Geophys. J. Int. (2003) **152,** 185–201

Seismic investigations along the western sector of Alpha Ridge, Central Arctic Ocean

Wilfried Jokat

Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse, 27568 *Bremerhaven, Germany. E-mail: jokat@awi-bremerhaven.de*

Accepted 2002 August 1. Received 2002 August 1; in original form 2001 December 18

SUMMARY

During the summer of 1998 a two-ship experiment with the Russian nuclear icebreaker Arktika and RV Polarstern probed the central part of Alpha Ridge in the High Arctic. In total 320 km of multichannel seismic data were acquired along three profiles supplemented by four sonobuoys. The sonobuoys provided velocity control for the sedimentary sequences and for the upper crust. The sediment velocities range from 1.6 to 2.7 km s^{-1} and the sediment thicknesses vary between 500 and 1200 m. The units lie conformably on the basement. Only minor faulting is visible in the area of Lyons Seamount. In general, the sediments can be divided into two units. Their age is quite hypothetical: the upper unit is most probably to be of Cenozoic and the lower of Cretaceous age. The interpretation of the seismic velocities suggests oceanic basement. The basement velocities range from 4.3 to 6.7 km s^{-1}. In combination with a recovered basalt sample there is little doubt of the oceanic origin of Alpha Ridge, at least in its western sector.

Key words: Alpha Ridge, Arctic Ocean, seismic reflection.

INTRODUCTION

The present-day ice-covered Arctic Ocean hides a large number of geological structures, which are witnesses of past tectonic activities. They have been formed during the geological history of the Arctic Ocean from the Mid-Cretaceous to the present. Depending on its age and evolution the Arctic Ocean is divided into two basins, the Eurasian and Amerasian. The Cenozoic spreading along the Gakkel Ridge explains the opening of the Eurasian Basin and formed the margins between the Barents and Siberian continental margins and the Lomonosov Ridge. In contrast, the Amerasian Basin was formed by seafloor spreading during the Mesozoic. However, detailed information on the nature and the age of the Amerasian Basin and its subbasins (Canada and Makarov basins) and ridges (Alpha and Mendeleev ridges) is not available. As far as it is known, the oldest Arctic deep-sea basin (Canada Basin) was formed in the Cretaceous by seafloor spreading (Vogt *et al.* 1982; Grantz *et al.* 1998). During or after the opening of the Canada Basin, the Alpha-Mendeleev Ridge complex and the Makarov Basin formed. Investigators have suggested that this blocky ridge may be: (1) of continental origin; (2) a former spreading centre; (3) a result of 'hotspot' activity; and (4) a former region of subduction or compression (Sweeney *et al.* 1978; Vogt *et al.* 1984; Jackson & Johnson 1985; Jackson *et al.* 1990; Pogrebitsky *et al.* 1993; Lawver & Müller 1994). The width of Alpha Ridge ranges from 250 to 800 km. In bathymetric cross-sections it is roughly symmetrical with greatest elevation at the centre (Jackson *et al.* 1986). In areal extent it exceeds the European Alps. Today Alpha Ridge is the largest single submarine feature in the Arctic Ocean, for which the geological origin is still unknown. The evolution of the ridge complex in relation to the opening of the Canada Basin has had profound consequences for Arctic geodynamic models. Currently, models in which Alpha Ridge represents a former spreading centre or 'hotspot' trail are favoured.

The reason for such divergent models is the sparse and insufficient geophysical and geological data base. The Alpha Ridge region is by far the most remote area in the Arctic for surface ships. Owing to the extremely difficult ice conditions limited geoscientific data have been acquired in the past. In 1998 a renewed effort was launched to acquire geoscientific information in order to enhance the understanding of the origin of Alpha Ridge. In contrast to previous expeditions, which used large ice floes as a platform, the Arctic-98 expedition was the first attempt to reach Alpha Ridge directly with surface ships. Owing to heavy ice conditions the German RV 'Polarstern' and the Russian nuclear icebreaker 'Arktika' operated in a convoy (Jokat *et al.* 1999; Jokat 2000). While the research programmes were concentrated on RV Polarstern, the more powerful Russian ice breaker sailed ahead to guarantee easy and fast progress in the ice, especially for the seismic experiments based on RV 'Polarstern'. The geophysical programme was designed to resolve the sedimentary structure and its velocity distribution along Alpha Ridge and to discover areas, where Mesozoic sediment/basement samples could be retrieved with conventional gravity coring devices. During the Arctic-98 expedition it was possible to acquire two multichannel seismic (MCS) profiles along Alpha Ridge and one line parallel to the northern slope of the ridge (Fig. 1). Thus, the new data allow insights into the ridge fabric in its western part.

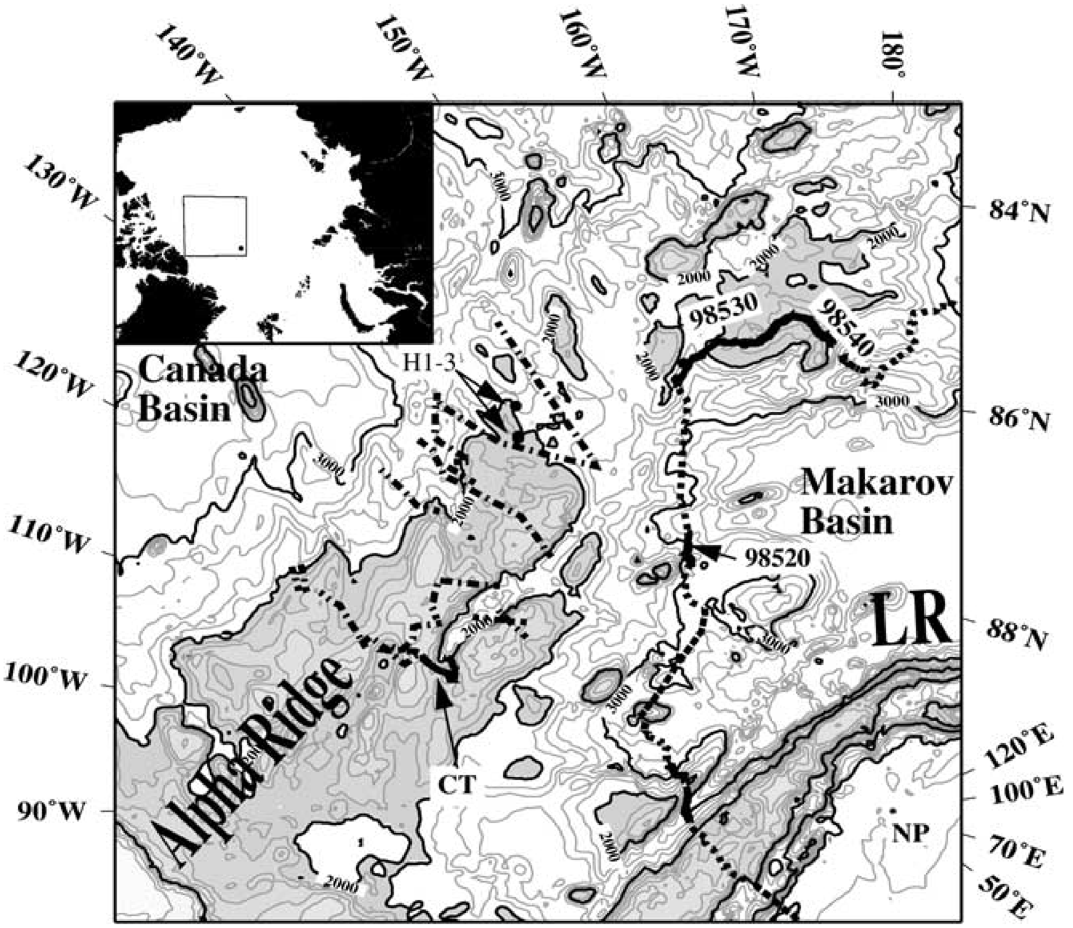
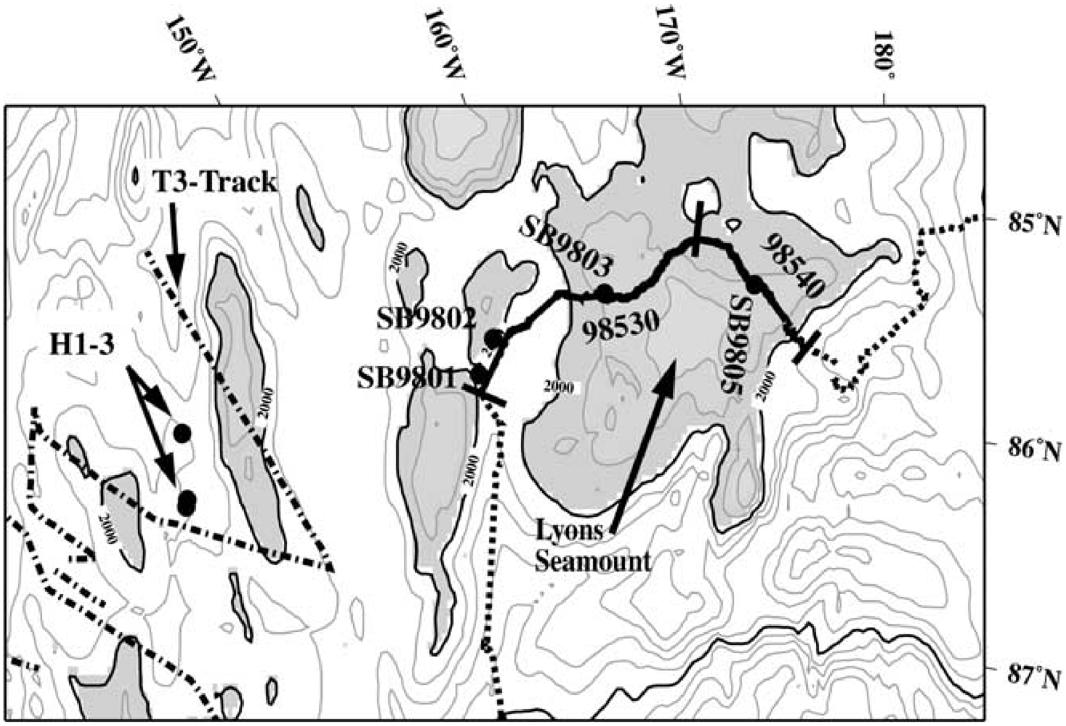


Figure 1. (a) Location of seismic profiles 98520 to 98540 (bold lines). The box in the inset shows the location of this chart within the Arctic Ocean. The seafloor topography (contoured in 200 m) is taken from the new Arctic bathymetry grid (Jakobsson *et al.* 2000). The grey-shaded areas indicate water depths shallower than 2000 m. The dotted line indicates the cruise track of the Arctic-98 cruise (1998 June 27–July 27); the dashed-dot-dashed line shows the drift paths of the T3-ice island across Alpha Ridge; CT, drift pattern of the CESAR experiment; H1–3 soundings performed by Hunkins (1961); NP, North Pole; LR, Lomonosov Ridge. (b) Enlarged part of Fig. 1(a) with the track of the ship (dotted line). The start and end of the profiles are marked by lines perpendicular to the track. The grey-shaded areas indicate water depths shallower than 2000 m. Dots indicate the position of sounding spots (H1–3) of Hunkins (1961) and the position of the sonobuoys (SB9801-05) deployed during the Arctic-98 experiment. A bold line marks the end/beginning of lines 98530 and 98540. The bathymetry is contoured in 200 m intervals (grey lines) and the 1000 m isobaths are labelled.

