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New geophysical results from the south-western Eurasian Basin (Morris Jesup Rise, Gakkel Ridge, Yermak Plateau) and the Fram Strait

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SUMMARY

The international multi-ship expedition ARCTIC'91 was able to collect a seismic transect between the Morris Jesup Rise and the Yermak Plateau. These conjugate plateau structures in the south-western part of the Eurasian Basin bound one of the slowest mid-oceanic spreading ridges in the world, the Gakkel Ridge. The seismic data reveal a sedimentary cover that is thin relative to the age of the oceanic crust at 83°N, 10°E and 85°N, 15°W. Close to the plateaus, thicker sequences are evident (Morris Jesup Rise, 500 m; Yermak Plateau, 1500 m). The seismic lines on the Morris Jesup Rise reveal only a thin sedimentary cover of 0.2 s TWT. In contrast, a layer with a thickness of almost 0.9 s TWT (1300 m) was found on the northernmost tip of the Yermak Plateau. The topography of the oceanic basement is very rough along the seismic lines, as could be expected at a slow spreading ridge. Depth variations of more than 1000 m are typical. Hydrosweep swath mapping provides the first detailed 3-D image from the Arctic mid-ocean ridge system at 87°N, 60°E and 84°N, 0°.

Key words: bathymetry, Fram Strait, Gakkel Ridge, Morris Jesup Rise, seismic reflection, Yermak plateau.

INTRODUCTION

Collecting seismic reflection data from the central Arctic Ocean has always been a difficult task for geophysical investigators. Logistical limitations during ice island drift experiments and heavy ice conditions when using single ice breakers prohibited any detailed insight into the seismic stratigraphy of this vast area. Bathymetric data as well as gravity data could only be collected on random paths and had to be combined with the rare published tracks of submarines crossing the Arctic basins. Despite these enormous problems, the persistent investigations of national and international expeditions revealed the main tectonic structures in the Arctic (Fig. 1a) and produced the first hypotheses of its evolution. However, a deeper understanding of the geology was prevented by the lack of high-quality seismic reflection data and deep-sea drill holes.

Geophysical investigations carried out during the international multi-ship expedition ARCTIC'91 yielded the first continuous multichannel seismic profiles in the Eurasian Basin. This included a 600 km long transect (Fig. 1b) through the southern Eurasian Basin from the Morris Jesup Rise (MJR) to the Yermak Plateau (YP), which is reported here.

Aeromagnetic surveys by US and Soviet institutions (Karasik 1968; Vogt *et al.* 1979) revealed that the MJR and YP once formed a single structure. The volcanism that generated the features may have started approximately 40 Ma BP and ceased at 35 Ma BP, when the Fram Strait began to open. Feden, Vogt & Fleming (1979) have related this event to the 'Yermak hotspot'. Furthermore, the elevated topography of both structures, when compared to their age, points toward anomalous crust of hotspot origin (Kristoffersen & Husebye 1985). The timing of the excessive volcanism corresponds closely to changes in relative plate motions in the Eurasian Basin, the Labrador Sea and the North Atlantic at chron 13 (Kristoffersen & Talwani 1977; Vogt *et al.* 1979; Srivastava 1985). However, sea-floor spreading close to chron 13 time separated the volcanic features into two distinct parts which then drifted away from each other.

The crustal structure of the plateaus is believed to be oceanic, at least in some parts. This assumption is derived from the presence of strong magnetic anomalies on both rises (700–800 nT, locally 2000 nT on MJR; more than 1000 nT on YP) (Feden *et al.* 1979; Kovacs & Vogt 1982). Only a few

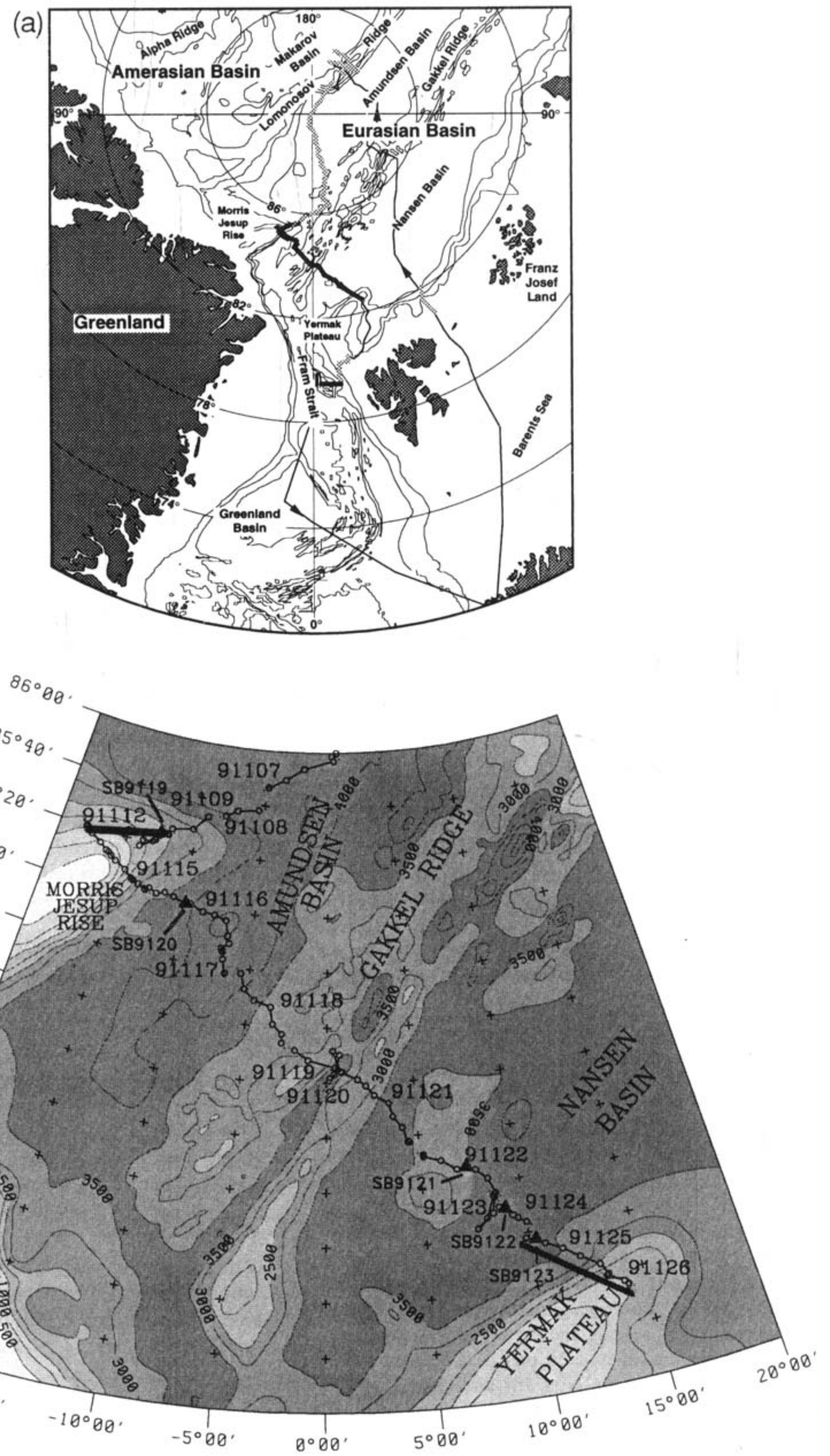


Figure 1. (a) Cruise track of the ARCTIC'91 expedition. The dotted and the bold lines mark the coverage with seismic lines along the track. Only data from profiles marked bold are discussed in this paper. (b) Location chart of the ARCTIC'91 seismic profiles and sonobuoys between the MJR and YP. The bold lines indicate the seismic profiles which are discussed in this paper. The circles along the tracks indicate approximately 500 shotpoints (≈ 500 CDPs = 12.5 km).

geophysical data sets have been collected from these areas. The MJR has been crossed by the ARLIS II ice island (Ostenso & Wold 1977). The MJR is about 200 km wide and trends north-eastward into the Amundsen Basin, extending the width of the North Greenland margin to about 300 km. It is characterized by steep, rugged sides (Dawes 1990). Seismic reflection data (based on a sparker source) constitute the first detailed geophysical data of this area (Ostenso & Wold 1977). The seismic lines indicate a thin sedimentary cover and a rough topography on the Gakkel Ridge-facing side. The crustal thickness of the rise is unknown. In contrast, on the northern Yermak Plateau only seismic refraction data and aeromagnetic data are available. The data indicate that the plateau can be divided into at least two structural units. One part is a predominantly oceanic block (northern part) and the southern part may be more continental in origin. Crustal velocities range from 5.0 km s^{-1} to 7.2 km s^{-1} in the north and from 4.3 km s^{-1} to 8.0 km s^{-1} in the south (Jackson *et al.* 1984). The crustal thickness is at least 18 km. No seismic reflection data are available from the northern Yermak Plateau.

