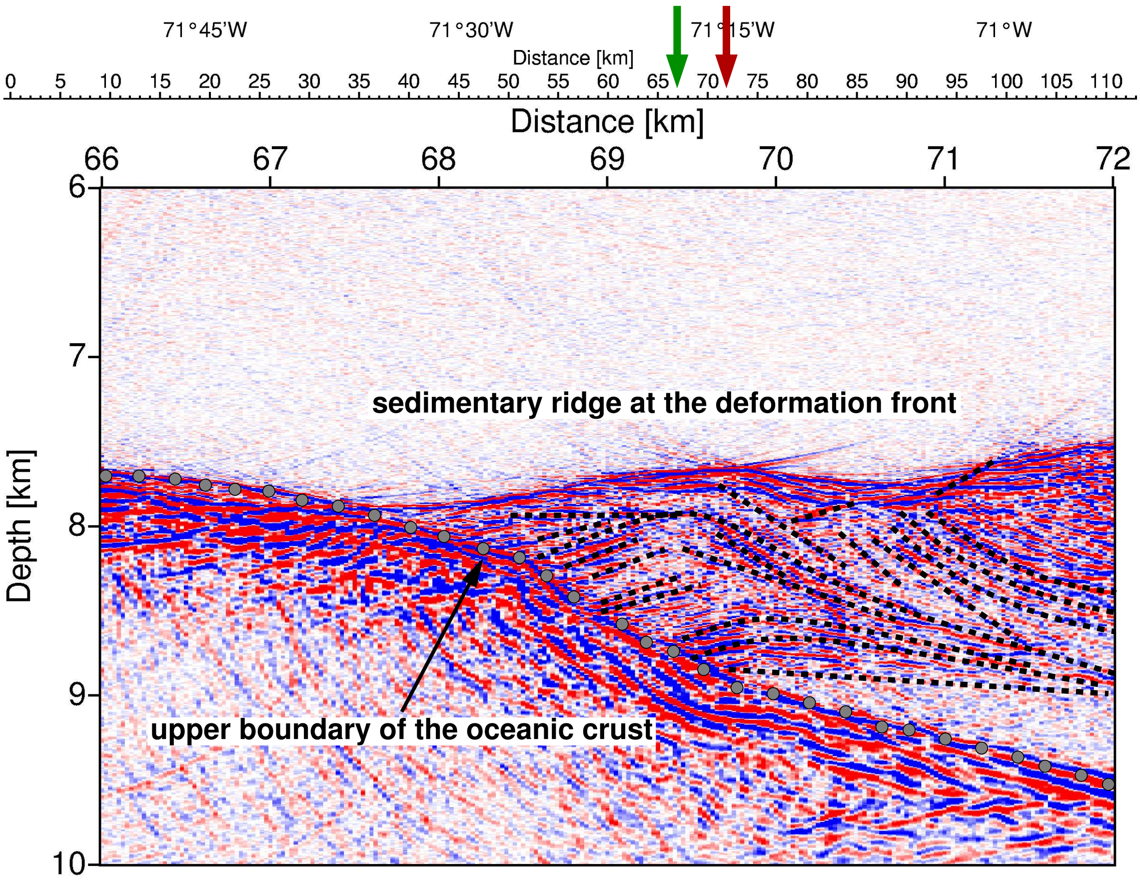


Figure 5.19: The trench region between 66 km and 72 km along profile. The grey circles mark the upper boundary of the oceanic crust. The frontal prism is transected by several faults and folds (dashed black lines).

15 km (grey circles in Figure 5.20). Three bumps are identified on the intra-plate boundary which indicate subducted horst-like structures at 73 km - 78 km, 81 km - 85.5 km and 90 km - 92 km along profile. Above the oceanic crust, several parallel oriented reflections appear (yellow circles and black arrows) dipping to the east with nearly the same angle as the slab. These faults surface at the location of trenchward facing escarpments visible in the continental slope (72 km, 78 km, 81 km and 85 km) to as much as 8 km above the plate interface. Between 90 km and 110 km a normal fault system is located (black arrows). It is landward rotated and bounded by a detachment at a depth of about 6 km - 7.5 km (green circles). The landward dipping strong reflectors on top of the normal fault system indicate a sedimentary deposit prior to tilting which is overlaid by sediments deposited after rotation. The plate parallel faults are interpreted to mark the upper part of the subduction channel where material is initially underthrust as large fault-bounded slabs (Sick *et al.*,

