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A seismic study along the East Greenland margin from 72°N to 77°N

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SUMMARY

Around 4370 km of new seismic reflection data, collected along the East Greenland margin between 71°30′N and 77°N in 2003, provide a first detailed view of the sediment distribution and tectonic features along the East Greenland margin. After processing and converting the data to depth, we correlated ODP-Site 913 stratigraphy into the new seismic network. Unit GB-2 shows the greatest glacial sediment deposits beneath the East Greenland continental shelf. This unit is characterized by the beginning of prograding sequences and has, according to our stratigraphic correlation, a Middle Miocene age. It might have been caused by rapid changes in sea level and/or glacial erosion by an early ice sheet or glaciers along the coast. A basement high, presumably a 360 km long basement structure at 77°N–74°54′N, prevents continuous sediment transport from the shelf into the deep sea area in times before 15 Myr. The origin of this prominent structure remains speculative since no rock sample from this structure is available. Seaward dipping reflectors at the eastern flank of this structure strongly support that it is a volcanic construction and is most likely emplaced on continental or transitional crust. The compilation of sediment thickness provide an insight into the regional sediment distribution in the Greenland Basin. An average sediment thickness of 1 km is observed. The north bordering Boreas Basin has a sediment thickness of 1.8 km close to the Greenland fracture zone (GFZ).

Key words: Controlled source seismology; Continental margins: divergent; Arctic region.

INTRODUCTION

During Permian and Tertiary times, rift systems separated Pangaea into North America, Eurasia and Gondwana (Moore *et al.* 1992a). The late Permian to Middle Jurassic initial phase of Pangaea breakup invoked the southwards and westwards propagation of the proto-Norwegian–Greenland Sea (NGS) and the Tethys rift systems, whereas the late Jurassic to Palaeoogene breakup phase was dominated by the stepwise northward propagation of the central Atlantic (Ziegler 1990). The rapid opening of the central Atlantic took place during the late Jurassic and Early Cretaceous and intensified rifting in the proto-NGS (Ziegler 1990). The tectonic evolution of the conjugate Greenland and Norwegian margins has faced compression, extension, magmatism and subsidence phases since the Devonian collapse of the Caledonian Orogene and until early Eocene continental breakup at 56 Ma (Talwani & Eldholm 1977; Skogseid *et al.* 2000). The Cenozoic geological history can be interpreted from the marine sediments and the crustal structure of the East Greenland margin.

First seismic investigations in the Greenland Sea were performed already before 1971 (Ewing & Ewing 1959; Eldholm & Windisch 1974). Only a few seismic refraction tracks are located along the Greenland continental margin. The data show a basement high between 75.3°N, 10.5°W and 76.4°N, 5°W, but the landward extension of this feature was not imaged (Eldholm & Windisch 1974). Ostenso & Wold (1971) published an aeromagnetic profile across the feature, which shows an abrupt decrease in anomaly amplitude, suggesting the presence of a magnetic quiet zone. Hinz *et al.* (1987) gave the first detailed insight into the sedimentary and tectonic structure of the northern East Greenland shelf, based on a seismic reflection profile recorded in 1981. This profile is located almost at the same position like profile 20030390 (Fig. 1) and covers the deep sea part of the Greenland Basin. However, it terminates just close to the shelf edge. ’Seaward dipping reflectors’ (SDRs) beneath the East Greenland continental slope were recognized on a structural high of which the dipping events create the seawards flank (Hinz *et al.* 1987). Within the basement structure, a basement scarp was identified, the Greenland Escarpment, and interpreted as the landwards limit of the structural high.

Mutter & Zehnder (1988) introduce results from two-ship expanded spread and wide aperture CDP profiling (ESP) measurements off the East Greenland margin. These measurements were made to investigate the deep crustal structure during the onset of seafloor spreading. Seaward of a region of low velocity crust SDRs occur within thick crust interpreted to be a product of voluminous melt production enhanced by convective partial melting processes (Mutter & Zehnder 1988). A structural high east of the Greenland Escarpment (GE)shows at the top a seismic velocity of 4 kms^{-1}. Existing studies show a volcanic influenced region south of 76°N.

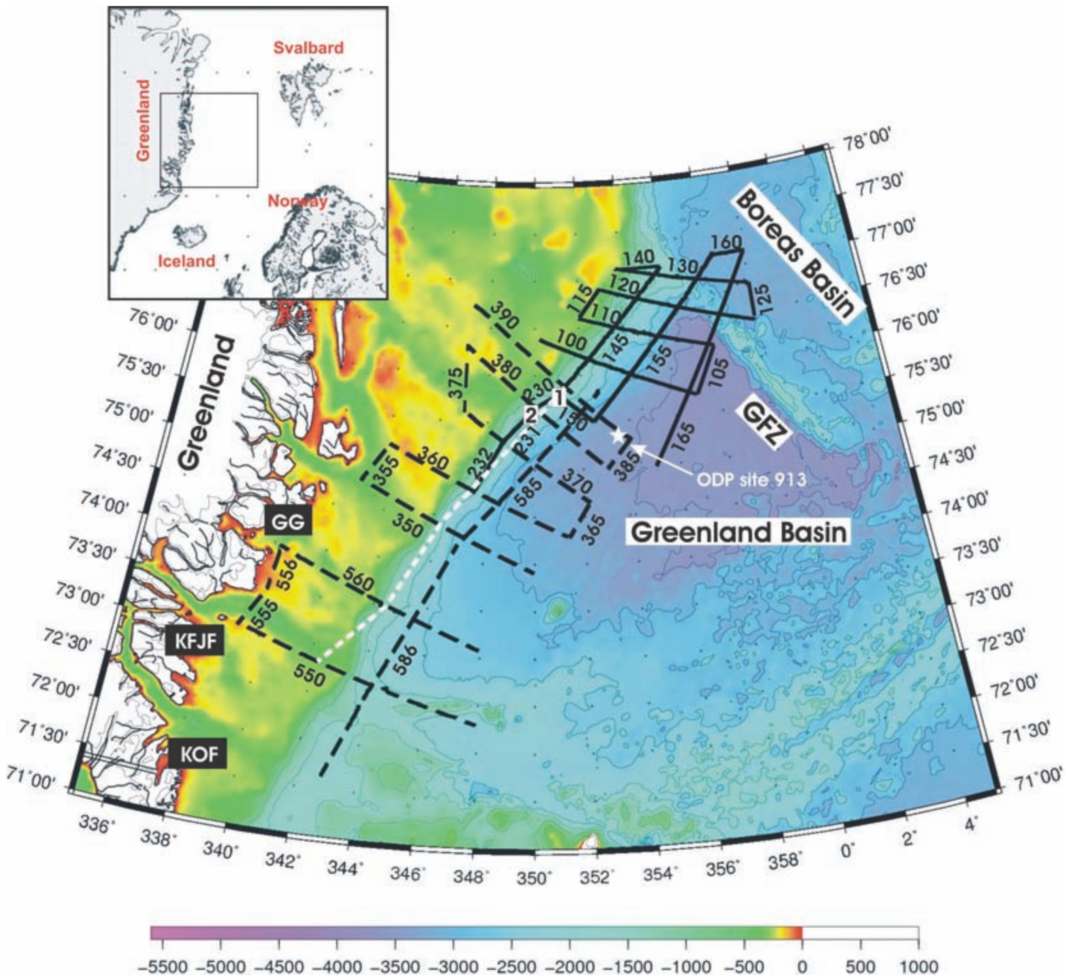


Figure 1. Location of the study area with bathymetric contours and the multichannel seismic (MCS) network recorded with RV 'Polarstern' in 2003. The black profiles were acquired with the 600 m long streamer, and the dashed black profiles were acquired with the 3000 m long streamer. ODP drill site 913 is marked with the white star, 17 km away from profile AWI-20030390. Numbers 1 and 2 show the location of the sonobuoys 19 (1) and 20 (2). The thin dotted white line along the East Greenland shelf represent the boundary of the ocean transition zone, published by Voss & Jokat (2007). GFZ, Greenland Fracture Zone; GG, Godthåb Gulf; KFJF, Kejser Franz Joseph Fjord and KOF, Kong Oscar Fjord.

The seismic database remained extremely poor across the margin since the sea ice prevented any systematic data acquisition. Another seismic experiment (KANUMAS), carried out in the years 1991–1995, gathered multichannel seismic data along the East Greenland shelf between 72°N and 79°N. In total, KANUMAS acquired 6839 km of multichannel seismic data (Hamann *et al.* 2005), mostly across the inner shelf. In spite of these geophysical investigations, geological structure of this part of the world is still relatively poorly known. Based on the same data set, Tsikalas *et al.* (2005) tried to make a first correlation with the KANUMAS data, based on reflection character, regional considerations and onshore Greenland geology (Stemmerik 1993). They divided the sedimentary column into two units: Plio/Pleistocene and Tertiary sediments. In their model, all prograding sediments at 76°N are of Plio/Pleistocene age.

Magnetic data from the Geological Survey of Norway (NGU) (Olesen *et al.* 1997) provided a first information for the location of the continent–ocean boundary in the Greenland Basin, based on the identification of seafloor spreading anomalies. Other markers typical of continent–ocean transition zones (COT) are volcanic SDRs, which have been identified at the conjugate margins off Norway (Hinz *et al.* 1987; Tsikalas *et al*. 2005) and off southeast Greenland (Planke & Alvestad, 1999). Recent deep seismic sounding data off East Greenland provided good constraints for the structure and width of the continent–ocean transition (Voss & Jokat 2007). It seems to be located more or less underneath the present shelf edge.

A little more is known about the glacial sediments. The East Greenland shelf might have been influenced since the middle Late Miocene (∼7 Ma; Larsen *et al.* 1994) by advancing and retreating glaciers/ice streams as documented in progradational and aggradational sequences of glacio-marine sediments (Vanneste *et al.* 1995). A large glacio-marine fan system exists off Scoresby Sund at 70°N (O'Cofaigh *et al.* 2001). Further to the north, the margin exhibits a series of large submarine fans and glacial troughs at 72°N, 73°N and 74°N (Fig. 1). These are locations where rapid ice streams flowed, and therefore, where the highest flux of glacial debris across the continental margin can be expected (Dowdeswell 1996).

