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First high-resolution chirp sonar profiles from the central Arctic Ocean reveal erosion of Lomonosov Ridge sediments

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Abstract

The Swedish 'Arctic Ocean-96' expedition to the central Arctic Ocean with the icebreaker *Oden* carried out a geological/geophysical program focused mainly on Lomonosov Ridge sediments. Approximately 195 km of high-resolution seismic data from the ridge crest and slope were collected with a chirp sonar system providing new insights into the sediment stratigraphy and the accompanying depositional history. These data reveal evidence of substantial erosion that acted in laterally limited areas on shallow parts of the investigated ridge segment. More than 50 m of sediment stratigraphy is missing in the most eroded parts. Moreover, the chirp sonar records indicate that, below the erosional surface, the ridge crest and slope is characterized by a low-energy sedimentary environment. The termination of the erosional phase is indicated by a prominent reflector. The subsequent depositional phase resulted in an approximately 3 m thick stratigraphic unit. The cause of the erosion is attributed to either ice grounding or current erosion. Furthermore, *Oden* echo sounding data has been used together with data from the US Navy SCICEX program in order to update existing bathymetric charts in the 'Arctic Ocean-96' working area. The update shows a narrower ridge crest with a different outline than in previously published charts with a minimum depth of 607 m which is the shallowest depth of the Lomonosov Ridge recorded (in the public domain) in the central Arctic Ocean. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Arctic; reflection seismic; ice grounding; current erosion

1. Introduction

The central Arctic Ocean is divided into the Eurasian and Amerasian basins by the 1500 km long, 50–70 km wide Lomonosov Ridge (Fig. 1). This bathymetric barrier, considered to be of continental origin, rifted from the Barents–Kara Sea margin during the opening of the Eurasian Basin (Wilson, 1963; Lawver et al., 1988; Jokat et al., 1992). The ridge subsided below sea-level around 50 Ma (Chron 22) and moved to its present position by sea floor spreading (Jokat et al., 1995).

The Arctic Ocean and its marginal seas play a fundamental role in the global ocean/climate system. Studies of sediments deposited in a pelagic setting on topographic highs in the central Arctic Ocean, such as those on the crest of the Lomonosov Ridge, are important in order to decipher the environmental history of this poorly known region. Several major scientific questions, such as the history and distribution of Arctic sea-ice cover, the history and distribution of glaciations on surrounding land masses, and the history of Arctic Ocean circulation during glacial versus inter-glacial times remain to be answered.

The Swedish Polar Secretariat organised an ex-

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pedition to the central Arctic during summer 1996 (Arctic Ocean-96), using the icebreaker *Oden*. The geologic and geophysical component of the program focused on coring and seismic data acquisition in a sector of the Lomonosov Ridge between about 85° and 90°N.

Prior to the 'Arctic Ocean-96' expedition, high-resolution seismic reflection data (chirp, Parasound and 3.5 kHz data are here referred to as high-resolution seismics) were collected from the Lomonosov Ridge on two occasions, one from the LOREX ice station (Blasco et al., 1979) and the other from R/V *Polarstern* (Fütterer, 1992). These data, together with four airgun profiles crossing the ridge, comprise the entire available seismic reflection data base of the Lomonosov Ridge. Three of the airgun profiles were collected during the expeditions mentioned above and one from the Arlis II ice-drift station (Ostenso and Wold, 1977). The LOREX data revealed a ridge crest with irregular morphology suggestive of en-echelon fault blocks (Weber and Sweeney, 1990). The overlying ridge sediments had been exposed to current action inferred from seabed photographs which showed ripple marks, scouring and clean, coarse gravel pavements (Blasco et al., 1979). In the vicinity of the North Pole, current measurements carried out during the LOREX experiment indicated near bottom currents moving across the ridge with periodic peak speeds exceeding 12 cm/s (Aagaard, 1981). The high resolution seismic data from the R/V *Polarstern* at about 88°N show acoustically well stratified sediments, with an undisturbed sea-bed morphology, conformably draping the ridge (Fütterer, 1992).

The purpose of the present study is to present the seismic stratigraphy as derived from chirp sonar profiles and to revise the published bathymetric maps of a segment of the Lomonosov Ridge (85°20′–87°40′N, 135°–155°E). About 195 km of chirp data were collected from the ridge, providing new insights into late Cenozoic sediment stratigraphy and the accompanying depositional history.