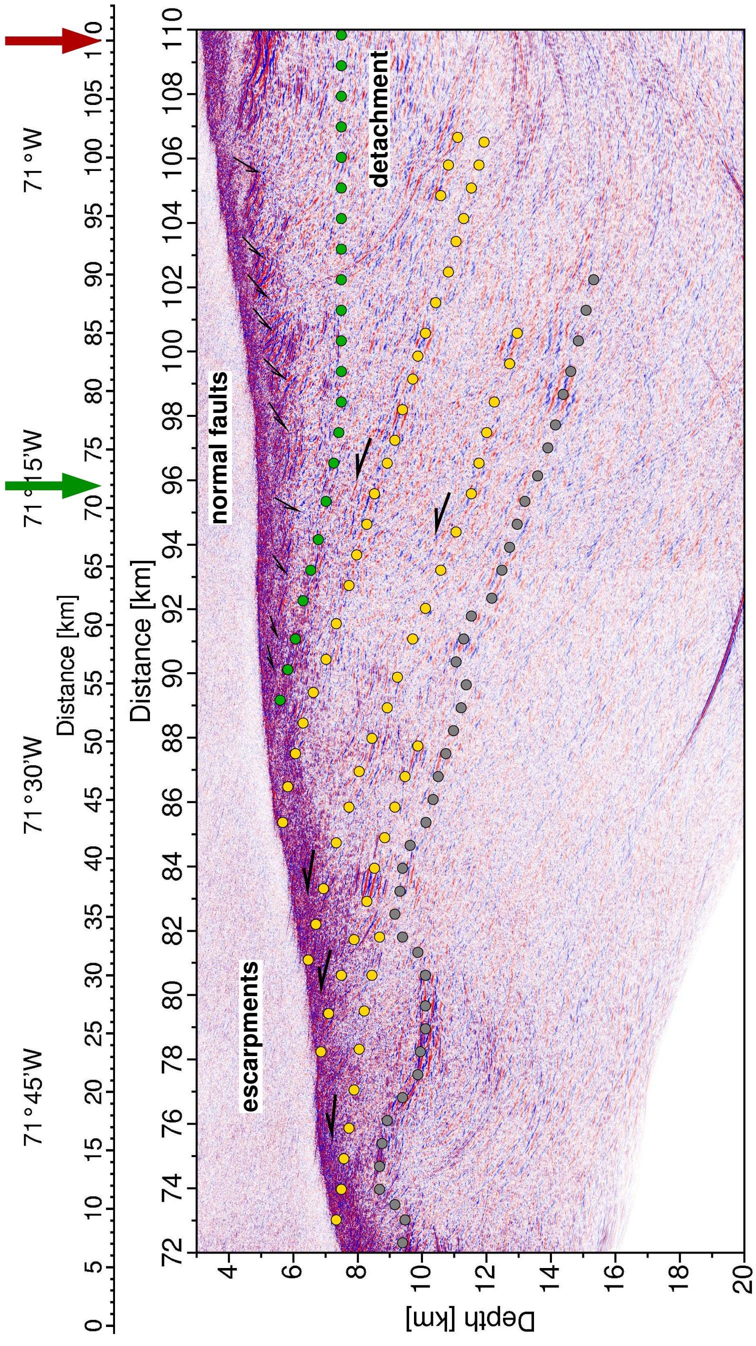
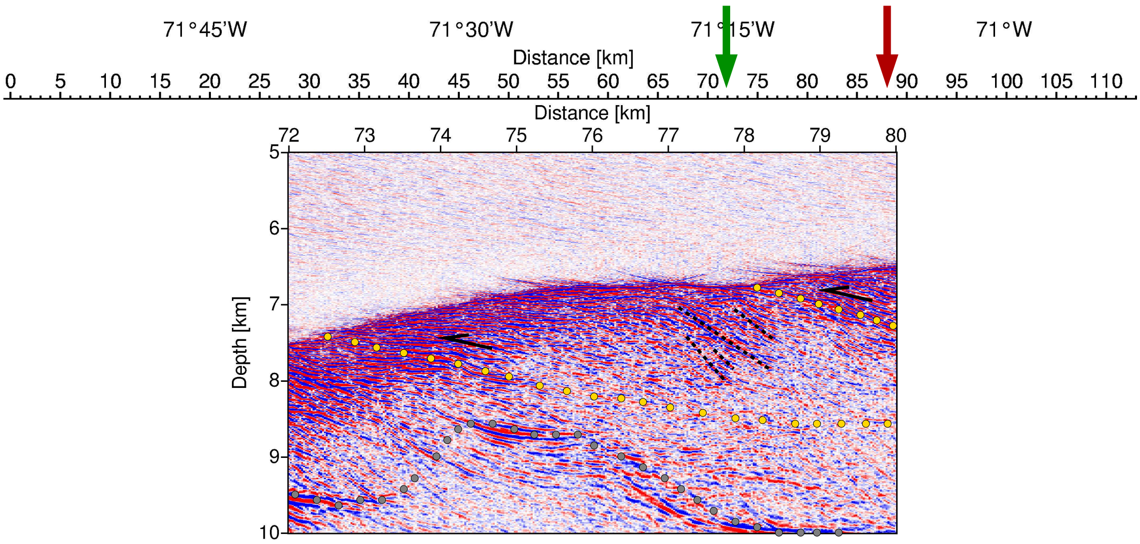