The existence of Northern Hemisphere ice sheets can be demonstrated back to the middle Miocene, on the basis of proxy data and ice-rafted debris (IRD) from the Nordic seas (Helland & Holms 1997; Winkler *et al.* 2002). Eldrett *et al.* (2007) actually suggest the existence of (at least) isolated glaciers on Greenland between 30 and

38 Ma, based on results of site 913. However, the early glaciation history of the Northern Hemisphere is a subject of controversy.

Only one drill hole exists in the Greenland Basin. Ocean Drilling Program (ODP) hole 913 is located in the northwestern Greenland Basin (Fig. 1), where it provides information on the sediment composition and ages (Myhre *et al.* 1995). On the basis of the drilling results, those authors introduced seven different lithological units. The oldest unit has a middle Eocene age [674.1–770.3 m below the seafloor (m b.s.f.)] and consists of laminated and massive silty clay (Myhre *et al.* 1995). Basement material could not be recovered.

To advance in the understanding in the tectonic and glacial history of this margin, seismic reflection data were collected with 'RV Polarstern' in the NGS during the expedition ARK XIX/4 (Jokat *et al.* 2004). The new seismic data in the NGS comprise 15 profiles recorded with a 600 m long streamer (2309 km) and 13 profiles recorded with a 3000 m long streamer (2062 km). The profiles were arranged parallel and perpendicular to the shelf break (Fig. 1), with a line spacing of approximately 50 km. This contribution describes the results of the seismic reflection data interpretation in the Greenland Basin between 71°30′N and 77°30′N and provides new insight into the sedimentary structure, glacial history and tectonic evolution of prominent geological formations of this area.

SEISMIC DATA ACQUISITION/PROCESSING AND MAPPING PROCEDURE

The multichannel survey between 72°N and 78°N was carried out with a cluster of eight VLF-Guns × 3I (used for measurements with the 600 m streamer) and five G-Guns × 8.5I (used for measurements with the 3000 m streamer). Heavy ice in summer 2003 north of 77°N forced the use of the 600 m streamer with 96 channels (Fig. 1, black lines) and a hydrophone group spacing of 6.25 m. A 3000 m streamer was used in the south (Fig. 1, black dashed lines) with 240 channels and a hydrophone group spacing of 12.5 m. The shot interval on these configurations was 15 s, which resulted in a shot distance of about 35–40 m. In summer 2004, three seismic reflection profiles and two sonobuoys were additionally recorded along the East Greenland margin to complement the network.

We processed the multichannel seismic data using standard methods. After demultiplexing and applying a spherical divergence correction, the data were sorted and binned into 25 m spaced CDPs. We frequency filtered the data before stacking (15–80 Hz for the 600 m long streamer and 10–100 Hz for the 3000 m long streamer). For the 3000 m streamer data, a f-k filtering was also applied to suppress the water bottom multiples on the shelf region.

The short streamer provided only limited velocity information for depth conversion because of the small offset compared with the water depth (>1500 m). Representative velocities for this region are derived from the 3000 m streamer data. The velocity model for profile 20030390 is imaged in Fig. 2. The specified velocities are interval velocities determined by seismic velocity analysis and range between 1.5 and 2.3 km s^{-1} for the upper part of the shelf region (CDP: 7350–10400). For depths greater than 2 km, velocities of 3.2 and 4.3 km s^{-1} were used from seismic refraction measurements (Voss & Jokat 2007). The velocities of deeper reflections were checked by ocean-bottom seismometer deployed along four of the west–east seismic reflection profiles (Voss & Jokat 2007) and sonobuoy data (Jokat *et al.* 2005). Acoustic basement velocities were generally extracted from deep sounding data (Voss & Jokat 2007; Voss & Jokat 2008). These detailed velocity information is the base for the depth conversion. For profiles north of profile 20030390, we have interpolated the interval velocities of this line to determine an uniform seismic depth section for the entire network.

The greatest inaccuracies are given by the interpolation of the interval velocities along the short streamer profiles in the northern Greenland Basin. In general for the interval velocities, we compute a uncertainty of ± 150 m s^{-1} for velocities and that means for a prominent reflector at profile 20030390 in a borehole (CDP 1252) depth of 360 m b.s.f. an inaccuracy of ± 45 m.

To create sediment thickness maps, the data were gridded along the seismic reflection profiles and extrapolated to a distance of 3 km on each side of the lines, using the surface utility from the GMT v4.2.0 package.

PROFILE DESCRIPTION

Because of different used streamer lengths and different structural information of the seismic profiles, we divide our description into two parts. The northern Greenland Basin was investigated using the short streamer. Here, only the slope and abyssal plains were mapped. Additionally, in the southern Greenland Basin, the shelf region could also be investigated. Some lines in the southern part of the basin were acquired to the present coast line.

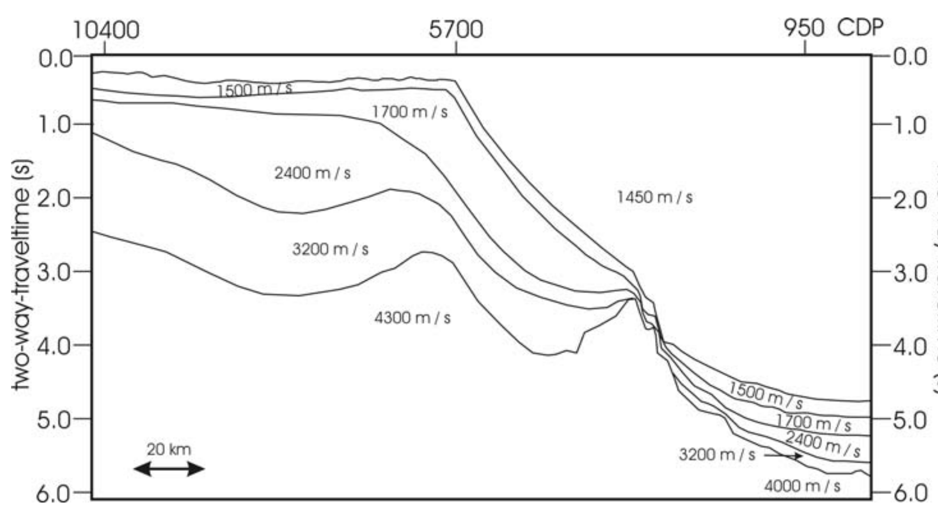


Figure 2. Velocity model of profile AWI-20030390 used for depth conversion.

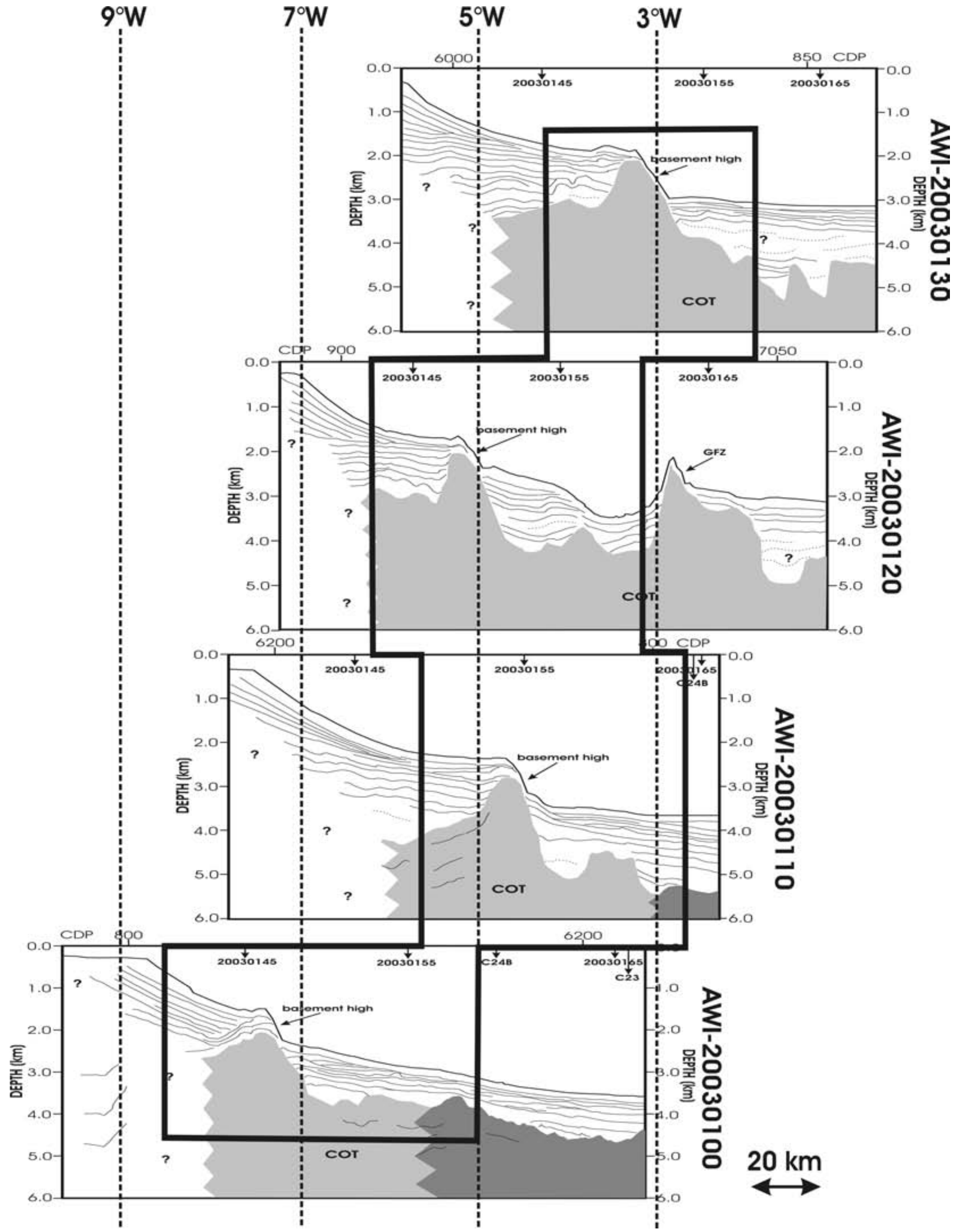


Figure 3. (a) Line drawings of profiles AWI-20030130, AWI-20030120, AWI-20030110 and AWI-20030100 (northern Greenland Basin), arranged from north to south and oriented on longitudes 3°W up to 9°W. The numbers at the black arrows represent the ties with crossing profiles at this position. The locations of the magnetic spreading anomalies are marked (C24B = 56 Myr, C23 = 51 Myr, Gradstein *et al.* 2004). The heavy black box indicates parts of profiles shown in Fig. 2(b). The basement is divided into oceanic basement (dark grey) and continent–ocean transition zone (COT, light grey). GFZ, Greenland Fracture Zone. (b) Parts of the seismic depth sections of profiles AWI-20030130, AWI-20030120, AWI-20030110 and AWI-20030100. The dashed white line illustrates the water bottom multiple reflection, and the white line represents the top of the acoustic basement. The numbers at the black arrows represent the crossing profiles at this position.