2. Methods

The high-resolution sub-bottom profiling equipment consisted of an X-Star chirp sonar system using a SC-512 tow fish. This system can be operated in a frequency range of 0.5–12 kHz, carrying four mounted wide band piston type transducers and a ceramic line array as the acoustic receiver. The acoustic signal was digitally recorded in a deck unit where the transmitted pulse and a correlation filter are stored in order to perform real time correlation processing (Schock et al., 1989). A 100 ms long chirp pulse with a frequency range of 2–4 kHz was mainly used during the survey resulting in a penetration between about 40 and 90 ms (TWT; all acoustic travel times are henceforth given as TWT) with a resolution of approximately 0.5 ms. The acoustic penetration corresponds to a sediments thickness of approximately 30 to 70 m. A time varied gain (TVG) of 4 dB/10 m was used.

Collecting chirp data with a fragile tow vehicle is difficult in ice-covered waters (8–9/10 to 10/10 ice conditions). The chirp vehicle was generally towed at 20 m depth and mainly used in relatively open leads, although the presence of blocks of ice in the leads represented continuous hazards and the cause for frequent stops. Some profiles were collected after breaking fresh leads in solid sea-ice, which generally resulted in lower quality chirp records; clogging and churning of ice in the propeller system created noise that disturbed the chirp sonar system. The experience from the 'Arctic Ocean-96' expedition suggests that the gathering of seismic data along straight grid-lines may only be achieved from submarine platforms.

A velocity of 1450 m/s has been used for the speed of sound in water, based on unpublished CTD-measurements performed during the expedition (P.-I. Sehlstedt, pers. commun.). This value was used for the reconstruction of the bathymetry from echo-sounding data. Bathymetric data were collected more or less continuously during the main part of the expedition using a hull-mounted Atlas system with a 15 kHz transducer.

3. Results

3.1. Bathymetry

The bathymetric data collected during the 'Arctic Ocean-96' expedition show that details of available published bathymetric charts are inadequate in the

