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On sediment deposition and nature of the plate boundary at the junction between the submarine Lomonosov Ridge, Arctic Ocean and the continental margin of Arctic Canada/North Greenland

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Abstract

The first seismic reflection data from the shallowest part of the submarine Lomonosov Ridge north of Arctic Canada and North Greenland comprise two parallel single channel lines (62 and 25 km long, offset 580 m) acquired from a 10 day camp on drifting sea ice. The top of southern Lomonosov Ridge is bevelled (550 m water depth) and only thin sediments (<50 ms) cover acoustic basement. We suggest erosion of a former sediment drape over the ridge crest was either by a grounded marine ice sheet extending north from Ellesmere Island and/or deep draft icebergs. More than 1 km of sediments are present at the western entrance to the deep passage between southern Lomonosov Ridge and the Lincoln Sea continental margin. Here, the uppermost part (+0.3 s thick) of the section reflects increased sediment input during the Plio–Pleistocene. The underlying 0.7 s thick succession onlaps the slope of a subsiding Lomonosov Ridge. An unconformity at the base of the sedimentary section caps a series of NW–SE grabens and mark the end of tectonic extension and block faulting of an acoustic basement represented by older margin sediments possibly followed by minor block movements in a compressional regime. The unconformity may relate to termination of Late Cretaceous deformation between Lomonosov Ridge and Alpha Ridge or be equivalent to the Hauterivian break-up unconformity associated with the opening of the Amerasia Basin. A flexure in the stratigraphic succession above the unconformity is most likely related to differential compaction, although intraplate earthquakes do occur in the area.

Keywords: Arctic Ocean; Lomonosov Ridge; seismic reflection; sediment drift; sheared margin

1. Introduction

The presence of Lomonosov Ridge, a major Arctic submarine structure which extends from the northern Canadian/Greenland continental margin to the margin of Siberia was first recognized from its effect on basin

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circulation (Harris, 1904; Fjeldstad, 1936). The ridge has restricted deep waters to circulate internally within the two main sub-basins (Amerasia and Eurasia basins), and the intermediate waters to form contour-following currents (1000–1700 m depth) along the ridge flanks (Aagard et al., 1985; Rudels et al., 1994; Nøst and Isachsen, 2003). Polar glacial environments are reflected by reduced surface productivity and large input of terrigenous sediments and ice rafted debris (Clark et al., 1980) as well as evidence of erosion of the seabed by deep draft icebergs down to near 1000 m present water depth (Polyak et al., 2002; Kristoffersen et al., 2004).

Seismic reflection measurements and sediment coring was part of the multidisciplinary Greenland Arctic Shelf Ice and Climate Experiment (GreenICE) to study the structure and dynamics of the sea ice cover and attempt to relate these to a longer term record of climate variability retrieved from sediment cores. The main experiment was carried out from a two-week field camp deployed by Twin Otter aircraft on drifting sea ice at 85°N, 65°W, ca. 170 km north of Ellesmere Island in the Canadian Arctic archipelago (Fig. 1). Statistically, the sea ice drift would be in the sector 90–180°, but wind stresses from persistent easterly winds resulted in a drift trajectory of 245 ± 15°