In this paper we will discuss results of geophysical investigations during the ARCTIC'91 cruise along the transect (Fig. 1b). We will describe seismic lines between the MJR and the YP as well as bathymetric data from two crossings of the Gakkel Ridge. The seismic lines collected in the area under discussion reveal new information about the plateaus and the oceanic basins that separate them. The almost 500 km long transect consists of 12 seismic profiles with varying lengths of 12–100 km (Fig. 1b). The transect starts at the western part of the MJR, crosses the Gakkel Ridge, and meets the YP at its northernmost tip. In addition, we deployed four sonobuoys for detailed velocity determination of the sedimentary cover (SB9120-9123 in Fig. 1b). Previous seismic refraction experiments in the vicinity of our area of investigations reported an anomalously thin oceanic crust in parts of the Eurasian Basin (Jackson, Reid & Falconer 1982). The results led to the

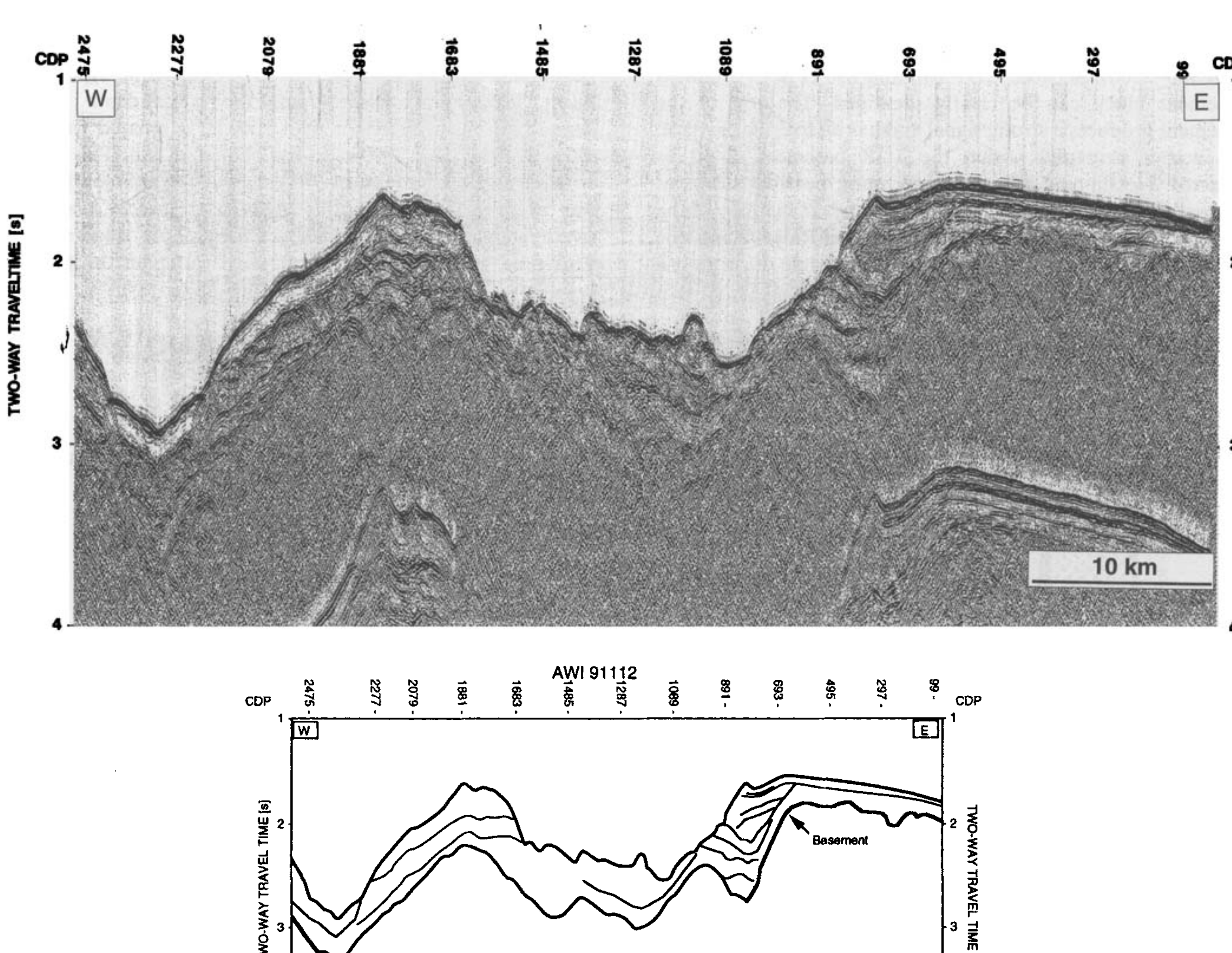


Figure 2. Line 91112 (100 CDP≈2.5 km). This line is located on the top of the Morris Jesup Rise (Fig. 1b) and shows only a thin sedimentary cover of 0.2 s TWT at CDP 297. On its western flank, where the topography is more rugged, the sediment thickness along the profiles increases to approximately 0.8 s TWT.

suggestion that the thickness of oceanic crust may vary with spreading rates. Unfortunately, no new information about the crustal thickness of the oceanic crust could be derived from this experimental set-up to test this hypothesis. For details concerning the acquisition parameters and problems, see Jokat *et al.* (1992).

RESULTS

Seismic reflection data from the Morris Jesup Rise

The Morris Jesup Rise was approached from the north-east (Fig. 1b). The water depth decreased from 4300 m in the Amundsen Basin to 900 m at the top of the plateau. The swath bathymetric data confirm the flat top of the rise as discussed by Ostenso & Wold (1977). The water depth increases to values of 2200 m at its western flank. Unfortunately, we were not able to cross the plateau completely to the west in order to map the transition of the rise into the Amundsen Basin. While we found only a thin sedimentary cover of 0.2 s TWT in the north-eastern part, the basement is faulted towards the west and has thicker sediment layers (0.5 s TWT) (Fig. 2, CDP900–2300). Between CDP 690 and 890 (Fig. 2) a faulted basement block can be clearly identified. The top of the basement produces a strong signal and has an irregular surface. No deeper structures within the MJR basement could be detected. No dipping reflectors, indicating possible subaerial volcanism during break-up, could be found at the foot of the rise. Bathymetric data reveal that the Gakkel Ridge-facing side of the rise is marked by a steep scarp (25°), while the northern tip shows a dip of 20°. A sonobuoy deployed on the plateau failed to record reliable seismic data.

Heading towards the mid-ocean rift system of the Eurasian Basin it is of interest to note that the rough oceanic basement topography has only a thin sedimentary cover (0–500 m) relative to its age. A compilation of all profiles reveals the variable sea-floor topography along the whole transect (Fig. 3).