Northern Greenland Basin

Starting in the north, profile 20030130 is located north of the Greenland fracture zone (GFZ) and profile 20030120 is located at the junction of the GFZ with the East Greenland shelf (Fig. 1). On 20030120 (Figs 3a and b), a gap between the GFZ and a basement high beneath the shelf is clearly visible in contrast to the northernmost profile. On both profiles, seaward of the GFZ, rough basement is imaged. A basement high is located at the continental slope, and despite different water depths (1450–2350 m) and varying size and extent (12.5–20 km), these basement highs look very similar from one line to another. Thick sediment depositions are situated west

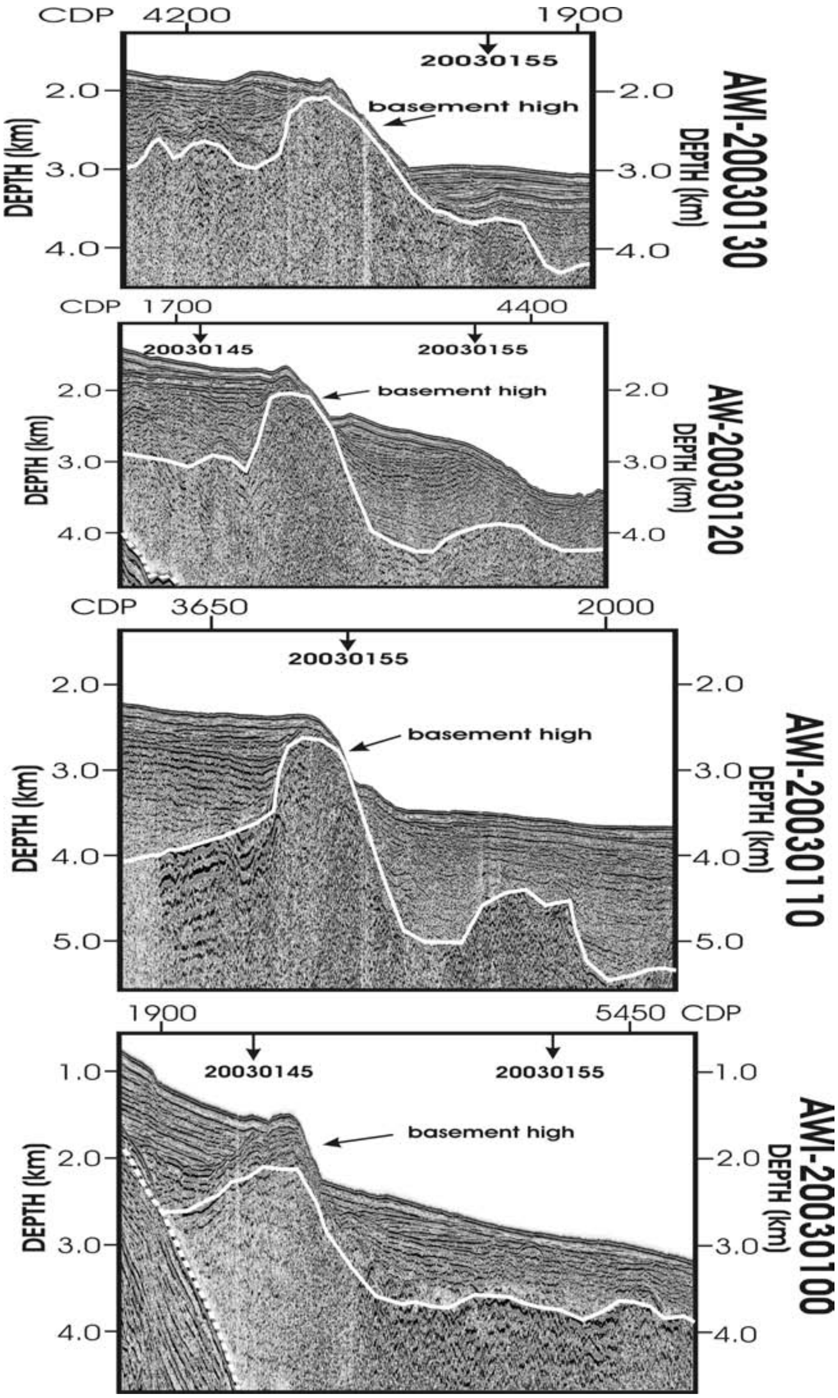


Figure 3. (*Continued.*)

of the basement highs in the slope region. This structure acted like a wall for the sediment transport into the deep sea. These profiles provide no information on the depth and structure of the acoustic basement beneath the shelf since the water bottom multiples mask any deeper signals.

Southern Greenland Basin

The next profile (Figs 4a and b; 20030390) recorded with the 3000 m streamer is nearly identical with the profile of Hinz *et al.* (1987) across the East Greenland continental margin and has a total length of 258 km. ODP-Site 913 (Figs 4a and b) is 17 km offset from this line. The age information were extrapolated to this profile at CDP 1252 in a water depth of 3350 m.

All west–east profiles show prograding sequences at the East Greenland shelf. These units are clearly visible in the subsurface layers over a distance of about 60 km west of the shelf break on profile 20030390. P-wave velocities in the upper part of the shelf region, determined by seismic velocity analysis, range between 1.8 and 2.3 km s^{-1}. Velocities of 3.2 and 4.3 km s^{-1} were used from seismic refraction measurements (Voss & Jokat 2007) for depths greater than 2 km, in this region, to convert the data to depth.

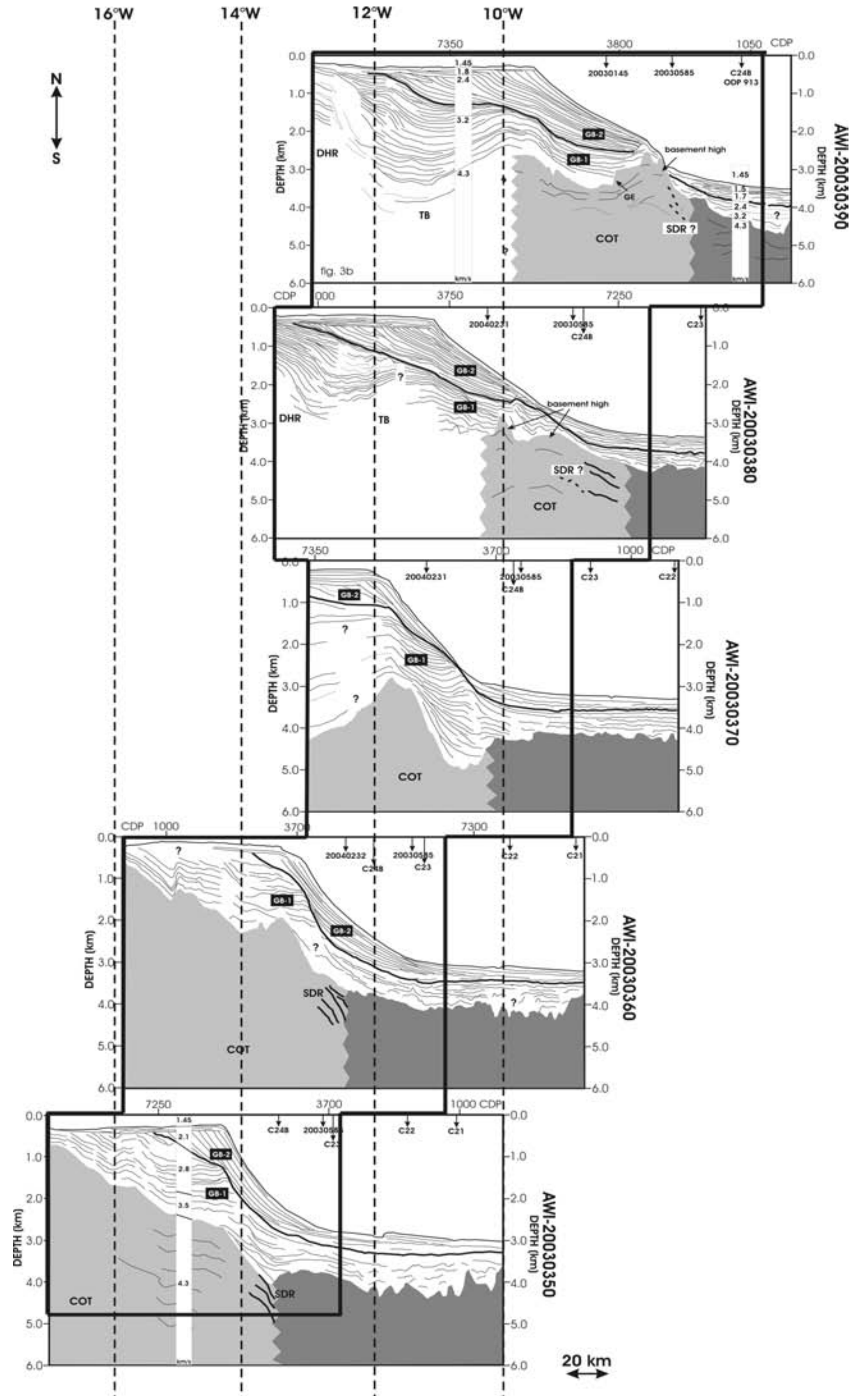


Figure 4. (a) Line drawings of profiles AWI-20030390, AWI-20030380, AWI-20030370, AWI-20030360 and AWI-20030350 (southern Greenland Basin) arranged from north to south across the East Greenland continental margin (longitudes 10°W up to 16°W). The numbers at the black arrows represent the ties with crossing profiles at this position. The location of the magnetic spreading anomalies is marked. C24B, 56 Myr; C23, 51 Myr; C22, 49 Myr and C21, 47 Myr (Gradstein *et al.* 2004). ODP-Site 913 is located in the deep sea area on profile AWI-20030390. The heavy black box represents parts of profiles shown in Fig. 3(b). The basement is divided into oceanic basement (dark grey) and continent–ocean transition zone (COT, light grey). DHR, Danmarkshavn Ridge; TB, Thetis Basin; SDR, seaward dipping reflectors; GE, Greenland Escarpment; GB-1 and GB-2, seismic units. (b) Seismic depth section of profile AWI-20030390 recorded with the 3000 m long streamer, illustrating the outer shelf, slope and deep sea of the Greenland Basin. The dotted white line represents the interpreted horizon, which divides the sediment package into GB-1 and GB-2; SDRs, seaward dipping reflectors. (c) Parts of profiles AWI-20030390, AWI-20030380, AWI-20030370, AWI-20030360 and AWI-20030350. Part of the section is zoomed in to show the area of the SDRs in greater detail.