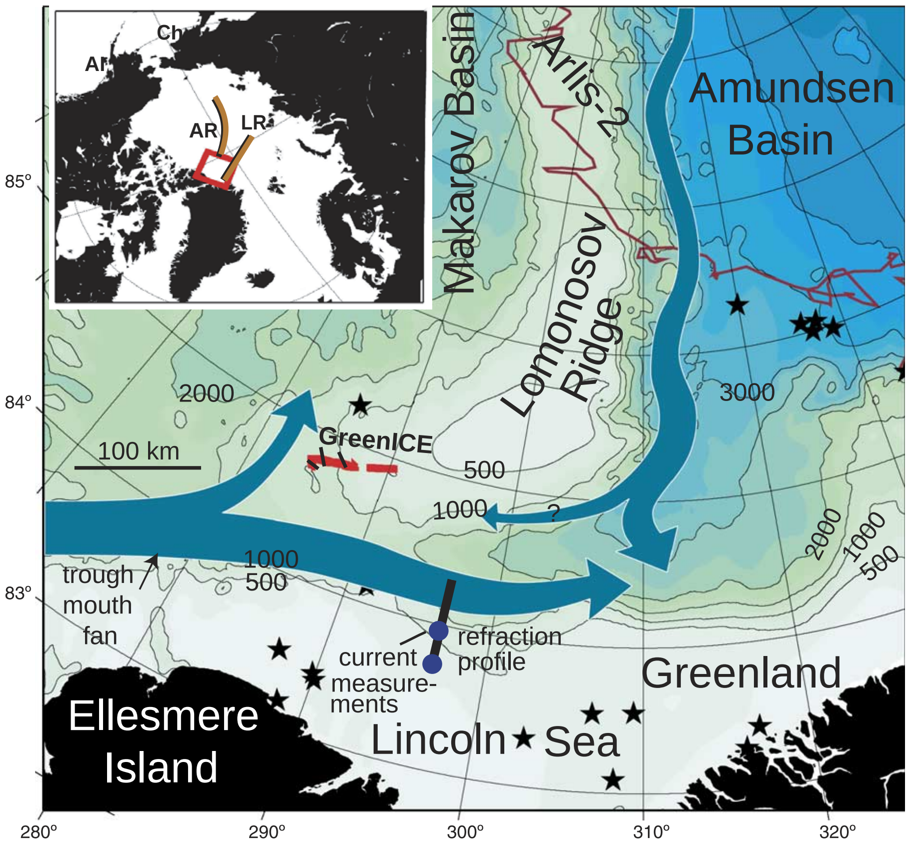

Fig. 1. Bathymetry of the deep passage between the continental margin of Arctic Canada/North Greenland and the adjacent part of Lomonosov Ridge, Arctic Ocean from Jakobsson et al. (2000). Drift path of the GreenICE sea ice camp shown by heavy red line and the track of U.S. ice station Arlis-2 from 1965 (thin red line). The N–S seismic refraction profile of Argyle et al. (1994) on the Lincoln Sea continental margin is located by heavy black line and current measurements of Newton and Sotirin (1997) by blue dots. Earthquake epicentres (stars) are from the catalogue available at http://www.seismo.nrcan.gc.ca. The general oceanic circulation from Newton and Sotirin (1997), Rudels et al. (1994, 1999) and Nøst and Isachsen (2003) is shown schematically. Major features in insert map are: Alpha Ridge (AR) and Lomonosov Ridge (LR) shown in brown color, and Alaska (Al) and Chukota (Ch). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1). Here, we report results of the seismic reflection program which show a 1 km thick sediment accumulation comprising three distinct phases in the depositional and tectonic environment on the southern Lomonosov Ridge and the western entrance to the deep passage between Lomonosov Ridge and the Lincoln Sea continental margin.

2. Geological and oceanographic setting

A ca. 250 km long section of the Lomonosov Ridge north of Canada and Greenland has water depths less than 1000 m and represents the widest and shallowest part of the entire submarine ridge (Fig. 1). Aerogeophysical potential field surveys have greatly advanced our definition of regional lithosphere properties and domains in the Arctic Ocean (Glebovsky et al., 2000; Brozena et al., 2003), but the only seismic transects over the Lomonosov Ridge between Canada/Greenland and the North Pole obtained to date are from ice station Arlis-2 in 1964 (Ostenso and Wold, 1977) and North Pole-28 in 1988 (Gramberg et al., 1991) more than 250 km to the north of the present survey area (Fig. 1). The collective geophysical and geological characteristics such as stratigraphic architecture, tectonic style and crustal properties all favour an origin of the ridge as a continental sliver representing the pre-Cenozoic Barents–Kara sea continental margin (Wilson, 1963; Sweeney et al., 1982; Jokat et al., 1992). At least the central part of the ridge was peneplained at or above sea level and subsided in the early Cenozoic to receive a blanket of 450 m of hemi-pelagic sediments (Jokat et al., 1992; Shipboard Scientific Party, 2005).

The general oceanographic circulation pattern is inferred from dynamic computations (Jones et al., 1995; Rudels et al., 1999; Nøst and Isachsen, 2003). The only direct current measurements are limited to the upper slope off Lincoln Sea shelf (Fig. 1) where velocities less than 10 cm/s are observed (Newton and Sotirin, 1997). An eastward flowing boundary undercurrent along the continental slope of Arctic Canada branches off to the north along the Amerasia Basin side of Lomonosov Ridge (Fig. 1). The main body of water flows east through the deep passage between the

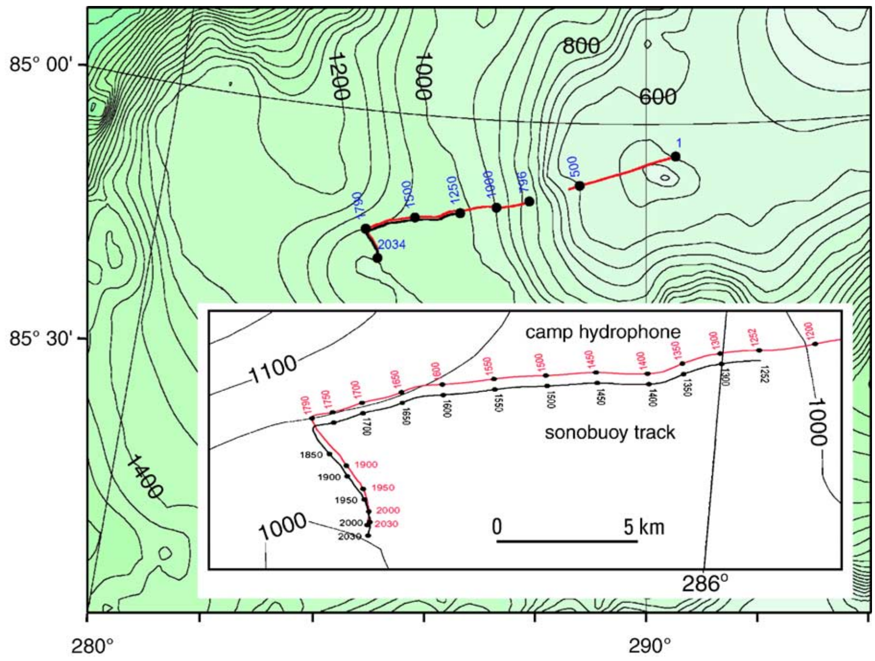

Fig. 2. Location of shot points for the signals recorded by a hydrophone at the GreenICE camp and the corresponding midpoints of the reflections recorded via the sonobuoy radio link.