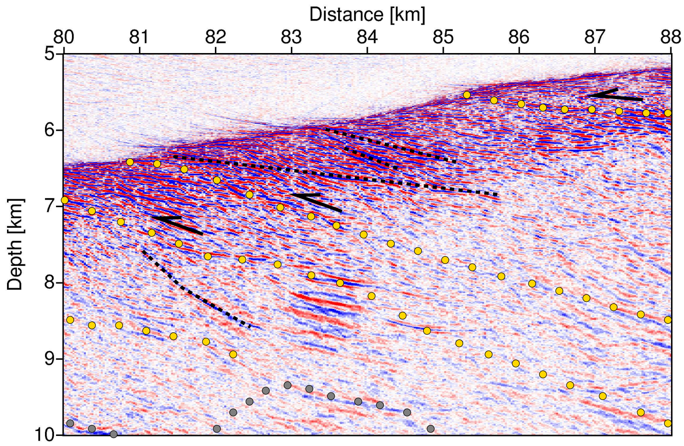
Figure 5.20: Fresnel image of the lower and middle continental slope. The upper boundary of the downgoing Nazca plate is illustrated as grey circles. Reflectors within the continental crust are marked by yellow circles and respective arrows. Between 90 km and 110 km, a normal fault system is marked by black arrows and the corresponding detachment is depicted by green circles. Some enlargements of this region can be found in Figures 5.21 and 5.22.

2005). An explanation for the strong reflectivity of these faults might be given by a high fluid content, but also material contrast or a cataclastic fabric are reasonable interpretations.

The uppermost interface parallel fault structure, which emerges at 88 km at the seafloor and which reaches a depth of about 12 km at 108 km along profile, was interpreted in an earlier study as the base of the La Negra formation (von Huene *et al.*, 1999). Salarès & Ranero, 2005 pointed out that the latter feature is the lower boundary of a low velocity zone situated directly below the detachment (green circles). However, it dips with nearly the same angle as the plate parallel reflectors



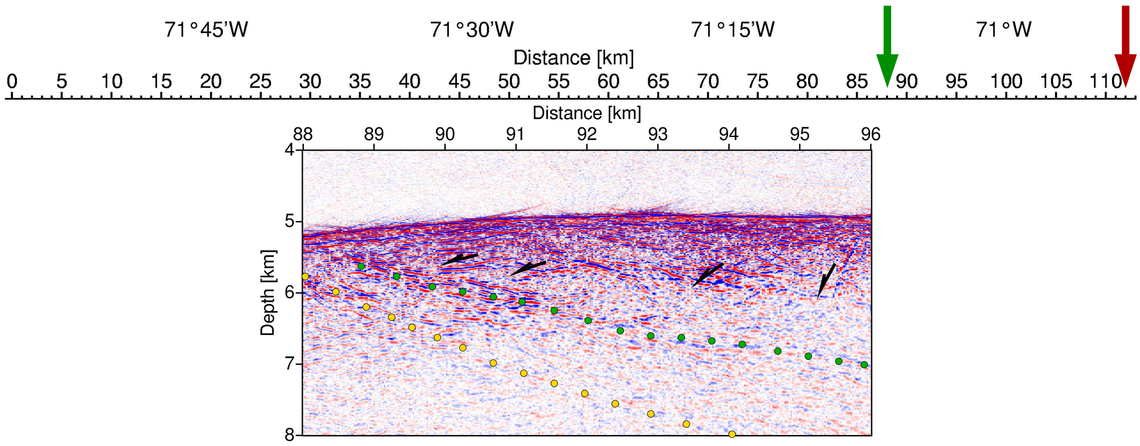
(a) Enlargement of the region between 72 km and 80 km.