According to the naming of Hamann *et al.* (2005) and Tsikalas *et al.* (2005), the line crosses the Thetis Basin (CDP 6250 to 9200) and the Danmarkshavn Ridge (Fig. 4a; CDP 9200 to 10170). The top of basement is well imaged on the eastern side of the high. A basement structure at CDP 3090 has a northwest–southeast extent of approximately 32 km and an elevation of 750 m. It is found at a water depth of 2500 m. Furthermore, this structure shows a break at 3000 m (CDP 4170), and we observe a small irregularity in the

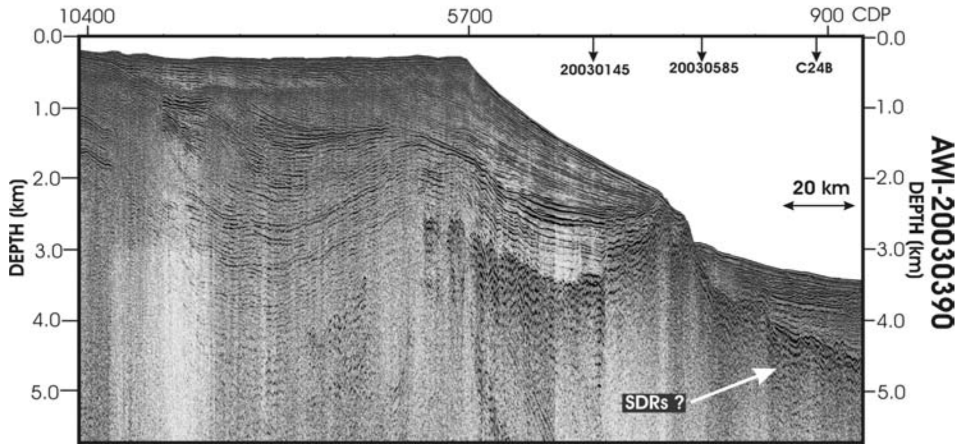


Figure 4. (*Continued.*)

basement topography (CDP 1870–2525) on its eastern flank. Hinz *et al.* (1987) called this step (Figs 4a and b; CDP 4170), Greenland Escarpment (GE). A transparent reflection character is found within deeper sediment layers between CDP 1050 and the eastern end of the profile, defined as slump deposits by Myhre *et al.* (1995) on the basis of drilling results at ODP site 913.

The position of the COT (Fig. 1) was adopted from Voss & Jokat (2007) for profiles 20030390, 20030350, 20030550 and 20030560. Between profiles 20030390 and 20030350, the position of the COT was interpolated, whereas profiles 20030380, 20030360 and 20030350 show weak internal basement reflections, which we interpret as SDRs (Fig. 4a). The appearance of SDRs on these profiles confirm the eastern termination of the COT by Voss & Jokat (2007). On profile 20030370, SDRs could not been identified.

Sediments with progradation and aggradation sequences on profile 20030380 show great similarity to profile 20030390. Also the deeper transparent part of the Thetis Basin and Danmarkshavn Ridge looks identical with line 20030390 (Fig. 4a). More eroded topsets are visible towards the shelf break in contrast to the northernmost profile 20030390 (Fig. 4c). Profiles 20030390 and 20030380 show well-developed prograded sequences caused by advances and retreats of the East Greenland ice shield (Fig. 4c). More aggradation is imaged on the outer shelf on profiles 20030370, 20030360 and 20030350 (Fig. 4c). Diffuse layering with changing inclination within the upper shelf sediments are observed on profile 20030350 (Figs 4a and c; CDP 7400–8650). Furthermore, the top of acoustic basement was well imaged along these lines. The basement high north of profile 20030370 is located in the lower slope region (Figs 3a and 4a). On profiles 20030370 and 20030360, the basement high is visible beneath the shelf break (Figs 4a and b; 20030370: CDP 5000–6450; 20030360: CDP 3000–4250) and is overlain by around 2 km of sediment in comparison with the northern profiles with up to 500 m of sediment.

The two southernmost profiles (Figs 1 and 5) located in the prolongation of Godthåb Gulf (20030560) and the Kejser Franz Joseph Fjord (20030550) are identical with seismic refraction profiles described by Voss & Jokat (2007). Not only the location of the top of basement within the shelf were adopted from the deep sounding data but also sediment velocities (2.7 to 3.7 km s^{-1}) for units deeper than 1 km, to convert the seismic data into depth. In contrast to profile 20030560, a prominent basement structure in the oceanic domain is imaged on profile 20030550 (Fig. 5; CDP 1580–3350). This ridge and the outer shelf forms a 68 km wide basin (CDP 3350 up to 6370) filled with 1600 m of sediment.

The north–south trending profiles 20030585 and 20030586 (Figs 6a and b), as well as profiles 20030145, 20040230, 20040231 and 20040232 (Figs 7a and b), are important tie lines for the stratigraphic correlations within the network. The top of oceanic basement (Fig. 6a) could not be detected with great certainty at the southern termination of profile 20030586. Great variations in sediment thickness exist and range between 300 m at the northern end of profile 20030585 and up to ~2000 m at CDP 9340 on profile 20030586 (Fig. 6a).

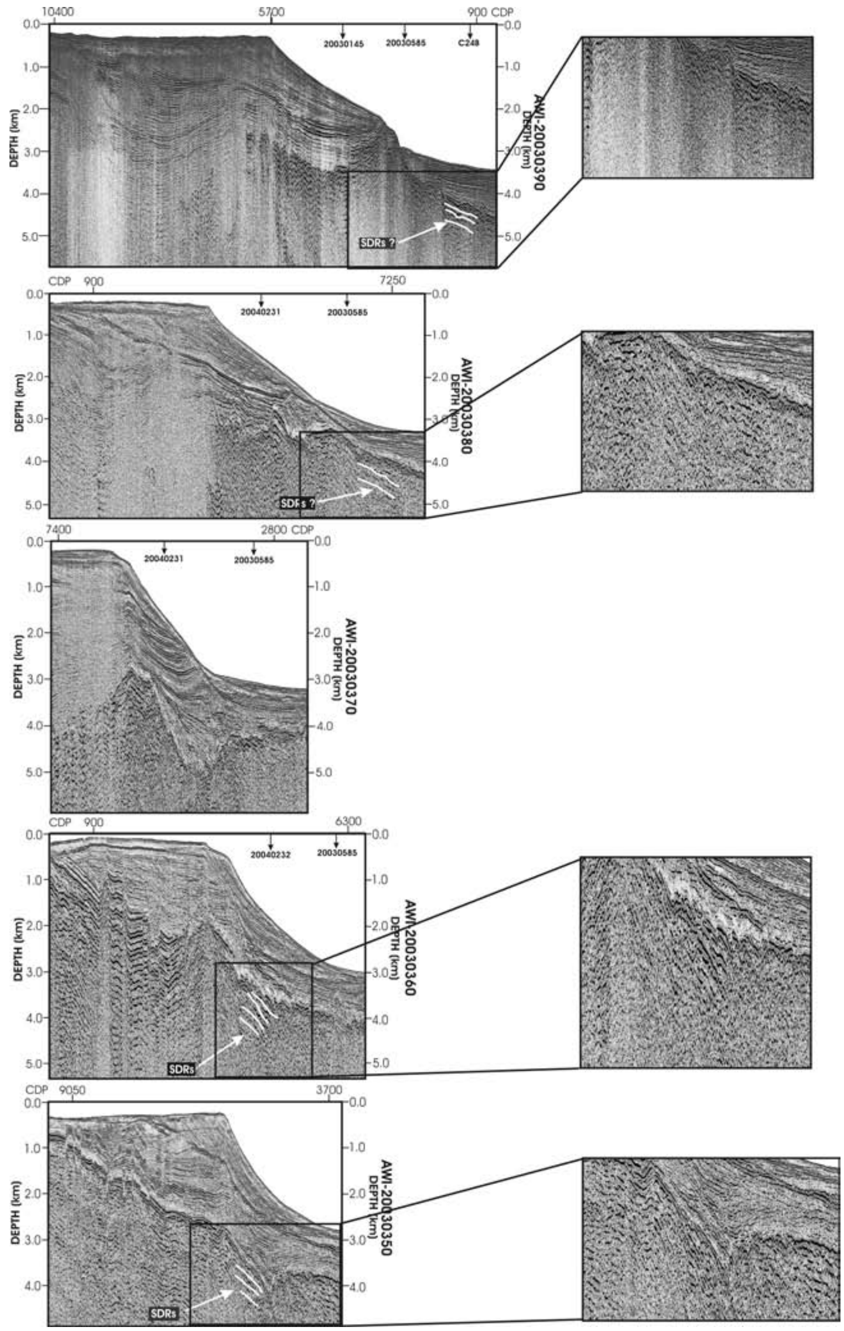
Identifiable reflected signals from sonobuoy data along profiles 20040230 (Fig. 7a; SB 19) and 20040231 (Fig. 7a; SB 20) were additionally used to control the correlation of horizons and check the seismic velocities for time to depth conversion on crossing profiles. The sediments from lower levels left and right of CDP 1950 (Fig. 7b; 20040232) crop out or almost reach the seafloor (Fig. 7b; 20040231: CDP 875 to 1345 and 20040232: shot CDP 400 to 2520). The layering of the sediments below 2.5 km is less disturbed.

STRATIGRAPHY

Available age information

In 1993, the RV 'Joides Resolution' voyaged the East Greenland margin. During this cruise (Leg 151), seven deep sites were drilled (Myhre *et al.* 1995). Site 913 was drilled in the deep Greenland Basin, south of the GFZ at 75°29′N, 6°96′W (Fig. 1). The hole was drilled in a water depth of 3318 m and penetrated to 770 m b.s.f. (Figs 4b and 8). The oldest magnetic seafloor spreading anomaly in this region is Anomaly 24B = ~56 Myr (Talwani & Eldholm 1977).