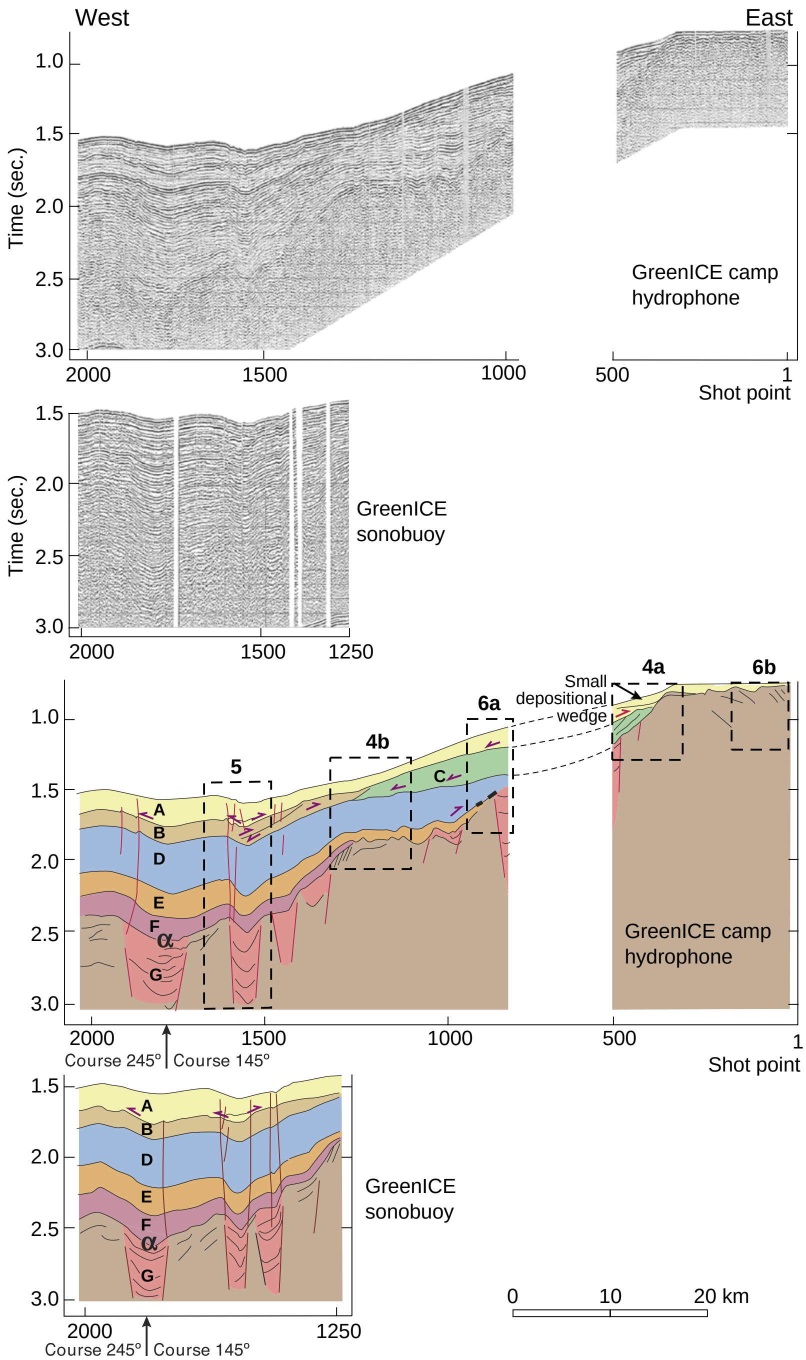

Fig. 3. Seismic reflection profiles and interpretive line drawings. Arrows above sequence boundaries represent onlap and downlap directions. Dashed boxes refer to locations of seismic sections shown in Figs. 4–6.

ridge and the continental margin north of Arctic Canada and Greenland and merge with contour currents flowing south along the Eurasia Basin slope of Lomonosov Ridge.

3. Methods

Seismic reflection measurements from camps on drifting sea ice may be carried out with a very simple experimental set-up as the ambient noise level in an ice covered ocean is well below sea-state zero of open-ocean conditions (Knudsen et al., 1948; Wenz, 1962; Dyer, 1984). The seismic source was a 0.15 l air gun suspended at 5 m depth through a hole in the ice and signals were recorded by a hydrophone at the same depth at 35 m offset as well as by a sonobuoy at an offset of 1.18 km perpendicular to the main drift direction (Fig. 2). The sonobuoy-offset distance was constrained to be less than the critical distance for refracted arrivals from the seabed. The ice surface moved at a rate of 3–10 km/day and the air gun was triggered at 4–12 min intervals to obtain a nominal shot point distance of 35 ± 7 m. During a 10-day period, 62 km of seismic data was acquired using the camp hydrophone and 26 km by the sonobuoy. The seismic data was edited, bandpass filtered, deconvolved, and migrated before final display (Fig. 3). Seismic velocities from the refraction experiment of Argyle et al. (1994) were used for calculations of normal move-out corrections for the sonobuoy data.

4. Results

Seismic reflection events interpreted as acoustic basement are close to the seabed on top of the southern end of Lomonosov Ridge and deepens into the basin with strongest amplitudes on local highs (Fig. 3). The overlying stratified sediments reach a thickness of 1 s two-way travel time below the lower slope.

Stratal geometries within the sediments suggest at least seven depositional units (units A–G) which reflect changes in the depositional environment (Fig. 3). The uppermost unit A is thickest in the deep passage and on the upper slope (<0.15 s). The basal part of the unit infill depressions in the deep passage and onlap the lower slope at higher stratigraphic levels in this area (Fig. 3, arrows in line drawing and Fig. 5). The locally thicker part of Unit A below the upper slope is remarkable in that it downlaps on the substratum at its lower end and onlaps upslope (Fig. 3, arrows in line drawing, and Fig. 4A). A small depositional wedge forms the upper part of Unit A on the upper slope (Figs. 3 and 4A) and only a thin (<0.05 s) veneer of sediments are present above an “acoustic basement type” reflection on top of the bevelled shallow southern end of Lomonosov Ridge. Unit B forms a 0.13 s thick wedge onlapping the lower slope. The upslope termination of Unit B is partly obscured by a pegleg multiple in the primary reflection image, but inspection of the first multiple reflection clearly shows its relation to the underlying Unit C (Fig. 4B). Unit B appears internally complex as a basal subunit show local basinward downlap and upslope onlap while the bulk of Unit B onlaps this subunit (Fig. 3, line drawing). The underlying Unit C has a lenticular cross section (thickness <0.35 s) and is confined to the middle slope (Fig. 3). Unit C onlaps upslope on acoustic basement and display basinward downlap on the underlying unit D. Unit C thins or is erosionally truncated below the lower slope (Fig. 3, line drawing and Fig. 4A). Unit D is 0.4 s thick below the lower slope and becomes attenuated upslope by basal onlap (Fig. 3). Acoustic stratification appears laterally uniform below the upper slope, but show evidence of local truncations and mound-like structures in the upper middle part of the unit below the lower slope (Fig. 5). Unit D is bounded below at its upslope end by a distinct reflection segment which form the top of an acoustic basement high and extend ca. 700 m beyond the fault scarp (Fig. 6A). The underlying units E and F terminate against isolated basement highs and are bounded by unconformities which stratigraphically represent different basement levels (Figs. 3, 4B and 6A). Reflection amplitudes within Unit E appear to be highest near the upslope termination of individual acoustic horizons and decrease laterally downslope (Fig. 3). Below the lower slope, acoustic stratification appears laterally uniform in both units, except local truncations associated with a small downward convex reflection within Unit E below the base of slope. A short conspicuous high