Bathymetric data from the Gakkel Ridge

No seismic reflection data could be collected in the central valley of the Gakkel Ridge (almost 12 km wide). Only bathymetric data are available there. The first crossing over the ridge system was made during the eastern track towards the Lomonosov Ridge (Fig. 4). Approaching the central valley from the Nansen Basin we found a pronounced decrease of the water depth to 1100 m at 86.6°N, 60°E (Fig. 4). Due to ice conditions, the ship's track headed for almost 25 km along the strike of the median valley. Here, the central valley of the ridge is approximately 15 km wide and almost 4850 m deep. The highest elevation of the Amundsen Basin's flank is 3300 m. Thus, the bathymetric swath data indicate that the Nansen Basin-flank basement is elevated relative to the Amundsen Basin. In the investigated area the mean depth in the Amundsen Basin is greater than 3000 m, compared with significantly less than 2000 m in the Nansen Basin. The second crossing of the ridge (almost 550 km away towards south-west) was accomplished along the MJR–YP transect. Again the swath bathymetric data reveal an asymmetric ridge system. This time we find a more pronounced jump in the Gakkel

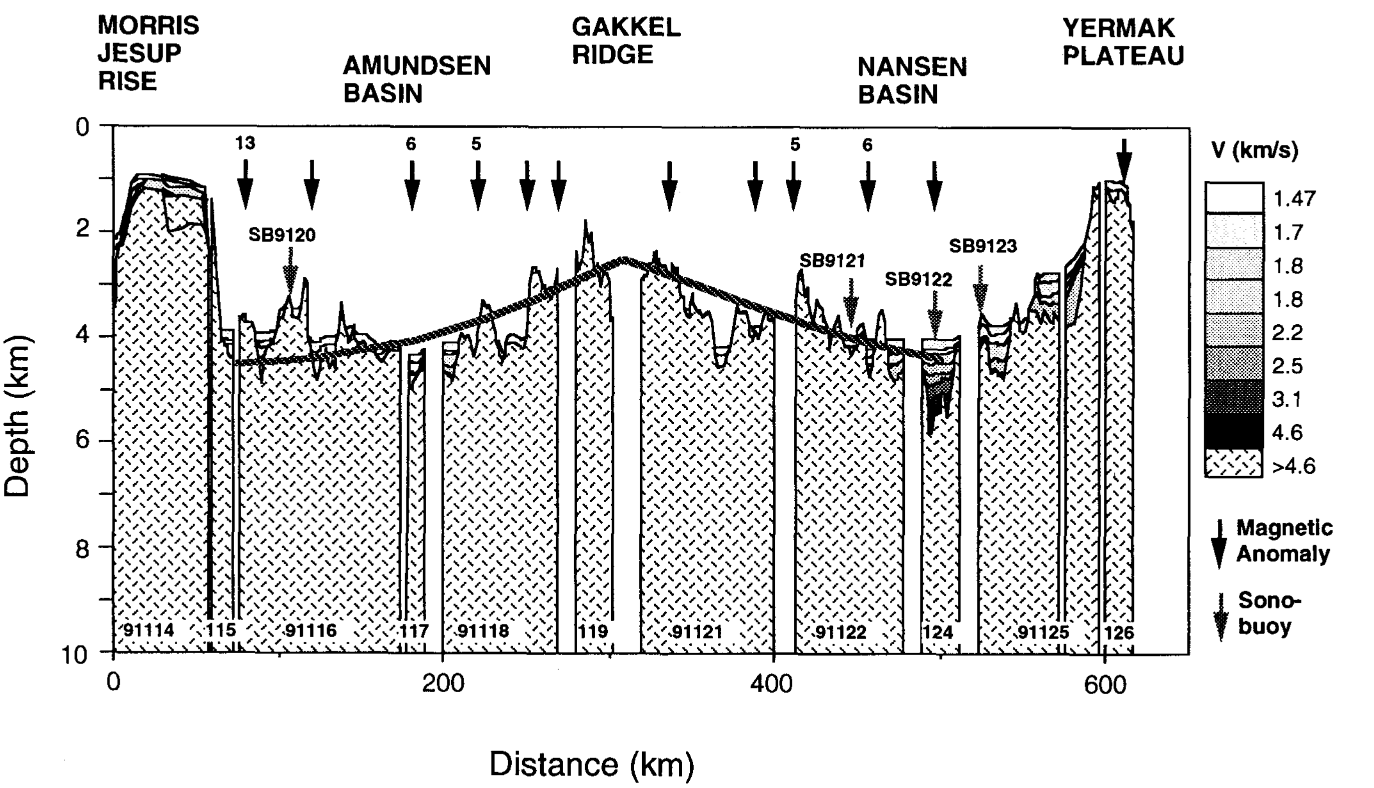


Figure 3. Compilation of the seismic lines (depth sections) belonging to the Morris Jesup–Yermak Plateau transect. The dashed lines mark the theoretical curve for subsidence of oceanic basement after Parsons & Sclater (1977). The naming of the magnetic anomalies is taken is from Vogt *et al.* (1979).