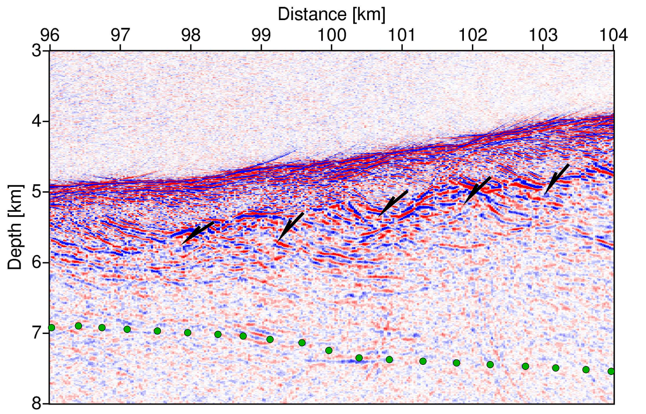
(b) Enlargement of the region between 80 km and 88 km.

Figure 5.21: Enlargements of the lower continental slope. The grey circles mark the location of the intra-plate boundary. The plate parallel faults are illustrated as yellow circles. Additional structures are depicted as dashed black lines.

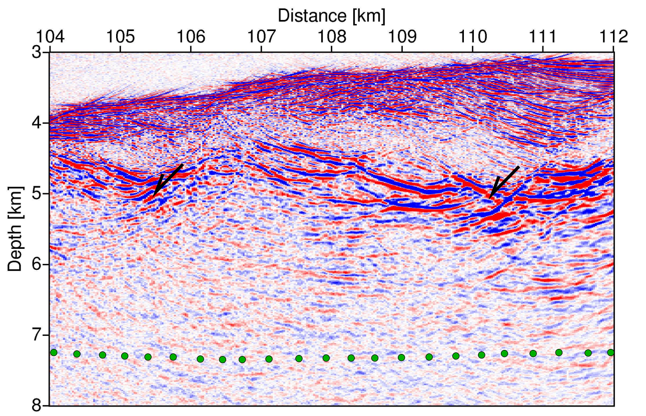
located further to the west (yellow circles). Also its outcrop correlates with a small



(a) Enlargement of the region between 88 km and 96 km.



(b) Enlargement of the region between 96 km and 104 km.



(c) Enlargement of the region between 104 km and 112 km.

Figure 5.22: Enlargements of the middle continental slope. Here, the normal faults are marked by black arrows and the detachment by green circles. Plate parallel reflectors are illustrated by yellow circles.

escarpment at the seafloor.

The plate parallel faults and the corresponding escarpments at 72 km, 78 km, 81 km and 85 km are illustrated in the enlargements of the lower continental slope (Figure 5.21). Both pictures exhibit a possible subducted horst structure (grey circles; Figure 5.21(a): 73 km - 78 km; Figure 5.21(b): 81 km - 85.5 km). Additional structures can be identified crossing the sediments and the uppermost part of the continental crust between 77 km and 78.5 km in Figure 5.21(a) (dashed black lines). In Figure 5.21(b) similar features are located between 81 km and 85.5 km. At depths between 7.5 and 8.5 km another fault arises (dashed black line). A strong reflection event appears above the horst structure in Figure 5.21(b) at about 83 km along the profile. It allows several possible interpretations where two of them might be: it is a part of the subducting Nazca plate and thus it indicates a part of the subducted horst-like structure or it is a part of the plate parallel fault between 8 km and 9 km depth as illustrated in Figure 5.21(b).