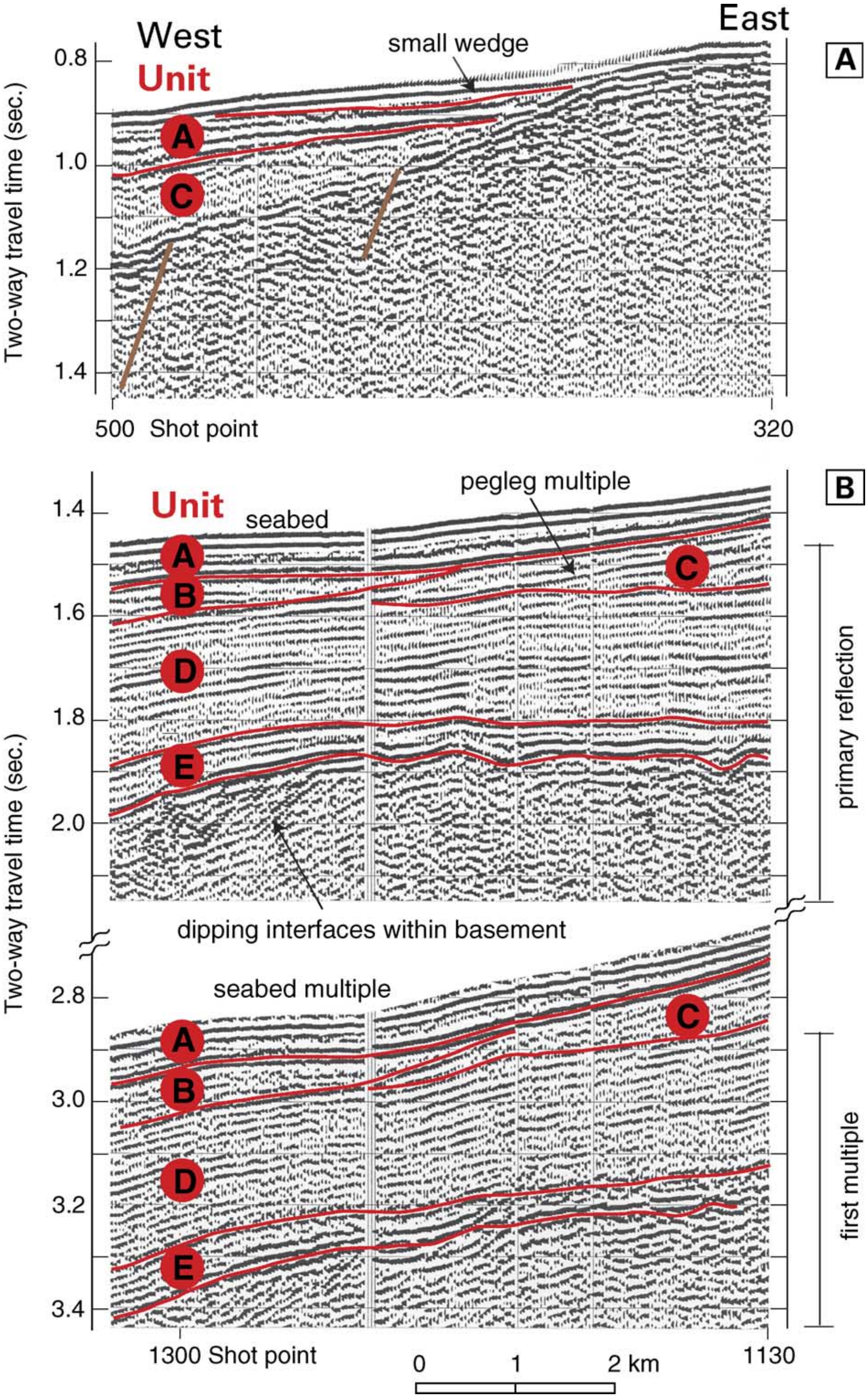

Fig. 4. Parts of the GreenICE seismic profile with interpreted sequence boundaries (red) illustrating the small depositional wedge (A) and the relation between units B and C (B). Location of profile interval is shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