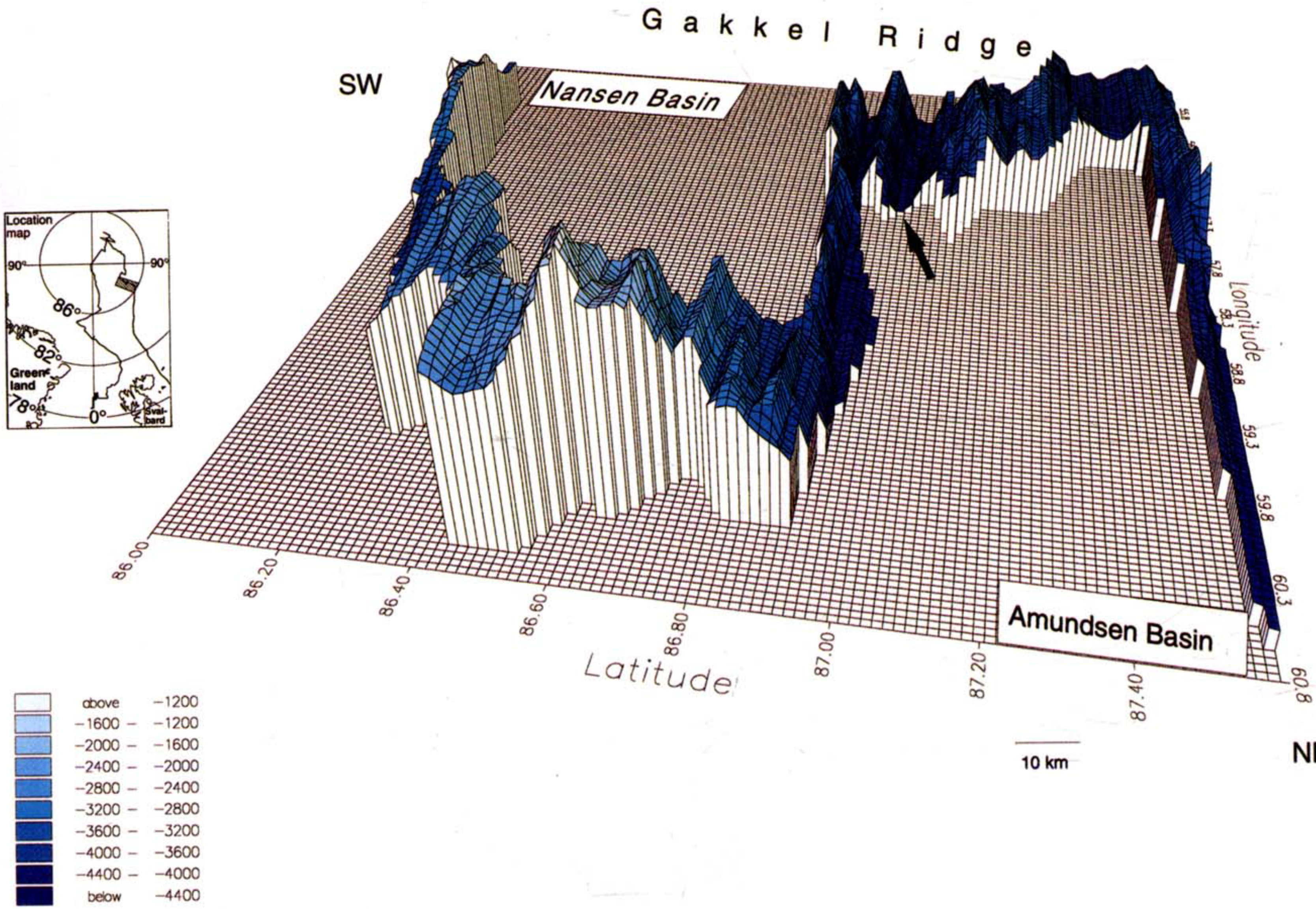


Figure 4. Multibeam swath bathymetry of the Gakkel Ridge at 87°N, 60°E. Note the pronounced bathymetric peak of 1100 m at 86.6°N and the asymmetry between both flanks of the Gakkel Ridge. The central valley exhibits at the crossing a water depth of 4850 m (arrow). West of the shoulder (3500 m) a second deep valley with a water depth ranging between 4300 and 4400 m can be observed.

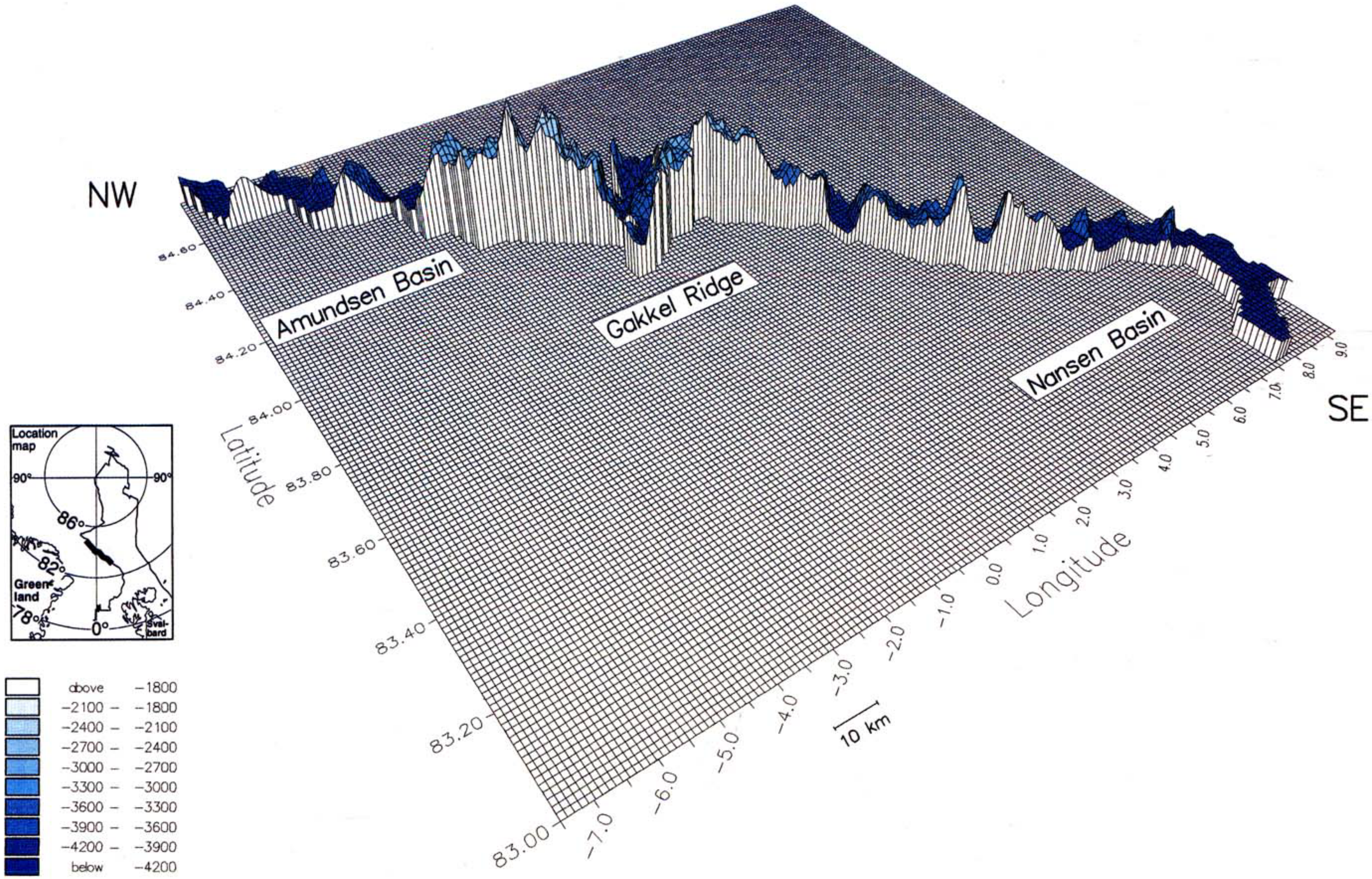


Figure 5. Multibeam swath bathymetry of the Gakkel Ridge at 84°N, 0°. Here, the flanks again show an asymmetry in depth. The asymmetry is not as pronounced as at 87°N, 60°E.

Ridge-flank topography on the Amundsen Basin side (2600 m change in depth) than on the Nansen Basin side (2000 m change in depth; Fig. 5). In conjunction with a seismic refraction survey in the central valley, it was possible to map the valley for almost 40 km along strike (Fig. 6). Here, the central valley is 12 km wide and 4000 m deep on average (maximum 4350 m).

Seismic reflection data from the Yermak Plateau

On the approach to the Yermak Plateau we found the greatest sedimentary thickness along this transect. The interval velocities were clearly revealed by sonobuouy 9122 (Fig. 7). The sediments are deposited on basement which is at least 30 Ma old (Vogt *et al.* 1979). Using the sediment thickness of almost 1500 m, we calculated a mean sedimentation rate of 5 cm ka^{-1} since late Oligocene times.

Approximately 50 km west of the Yermak Plateau, profile 91125 (see Fig. 1b for its location) shows pronounced jumps in bathymetry from 4000 to 3700 m, 3700 to 2800 m ($\approx$CDP1290, Fig. 8) and 2800 to 1000 m ($\approx$CDP2670, Fig. 8). The scarps are separated by relatively flat plateaus. The seismic image of the basement between CDP 1400 and 2470 is less clear. The basement is covered by sediments (max. 1.9 s TWT) which, in the deeper areas, have obviously been affected by faulting. We interpret these blocks as being part of the YP. They represent, in our interpretation, faulted and rotated crustal blocks which formed during the initial stretching of this area. The edge of the YP is marked by a scarp with a 13° dip (Schöne & Döscher 1992), similar to that of the Morris Jesup Rise. The seismic data have signals from deeper levels on the edge of the plateau. A closer inspection of the scarp indicates that it is highly faulted basement covered by sediments. Part of the flat top of the plateau is imaged by line 91126 (Fig. 1b). Although the basement signals are not well developed, the data reveal a half graben with a sedimentary