EXISTING GEOPHYSICAL AND GEOLOGICAL INFORMATION

The first geoscientific experiments were carried out from scientific ice stations operated by US and Canadian institutions. The ridge was discovered by the US ice station Alpha (Hunkins 1961), during its drift in the years 1957–1958, which acquired the first information on the topography of the ridge and sedimentary thickness. 'Vertical reflection soundings were made daily during the winter and twice daily during summer. As the average drift of the floe was 6.5 km d^{-1}, these soundings were spaced from 1.8 to 7 km apart along an irregular track. For the reflection shots, 0.11 kg charges of dynamite were exploded at a depth of 3 m below the water surface' (Hunkins 1961). No detailed sediment velocities could be calculated from the experimental set-up. The largest single-channel seismic data set was gathered during the drift of the US ice station T-3 from 1967 February to 1970 June (Hall 1973). The sound source was a 9000 J sparker suspended 8 m below the sea ice. Two hydrophones 4 m below the sea ice and approximately 25 m away from the source recorded the data. During the T-3 ice drift approximately 4000 km of seismic profiles were acquired in the Amerasian Basin. According to published line drawings by Hall (1973) a subset of approximately 1700 km is located on the Alpha Ridge between 150°W and 110°W (Fig. 1). The other data were acquired across the Mendeleev Ridge and in the adjacent basins. The line drawings indicate a sediment thickness between 500 and 1000 m across Alpha Ridge. The Canadian Expedition to Study the Alpha Ridge (CESAR; Jackson *et al.* 1985) in 1983 acquired approximately 90 km of single-channel seismic data during its 40 d drift (Fig. 1). Here, a small airgun (0.655 l) fired every 5 min was used as a sound source. The shot spacing was irregular because of the variable drift speed of the ice floe. The seismic reflection data indicate the presence of a thin sedimentary cover with an estimated thickness of only 500 m. To calculate sediment thickness a mean seismic velocity of 2.0 km s^{-1} was assumed by the investigators.

In summary, the existing single-channel seismic reflection lines acquired from ice stations Alpha, T-3 and CESAR (Hunkins 1961; Hall 1973; Jackson *et al.* 1985) show that Alpha Ridge is mainly



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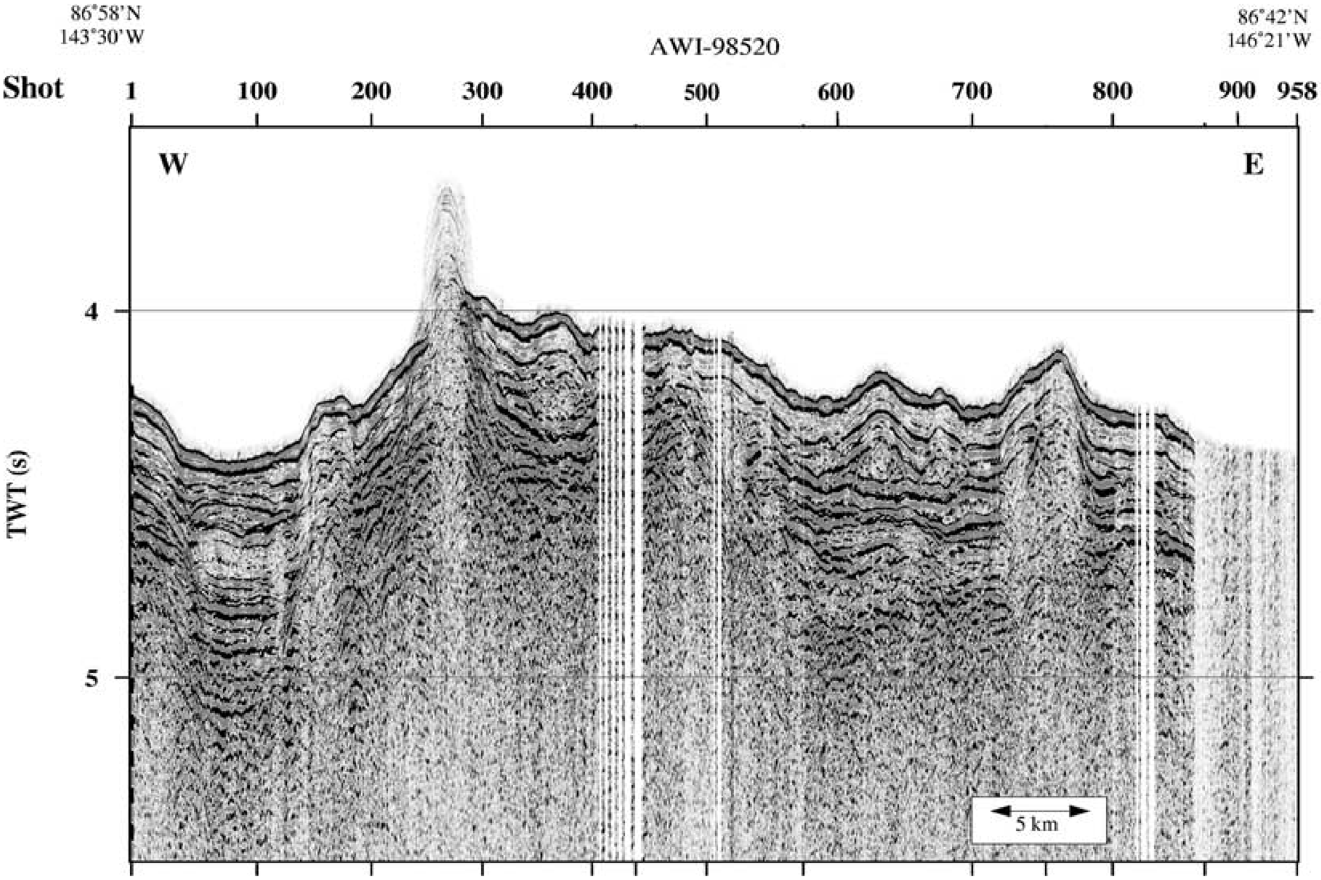


Figure 2. Seismic reflection profile 98520 over the northern slope of Alpha Ridge. The vertical white areas in the section are very noisy stacked traces and have been deleted. Here, the streamer was towed across the ice. At the end of the line (shot point 900) both ships stuck in the ice and the noise is higher than the seismic signals.