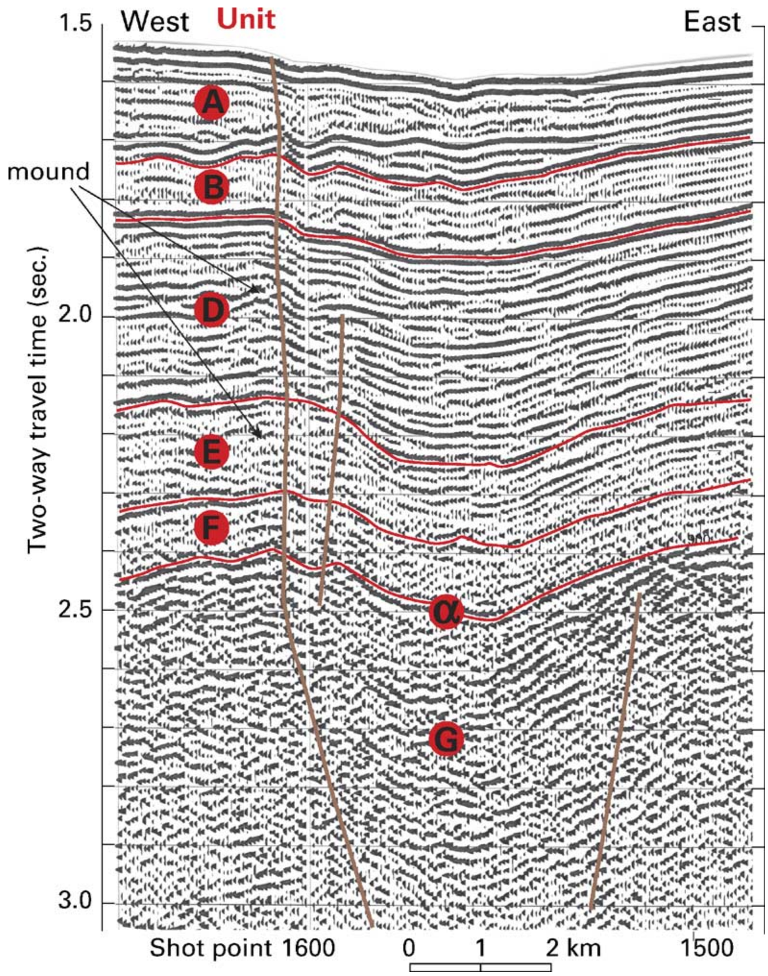

Fig. 5. Part the GreenICE seismic profile with interpreted sequence boundaries (red) demonstrating the relation between the deep grabens and deformation in the overlying depositional sequences. Interpreted fault traces shown by brown lines. Location of profile interval is shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

amplitude reflection segment is present at the upslope termination of units E and F and the base of Unit D on top of a basement high (Figs. 3 and 6A). The base of Unit F (reflector α) represents the most distinct unconformity within the entire stratigraphic section (Figs. 3 and 5). Below this level, Unit G fills small grabens with a more than 0.6 s thick succession. Grabens below the lower slope are <3 km wide, and is not possible to ascertain whether a single large graben or several smaller grabens are present below the upper slope where data are missing (Fig. 3, shotpoint 500–800). Note that the apparent width of the graben at shot point 1750–1850 is due to a course change and crossing of the same boundary fault (Figs. 2 and 3). The thickness of internal layers within Unit G appears uniform within the resolution of the data with some lateral attenuation towards the bounding faults.

Acoustic basement is generally defined by distinct reflection events below the slope, but more obscure in the deep basin (Figs. 3 and 4). East dipping reflection events are present within acoustic basement on top of Lomonosov Ridge (Figs. 3 and 6B), while a basement high below the lower slope show internal west dipping events. A flexure including minor offsets in the sedimentary succession extends to the seabed and

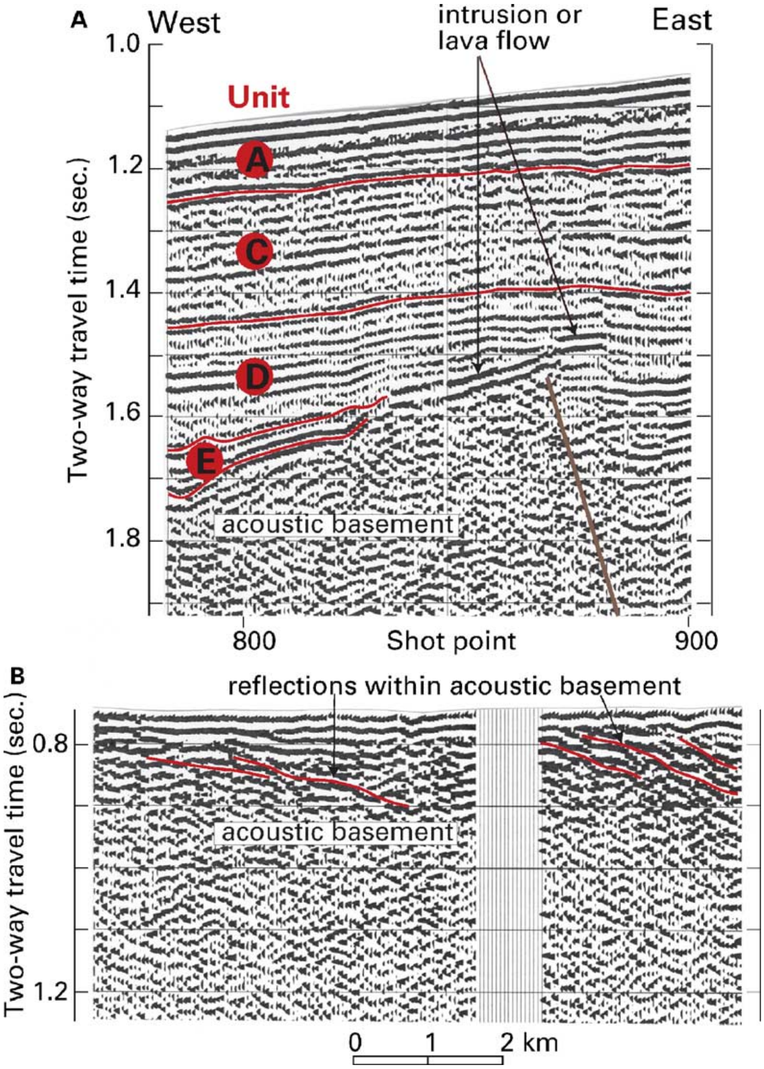

Fig. 6. Details of GreenICE seismic section showing the reflection event interpreted as lava flow or intrusion (A), and dipping events within acoustic basement on top of southern Lomonosov Ridge (B). Interpreted fault trace is shown by brown line. Location of profile intervals is shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

appears to be spatially related to a basement graben below (Figs. 3 and 6).