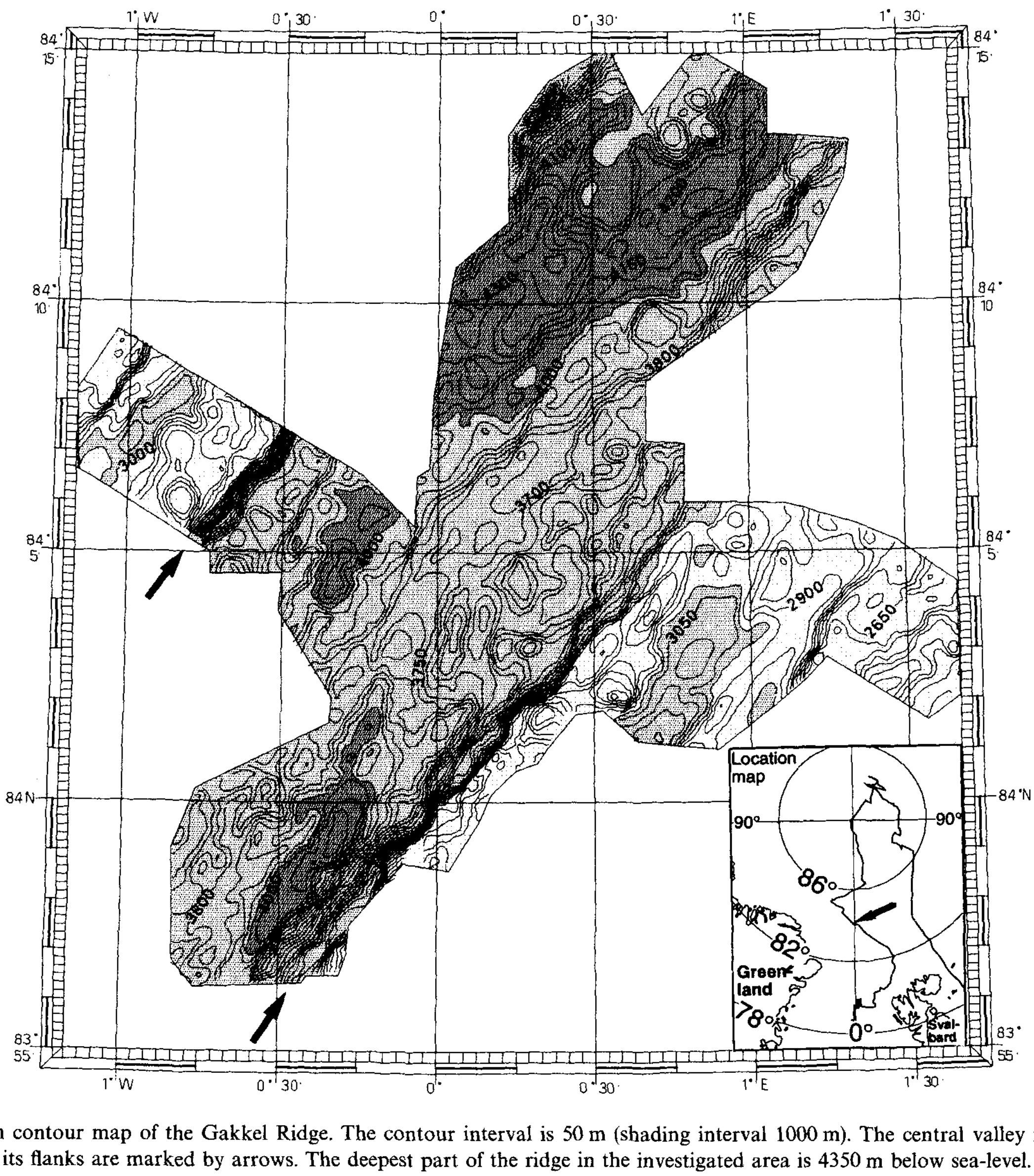


Figure 6. Depth contour map of the Gakkel Ridge. The contour interval is 50 m (shading interval 1000 m). The central valley is approximately 12 km wide and its flanks are marked by arrows. The deepest part of the ridge in the investigated area is 4350 m below sea-level.

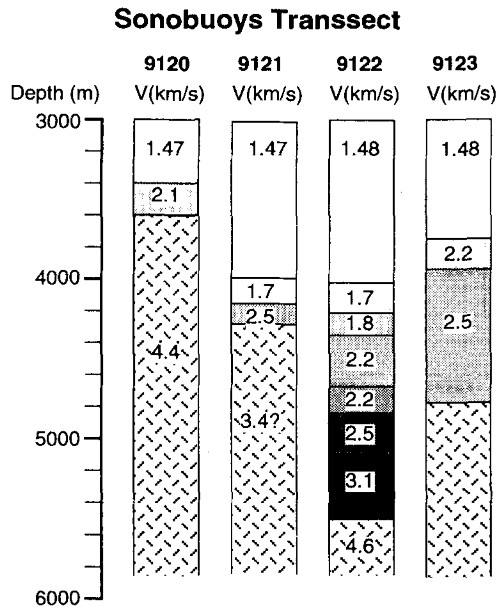


Figure 7. Results of sonobuoy recordings deployed during the Morris Jesup Rise–Yermak Plateau transect.

thickness of 0.9 s TWT ($\approx$1300 m) on line 91126 (Fig. 9). The sediment infill is highly faulted and poorly imaged. Bathymetric data reveal that the flat top of the plateau is only 15 km wide at its northernmost tip. The flank on the eastern side of the rise is less pronounced.

Seismic reflection data from the Fram Strait/Molloy Ridge

Close to the end of the ARCTIC'91 expedition we shot a seismic profile from the Svalbard shelf towards the Molloy Ridge (Figs 1a and 10a). The section images a part of the North Atlantic Mid-Ocean Ridge system, which was generated by a strike-slip movement between Svalbard and Greenland during the Oligocene. Oceanic basement is imaged between CDPs 1700 and 2900 (Fig. 10b). It shows a rough topography and only a thin sedimentary cover. The landward flank of the ridge is covered by approximately 0.8 s TWT of sediment. The base of these sediments is highly faulted, with decreasing disturbances in younger layers. In the eastern part of the profile we find 0.4 s TWT thick sequences which overlie an angular and in parts erosional unconformity. The sediment package thickens towards the Molloy Ridge. No erosion along the unconformity took place beyond CDP 750. Here, the boundary rests directly on the deeper faulted layers. The strata below the angular unconformity are nearly horizontal. Only the deepest unit (Fig. 10b, CDP 100, 4 s TWT) is inclined towards the ridge. Below this we find only weak coherent signals which dip strongly to the west. These seaward-dipping reflectors may indicate subaerial volcanism during break-up. In this case the reflectors must be related to the excessive volcanism which generated the MJR and YP. Investigating the data more closely at the angular unconformity, it is obvious that the boundary is geologically complex. The sediments between 3 and 3.8 s TWT at CDP 100 seem to be continuously deposited from chron 13 time on. The termination of layers between 3 and 3.5 s TWT towards the unconformity is less clear. They seem to be eroded and/or deposited in a highly dynamic current system. From 3 s TWT to the present sea-floor, the data indicate no obvious erosional event.