The subsurface of the middle slope is characterized by normal faults (marked by arrows in Figure 5.22). As discussed above, this fault system is bordered by a detachment at a depth of about 6 km - 7.5 km (green circles). The reflection event, marked by yellow circles in Figure 5.22 illustrates a part of a plate parallel reflector. The landward tilted blocks are clearly visible below the ocean bottom in Figures 5.22(b) and (c). Also the rotated sedimentary layers can be well identified at a depth of approximately 500 m - 600 m (Figure 5.22(b)) and respectively 600 m - 1300 m (Figure 5.22(c)) below the seafloor. At 106.5 km along profile (Figure 5.22(c)) another escarpment is visible.

A comparison of the enlargements of the middle slope with the corresponding Kirchhoff Prestack Depth Migration results can be found in appendix A (Figure A.5).

5.4.4 The oceanic Moho

Fresnel Volume Migration with the wide-angle model results in an image that shows some weak reflection events between 1 km and 31 km along profile at a depth of about 6 km - 7 km below the seafloor (Figure 5.23). This reflector segments are, however, very weakly imaged but they might be connected with the oceanic Moho. This depth range corresponds to the expected Moho depth as known from further investigations (e.g. Hinz *et al.*, 1995).

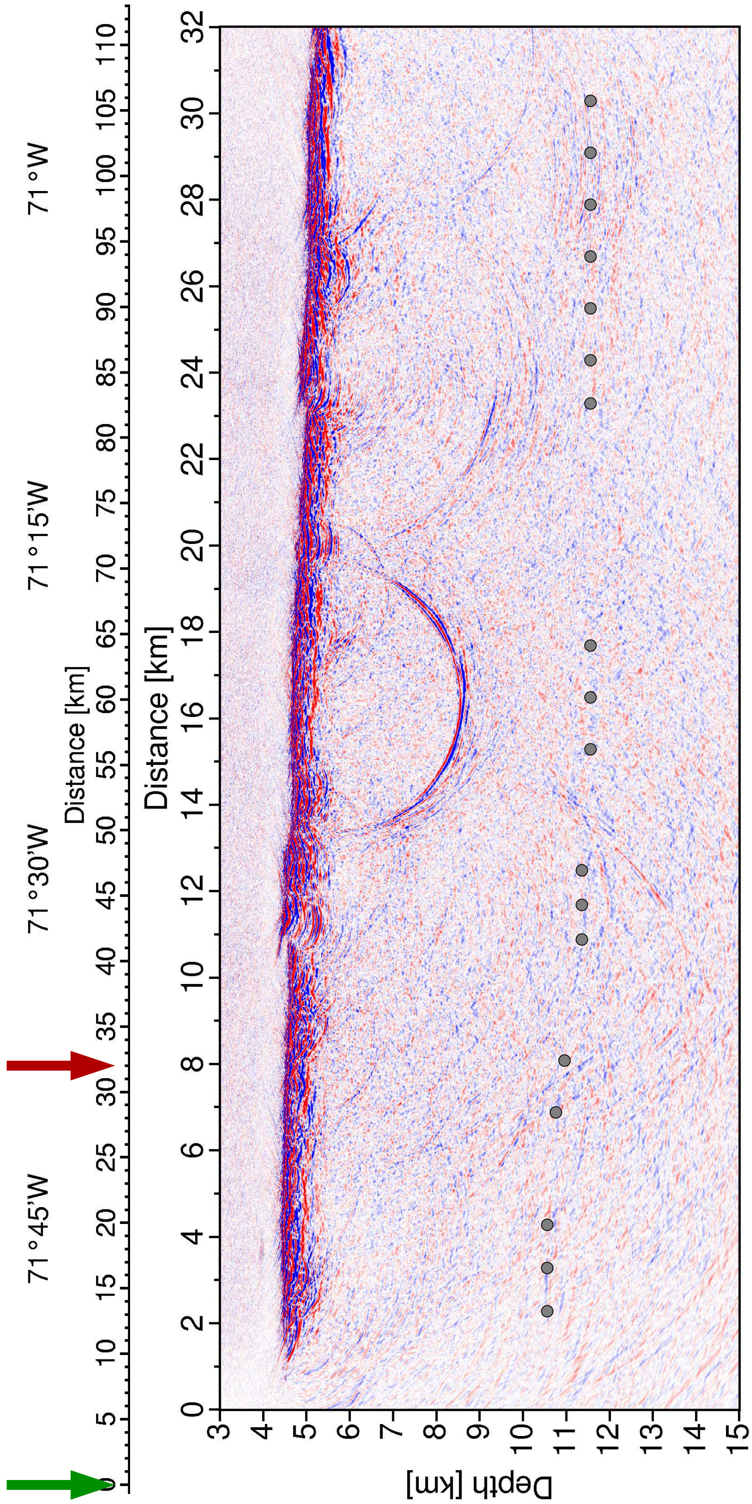


Figure 5.23: Fresnel image of the region between 0 km and 32 km along profile obtained from migration with the wide-angle model. The grey circles mark possible Moho reflections.