5. Interpretation

The absence of a sediment drape on southern Lomonosov Ridge, a difference in overall geometry between the upper units (A, B and C) and the lower units (D–F) on the slope together with a distinct unconformity α between units G and F are the first order stratigraphic characteristics of the east–west seismic section on the slope of southern Lomonosov Ridge (Fig. 3). The thin unit (<0.05 s) covering undulating acoustic basement topography on top of the southern Lomonosov Ridge (Fig. 3) contrasts with documentation for the presence elsewhere of a +450 m thick sediment drape capping older rocks in the crestal region on Lomonosov Ridge. A drape is observed from less than 300 km north of the Green-ICE area (Fig. 1) to the Siberian continental margin (Ostenso and Wold, 1977; Jokat et al., 1992; Kristoffersen, 2000; Shipboard Scientific Party, 2005). The southern Lomonosov Ridge may either have been an area of persistent non-deposition, or a sediment drape was deposited but later removed by erosion. Evidence of ridge top erosion is reflected in a bevelled seabed and the presence of a small depositional wedge within Unit A below the uppermost slope (Figs. 3 and 4A). Bottom currents may erode unconsolidated sediments, but bevelling of a bathymetric high most likely imply erosion at or near sea level with subsequent rapid subsidence (Shipboard Scientific Party, 2005), or depth limited erosion by deep draft glacier ice as observed on other ridges and marginal plateaus in the Arctic Ocean (Polyak et al., 2002; Kristoffersen et al., 2004). We propose that at least the uppermost 0.05 s thick wedge of Unit A on the upper slope (Figs. 3 and 4A) represents redeposited sediments eroded from the top of the ridge by deep draft glacier ice either represented by deep draft ice bergs en route to the Fram Strait exit or more efficiently by a marine ice sheet or an ice tongue extending 100 km north from the shelf edge north of Ellesmere Island (Fig. 1). In this respect, the dynamics of the present circum-Antarctic coastline includes several ice tongues advancing more than 100 km from the adjacent ice edge (Swithinbank et al., 1988). Below the wedge, the apparent local thickness maximum of Unit A on the upper slope associated with onlap on the underlying Unit C below the small wedge and downlap farther downslope (Figs. 3 and 6A, shot point 450–1000) may represent crossing of the flank of a depositional lobe or possibly a convex-upward aggradation of an elongated, plastered sediment drift (Faugères et al., 1999). A single seismic profile and the data gap (Fig. 3, shot point 500–800) is insufficient to distinguish between these possibilities. We note however, that infilling of lows in the deep passage and onlap in the lowermost slope within Unit A suggest significant contribution by turbidities and minor control of deposition by bottom currents which makes interpretation of Unit A as a sediment drift less likely.

Within the context of our limited data set, Unit B forms a wedge restricted to the deepest slope. The internal stratal geometry appears complex with the lowermost part of the unit forming a confined, low-relief mound below the lower slope while the basinward part of Unit B onlaps this mound (Fig. 3, line drawing). Possible erosional truncations cannot be resolved in the data. Deposition of Unit B may have been sourced by gravity driven flows originating from Lomonosov Ridge or possibly from the Canadian continental margin as well. The origin of the basal mound-like deposit remains enigmatic.

The geometry, position and regular internal structure of Unit C resembles the overlying part of Unit A on the upper slope (Figs. 3 and 4). Basinward, Unit C downlap on the underlying Unit D and onlap can be observed below the uppermost slope. However, the data gap (shot point 500–800) precludes a safe distinction between the possibilities of Unit C being a prograding wedge sourced by erosion of the Lomonosov Ridge or a convex-upward accumulation representing either an offset crossing of a depositional lobe or a sediment drift deposit plastered on to the upper slope (Fig. 3). Sediment drifts are considered to form where the gradient in bottom current velocity is low (Faugères et al., 1999). It appears clear, however, that the geometries and spatial variability of units A–C represent more variable and energetic depositional environments than the units below.

Unit D has an overall geometry characteristic of an onlap sequence on a subsiding margin. In general, seismic horizons are laterally continuous and suggest bottom currents had no significant influence on sediment deposition except for a stratigraphic interval in the middle-upper part of the unit below the lower slope. Amplitudes show considerable lateral variations below the lower slope and reflectivity is higher in the upper part relative to the lower part (Fig. 3). Possible explanations may be acoustic tuning effects of subunit thickness variations, lateral variation in clay content or possibly change in sand fraction. We interpret Unit D as an accumulation of silty/sandy clay most likely sourced from the adjacent part of Lomonosov Ridge situated at or near sea level.

Units E and F are similar in that the bounding reflection events merge upslope with the top of basement highs at their respective stratigraphic levels (Fig. 3). The distinct reflections (Figs. 3 and 6A, shot point 900–1300) within Unit E may be due to sandier facies proximal to the source area. Relict mounds and/or channels appear to be present within Unit E below the lowermost slope (Fig. 5). We suggest units E and F represent the sedimentological response of two successive events of margin subsidence.

Reflector α represents a dramatic change in the tectonic environment where the underlying Unit G infill a series of small grabens, minor half-grabens and small offsets in acoustic basement at the western entrance to the deep passage between Lomonosov Ridge and the Lincoln Sea margin (Figs. 3 and 5). Although the geometry of acoustic interfaces within Unit G are not well resolved in our data, infill synforms appear to have near parallel internal acoustic layering with some attenuation towards the boundary faults (Fig. 5). We suggest this is partly due to deformation from movement of adjacent basement blocks and partly primary depositional dips from erosion of adjacent block shoulders. Alternatively, this may be the combined result of longitudinal sediment input along the axis of the graben and differential compaction. Normal faulting and graben formation reflect an early extensional regime while later block movements and deformation of Unit G may have been in response to a component of compression. A flexure (Figs. 3 and 5, shot point 1560–1610) constitutes the largest topographic undulation on the upper surface of Unit G. The flexure amplitude is progressively attenuated upsection towards the present seabed (Fig. 5). This deformation of units A–F may be the combined effect of differential compaction and probably also a response to minor relative movements of adjacent basement blocks.