The uppermost Unit I (Fig. 8; Unit IA and IB) includes large dropstones ranging from 4 to 28 m^{-1}. This interval from 0 to 144 m b.s.f. is dominated by glaciomarine materials (Myhre *et al.* 1995) with an age of Pliocene to Quaternary (0–3 Myr). Their model results in a sedimentation rate of 4.8 cm kyr^{-1} (Unit I). The description of the upper and lower boundary of Unit II is problematic because of the poor recovery (2.8 per cent). The thickness of Unit II is given with 235 m (144–379 m b.s.f.). Below the top of the boundary Unit II, only a few large dropstones occur, and the lower boundary is placed at the lowest occurrence of beds of clayey, silty and sandy muds (379 m b.s.f.). The few large dropstones in the interval between 220 and 423 m b.s.f. are originally interpreted to be drilling contaminations (Myhre *et al.* 1995). Following this interpretation, the boundary between Unit II and Unit III represents a change from primarily non-glacial to glacial sediment deposition. The authors also



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describe the lack of dropstones below the upper boundary of Unit II as little ice-rafting activity during the middle Miocene to Pliocene. The middle Miocene age were dated at sediments containing an assemblage of moderately well-preserved Miocene diatoms and radiolarians (Myhre *et al.* 1995). Due to this information, it is difficult to estimate an age of the Unit II/Unit III boundary (379 m b.s.f.).

The deeper lithologies (Unit III and Unit IV) are described as massive and laminated silty clay and clay, with a maximum age of middle Eocene determined at 770 m b.s.f. (Myhre *et al.* 1995). The top of oceanic basement was not reached. With a biostratigraphic analysis on dinoflagellate cysts (Eldrett *et al.* 2004), it was possible to set up a new biostratigraphy for the Eocene–Oligocene interval between 425 and 722 m b.s.f. The good recovery (Fig. 8, 84.1 per cent) and the detailed age analysis within this interval represents the most complete and best-preserved record of the Eocene and Oligocene in the Northern Hemisphere high latitudes. Thus, the age of Unit IIIB, IIIC and a part of Unit IV (674–722 m b.s.f.) have been specified with 35.3–39.5 Ma (Unit IIIA), 39.5–48 Ma (Unit IIIB) and 48–51 Ma (Unit IV, Eldrett *et al.* 2004).

Age correlation and seismic stratigraphy

Previous age information on the East Greenland shelf (Tsikalas *et al.* 2005) are based on reflection character, regional considerations and onshore Greenland geology (Stemmerik 1993). Our correlation is mainly based on marker horizons and reflection character using

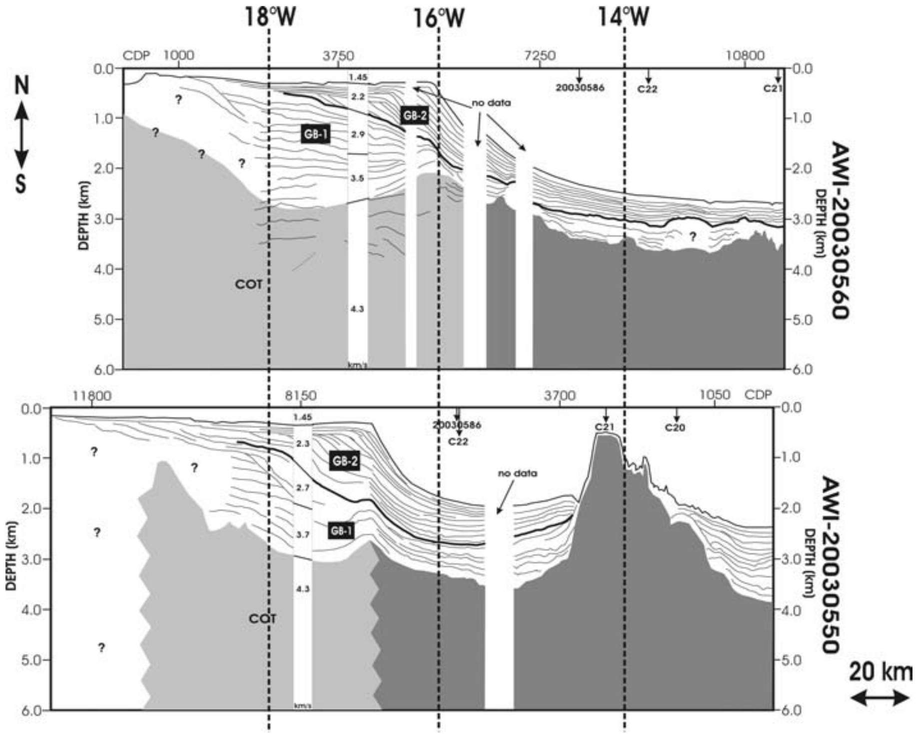

Figure 5. Line drawings of profiles AWI-20030560 and AWI-20030550 (southern Greenland Basin) arranged from north to south and oriented on longitudes 14°W up to 18°W. The numbers at the black arrows represent the crossing profiles at this position. The location of the magnetic spreading anomalies is marked. C22, 49 Myr; C21, 47 Myr and C20, 43 Myr (Gradstein *et al.* 2004). The basement is divided into oceanic basement (dark grey) and continent–ocean transition zone (COT, light grey).

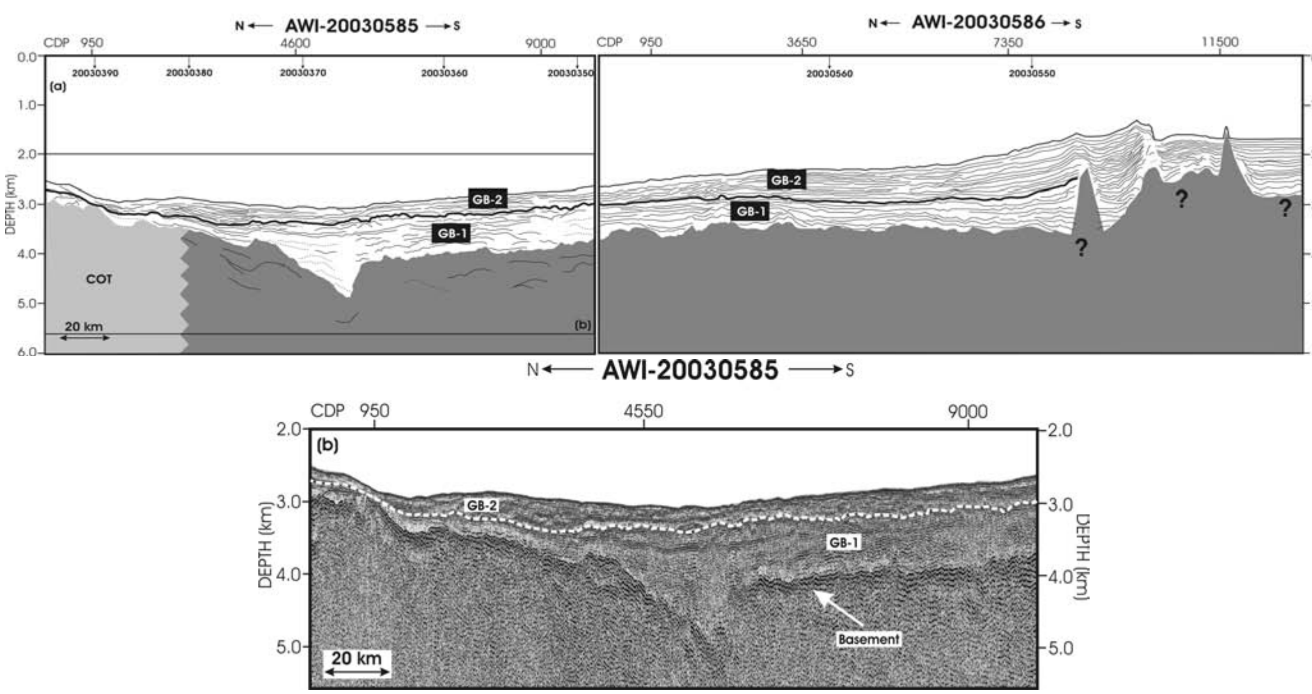

Figure 6. (a) Line drawings of profiles AWI-20030585 and AWI-20030586, north–south oriented profiles along the East Greenland margin (Fig. 1). The location of the crossing profiles are marked. Dark grey show oceanic basement, GB-1 (0–3 Ma) and GB-2 (3–56 Ma), seismic units; COT, continent–ocean transition zone. (b) Seismic depth section of profile AWI-20030585 recorded with the 600 m long streamer. The white dotted line represents the interpreted horizon, which divides the sediment package into GB-1 and GB-2.