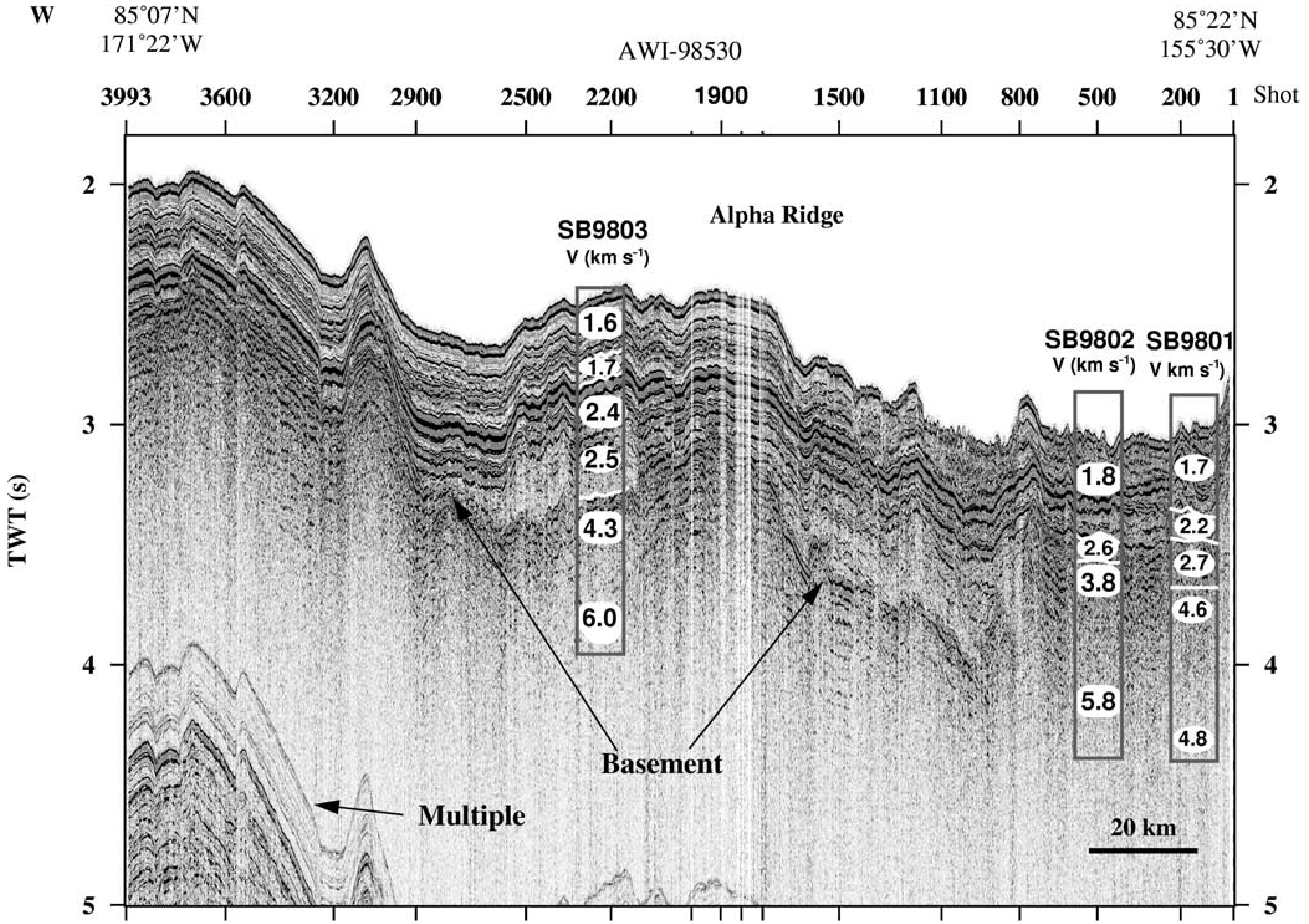
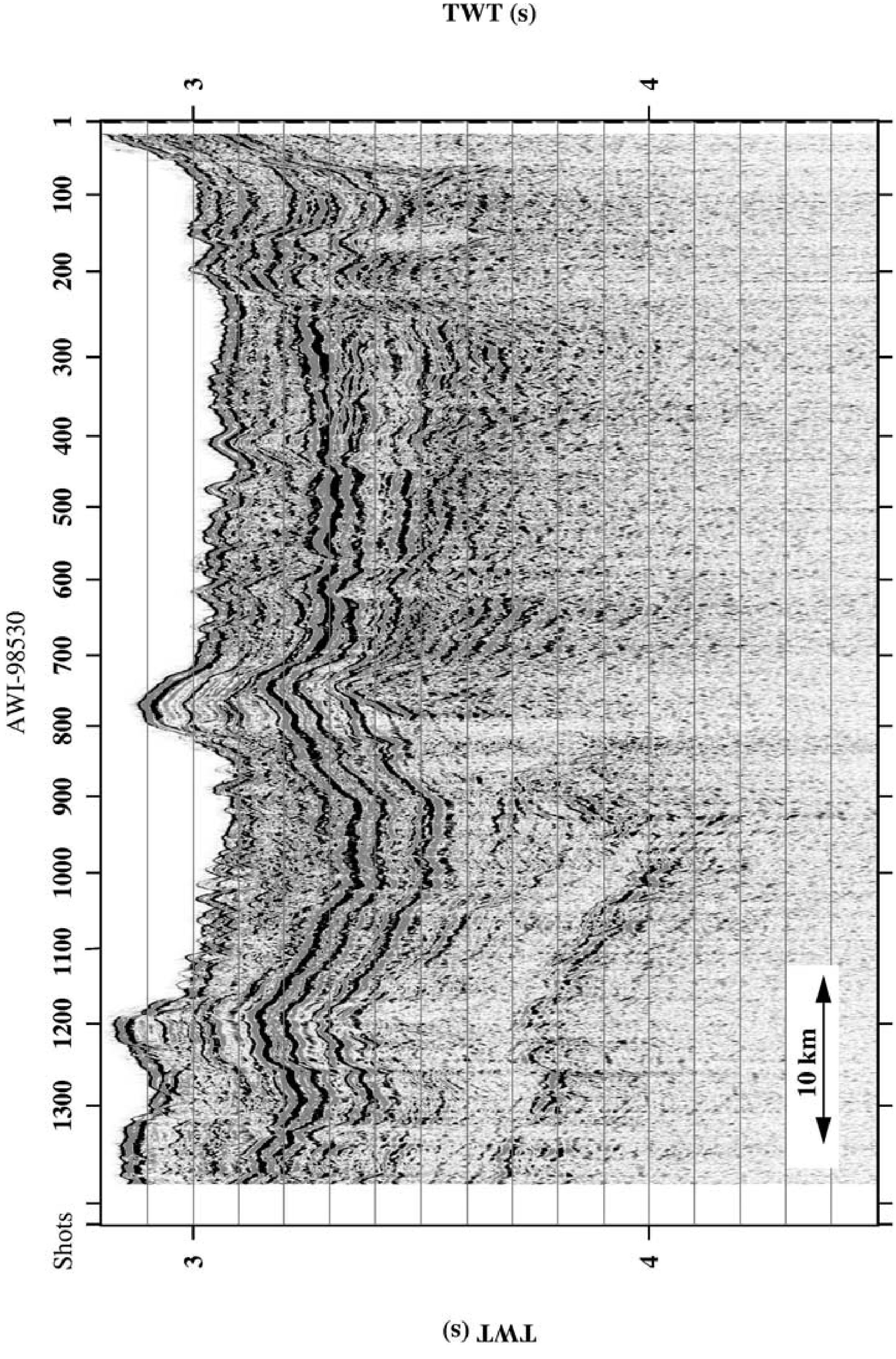


Figure 3. (a) Seismic reflection profile 98530 along the crest of the westernmost part of the Alpha Ridge with the results of the sonobuoy modelling. (b) Enlarged portion of the beginning of profile 98530 showing the poor resolution of the sediment–basement boundary. (c) Enlarged portion of profile 98530 in the area of Lyons Seamount. Note the faulting of seismic layers.



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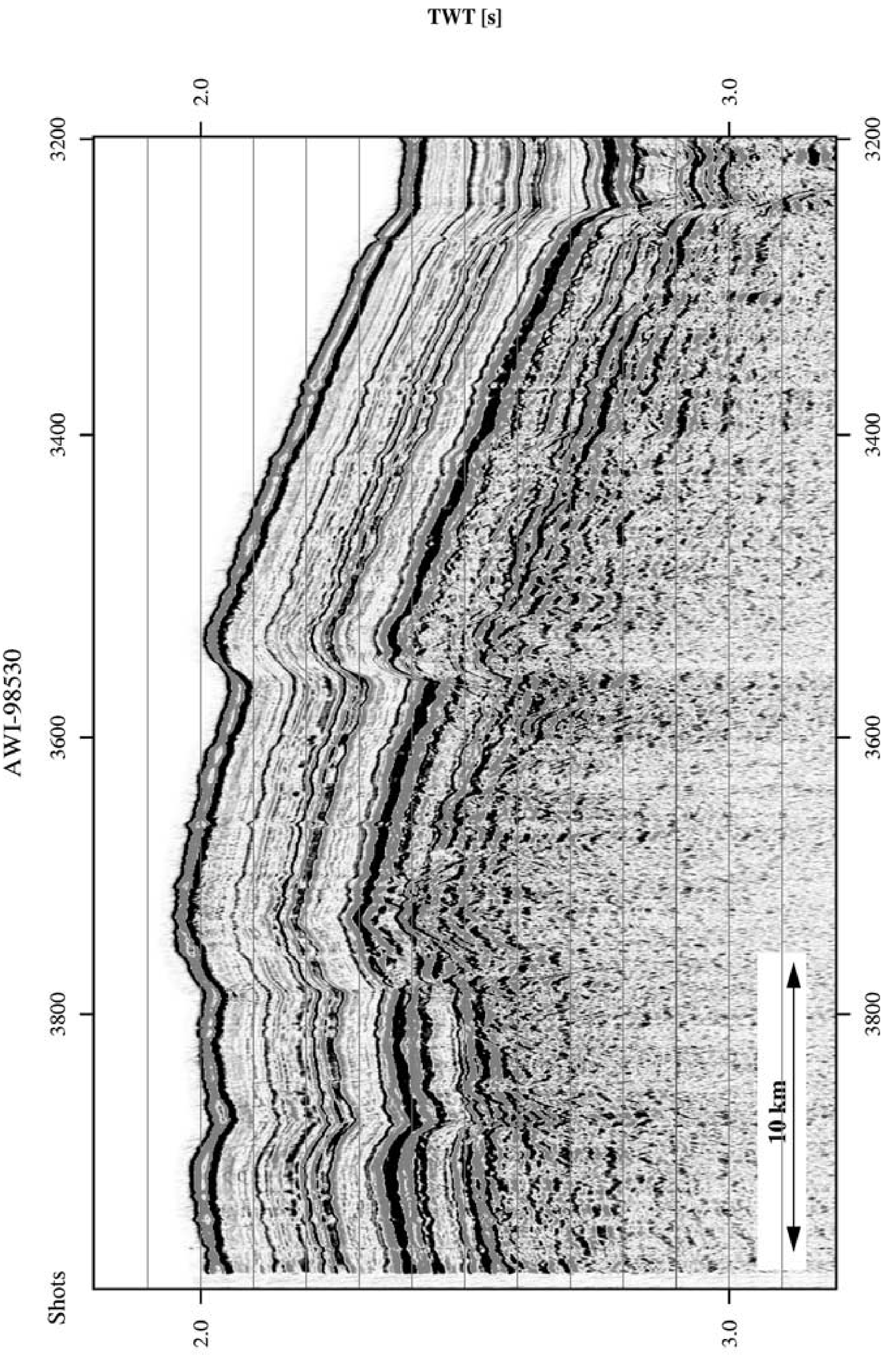