Acoustic basement is likely to be blocks of older margin sediments displaced by a series of faults as documented by the internal acoustic layering. A local distinct and spatially confined reflection event at the base of Unit D (Figs. 3 and 6A) may represent a basalt flow or intrusion. While no velocity information is available from this survey to characterize the ca. 1 km thick sediment accumulation and acoustic basement, we note the refraction profile of Argyle et al. (1994) about 100 km towards the southeast (Fig. 1) which report an upper, ca. 1 km thick layer with velocity <2 km/s overlaying a unit of similar thickness with velocity 3.4–3.6 km/s. The latter unit extends from the Lincoln Sea shelf into the basin. What is here defined as acoustic basement is likely older sedimentary rocks with velocities >3.5 km/s. An apparent eastward dip of strata within the high standing acoustic basement on top of Lomonosov Ridge (Figs. 3 and 6B) may be a primary depositional feature or a result of block rotation. If primary, the sediment source directions had to be from a SW–W–NW sector. The opposite westward dip within fault blocks below the slope suggest tectonic rotations are also involved.

6. Discussion

6.1. The depositional environment

The presence of hemi-pelagic sediments draped over the entire length of Lomonosov Ridge surveyed to date (ca. 80%) documents a Cenozoic environment with weak bottom currents, except for a major hiatus at the Paleogene–Neogene transition observed at the ACEX site (Shipboard Scientific Party, 2005). Assuming similar oceanographic conditions existed for the southern Lomonosov Ridge, the bevelled crest and thin (<50 m) cover of unconsolidated sediments smoothing crestal basement topography suggest non-deposition or erosion of a sediment cover of unknown original thickness. Non-deposition at water depths comparable to the present is less likely from the arguments given above, whereas non-deposition on a more elevated ridge segment and subsequent subsidence remains an open possibility not possible to document at present. Consider adding a cover of uniform and undisturbed hemi-pelagic drape (thickness >400 m) to the present elevation of acoustic basement (550 m) on the southern Lomonosov Ridge. Adjusted for isostasy, it implies a water depth of less than 350 m and the shallow southern Lomonosov Ridge would have represented a major Pleistocene sediment source area for the adjacent slope and basin mobilized by eroding agents such as drifting deep draft icebergs (Polyak et al., 2002; Kristoffersen et al., 2004) or a grounded marine ice sheet extending 100 km to the north form the shelf edge north of Ellesmere Island. Both agents may have operated at separate times.

We propose that Unit A was most likely sourced from erosion of a pre-glacial hemi-pelagic cap on the southern Lomonosov Ridge (Fig. 3). Also, Unit B may relate to this event. The unconformity defined as acoustic basement on the ridge crest may relate to erosion while the ridge was at or near sea level during the Paleogene (Shipboard Scientific Party, 2005). Erosion by mountain glaciers and subsequently by extensive ice sheets associated with Northern Hemisphere glaciation represented a dramatic input of sediments to the Arctic continental margins (Rasmussen and Fjeldskaar, 1996) with enhancement of the near bottom nepheloid layer on the continental slopes and rises. The deep passage between the Lincoln Sea continental margin and the southern end of Lomonosov Ridge (Fig. 1) received sediment input at its western end from a trough mouth fan formed by ice streams from Ellesmere Island through fjords and inlets and in the east by material transport across the Lincoln Sea shelf and upper slope from ice coming through Nares Strait or from northern Greenland (England, 1999). Turbid water associated with down-slope sediment transport events would be entrained in along-slope bottom currents and the suspended load redeposited in part as contourite contributions to accumulations such as the upper slope part of Unit A as well as Unit C (Fig. 3).

The change in stratal geometry between the upper units A–C and underlying units reflects a change in the depositional environment with striking similarities to other ridges such as Jan Mayen Ridge in the Norwegian–Greenland Sea (Kuvaas and Kodaira, 1997) and Broken Ridge in the eastern Indian Ocean (Driscoll et al., 1991) where the geological history has been tested by scientific drilling. Onlap sequences were deposited along the foot of slope as these ridges were at or above wave base, and ridge submergence is characterized by deposition of sediments capping the top erosional surface. We consider Unit D as well as underlying units E and F to be sourced from subaerial erosion of southern Lomonosov Ridge. The basinward change in reflectivity of the deeper units (E and F) in the proximity of acoustic basement highs suggest they were close to the source area i.e. relatively shallow water while the sediments in Unit D was deposited in a more distal position and deeper water. This implies accelerated basin subsidence.