DISCUSSION

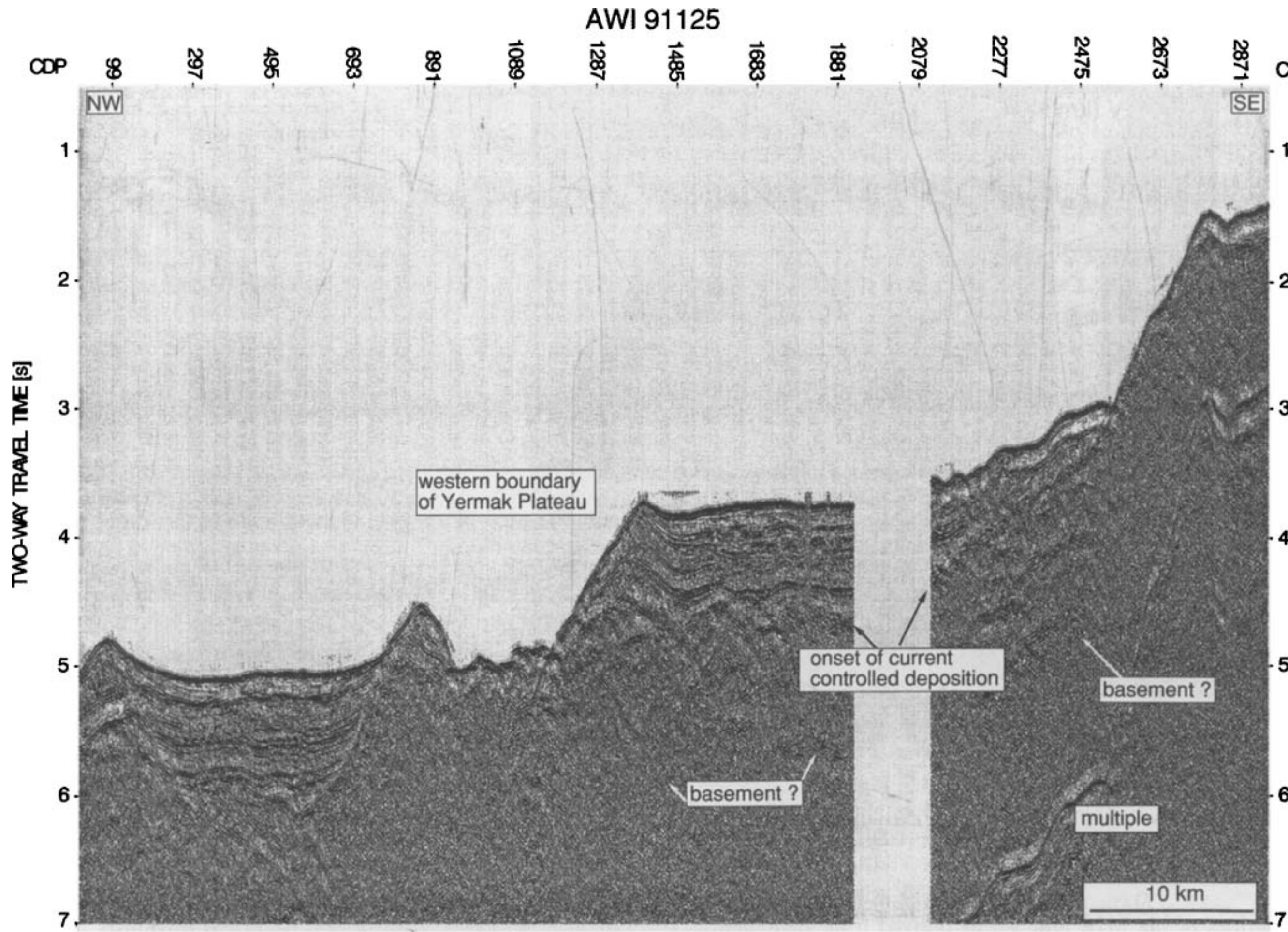
The thin sedimentary cover (100–200 m) on the flat top of the MJR suggests current-influenced deposition/erosion. However, the lines contain no obvious evidence for erosion let alone when it took place on the MJR. As we could not fully cross the rise towards the west, we found no seismostratigraphic evidence for a subsidence history of the plateau. In the east, the topography of the oceanic basement is too rough to allow any stratigraphic correlation and/or interpretation. At the foot of the MJR we found a sediment thickness of approximately 500 m.

The oceanic basement between the plateaus is dominated by a rough topography. Sediments could only be detected in the pockets and valleys between the topographic highs. Here, slumps from the elevated basement most likely dominate the sedimentation. Close to the central valley of the Gakkel Ridge the basement depth decreases to 1100 m at 86.6°N, 60°E. Unfortunately, the limited amount of bathymetric data along the ridge system prevents us from determining more about the extent and distribution of its topography.

The oceanic basement between the MJR and YP is covered by thin sediments considering its age. Only close to the plateaus did we find sediment thicknesses of 500 m (MJR) and 1500 m (YP). This indicates that since early Oligocene, current velocities may have been high enough to allow only low sedimentation rates and/or to have caused erosion of sediments.

Multibeam swath bathymetry of the Gakkel Ridge central valley revealed no significant transform faults in the small area of our investigations. In the past it was found that the oceanic basement depth-to-age correlation (Parsons & Sclater 1977) does not hold in the Eurasian Basin (Johnson, Grantz & Weber 1990). Johnson *et al.* (1990) claim that, compared to standard curves derived from measurements in the North Pacific, the Gakkel Ridge and adjacent areas are elevated. This is not obvious from our data (Fig. 3). Here, the basement depths follow the theoretical curve reasonably well. Different depths elsewhere may indicate strong vertical movements of crustal blocks along the ridge. Close to the MJR and the YP we found strong deviations from the theoretical subsidence curve (Fig. 3). The structures bordering the basins (MJR, YP) are also highly elevated considering their age (Kristoffersen & Husebye 1982), if they are indeed of oceanic origin.

Approaching the Yermak Plateau at its northernmost tip we found a seismic character different from that on the MJR. Along line 91125 we detected faulted blocks, which most likely subsided after the initial opening of the Fram Strait. We believe that the plateau extends approximately 50 km into the Nansen Basin. The sediments on the plateau have a minimum thickness of 1300 m (0.9 s TWT) and are highly disturbed and faulted. They infil a half graben. Therefore, the flatness of the northern YP does not reflect the basement topography but rather it is generated by synrift sedimentation and subsequent current-controlled deposition/erosion. Line 91126 crossed the plateau in an area of high magnetic anomalies (Feden *et al.* 1979; Jackson *et al.* 1984). This part of the plateau is considered to be oceanic crust. However, our seismic data reveal no information about the origin of the highly magnetic crust. The



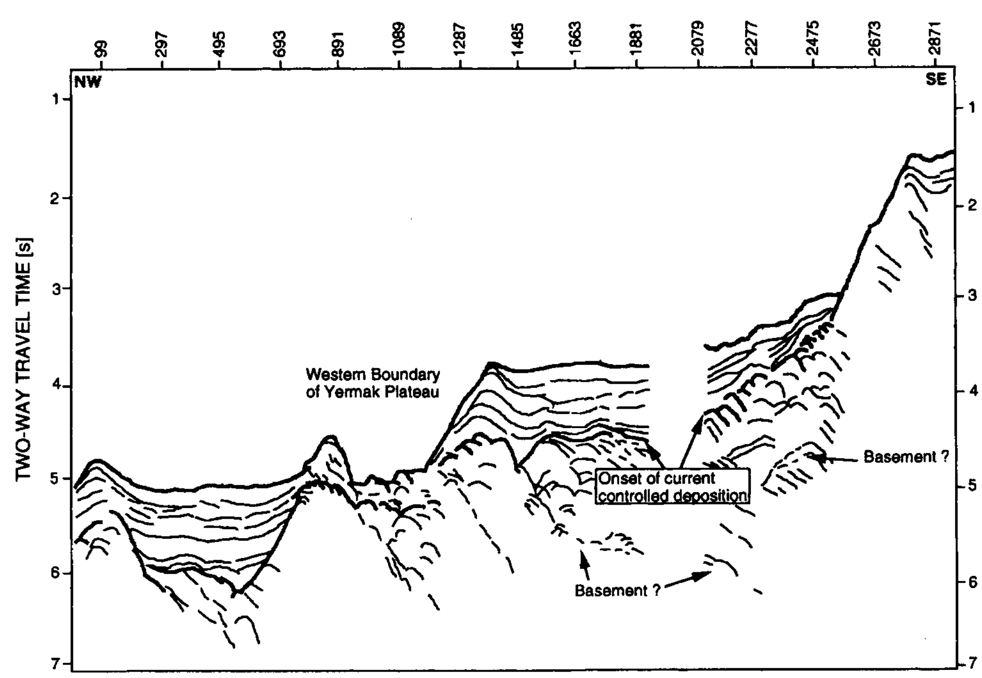


Figure 8. Line 91125 approaching the Yermak Plateau (100 CDP≈2.5 km); for location see Fig. 1(b). The lower part of the section (from approximately 4.6 s TWT to 5.5 s TWT at CDP 1683) is dominated by deposits created by mass wasting from the plateau. They show no clear seismic pattern. From 4.6 s TWT (CDP 1683) to the sea-floor (thickness 1.0 s TWT) the seismic signals show a more continuous character. We suggest that here the deposition has been dominated by currents and occasionally by slumps from the plateau.