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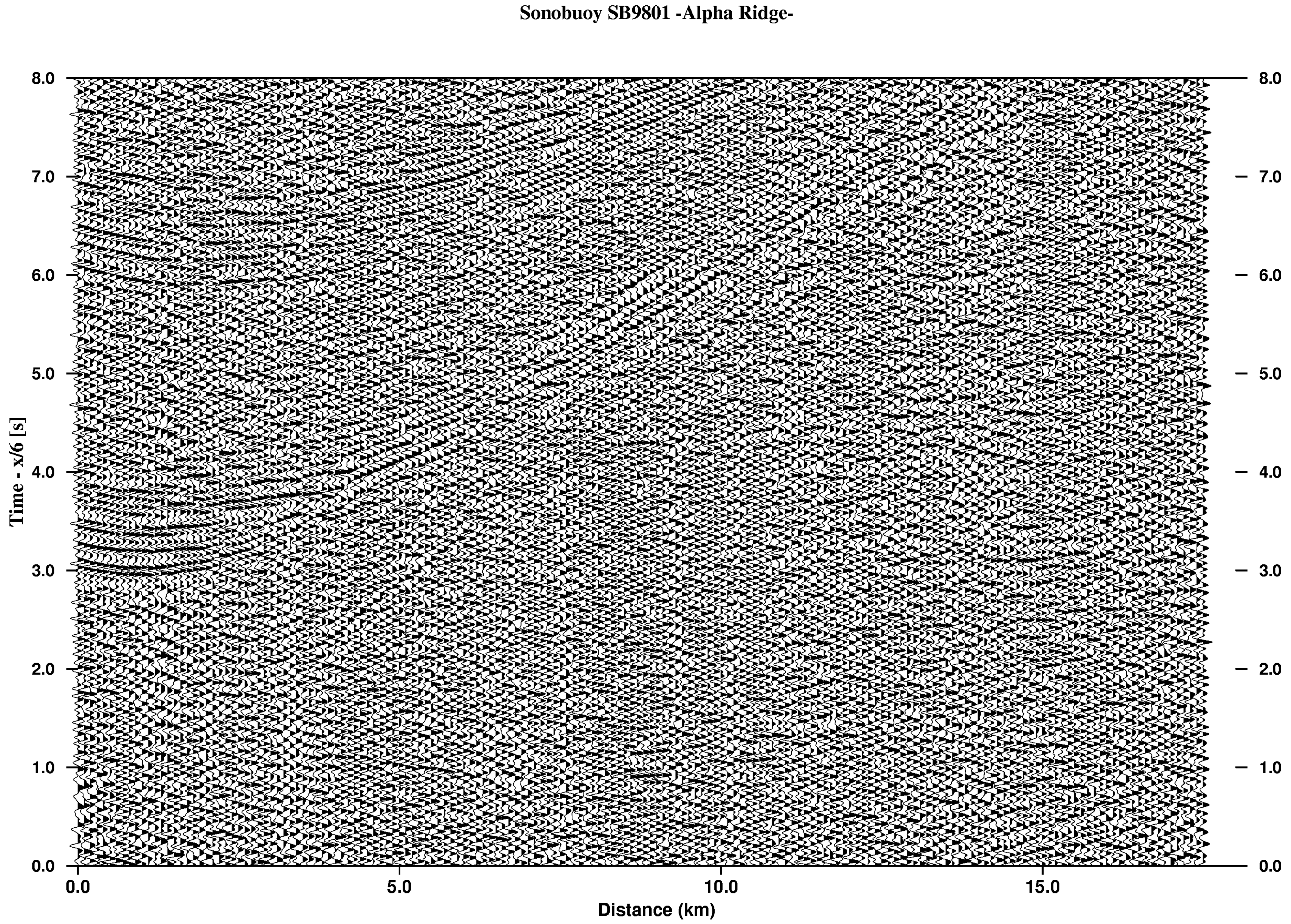

Figure 4. (a) Sonobuoy SB9801 at 85°19.8′N 155°45′W displayed with a reduced traveltime of 6 km s^{-1}. It has the worst data quality of the buoys shown here. The data processing is limited to a frequency filter (6–15 Hz) and an automatic gain control (AGC) with a 0.3 s window. The arrows indicate the weak refraction arrivals picked for the velocity modelling. (b) Picked traveltime data and the ray tracing results for SB9801 are shown. Reflected arrivals from the seafloor and the base of the sediments are modelled. A linear velocity gradient is assumed between both interfaces. The refracted waves have a velocity of $\geq$4.6 km s^{-1} and might indicate oceanic basement. For more details see fig. 9.

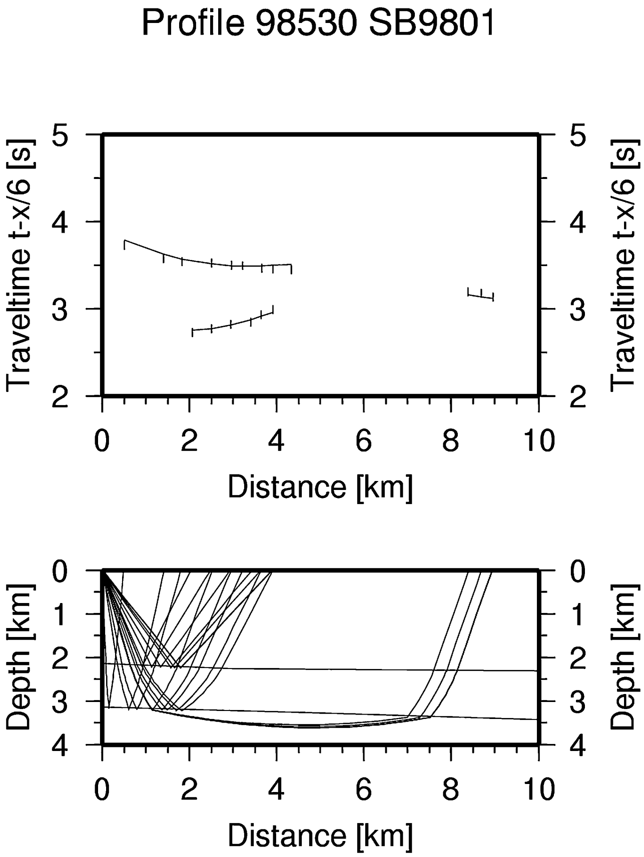

Figure 4. (*Continued.*)

covered by a sedimentary sequence that can reach up to 1000 m in thickness. Along most of the profiles the sediments lie conformably on the basement.

Hunkins (1961) conducted the first seismic refraction measurements across Alpha Ridge. The experiments were performed at three locations on the ridge during the drift of station Alpha in 1958 (Fig. 1). A geophone array and explosives were used. Hunkins (1961) reported the presence of a 4.7 km s^{-1} velocity layer at approximately 85°N 138°W. At two locations seismic velocities of 5.5 and 6.4 km s^{-1} were observed. The short and unreversed refraction lines indicate an average of 380 m of unconsolidated sediments, covering a 2.8 km thick layer of 4.7 km s^{-1} that overlies a 6.4 km s^{-1} 'oceanic' layer of undetermined thickness (Hunkins 1961). However, the experimental set-up was not designed to give information on the deeper crustal structure. This was one goal of the CESAR expedition in 1983. Three reversed seismic refraction profiles with a total length of 700 km and offsets of up to 200 km were acquired across the eastern part of the ridge. Upper crustal velocities of 5.2 km s^{-1} underlain by layers with seismic velocities of 6.4 and 7.1 km s^{-1} were calculated from the data (Forsyth *et al.* 1986a,b). Forsyth *et al.* (1986b) interpreted this velocity structure as being similar to oceanic plateaux (Carlson *et al.* 1980). The seismic velocity of the layer below ranged from 6.45 to 6.8 km s^{-1} and at a depth of 20 km a velocity of 7.3 km s^{-1} was measured. The depth of the crust–mantle boundary is 23 km at the flanks and 38 km in the crestal area. Sedimentary layers could not be resolved by the experimental set-up (Forsyth *et al.* 1986b).

The most important and complete data sets for unravelling the geological history of the ridge are aeromagnetic and aerogravity data acquired by US and Russian researchers. The magnetic data across the Alpha Ridge indicate the presence of mostly irregular magnetic anomalies up to 2000 nT. No clear evidence of magnetic seafloor spreading anomalies has been obtained. Based on the existing geophysical data various researchers suggested that the ridge must have been formed during the Cretaceous positive polarity chron from 124 to 83 Ma, if the irregular magnetic anomalies are caused by oceanic basalts (Vogt *et al.* 1984; Weber 1986; Jackson *et al.* 1986; Laxon & McAdoo 1994). This model is supported by bottom samples. At three locations Cretaceous and Early Cenozoic sediments were recovered from Alpha Ridge (Kitchell & Clark 1982; Bukry 1984; Clark & Byers 1984; Mudie & Blasco 1985). Dredged material recovered by the CESAR expedition from the elevated basement provided a fragmented and weathered alkaline volcanic rock (Van Wagoner & Robinson 1985). Dating of the sample was not possible. Thus, no direct information on the age of the Alpha Ridge basement exists.

EXPERIMENTAL SET-UP

At least one crossing perpendicular to Alpha Ridge was planned to obtain a first view of its general fabric in the investigated area. However, ice conditions and time limitations did not allow crossing the Alpha Ridge from the Makarov Basin into the Canadian Basin. Consequently, the research area was shifted to the western segment of the ridge between 160°W and 170°W, where most of the sampling and seismic profiling was concentrated (Jokat 2000). The three profiles 98520–98540 are located on the crest of the ridge and along its northern flank (Fig. 1a). All lines were acquired in 10/10 ice coverage sailing in the track of the leading ice breaker. Problems acquiring seismic data only arose during pressed ice conditions, which occurred several times during this leg. In total 320 km of multichannel seismic profiles were collected in the area of Alpha Ridge. At the beginning a 500 m streamer with an active length of 300 m (48 channels) was used. After it became caught in an ice press close to the Barents Shelf, two streamer sections were lost. For safety reasons the streamer was shortened to 400 and later to 350 m (32 channels). The seismic source was a 24 l airgun cluster (Jokat *et al.* 1995a) mounted on a steel frame. Although the frame was dragged several times over ice floes only minor damage to the airguns occurred. In parallel with the acquisition of seismic reflection profiles sonobuoys were deployed to record more accurate velocity information from the sedimentary subsurface.

For an accurate stack all seismic data were CDP sorted. The bin size is 25 m for all profiles. First-order velocity analyses were performed every 5 km only in areas where the water depth was less than 1000 m. In deeper areas stacking was conducted only to enhance the signal-to-noise ratio. Dead traces were removed and editing of noisy traces arising from streamer–ice floe interactions was kept to a minimum. Detailed investigations of the processing of Arctic seismic data (Jokat *et al.* 1995a) have shown that applying a median stack is, in most cases, as effective as detailed editing of each CDP in removing that type of random noise. Standard processing techniques such as frequency and coherence filtering as well a trace mixing were applied to further reduce the noise level.