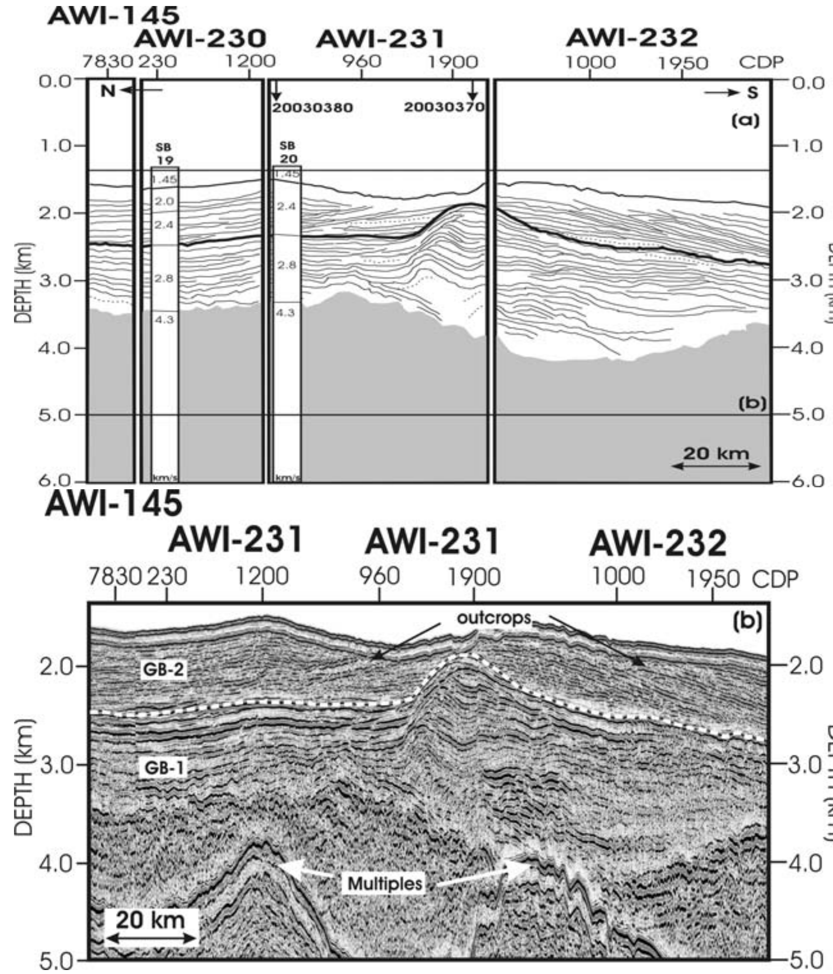

Figure 7. (a) Line drawings of profiles AWI-20030145, AWI-20040230, AWI-20040231 and AWI-20040232 situated parallel to the East Greenland slope in north–south direction (Fig. 1). Sonobuoy 19 (SB 19) and sonobuoy 20 (SB 20) show seismic velocities in km s^{-1} used for the depth conversion. The basement (light grey) represents the continent–ocean transition zone. GB-1 and GB-2, seismic units. (b) Seismic depth section of profiles AWI-20030145, AWI-20040230, AWI-20040231 and AWI-20040232 recorded with the 600 m long streamer, illustrating the upper slope region. The white dotted line represents the interpreted horizon, which divides the sediment package into GB-1 and GB-2.

ODP site 913. At CDP 1252 on profile 20030390, some seismic horizons are observable. The units after Myhre *et al.* (1995) can be identified at this location. A direct correlation of these horizons into the shelf region is prevented by a basement high in the slope region, since the sediments vanish almost above this structure. Therefore, we acquired tie lines to transfer the age of sediment from site 913 onto the shelf. The correlation starts in the deep sea of profile 2000390 and was carried out along lines 20030385, 20030380, 20030585, 20030360, 20040232, 20040231, 20040230 and 20030145 (Fig. 8: inset). East of the high the sediment structure looks chaotic and is interpreted as slump area, following the assumption of Myhre *et al.* (1995). A prominent horizon at a depth of 360 m b.s.f. has very high amplitudes and could be identified outside the slump area along lines 20030585 and 20030586. The other lithostratigraphic units of site 913 were difficult or impossible to correlate into our network. They only have continuity close to the drill site. Away from the site, these signals vanish or become highly subdued, which makes a sound stratigraphic correlation impossible. The prominent horizon is marked with a thick black line in Figs 4(a), 5, 6(a) and 7(a) and by a white dashed line in Figs 4(b), 6(b) and 7(b).

Age information combined with seismic reflection data at the borehole location are summarized in Fig. 8. The grey area in Fig. 8 marks the part of the borehole with good recovery and precise age information. For shallower parts, a lot of data gaps exist.

For the depth conversion of the seismic section, we have used only the seismic velocities from the velocity analysis of the seismic reflection profile. Due to the results of the correlation, we have merged units IA, IB, II (Myhre *et al.* 1995) to unit GB-2 and units IIIA, IIIB, IIIC, IV (Myhre *et al.* 1995) to unit GB-1. According to the found Miocene diatoms and radiolarians at a depth of 375 m b.s.f. (Myhre *et al.* 1995), an age of 15 Myr could be determined for the GB-2/GB-1 boundary (Fig. 8).

The depth differences of the lower boundary between GB-2/GB-1 (375 m b.s.f.) and the depth of the prominent reflector (360 m b.s.f.) may be due to inaccuracies in final depth conversion and the extrapolation of age information from site 913 to line 20030390 (17 km). Because of the dropstones at larger depths (308 and ∼400 m b.s.f., Myhre *et al.* 1995) and the classification of the boundary of non-glacial to glacial sediments (unit II/unit IIIA) by Myhre *et al.* (1995), we suggest that sediment at 360 m b.s.f. were transported in middle Miocene times under glacially conditions.

The result of our correlation shows a division of sediments in the Greenland Basin and the adjacent East Greenland shelf into: primarily non-glacial sediments deposited between 15 and 56 Ma and

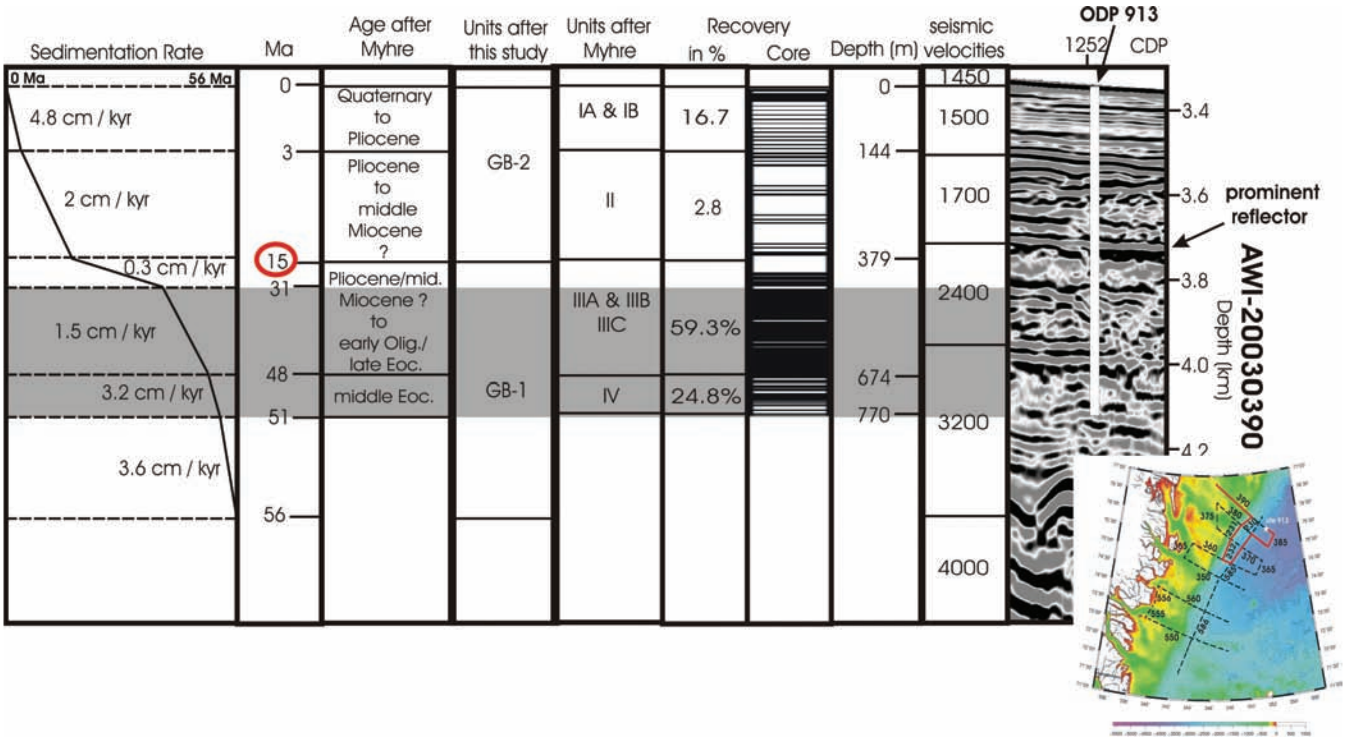

Figure 8. Stratigraphic model for the deep-sea part of the Greenland Basin. Information on ODP drill hole 913 was taken from Myhre *et al.* (1995) and Eldrett *et al.* (2004). The age classification by Eldrett *et al.* (2004) is imaged as grey area. Seismic velocities are determined on the basis of seismic velocity analysis. Definition of unit GB-1 and unit GB-2 was carried out on one prominent horizon visible on profiles located in the southern Greenland Basin. The emphasized age of 15 Ma represents the age of the prominent reflector in the drill hole depth of 360 m b.s.f. The inset map shows the profiles, which were used to correlate the age information of site 913 onto the shelf.

glacial sediments accumulated between 15 Ma and present times. Based on this classification, we follow the speculation of Winkler *et al.* (2002) that ice-rafting has probably occurred since the middle Miocene.

INTERPRETATION AND DISCUSSION

Basement structures

A basement high was discovered beneath the East Greenland margin at the same position (75°43′N, 7°58′W) by Hinz *et al.* (1987). Eldholm and Windisch (1974) have introduced a high overlain by sediments of 0.6 s thickness (75.3°N, 10.5°W and 76.4°N, 5°W). A bit south seismic refraction data from Mutter and Zehnder (1988) show also a basement high, which is landward terminated by an escarpment. No geological age for this feature is available. It was unknown if this structure represents one large slope-parallel feature or consists of a series of local highs. From the new seismic network and the additional bathymetric information, we note that the highs do not occur at a constant water depth. The structural appearance also varies from line to line. Figs 3(a) and 4(a) summarize the results of the E–W seismic profiles. The line drawings show that the basement high is present between lines 20030130 and 20030360. However, the structure is not aligned along a straight line. The bathymetric data do not provide any evidence for fault-controlled offsets that might separate it into several fragments.

Fig. 9 shows the relationship of seafloor spreading anomalies between 74°54′N and 77°N to the seismic profiles of this study. The oldest anomaly identified in this region is anomaly C24B (Talwani & Eldholm 1977). In Fig. 9, all crossings of the basement structure are located landwards of the oldest magnetic anomaly. The nature and age of the crust is unknown between the oldest anomalies and the basement high. However, there are several interesting observations:

(1) The distance between the basement high and chron C24B increases towards the north. This might suggest that this structure formed diachronously.

(2) As mentioned earlier, the continuous structure is not a straight lineament and occurs today at different water depths.

(3) An increasing dip of sediments on both sides at the basement high is not visible, which could point to an uplift after the breakup.

(4) Some profiles (Fig. 4c: 20030390, 20030380, 20030360, 20030350) show evidences for SDRs seawards of the prominent basement structure.

(5) The seismic data show no layering within the basement, which argues against a sedimentary origin (Tsikalas *et al.* 2005). Furthermore, seismic velocities of the rocks at the top of the high is around 4.3 km s^{-1} (Voss *et al.* 2007)

Mutter & Zehnder (1988) calculated a velocity of 4.0 km s^{-1} for the upper part of the high at 75°40′N and 7°50′W. Similar velocities are found by Voss *et al.* (2007). Voss *et al.* (2008) also interpret the basement high, on the basis of seismic refraction data, as basaltic material.