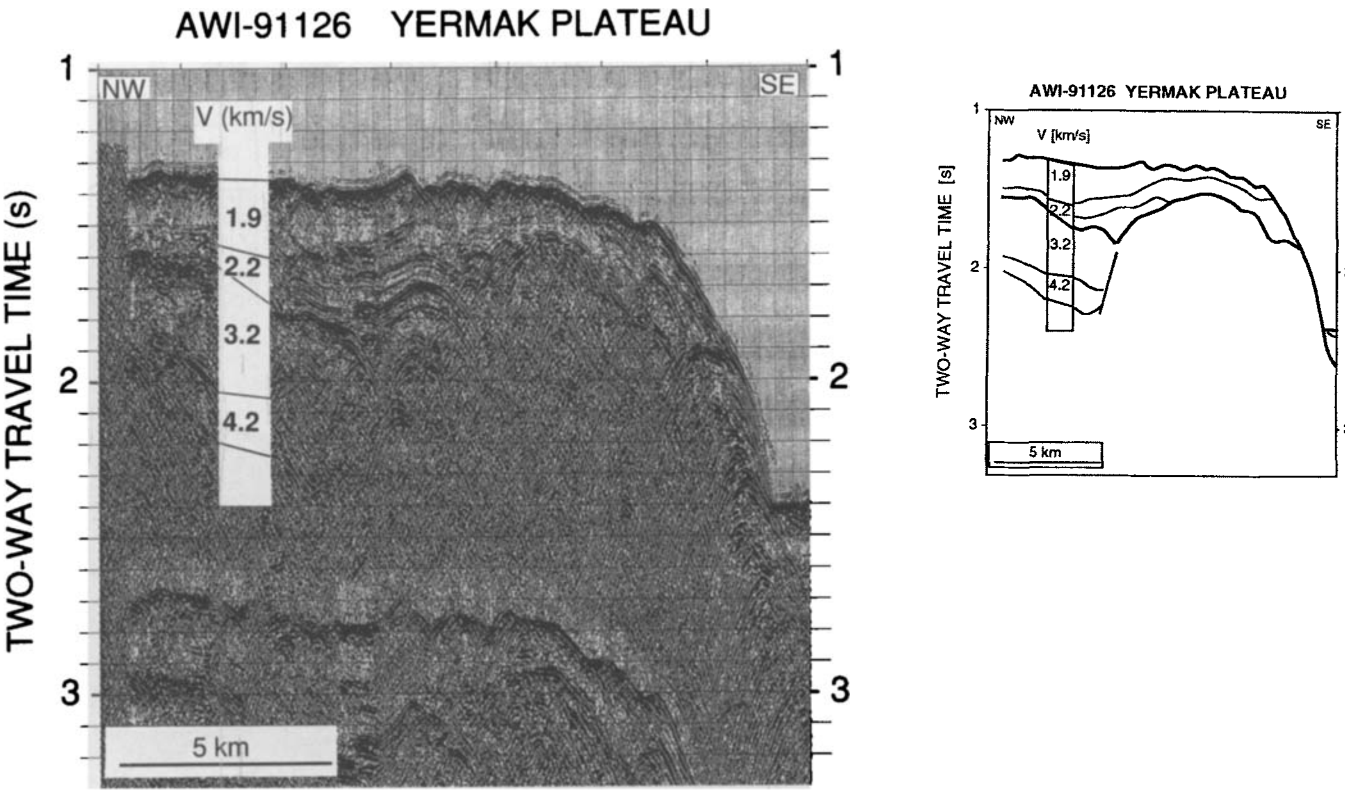


Figure 9. Line 91126 imaging the summit and western termination of the Yermak Plateau (from 82° 40′N, 13° 17′E to 82° 34′N, 14° 10′E; see Fig. 1(b) for its location). The velocities are derived from detailed velocity analysis of the CDP gathers (Streamer length 500 m).

similarities of the MJR and YP as derived from bathymetric and aeromagnetic data cannot be confirmed by our seismic data. The Yermak Plateau shows thicker sediments than the Morris Jesup Rise. This may indicate an asymmetric break-up of the plateaus. Here, the Yermak Plateau seems to be altered mainly by stretching.

A single line shot from the Svalbard Shelf towards the Molloy Ridge allows some weak correlation to be made with similar deposits in the Amundsen Basin. The question is, therefore, whether we can relate the observed units to the layers in the Eurasian Basin (Jokat *et al.* 1995). Analysis of seismic data in the Amundsen Basin gives some weak indications that the 'modern' depositional system in the Arctic Ocean was established close to chron 5 time. This is documented by a constant layer thickness of 0.2 s TWT throughout the investigated area of the Amundsen Basin. This layer was named AB8 (Jokat *et al.* 1995). In general, we also observe a similar change in depositional style on line 91134 (Fig. 10b). The upper 0.35 s TWT of this section may reflect the sedimentary record since the late Miocene (10 Ma), which is believed to be the period when an effective gateway between the Arctic Basin and North Atlantic was established. This layer is bounded at depth by an angular unconformity.

The few seismic profiles in the Nansen Basin indicate that the sedimentary cover here is thicker than in the Amundsen Basin (Rzhevsky 1975; Kovacs & Vogt 1982). The difference is approximately 1000 m. Three sonobuoy recordings allowed us to establish a detailed velocity model for the sediments. The velocities are similar to those we found in the Amundsen Basin (Jokat *et al.* 1995). The Nansen Basin has obviously received more sediments than the Amundsen Basin from the adjacent continental margins since early Oligocene time. The most likely source area for the region investigated is the Barents Sea. This has also been reported by other authors (Gramberg & Kulakov 1975; Kristoffersen & Husebye 1985).

CONCLUSION

The data presented clearly show that seismic lines between the Morris Jesup Rise and Yermak Plateau do not allow the establishment of a conclusive seismic stratigraphy. The sedimentary cover is highly influenced by currents, and the seafloor topography is very rough. The seismic reflection data across the investigated parts of MJR and the YP reveal different depositional styles. While the MJR is covered by only a thin sedimentary cover (100–200 m) below its flat part, sediment thickness at the northern tip of the YP is significantly greater (≈ 1300 m). From the existing data, it is not clear if the differences in sedimentary thickness of both plateaus are generally valid. The central valley of the Gakkel Ridge was surveyed with multibeam swath bathymetry for almost 60 km (the total length of the Gakkel Ridge is approximately 2000 km) along two crossings 550 km apart. Along the investigated part of the ridge system no major transform fault was detected. The flanks of the central valley are not symmetric in water depth. The shallowest part of the ridge system in the investigated area had a water depth of 1100 m. Both crossings of the ridge