6.2. On the age of stratigraphic units

If Unit A and possibly units B and C represent redeposited material partly derived from a former hemi-pelagic drape on the southern part of Lomonosov Ridge eroded by ice, it would require ice streams calving at the circum-Arctic continental margin. Presently, the earliest direct evidence of glaciation is from Banks Island about 200 km from the shelf edge in the western Canadian Arctic. Sediments younger than 1.77 Ma have recorded two and possibly five full continental glaciations below the Bruhnes–Matuyama boundary (0.78 Ma) and three within the geomagnetic normal polarity zone (Barendregt et al., 1998). We tentatively assign a middle-late Pliocene age to units A and B. The accumulation of Unit C indicates high sediment input and/or an altered or more vigorous bottom current circulation. The most likely environment is enhanced terrestrial input from erosion by mountain glaciers or extensive ice sheets on the neighbouring continents and their margins during the Plio–Pleistocene intensification of Northern Hemisphere glaciation. The sediment source area for Unit D is considered to be the adjacent southern Lomonosov Ridge at least in part exposed subaerially. Here, acoustic basement is ca. 0.5–1 km higher than elsewhere on the Lomonosov Ridge, and the subsidence of this southern block following the Paleogene separation from the Svalbard margin, must have been less and/or slower. Unit D is locally intruded by a sill or resting on a basalt flow capping acoustic basement (Figs. 3 and 6A). About 200 km to the south on northern Ellesmere Island, most of the volcanism took place during the late Cenomanian–Maastrichtian (Embry and Osadetz, 1987; Estrada and Henjes-Kunst, 2004), and if correlative, the base of Unit D may be Late Cretaceous or younger. At a deeper level, reflector α marks the end of a tectonic active phase with deposition of graben fill (Unit G) and shift to sediment deposition in a subsiding basin (units F and E). In this sense, the interface may be a possible stratigraphic equivalent to the Hauterivian break-up unconformity of Embry and Dixon (1994) or relate to a postulated younger Late Cretaceous deformation event between the Lomonosov Ridge and Alpha Ridge (Jackson and Gunnarsson, 1990).

6.3. Plate boundary issues

There is considerable uncertainty as to the nature and tectonic history of the plate boundaries related to the Lomonosov Ridge (Jackson and Gunnarsson, 1990). In the Makarov Basin, the foot of Lomonosov Ridge is associated with the pre-Cenomanian (Chron 34) plate boundary of polar Europe. Several workers suggest the Canada Basin evolved throughout the Late Jurassic/Early Cretaceous by rifting of a platelet comprising Arctic Alaska and Chukota away from the Canadian craton with a strike slip boundary along the former Barents–Kara Sea margin (Green et al., 1986; Embry and Dixon, 1994; Grantz et al., 1998). Plate tectonic reconstructions also indicate compression between Lomonosov Ridge and Alpha Ridge for the subsequent period between Chron 34 and Chron 24 (Jackson and Gunnarsson, 1990) as well as slight relative motion between Lomonosov Ridge and Ellesmere Island and Greenland (Srivastava and Tapscott, 1986; Brozena et al., 2003). The two parallel seismic lines acquired from the GreenICE camp define a NW–SE strike of tectonic structures (Fig. 1) which is parallel to well defined magnetic trends in the area (Nelson et al., 1998). Acoustic basement offset by normal faults and graben formation indicate extensional disruption of the sediments of a former continental margin trending near parallel to the Lomonosov Ridge (Fig. 1). The style of deformation of Unit G is not well resolved in our seismic data, but indicate minor compressive movements prior to development of reflector α (Figs. 3 and 5). Alternatively, the internal geometry of Unit G is a seismic expression of a negative flower structure indicative of shear between basement blocks (Harding et al., 1985). Some faults project from the edge of basement blocks through the younger sediments to the seabed (Figs. 3 and 5). Part of the deformation is most likely due to aseismic differential compaction, although intraplate earthquakes do occur in the area (Fig. 1). The present seismicity along the continental margin (Fig. 1) is considered to result from a combination of sediment loading and glacial rebound (Fujita et al., 1990). The seismic reflection event interpreted as a basalt intrusion (Figs. 3 and 6A) may relate to the question of continuity of coeval basalt provinces in the Barents Sea (Grogan et al., 1999), Franz Josef Land and the Canadian Arctic Islands (Embry, 1994). About 600 km to the north of the survey area, seismic reflections interpreted as basalt are present below 600 m of sediments on top of the central part of Lomonosov Ridge (Kristoffersen, 2000). However, the continuity of these isolated postulated basalt occurrences is uncertain as a few magnetic anomaly highs between the two areas suggest only isolated magmatic overprints (Brozena et al., 2003).

7. Conclusions

While an ocean covered by sea ice offers a quiet acoustic environment and a “rigid” framework for deployment of sensors for seismic measurements, the actual drift path (WSW) is governed by the local wind field rather than statistics of past ice floe trajectories (ESE). Signals from a small air gun source (0.15 l) recorded at a camp hydrophone and by a sonobuoy (offset 1.18 km) yielded two parallel seismic lines (0.59 km apart) with up to 1.5 km of sub-bottom penetration in 1 km water depth. This represents the first seismic reflection data from the shallowest part of Lomonosov Ridge and slope into the passage between the ridge and the continental margin of Arctic Canada and Greenland.

The top of Lomonosov Ridge (550 m water depth) has been planed by erosion and acoustic basement formed by eastward dipping stratified rocks are covered by a thin veneer (<0.05 s) of unconsolidated sediments. A former hemi-pelagic drape has most likely been eroded by a grounded marine ice sheet and/or deep draft icebergs. On the southwestern slope of Lomonosov Ridge, a more than 1 s thick section onlaps the ridge slope and show three distinct depositional phases; an upper ca. 0.3 s thick part (units A–C) where sediment input was relatively high, a middle part (units D–F) ca. 700 m thick which onlaps a subsiding ridge slope, and below a basal unconformity (α) partly deformed graben fill (Figs. 1 and 3). Increased sediment input is considered to relate to intensification of Northern Hemisphere glaciations during the Plio–Pleistocene with erosion by ice of a former sediment drape on top of Lomonosov Ridge. Sediment source area for the underlying units D–F were probably an adjacent subaerial part of Lomonosov Ridge. The basal unconformity marks a termination of tectonic movements which include normal faulting and graben formation followed by minor compressive movements. The unconformity could be associated with termination of postulated Late Cretaceous deformation between Lomonosov Ridge and the Alpha Ridge (Jackson and Gunnarsson, 1990) or the equivalent of the Hauterivian breakup unconformity related to opening of the Amerasia Basin (Embry and Dixon, 1994). Acoustic basement is formed by NW–SE trending blocks of older sediments. Minor deformation of the stratigraphic succession above the main unconformity is most likely a result of differential compaction, but intraplate earthquakes do occur in the area.

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