Another problem is the varying depth of the streamer. The icebreaker carrying the seismic gear cannot maintain a constant speed even in the wake of the stronger icebreaker. There are always situations when the leading ship has to break through an ice ridge so that the following seismic vessel has to reduce its speed. In this case the streamer sections may sink to well below 50 m. Changes in speed of the seismic vessel are indicated by a varying time between the seafloor reflection and its ghost signal. Stacking such data produces

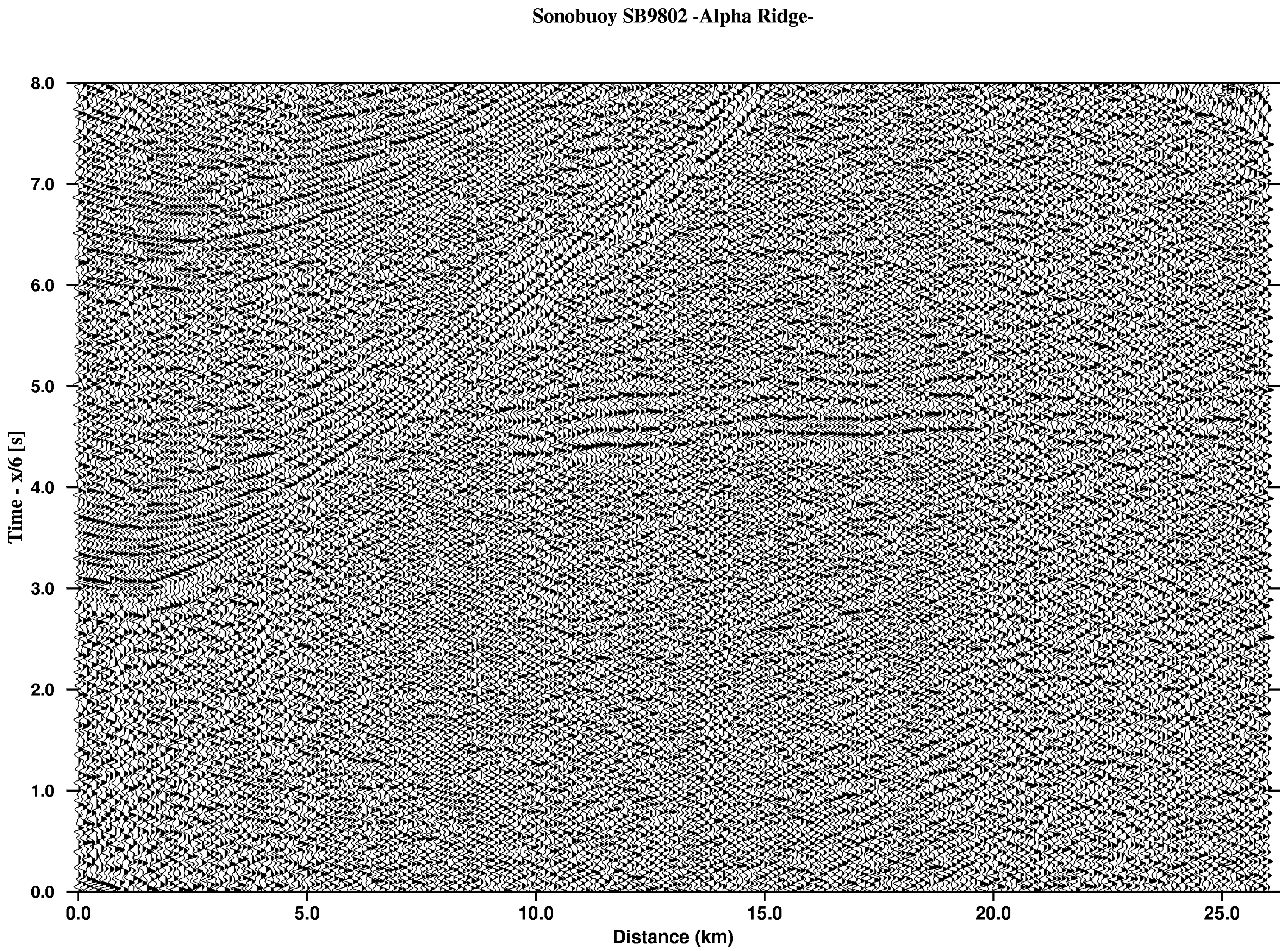

Figure 5. (a) Sonobuoy SB9802 at 85°12.4′N 157°10.3′W displayed with a reduced traveltime of 6 km s^{-1}. The data are bandpass filtered from 6 to 15 Hz and an AGC with a 0.3 s window is applied. The data quality is significant better than SB9801 and the record section shows clear refracted signals from the basement. (b) Picked traveltime data and the ray tracing results for SB9802 are shown.

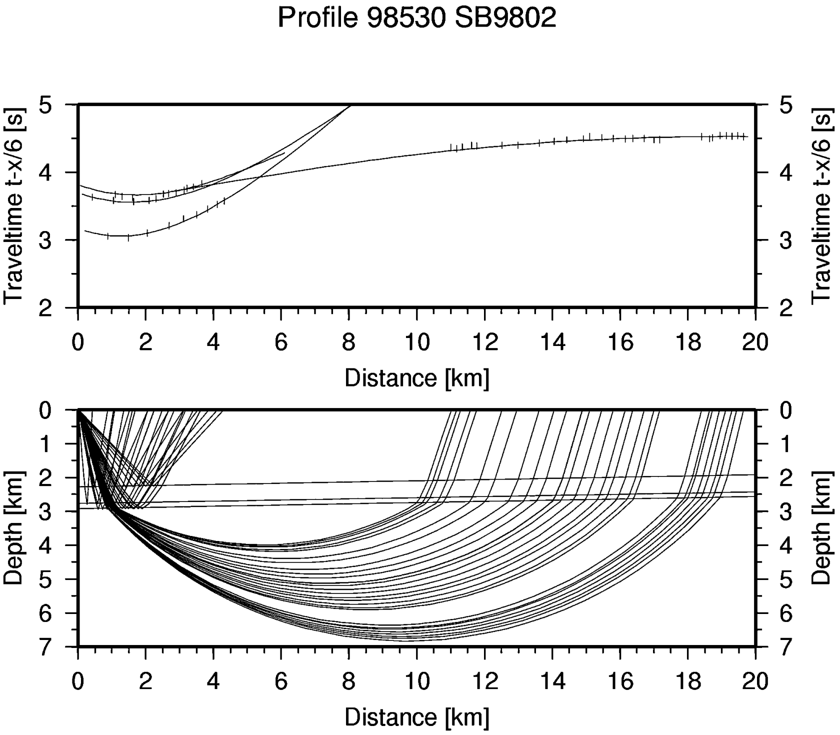

Figure 5. (*Continued.*)

bull-eye-like features. Radical editing of such signals produces a lot of gaps in the seismic section and makes the deeper part of the section difficult to read. Deconvolution techniques were applied with minor success as the signal–ghost distance varies almost with every shot. Therefore, such parts of the profile were accepted as possibly showing only ice-induced noise.

MODELLING PROCEDURES AND ERRORS

Velocities for the sediments were calculated from the reflection hyperbolae recorded by the sonobuoys, which were analysed up to 6 km offset. Interval velocities were calculated using the Dix formulae. Seismic velocities greater than 4.0 km s^{-1} generated refracted signals. Traveltime branches of refracted signals from upper crustal levels are visible on the recordings between 6 and 7 km offset onwards.

No reflections from these levels are observed in the record sections. The traveltime curves from a crustal basement show smooth gradients rather than distinct layering. The velocity–depth functions were modelled by 2-D-ray tracing (Zelt & Smith 1992). Both, reflected and refracted arrival times were inverted. Errors of 50 ms, and exceptionally 100 ms, for the traveltime picks are taken into account. As the topography of the seafloor and the geometry of the sediment units are known from the seismic reflection data true dips were used for the ray tracing model. However, the depth model was kept simple because of the track of the non-linear ship and the data quality. An important criterion for the reliability of the calculated distances was to check the traveltime of the signals that travelled within the water column. The direct wave in the water column did not deviate significantly from a straight line on the sonobuoy record sections presented here. This means that the buoy did not move a considerable distance parallel to the line during the data transmission of 2–3 h. However, the seismic reflection profiles acquired in parallel provide a good structural control for the modelling. This information is incorporated into the ray tracing models. Since the profiles are unreversed and the sonobuoys drifted during the recording with unknown speed and direction a detailed analysis of the errors of the seismic velocities is not possible. The residual rms errors are 0.049 s for SB9801 (15 data points), 0.109 s for SB9802 (50 data points), 0.052 s for SB9803 (42 data points) and 0.052 s for SB9805 (35 data points). The overall error in calculating the seismic velocities is estimated to be ±0.2–0.3 km s^{-1}. In some cases it might exceed these values for a short portion of the traveltime branch (e.g. SB9805).

RESULTS

Line 98520

The line is 82 km long and is located over the northern flank of Alpha Ridge between 86°58′N 143°30′W and 86°42′N 146°21′W (Figs 1a and 2). It is almost parallel to the axis of the ridge. The signal quality is rather poor owing to the very thick sea ice. The seafloor is quite uneven, which is clearly related to the basement topography (Fig. 2). The sediments are up to 0.5 s TWT thick (approximately 500 m) (Fig. 2, shots 1–200, 600–700). Note that a broad reflector is visible at approximately 4.5 s TWT (Fig. 2, shot 700), which is also identified on the other two profiles. Since the basement is not very well imaged and no sonobuoys were successfully deployed along this line, no detailed information on the velocities and basement origin is available.