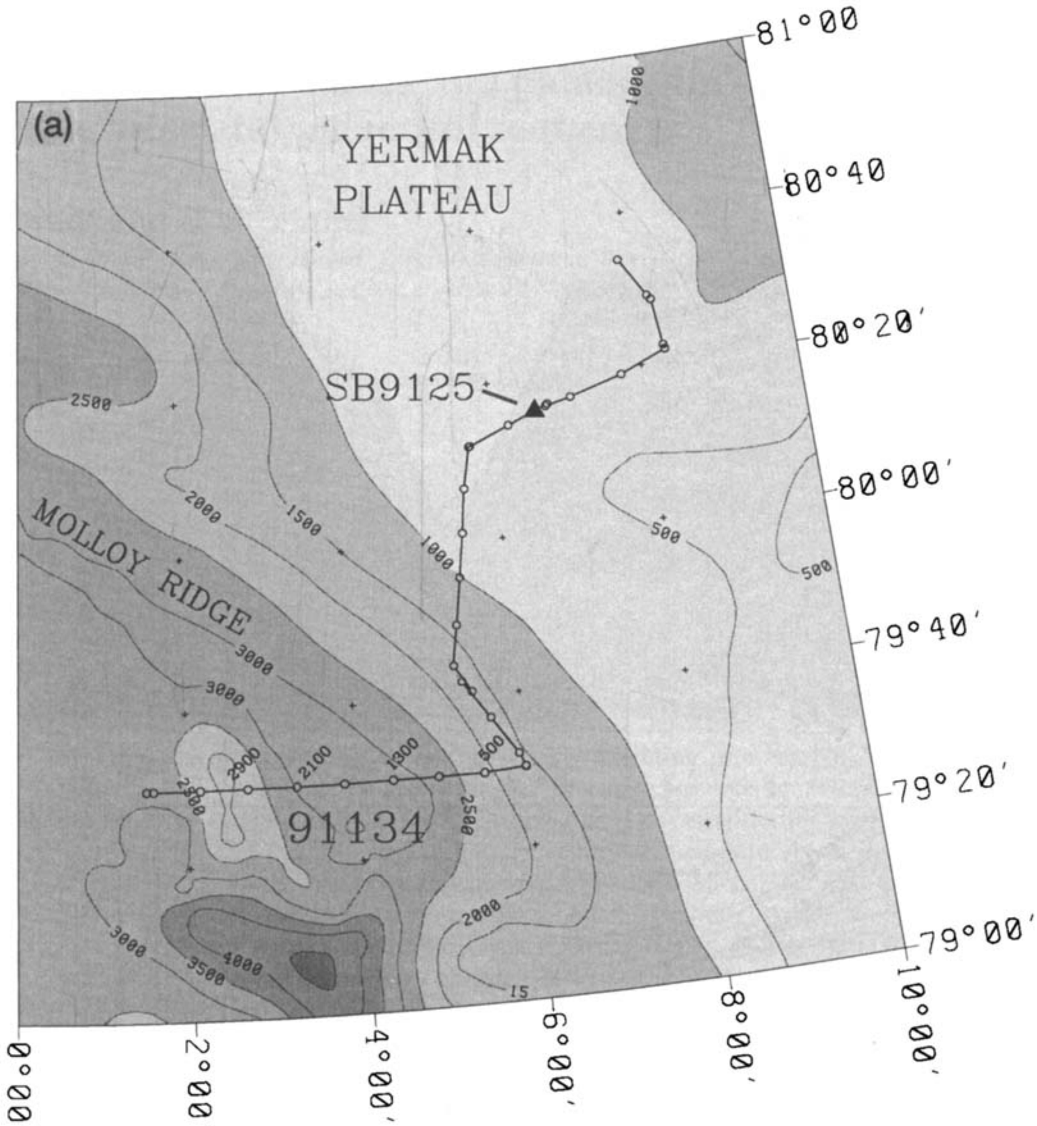


Figure 10. (a) Location map of our seismic profiles in the Fram Strait. (b) Line 91134. Seismic profile crossing the Molloy Ridge at 79° 50'N. The central valley of the ridge is at CDP 1700. The eastern flank of the ridge is fully covered by sediments of the continental slope (CDP 1110–1500).

show a central valley which is 12–15 km wide and 4350–4850 m deep.

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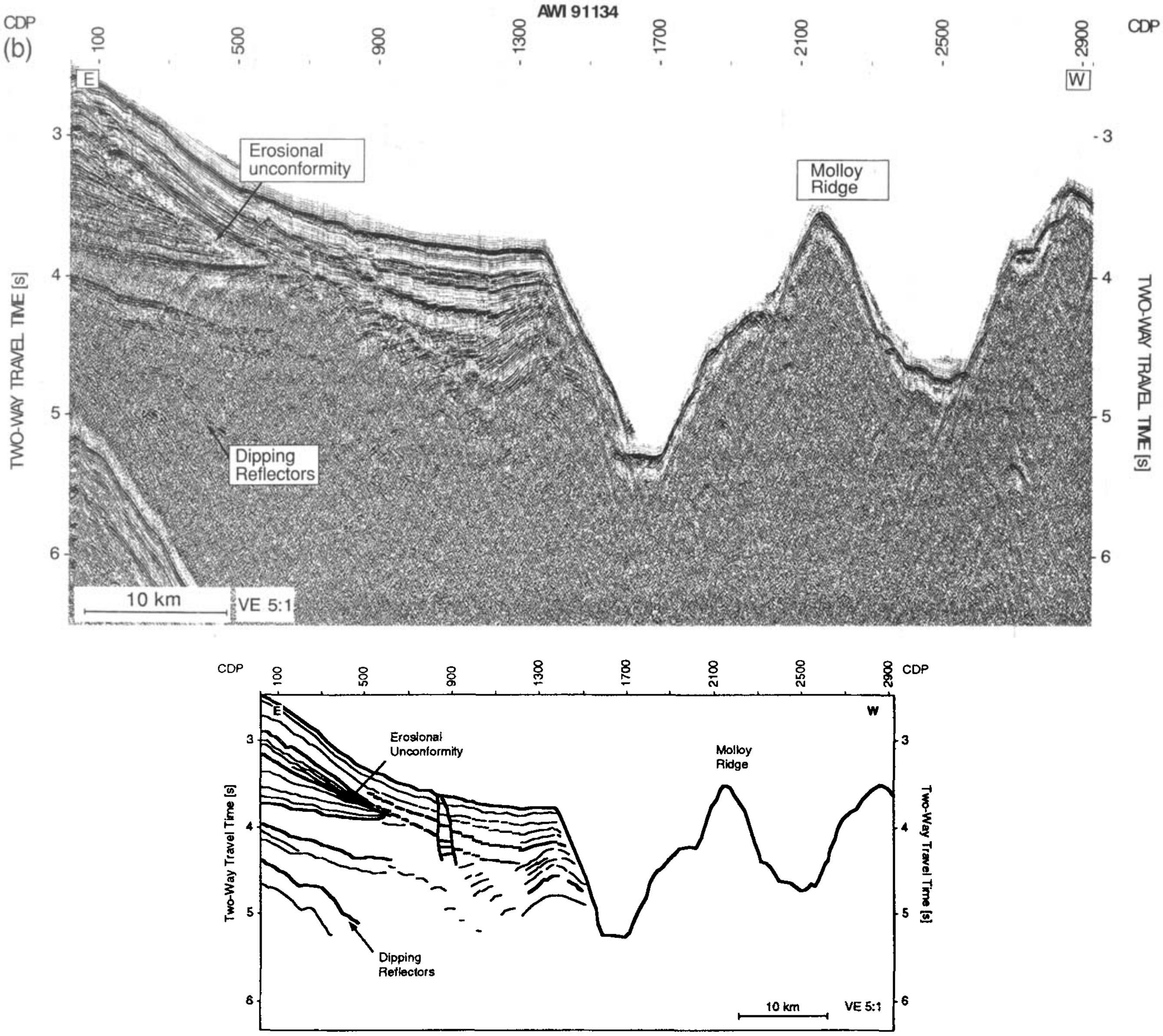

Figure 10. (*Continued.*)

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