5.5 Summary and discussion

In this chapter the results of Kirchhoff Prestack Depth Migration as well as the improved images obtained from Fresnel Volume Migration of line SO104-07 (21°S) and, respectively, of line SO104-13 (23.25°S) were presented. Two different velocity models were used, the IFM-model as an extention of an existing velocity field of the trench and outer forearc region, and the wide-angle model which was obtained by using the seismic boundaries and mean velocities resulting from earlier wide-angle observations. Especially the use of Fresnel Volume Migration provided new and clearer insights into the subsurface of the erosive margin off Northern Chile and revealed many additional structural details.

The influence of the used velocity models on the migration results was discussed since both migration methods require reliable information about the velocity structure in the subsurface. Depth sections obtained from migration with both velocity models showed significant differences. Due to the use of too high velocities in the wide-angle model, migration smiles from a possible reflection were increased and the thickness of the sedimentary layers was overestimated within the resulting images. These observations indicated overmigration. At greater depth, a possible Moho reflection was found, which was not observed in the results obtained with the IFM-model. In order to investigate the upper 1 km - 2 km of the oceanic crust the IFM-model was used whereas the study of deeper features was done with the wide-angle model.

The above presented investigations yielded new interesting information about the structural geometry of the surface and subsurface within the bending zone of the subducting Nazca plate. Also the depth images of the trench region and the continental slope revealed features which are of major interest for the understanding of the processes of an erosive type subduction zone.

The seafloor off northern Chile between 19°S and 26°S is rough and exhibits only a thin sedimentary cover (e.g. Hinz *et al.*, 1995). Besides a small seamount on line SO104-07, the ocean bottom to the west of the trench is dominated by apparent horst-and-graben structures. The frequency of these features increases laterally towards the trench. A comparison of the images of both lines (SO104-07 and SO104-13) has shown that these structures are more pronounced on line SO104-13 with flanks up to 1000 m. Reflection events in the Fresnel images of the region between 33 km and 37 km along line SO104-07 and of the plateau-like structure along line SO104-13 indicated rather thrust faults than normal faults. In other regions along both profiles only a few structures were clearly identified as normal faults. A possible explanation for the existence of those thrust faults might be given by the situation when a horst arrives at the actual subduction zone. Ranero & von Huene (2000) already pointed out that the geometry of erosive margins is strongly connected to the topography of the incoming oceanic crust. They argued that surface structures like seamounts, aseismic ridges or horst and graben structures arriving at the trench indicate a strong coupling between oceanic crust and forearc. This suggests that to a certain degree a subducting horst might block slab pull so that ridge push prevailed and features as the observed thrust faults were generated. The strong coupling also facilitates frontal erosion (Ranero & von Huene (2000)). The frontally eroded and subducted rocks may contain huge amounts of fluid especially when a graben transports part of the slope debris below the overriding plate. These fluids may then be discharged into the boundary between oceanic and continental crust. This results in an increasing pore fluid pressure and thus in a reduction of the friction along the plate interface (e.g. von Huene & Ranero, 2003).

The images of the trench region showed several details of the internal structure of the trench itself as well as of the frontal prism. The strongest reflection event on both lines was interpreted as the upper boundary of the subducting oceanic lithosphere. On line SO104-07 the geometry of the slab is ambiguous. Two reflectors have been observed and both are connected with the subducting slab. The lower reflector might be a result of underthrusting due to the possibly blocking horst-like feature observed directly at the trench. At the seafloor a small sedimentary ridge is located which was associated with the deformation front (von Huene *et al.*, 1999). It is slightly higher on line SO104-13 than on SO104-07. Underneath this ridge within the frontal prism a seaward rotated normal fault system has been observed on line SO104-07. It might be generated by erosion or entrainment of debris within a subducting graben. In contrast, the Fresnel image of the trench region of line SO104-13 illustrated folds directly below the ocean bottom which flatten with increasing depth. Here, nearly vertical reflectors have been found above the intra-plate boundary. They were interpreted as stratified detritus (e.g. von Huene *et al.*, 1999) which fills the downdip graben.