Line 98530

The longest profile 98530 (192 km) was acquired along the strike of the crest of the ridge at its western end (Figs 1 and 3a). Three sonobuoys (Figs 4–6) were deployed. They provided useful seismic

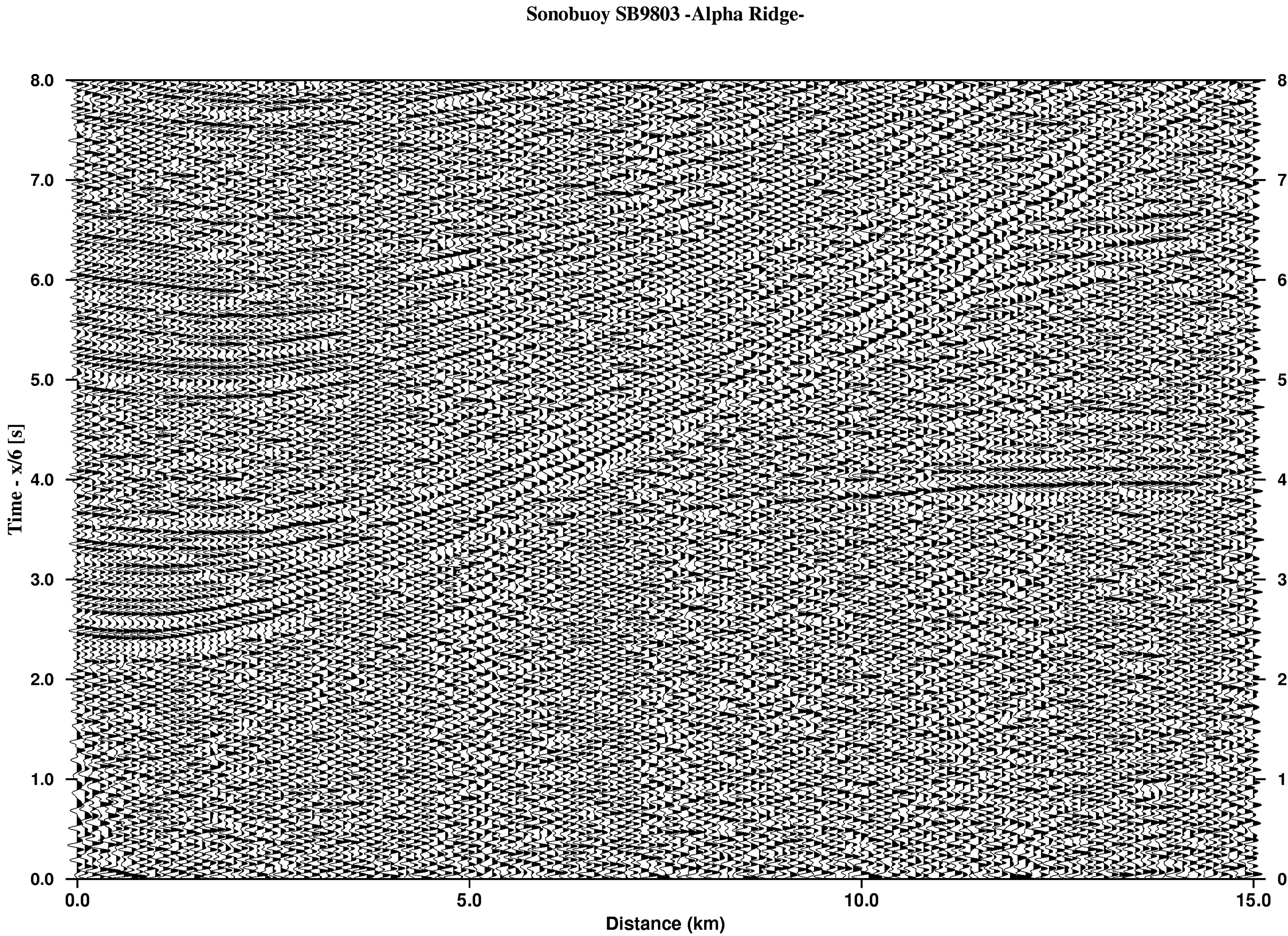

Figure 6. (a) Sonobuoy SB9803 at 85°12′N 164°22′W displayed with a reduced traveltime of 6 km s^{-1}. The data are bandpass filtered from 6 to 15 Hz and an AGC with a 0.3 s window is applied. (b) Picked traveltime data, ray tracing results for SB9803 are shown.

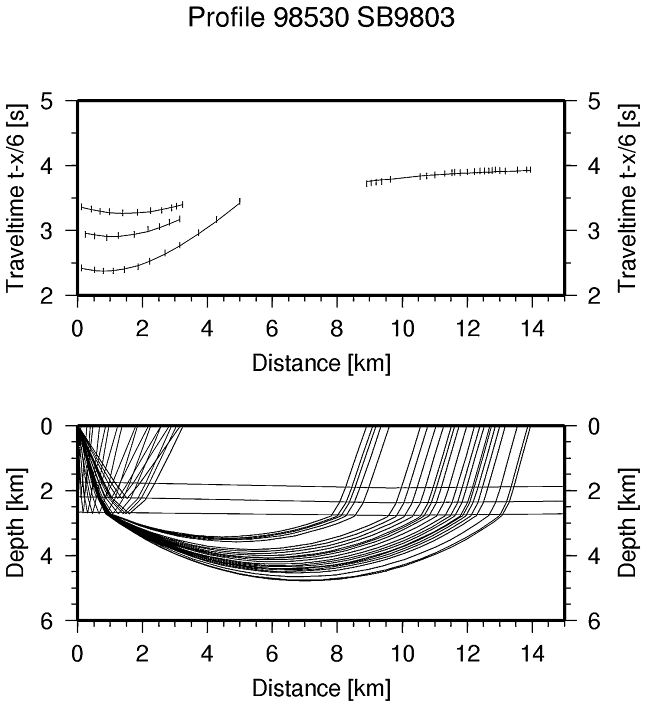

Figure 6. (*Continued.*)

signals up to a maximum offset of 20 km. At the beginning of the profile the seismic reflection profile shows a rough seafloor topography (Fig. 3b, shots 1–1200), which is most probably caused by strong currents across the ridge crest. In this part of the profile the basement signal is lost or very poor (Fig. 3b, shots 1–700). Looking at the more detailed bathymetry in Fig. 1(b) it is clear that the first part of the profile is located in a valley between two basement highs. Therefore, a channelling of currents along this valley is quite likely, if the bathymetry is correct. Further to the west the topography is smoother and shows few variations. The sediments lie conformably on the basement and are between 0.5 and 1.0 s TWT (Figs 3a and c) thick. They gradually thicken towards the east where they reach their maximum thickness of 1200 m. In the west, the sediments are affected by faulting (Fig. 3c, around shots 3200 and 3900), which might be evidence of ongoing weak extension in this area.

Sonobuoy SB9801 (Fig. 4) recorded visible seismic signals up to an offset of approximately 10 km. The analysis of the reflection hyperbolae reveals *P*-wave velocities of 1.7–2.7 km s^{-1} for the sediments. The weak refracted signals at 6 and 9 km offset have velocities of 4.6–4.8 km s^{-1}. Later arrivals cannot be identified. Similar velocities are derived from the record section of sonobuoy SB9802 (Fig. 5). Seismic refraction arrivals can be observed to an offset of 20 km. Interval velocities of 1.8–2.6 km s^{-1} are calculated from the reflection hyperbolae for the sediments. The refracted arrivals have velocities of 3.8–5.8 km s^{-1} (6–20 km offset). It is likely that the velocity of 3.8 km s^{-1} indicates the presence of sediments. The transition from sediments to basement beneath SB9802 is not well resolved either in the seismic reflection or wide-angle data. Sonobuoy SB9803 (Fig. 6) shows strong signals up to offsets of 15 km. Seismic velocities of 1.6–2.5 km s^{-1} are calculated from the reflection hyperbolae for the sedimentary layers. Upper crustal arrivals with velocities of 4.3–6.0 km s^{-1} are visible from 6 to 15 km offset. The sediment thickness varies for the three sonobuoys from approximately 1200 m (SB9801), 1000 m (SB9803) to 700 m (minimum estimate for SB9802).

Line 98540

Line 98540 (Figs 1 and 7) was acquired perpendicular to the ridge. The sediments thin towards the northeast. An escarpment of 800 m is present at approximately 85°30′N 175°W (Fig. 7, shot 1200). Gravity coring recovered several basalt samples from the slope of that escarpment (Jokat *et al.* 1999). North of it the basement becomes more rugged. Pockets are filled with faulted sediments at their base. Two sonobuoys were deployed, but only one of them recorded reasonable signals up to 25 km offset (Fig. 8). Velocities of 1.9, 2.0, 4.4 and 6.7 km s^{-1} are modelled from the recorded section. The velocity structure, however, remains homogeneous compared with line 98530. The existence of the 4.4 km s^{-1} refraction arrival fits very well with the top of basement reflection in the seismic reflection data. It is interpreted as representing the oceanic crust. The sediment thickness is approximately 800 m.

DISCUSSION

The new seismic data allow an unprecedented view of the sediments and upper crustal structure of Alpha Ridge. The velocity structure of the sediments is well resolved and can be directly correlated with the seismic reflection data acquired in parallel. The combined interpretation of wide and steep angle data show that the velocity of the upper part of the basement varies between 4.3 and 4.6 km s^{-1} in the area investigated (Fig. 9). The refraction traveltime curves of the sonobuoys confirm the seismic velocities reported by Hunkins (1961). The minimum distance between SB9801 and the soundings of Hunkins (1961) is 160 km. The velocity structure, at least for the upper part of the acoustic basement, seems to be similar for both data sets. The sonobuoy data show that the sediment thickness along the ridge varies between 800 and 1200 m. The seismic velocities of the sediments vary between 1.6 and 2.7 km s^{-1}, while the basement is characterized by seismic velocities of 4.3–4.6 km s^{-1} in its upper part. At deeper levels traveltime branches with seismic velocities of 4.8–6.7 km s^{-1} are identified. Higher velocities such as 6.0 and 6.7 km s^{-1} are not well constrained as they occur at the very end of the unreversed record section. However, all velocities higher than 4 km s^{-1} are interpreted to represent the uppermost basaltic layer of oceanic crust (Fig. 9). Sonobuoy SB9802 has not clearly imaged the top of the oceanic crust. On SB9802 the first identified basement-like velocity is 3.8 km s^{-1}, but it cannot be correlated with a basement reflection in the multichannel data.

A comparison with the CESAR seismic refraction results is difficult as that experiment was designed to resolve deep crustal structures. However, all sonobuoys show velocities of between 4.3 and 6.0 km s^{-1} for the upper part of the basement. Within the errors and the different experimental methods this layer coincides with the upper crustal layer of 5.1–5.2 km s^{-1} found on the CESAR records. Velocities higher than 6.0 km s^{-1} are not observed with great confidence. This is caused by the limited offsets of the Arctic-98 experiment.

In total more than 4000 km of seismic reflection profiles were recorded from several US ice stations (Hunkins 1961; Hall 1973) and the Canadian CESAR expedition (Jackson *et al.* 1985). Different sources (dynamite, sparker, airgun) and firing rates resulted in varying data qualities. A significant number of lines crossed Alpha Ridge and are the basis of our current understanding of this feature. These seismic profiles show sedimentary deposits varying in thickness from zero to approximately 1000 m (Jackson *et al.* 1990) and lying conformably on the basement, where visible. The seafloor topography perpendicular to the ridge is in most cases rough.