Tsikalas *et al.* (2002) suggest a segmentation of the East Greenland margin along fracture zones, which extend from oceanic crust onto the shelf. For example, the proposed existence of the Bivrost Fracture Zone at 74°40N, 12°W. The seismic network, especially in the deep sea, provides no evidence for the existence of any major fracture zones. Thus, our data do not support the proposed margin

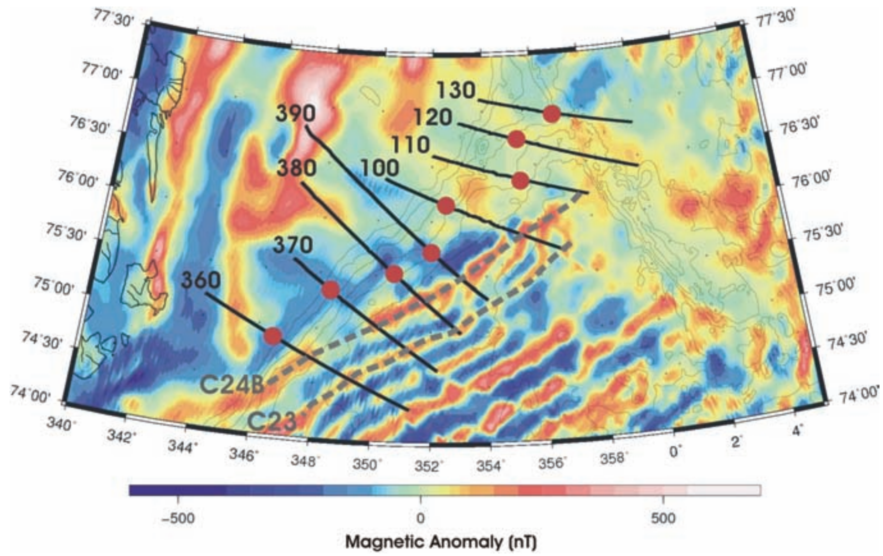

Figure 9. Magnetic anomalies off East Greenland. The black lines show the location of the seismic profiles across the East Greenland continental margin. Dashed grey lines are the oldest spreading anomalies found in the Greenland Basin (C 24B = 56 Myr and C 23 = 51 Myr; Escher & Pulvertaft 1995; Eldholm *et al.* 2002). Red dots locate the basement highs. GFZ, Greenland Fracture Zone.

segmentation. These findings are similar to results of Olesen *et al.* (2007), who identified navigation errors in the old magnetic data, which were interpreted as fracture zone. An new survey confirmed that the magnetic field is not offset by fracture zones.

From several publications, we know that Tertiary magmatism accompanied the final stage of rifting and the opening of the North Atlantic in Early Eocene times (White & McKenzie 1989; Eldholm & Grue 1994; Skogseid *et al.* 2000). The different rifting histories north and south of the Kong Oscar Fjord led to the assumption that pre-existing crustal structures had a controlling character for magmatic depositions (Schlindwein & Jokat 1999). Volcanic material intruded into the sedimentary basins and large amounts of flood basalts were extruded in the southern region around Scoresby Sund (Escher & Pulvertaft 1995). Hints for increased magmatic melt production in the lower crust in this region are given by Schlindwein & Jokat (1999), Voss & Jokat (2007). Deep seismic data in the prolongation of the Kong Oscar Fjord, Kejser Franz Joseph Fjord and Godthåb Gulf are interpreted as magmatic underplating of the East Greenland continental crust. This body vanishes in the northwards direction, and to north of Shannon Island, only slightly intruded lower crust is visible (Voss *et al.* 2007). The deep seismic data indicate that the volcanic activity decreases towards the GFZ. If such a basement high existed in the south, it might have been buried by younger volcanic material, which erupted prior to or during the breakup. Because of the lower amount of erupted material in the northern part of the Greenland Basin, this high might be visible. Another explanation is that the style of volcanism changed in the north and produced material only within a small corridor of the COT.

SDRs on the seaward flank of the high postulated by Hinz *et al.* (1987) are similar to dipping reflectors at the conjugate Vøring Plateau. SDR units on the Norwegian side were drilled and tholeiitic material were recorded (Eldholm *et al.* 1987). We assume the same composition for the conjugate East Greenland SDRs. Based on these observations, we follow the original interpretation of Hinz *et al.* (1987) and Voss & Jokat (2007) and consider the high as a volcanic structure. This volcanic structure might have been emplaced during the initial extensional phases of the opening of the Greenland Basin. The question, if it is a continuous structure or consist the basement high of several fragments, is difficult to answer, and a denser seismic reflection network is needed. However, we favour the interpretation that the basement highs form a prominent, diachronuously continuous structure with a N–S extent of approximately 360 km in different water depth, based on the structural symmetry of N–S and similar seismic refraction velocities (Voss *et al.* 2007; Mutter & Zehnder 1988).

Another prominent basement structure is the GFZ, as imaged on profile 20030120 (Fig. 3a). The GFZ separates the Greenland Basin from the Boreas Basin and has developed during the formation of the Greenland Basin since ~56 Ma (Talwani & Eldholm 1977). The GFZ represents a plate tectonic feature initiated at the transition between rifted and sheared continental margin segments (Faleide *et al.* 1993). During the Eocene, the proto-Greenland–Senja Fracture Zone (pGSFZ) comprised the Senja Fracture Zone along the SW Barents Sea margin and the GFZ along the southwest foot of the elongate, monolithic Greenland Ridge (Tsikalas *et al.* 2002). Faleide *et al.* (2001) speculate that the Greenland Ridge does not resemble a typical oceanic fracture zone and suggested that it may contain a continental sliver. Representative seismic velocities of the crust are not available, and until now, it is not clear if the GFZ is made up of oceanic crust, continental crust or a mixture of both.

A plate tectonic model for the evolution of the Greenland (GFZ)–Senja (SFZ) Fracture zone—Greenland Ridge system—is introduced by Tsikalas *et al.* (2002). In this model NW–SE movements dominate. The 360 km long volcanic structure found north of 75°N along the East Greenland margin is NE–SW oriented and seems to have an independent formation of the GFZ. Hence, the basement high on profile 20030130 (Fig. 3a, CDP 3060–3560) may mark the location, where the GFZ becomes decoupled from the East Greenland margin. In the absence of any deep seismic sounding data, it can only be speculated if this process was accompanied by excessive volcanism or not.

Total sediment thickness

The overall trend is an increase of total sediment thickness (Fig. 10) from the deep sea towards the East Greenland shelf break.

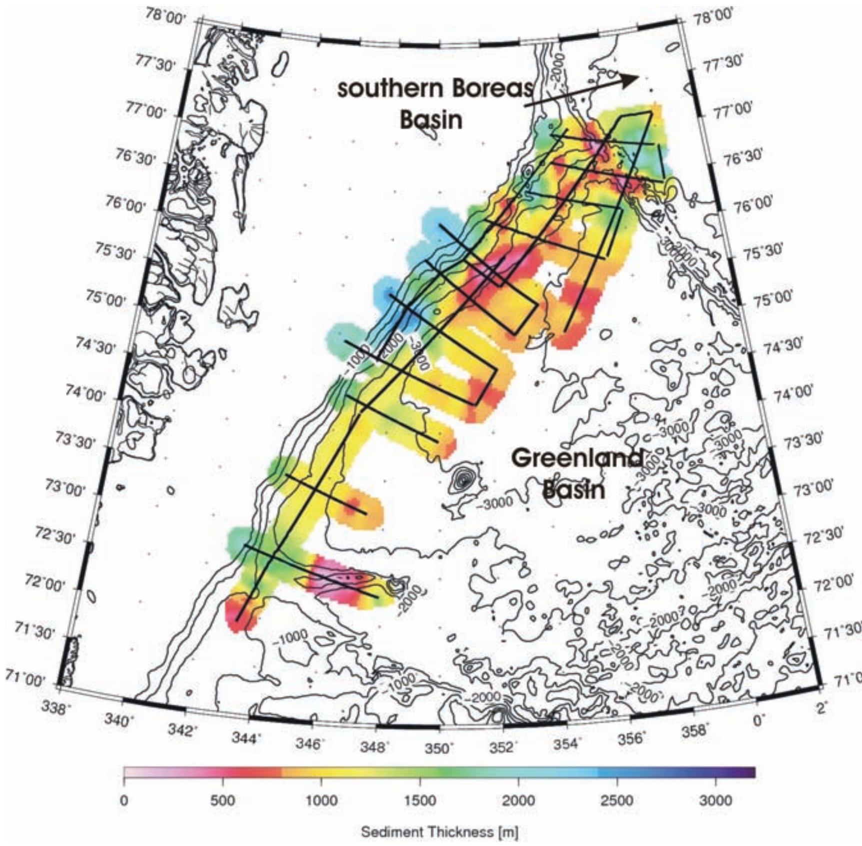

Figure 10. The sediment thickness grid shows a general trend of sediment distribution close to the Greenland margin. Only the parts of the seismic reflection network is shown (black lines), which provide information for this compilation. Bathymetric contours are plotted with a spacing of 1000 m.

The maximum sediment thickness of 3032 m is present on the continental slope at 75°18N. All W–E profiles longer than 100 km in the northern Greenland Basin show a marked decrease in sediment thickness, to less than 250 m, across the basement highs in the slope region. These prominent basement structures are, thus, likely to have formed an obstacle to sediment transport from the shelf into the abyssal plain. In general, the sediment thickness is approximately 1000 m in the Greenland Basin and on average 1800 m in the southern Boreas Basin (Fig. 10). The seismic data show approximately twice as much sediment in the Boreas Basin as in the Greenland Basin. One reason for this could be the absence of a barrier like the basement high on the continental slope. Alternatively or additionaly, the GFZ may have acted as a barrier to southward directed current transport of suspended material, originating from the northern margins of Greenland (77°N and 80°N). In support of this view, it is known that persistent currents are flowing southwards parallel to the margin, in this case, the East Greenland current (Rudels *et al.* 2002). A part of this current separates at the GFZ and enters the Boreas Basin (Rudels *et al.* 2002). We assume, during the separation, the current velocity decreases and more material could be accumulated north of the GFZ. Also the much wider East Greenland shelf north of the GFZ (Fig. 1) could explain that the erosion provided more material than south of 76°N. South of 77°N, well developed prograding sequences on the outer shelf and high velocities (1.8–2.3 km s^{-1}) near the top of the seafloor indicate that the shelf was glacially eroded. So we guess the major source areas for sediments are the Greenland mainland and the shelf. Obviously, the basement highs and the GFZ play an important role in the distribution of the sediment in the investigated area.