Landward of the trench, all depth sections provided sharp imagery of the position of the upper part of the subducting lithosphere. On both profiles it was observed down to a depth of about 12 km. While in the image of line SO104-07 only one possible subducted horst was present, we found at least three of such features in the images of line SO104-13. These subducted ocean bottom structures coincide with the coupling zone between the plates. With respect to the downgoing plate, the subduction angle in the outer forearc is almost the same on both profiles (about $10-11°$). This value corresponds with further observations from wide-angle seismics (e.g. Patzwahl, 1998).

Within the continental crust, a series of reflectors parallel to the subducted oceanic

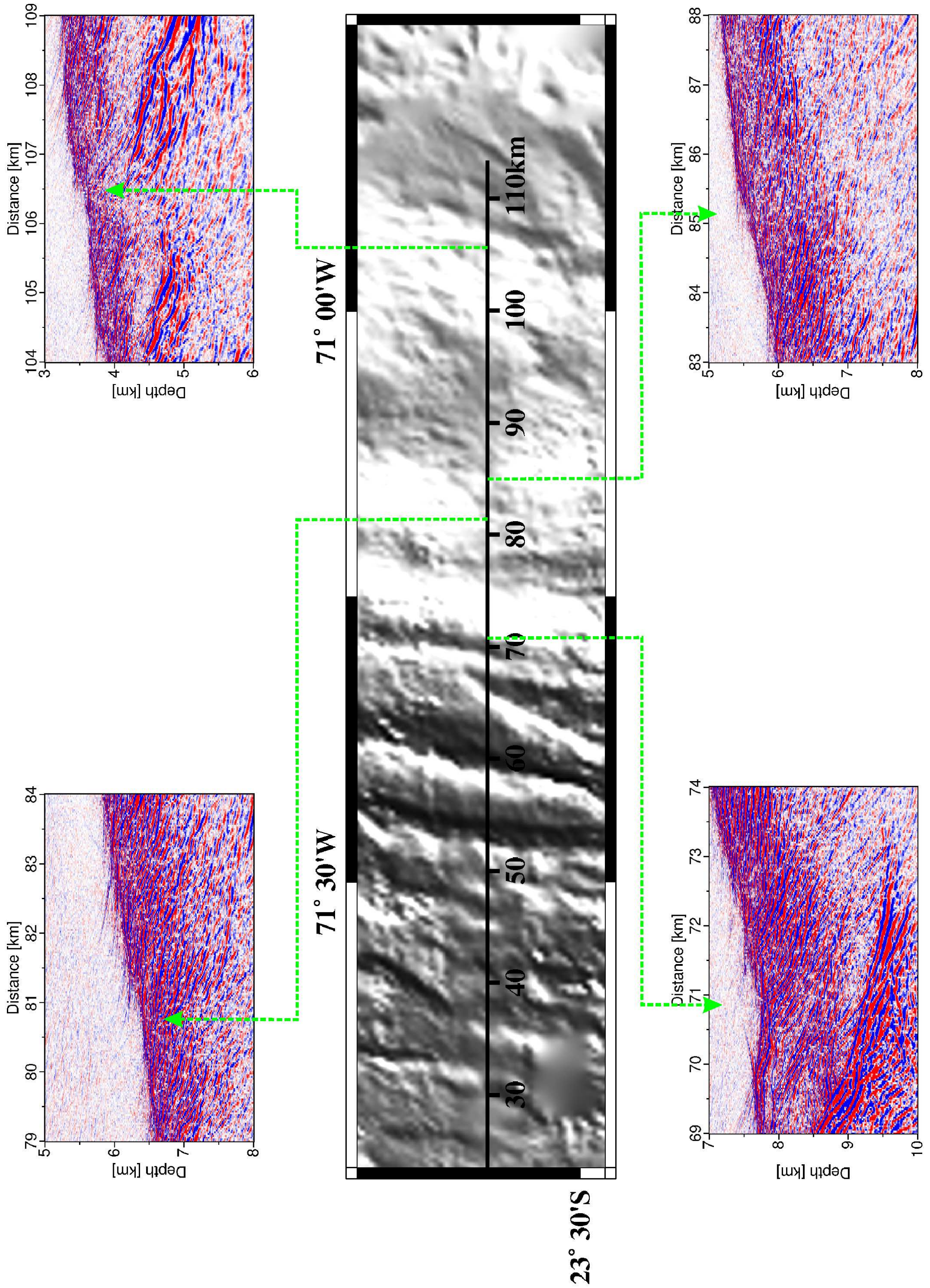


Figure 5.24: Comparison of the escarpments observed on line SO104-13 with the bathymetry. The bathymetry is illuminated by a light source located N-W.

plate was present on line SO104-13. In some cases, these reflectors extend through the continental crust to a depth of about 10 km. Similar features were visible in the depth images of line SO104-07. On both profiles, these faults surfaced at the location of escarpments visible in the continental slope. Figure 5.24 illustrates that the escarpments observed at 71 km, 81km and 85 km but also a seafloor structure at 107 km along line SO104-13 correlate with the bathymetric data. Here, the bathymetry is illuminated by a light source located N-W of the image. Thus the escarpments are marked by the change from dark (or grey) to bright areas but due to the small differences in elevation they map, in some cases, only as weak grey bands within the bathymetry. The plate parallel faults beneath the continental slope might also be generated by the strong coupling between the oceanic crust and forearc. The resulting compressional forces from horst-continent collision possibly caused parts of the overriding plate to move. Due to the latter, and from the fault geometry and from the shape of the escarpments, it can be concluded that they are active thrusts parallel to the plate boundary operating at low strain rates (Sick *et al.