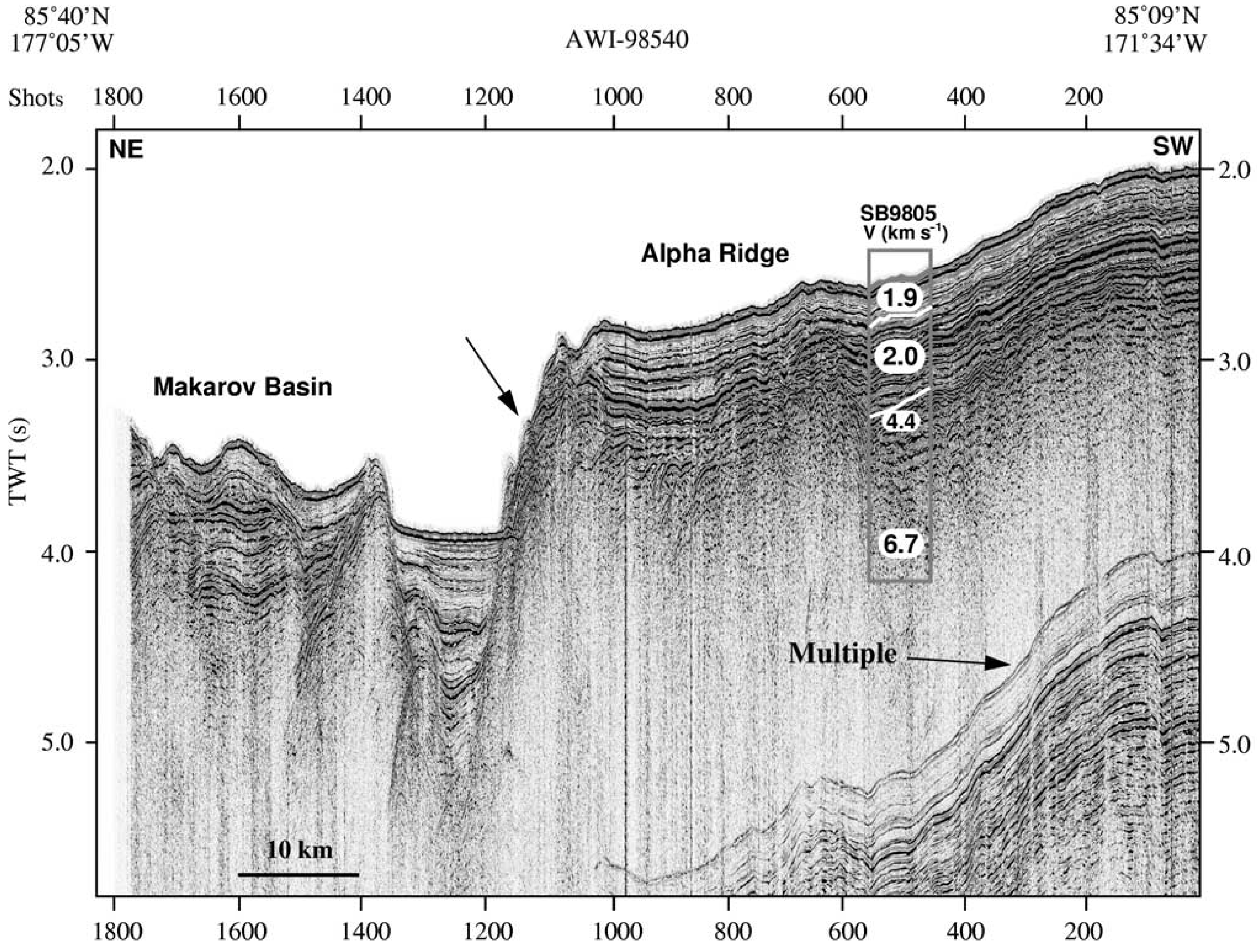

Figure 7. Profile 98540 running perpendicular to Alpha Ridge. The basement is rougher close to the escarpment near shot point 1200. Weak reflections indicate that older sediments might outcrop at the escarpment. Note that the prominent reflector at 2.4 s TWT (shot point 200) seems to also be present in the graben northeast of the escarpment. At least the seismic signature is similar. The arrow indicates the location, where basalt samples were recovered (Jokat *et al.* 1999).

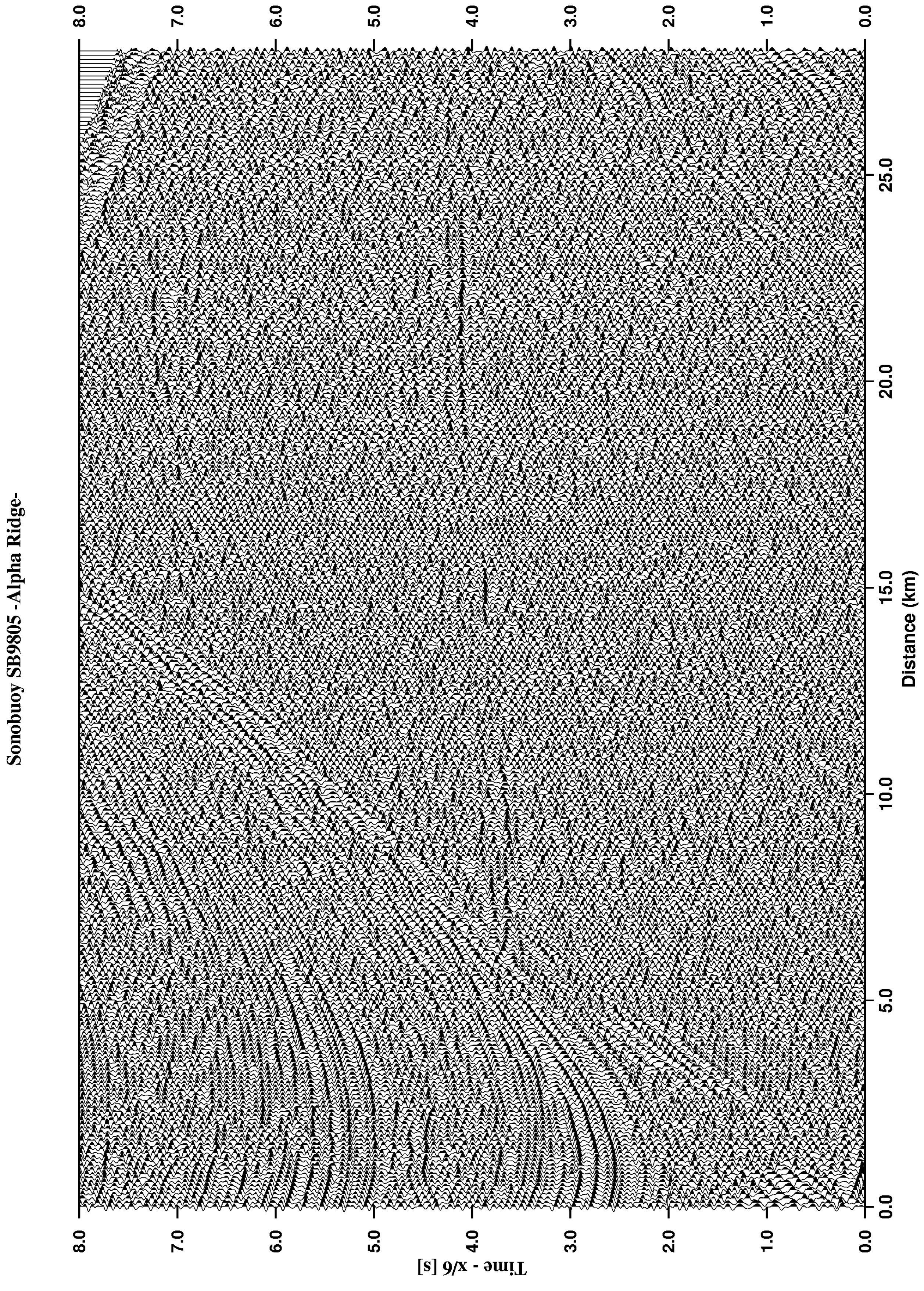

Figure 8. (a) Sonobuoy SB9805 at 85°16.5′N 172°36′W displayed with a reduced traveltime of 6 km s^{-1}. The data are bandpass filtered from 6 to 15 Hz and an AGC with a 0.3 s window is applied. (b) Picked traveltime data and the ray tracing results for SB9805 are shown.

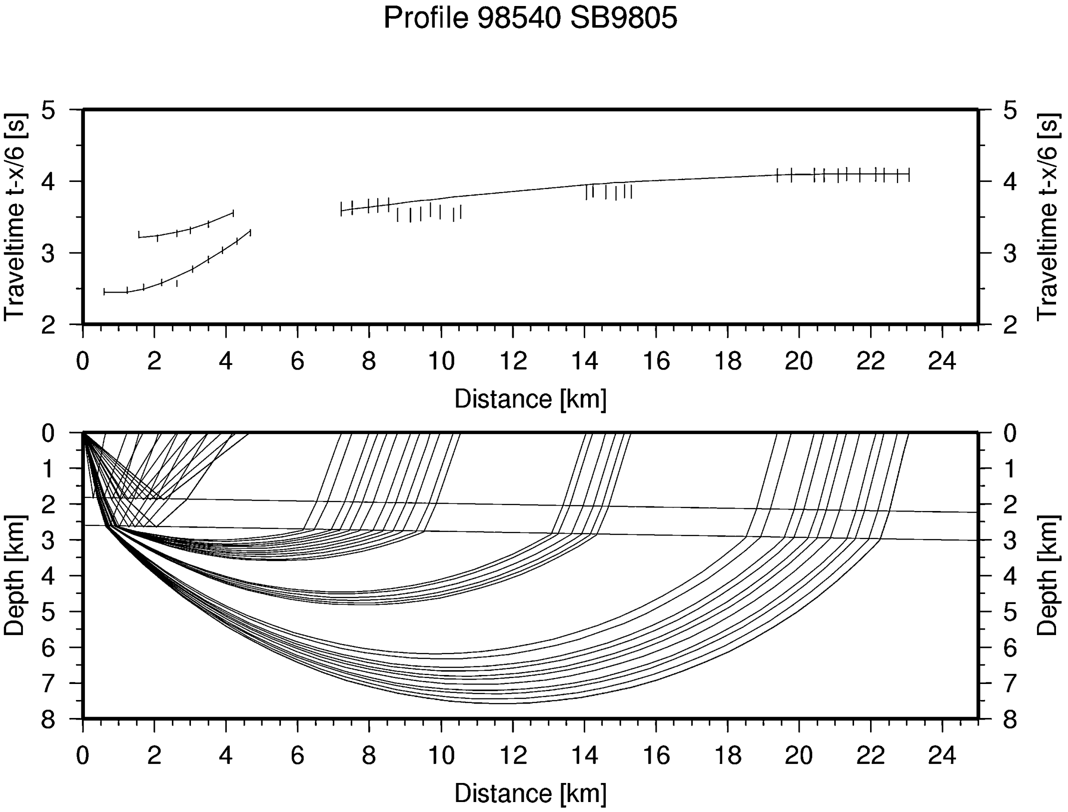

Figure 8. (*Continued.*)