Glacial–pre-glacial sediments

Pre-glacial sediment (GB-1) thickness (Fig. 11) was calculated as the depth difference of the top of acoustic basement and the top of unit GB-1 (15–56 Ma). Younger sediments (up to 15 Ma) are represented by the difference between the top of unit GB-1 and the seafloor (Fig. 12; GB-2).

The thickness of GB-1 (Fig. 11) varies between 34 m at the top of the basement high on profile 20030380 and 2720 m at the slope on profile 20030370 (Fig. 4a). Most of the accumulated sediments were found along the East Greenland slope between 74°30′N and 76°30′N. The basement highs visible on profiles 20030390 and 20030380 (Fig. 4a) represent a barrier for the ice rafted material. The top of the high shows almost no sediment deposits before 15 Myr, and the thickness of unit GB-1 decreases from approximately 1000 m in the west of the highs to 400 m in the east of the highs. Also notable is the continuous transition (72°30′N–75°N) of the sediment deposits from the slope to the deep sea where no basement highs could be observed. Sediments within layer GB-1 in the deep Greenland Basin between 73°45′N and 75°30′N increase from 200 m in the north to 1000 m in the south, caused by the disappearance of the basement highs in southern direction.

The thickness of glacial sediment deposits is mapped in Fig. 12 and range between 110 and 1670 m. The sedimentation rates (GB-2) are in general similar in the deep Greenland Basin (2.8 cm kyr^{-1}). However, south of 73°N the sedimentation rates increase to 4.8 cm kyr^{-1}. The transported sediments in the prolongation of the Kejser Franz Joseph Fjord (20030550) is representative of the tremendous sediment transport by glaciers.

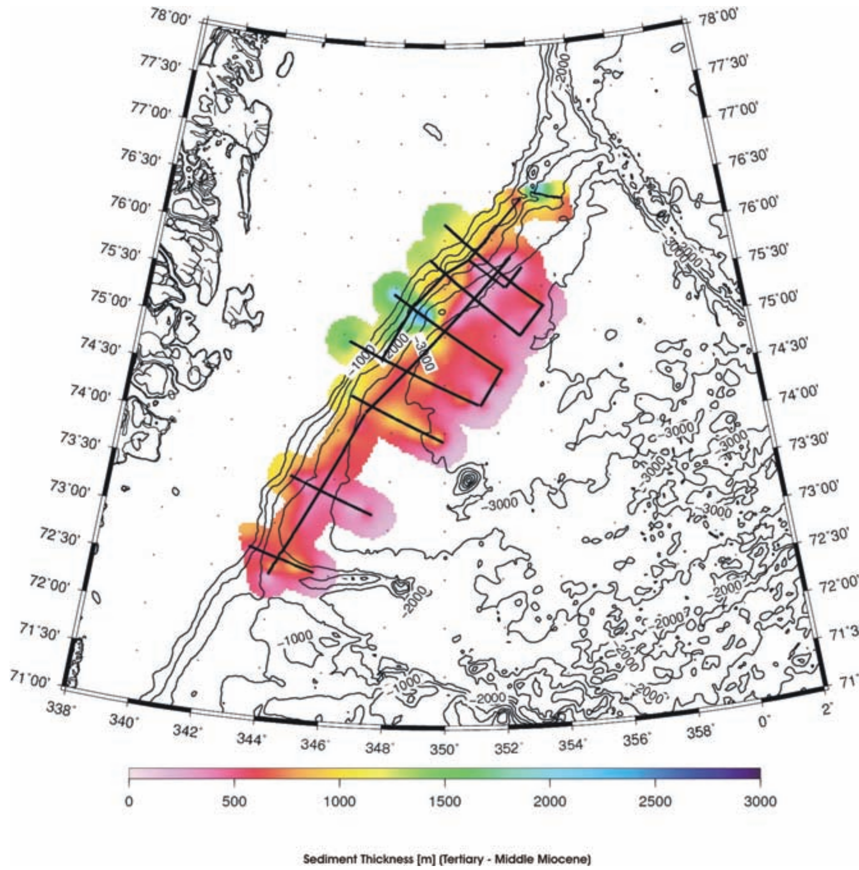

Figure 11. Gridded version of Middle Miocene–present sediment distribution (GB-1) in the Greenland Basin. Only the parts of the seismic reflection network is shown (black lines), which provide information for this compilation. Bathymetric contours are plotted with a spacing of 1000 m.

The largest thicknesses of glacial sediments of 1600 m are found beneath the shelf break. Here, prograding sequences developed in the late Cenozoic as a consequence of advances and retreats if glaciers/ice streams on the outer shelf (Figs 4a and b).

A comparison between sediments, which are younger (GB-2) and older (GB-1) than 15 Myrs show extremly low sedimentation rates for the interval between the continental breakup and the beginning of progradation (GB-1). An average sedimentation rate for the deep sea was calculated with 1.2 cm kyr^{-1}; only 40 per cent of glacial sediment deposits. That means, either most of the older sediments were transported away by deep sea currents or the glaciation of the northern hemisphere has resulted in massive increase of erosion of the Greenland mainland and shelf starting 15 Ma. By means of the broad prograding sequences on the East Greenland shelf over a distance of more than 60 km, we favour the last interpretation. In our interpretation, the sequences are caused as a consequence of sea level changes and glacial erosion. The extend of such an early glaciation is speculative. However, we propose that already in Middle Miocene times, some localised glaciers existed.

CONCLUSIONS

The new seismic profiles in the northern part of the Greenland Basin indicate that a basement high exists south of the GFZ. This basement structure is clearly visible between 74°54′N and 77°N and shows a N–S extent of approximately 360 km. By considering magnetic spreading anomalies and the position of seaward dipping reflectors in the southern Greenland Basin, the structure is located within the COT and seems to have developed parallel with the rifting in this area. We propose that the structure is a volcanic feature, with an age slightly older than 56 Ma. A continuation of this basement structure north of the GFZ seems not to be very probable, but the database in the Boreas Basin does not allow us to rule this out.

Furthermore, our data support the location of the COT termination more or less underneath the present day shelf edge, as proposed independently by deep seismic profiles. The location of this basement structure, together with weak volcanic seaward dipping sequences, support the location of the continent–ocean transition termination as determined by other deep seismic sounding studies. The multichannel seismic lines acquired in 2003 were used to compile a set of maps that provide insight into the sedimentary evolution of this basin. Problems in correlating the deep basin stratigraphy onto the shelf was caused by the presence of a 360 km long volcanic basement structure. A thickness of up to 1 km of glacial deposited sediments were found beneath the shelf break. Prograding sequences are observed over a distance up to 80 km. They started to develop since Middle Miocene times. Sediment thickness values of 1000 m are found in the Greenland Basin, compared with 1800 m in the adjacent Boreas Basin. This higher sediment accumulation might be explained by the separation of the East Greenland current north of the GFZ, the wider shelf area along the Boreas Basin and the absence of the volcanic structure in the slope region. We assume that sediment deposition in the Greenland Basin is mainly influenced by mass transport from the continental slope into the deep basin by fast travelling ice-streams and gravity-driven processes. Evidences for current controlled deposition are obvious. Based on these results,

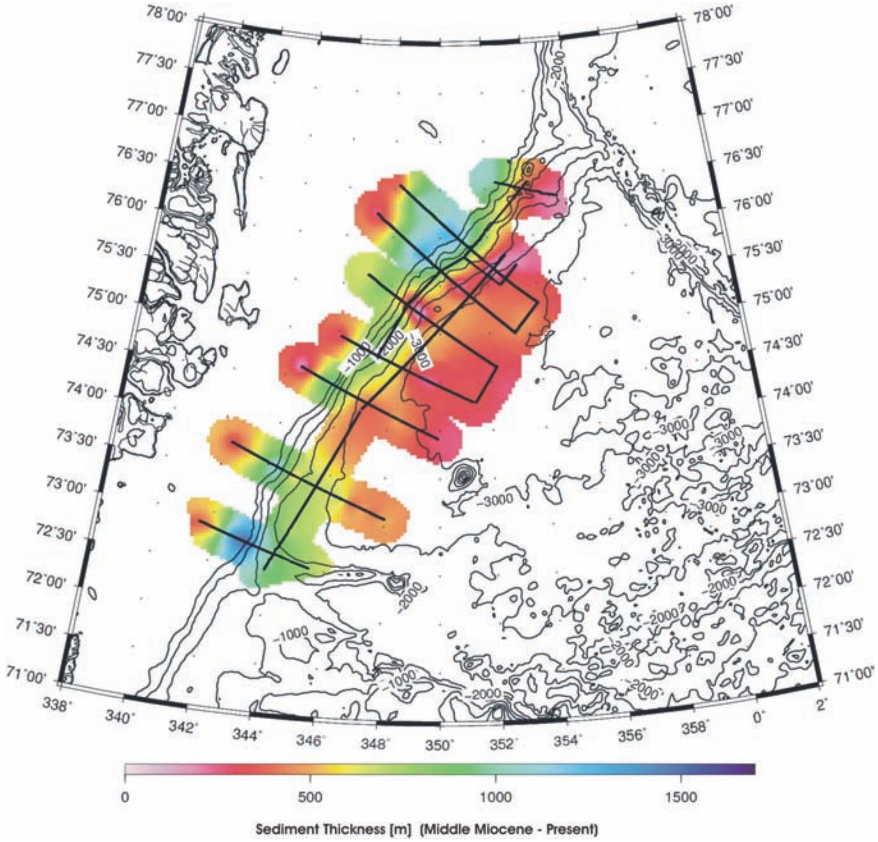

Figure 12. Gridded version of Middle Miocene–Tertiary sediment distribution (GB-2) in the Greenland Basin. Only the parts of the seismic reflection network is shown (black lines), which provide information for this compilation. Bathymetric contours are plotted with a spacing of 1000 m.

we assume that the glaciation of East Greenland caused a massive erosion of the mainland and might have started some 15 Ma.

Finally, a denser seismic network around site 913 is needed to correlate more units along the margin, for more detailed description of the sedimentary history.

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