*, 2005). The surface is offset, but there is no conspicuous evidence for large displacements from cross-cutting structures or overthrust sediment. Hence, these faults are interpreted to mark the upper part of the subduction channel where material is initially underthrust as large fault-bounded slabs (Sick *et al.*, 2005). A connection between the faults and the plate interface, possibly explains their strong reflectivity due to the infiltration of subducted fluids (e.g. Bangs & Shipley, 1999) or seawater (see Figure 5.25). However, material contrast or a cataclastic fabric are also reasonable interpretations for their strong reflectivity. Similar structures have been observed during sandbox experiments (Lohrmann *et al.*, 2005) and also reflection seismic profiles at other erosive margins revealed comparable structures (e.g. South Sandwich, Vaneste & Larter, 2002).

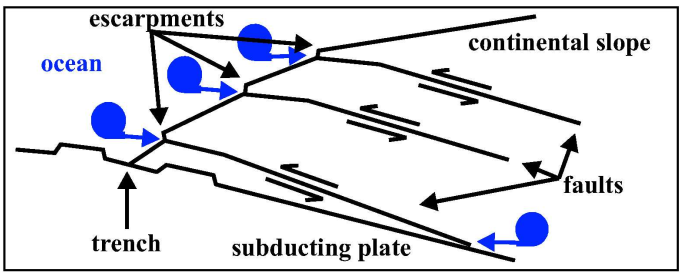


Figure 5.25: Sketch of fluids infiltrating into the plate parallel faults.

Landward rotated blocks, indicated by a normal fault system, are situated between 104 km and 118 km on line SO104-07 bounded by a detachment at a depth of about 5.5 km. Also in the image of the middle continental slope of line SO104-

13, between 100 km and 110 km along profile, a normal fault system was observed which transects the upper continental crust and merges into a slightly landward-dipping detachment. Both, the faults and the detachment are more pronounced on line SO104-13. Here, the detachment and the easternmost plate parallel reflector were interpreted by Salarès & Ranero (2005) as the upper and lower boundary of a low velocity zone. This low velocity zone might be a result of serpentinization of the upper mantle peridotite by water percolating through faults which transect the subducted oceanic crust (Ranero *et al.*, 2003; Ranero & Salarès, 2004).

The use of the wide-angle models revealed weak reflections at the beginning of both profiles at depths between 10 km and 11 km. This depth range corresponds to the expected oceanic Moho depth at about 7km below the seafloor. Earlier investigations of line SO104-13 detected the oceanic Moho further to the east also at a depth of approximately 7 km below the seafloor (Buske *et al.*, 2002).