The profiles collected during the Arctic-98 expedition show similar features, but with a much higher resolution. The sedimentary column can be divided into at least two units. The upper unit is characterized by low seismic velocities of 1.6–1.9 km s^{-1}, only slightly increasing with depth. Along profile 98530 its thickness of 300 ms (200–300 m) varies slightly. The age of this unit is speculative. Gravity cores with a maximum penetration of 6 m taken at the end of line 98530 indicate sedimentation rates varying from 1.25 to 2.7 mm ka^{-1} increasing with depth (Jokat *et al.* 1999). Using a constant sedimentation rate of 3 mm ka^{-1} an age of 100 Ma is obtained. This is quite old and may indicate that the sedimentation rate increases with depth. At the base of this unit a strong broad reflector is observed. Here, the seismic velocity increases to values well above 2.0 km s^{-1}. This reflector is visible along both lines on top of Alpha Ridge, along the flank (Fig. 2) and north of the escarpment. Since this reflector is found on all of the new profiles it may mark a major tectonic event in the Arctic Ocean, when the sedimentation environment changed significantly. Most probably it was the beginning of the rifting along the Barents and Siberian shelves, which finally led to the opening of the Eurasian Basin. The second, deeper unit is only 200 m thick on top of Lyons Seamount, but thickens to at least 1200 m (600 ms TWT) in the middle of profile 98530 (Fig. 3b, shot 950). Along the profiles it fills the deep basement depressions. Along line 98540 its thickness is more constant. Northeast of the escarpment (Fig. 7, shot 1200) the sediment unit is difficult to interpret. There are some indications of current-controlled deposition around shot point 1600 (Fig. 7), but the profile is too short for any detailed interpretation.

Since lines 98520 and 98530 run parallel to the strike of the ridge, the mapped topography is quite smooth. The variations in seafloor topography either represent basement outcrops or are caused by variations in the deeply buried basement surface. Along line 98540 a steep escarpment was crossed. Along this scarp the seismic data indicate that older sequences crop out at the seafloor. As the ice prevented any repositioning of the ships, the sedimentary outcrops were most probably missed during coring and part of the scarp was sampled where mainly basalts out crop (Mühe & Jokat 1999). Approximately 1 kg of massive rocks were sampled from the escarpment. The brownish volcanic rocks have been tentatively classified as alkali basalts, most probably of oceanic origin (Mühe & Jokat 1999). From the seismic data there is little doubt that these rocks represent the basement of Alpha Ridge and point to its oceanic origin. However, the seismic data do not constrain the age of Alpha Ridge.

500 m of Cenozoic sediments have been reported over the Lomonosov Ridge at 88°N for the same depositional regime (Jokat *et al.* 1992, 1995b). Here, the sedimentation rates are approximately 10 mm ka^{-1}. In the tectonic model (Jokat *et al.* 1995b) this sediment package was deposited some 50 Ma after the Lomonosov Ridge split off the Barents/Siberian shelves and subsided below sea level. The greater sediment thickness over the Alpha Ridge indicates that this feature might be significantly older than Lomonosov Ridge. Therefore, models that predict a Mesozoic age of Alpha Ridge are supported by the presented seismic data.

Recent high-precision whole rock Ar^{40}/Ar^{39} incremental heating dating gave a plateau age of 82 ± 1 Ma (O'Connor, pers. comm.) for the recovered Alpha Ridge basalt. This age strongly supports geophysical models that suggest a Late Cretaceous age for Alpha Ridge (Vogt *et al.* 1982; Lawver & Müller 1994). Here, the main argument is the obvious lack of coherent, high-amplitude marine seafloor spreading magnetic anomalies across the ridge. This suggests formation during the Cretaceous Quiet period (Vogt

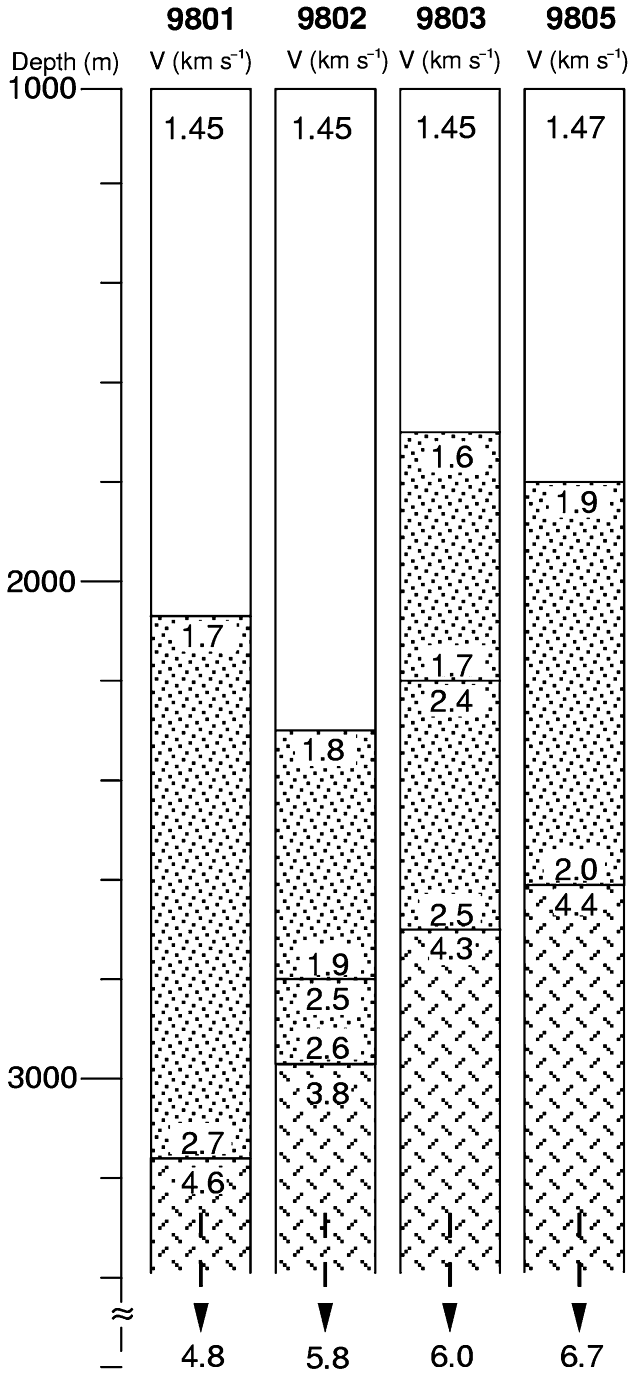

Figure 9. Velocity–depth functions for sonobuoys SB9801–9805 taken from the 2-D ray tracing models. Velocities derived from the reflection hyperbolae and refracted arrivals are shown. Velocities ≤ 3.0 km s^{-1} were calculated from the reflection hyperbolae of the sediment units. For the modelling the geometry of the sediment units along the seismic reflection profiles have been incorporated into the ray tracing. Refracted arrivals show velocities >4.0 km s^{-1} and are interpreted to represent basement. No depths for the highest basement velocities (SB9801, –4.8; SB9802, –5.8; SB9803, –6.0; SB9805, –6.7 km s^{-1}) are displayed in the columns since the record sections are unreversed.

et al. 1984). A more detailed discussion on the origin of Alpha Ridge based on petrological analyses, which are not yet available, is beyond the scope of this article and will be published later.

CONCLUSIONS

Along the 320 km of MCS profiles the sedimentary cover was well imaged for the first time in this region. The coincident sonobuoy records indicate sediment thickness of $\leq$1200 m. The sediments rest conformably on the basement along most parts of the profiles. Only on top of Lyons Seamount at the end of line 98530 may faulting of the sediments indicate extension. In general, a strong, broad reflector divides the sediment column into two units. Here the seismic velocity also increases. Since this reflector seems to be typical of the part of the ridge investigated it is suggested that the reflector was caused by a major tectonic event in the Arctic Ocean, which changed the sediment environment significantly at least during the deposition of that broad reflector. The most obvious candidate is the beginning of the rifting along the Barents and Siberian shelves. This hypothesis allows the interpretation that Alpha Ridge is significantly older than the rifting along the European shelves. Thus, the presumably complete sediment package includes information on the Mesozoic and Cenozoic history of the Arctic Ocean.

The velocity structure of the upper crust in the area investigated, and the seismic characteristics of the basement reflections, supports an oceanic origin of Alpha Ridge. The recovered basalt samples and their whole rock dating confirms a Late Cretaceous age of the central part of Alpha Ridge. This is in good agreement with published tectonic models based on aeromagnetic data.

Finally, the Arctic-98 expedition demonstrated that it is possible to reach Alpha Ridge with surface ships and to acquire geoscientific data of reasonable quality. It is suggested that the difficult ice conditions north of Alpha-Ridge are typical of the region. The support of an icebreaker of the Arktika class is essential when operating in this remote area.

ACKNOWLEDGMENTS

We thank the captains and crews of RV Polarstern and the Russian nuclear icebreaker Arktika for their excellent support during the expedition. I also thank all members of the geophysical group on-board RV Polarstern for their excellent teamwork. I also very much appreciate the support of O. Ritzmann, J. Rogenhagen and H. Kassens. The financial support by the Ministry for Education, Science, Research and Technology (BMBF) within the bilateral Russian–German multidisciplinary research project 'System Laptev Sea 2000' is gratefully acknowledged.

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