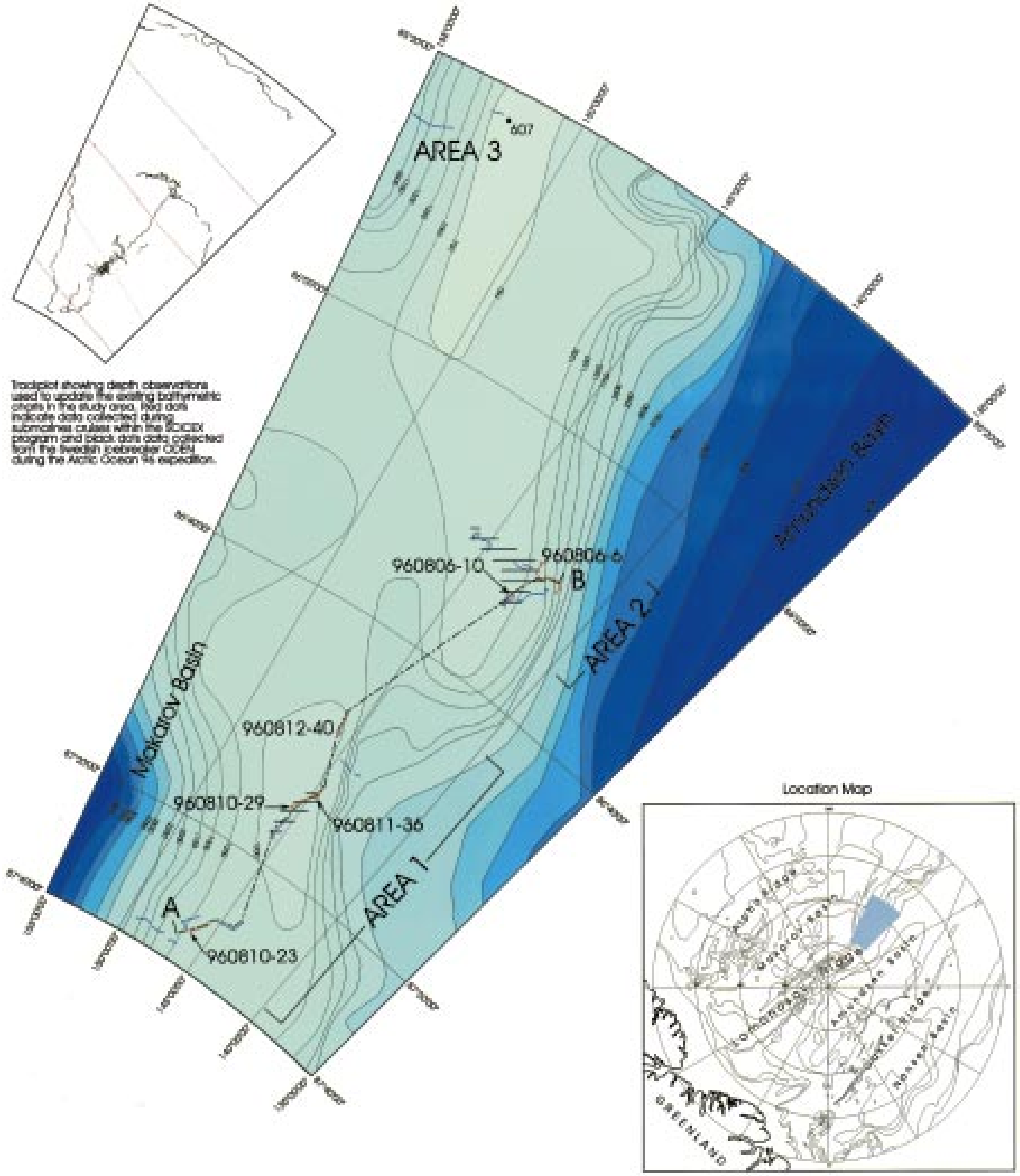

Fig. 1. Location map of the investigated areas. Violet and red lines indicate chirp sonar profiles carried out during the 'Arctic Ocean -96' expedition. Red marked profiles are presented in Figs. 2 and 3. The dotted line between *A* and *B* indicates the bathymetric profile shown in Fig. 3, where the acoustic stratigraphy is correlated. Areas where the chirp data from this study reveal sediment erosion are hatched with black lines.

eastern part of the Lomonosov Ridge. For example, the bathymetric map compiled by Perry et al. (1985) indicates a ridge depth between 1000 and 1500 m at about 85º25′N, where we recorded a shoal with a minimum depth of 607 m (Fig. 1). However, Perry's bathymetric map was used as reference to which the data collected from 'Oden-96' were added. Public-domain data from the US Navy SCICEX program were also merged, which permitted an update of the bathymetry in the survey area (Fig. 1). The compiled bathymetry in Fig. 1 suggests a somewhat narrower ridge crest with a different outline than previously published and the minimum depth of 607 m is the shallowest depth of the Lomonosov Ridge recorded (in the public domain) in the central Arctic Ocean. The bathymetric data, however, are still widely spaced and other topographic features are probably present.

3.2. High-resolution chirp sonar profiling

The tracklines are grouped into three survey areas (Fig. 1). Five acoustic reflectors, labelled A, B, C, D and E were selected and used to describe and correlate the acoustic stratigraphy. Reflectors A, C, D and E are recognised virtually everywhere in two of the three survey areas (Area 1 and Area 2). Reflector B was observed only on the shallowest parts of the ridge crest in two of the survey areas, and is typically represented by either an angular unconformity or a disconformity.

3.3. Area 1

Profiling was carried out along a transect across the ridge in Area 1. The transect consists of surveys on the slope of the ridge, towards the Makarov Basin, on the relatively flat ridge crest, and on the slope towards the Amundsen Basin (Fig. 1). The profiles on the ridge crest, above approximately 1360 ms (986 m water depth), show an irregular sea-bottom with abundant hyperbolic reflections (Fig. 2a). Below this water depth, the sea-bottom surface appears smooth in all Area 1 profiles (Fig. 2b, c). In those areas showing a smooth sea-bottom surface, the ridge is conformably draped by at least 90 ms of acoustically well stratified sediments. Reflector 1A is recognised continuously throughout Area 1. Reflector 1B appears only in water depths shallower than 986 m (Fig. 2a), where a change from a smooth to an irregular sea-bottom surface occurs. An acoustically transparent to semi-transparent unit with no internal reflectors is thus limited by reflectors 1A and 1B. Abundant, regularly spaced, overlapping hyperbolae with vertices tangent to reflector 1B are recorded at depths shallower than 986 m (Fig. 2a).

Reflectors 1C and 1D are traced in the acoustic records from below 986 m water depth and up to shallower depths on the ridge crest, where they are truncated by reflector 1B. The cutting of reflector 1D is clearly observed in profile 960810-29 (Fig. 2a), representing the southern part of Area 1. Reflectors 1C and 1D are also easily recognised in the northern part of Area 1 (Fig. 2c). Reflector 1E is continuously traced from the shallow crest to the upper slopes. This reflector, however, disappears below the acoustic penetration at water depths exceeding approximately 1000 m. Acoustic masking of reflectors, possibly caused by presence of gas, occurs locally in Area 1, and is pronounced in profile 960810-23 (Fig. 2c).

3.4. Area 2

Profiling took place on the ridge crest and on the slope towards the Amundsen Basin (Fig. 1). Profiles located in water depths shallower than approximately 1015 m (1400 ms) reveal an irregular sea-bottom with occurrences of hyperbolic reflections similar to those occurring in the shallow parts of Area 1 (Fig. 3, profiles 960806-6 and 960806-10). A transition from irregular sea-bed on the ridge crest to a smooth one on the slopes can be observed at about 1400 ms. Echo-sounding data were not collected along profile 960806-6 (Fig. 3) where the transition to the irregular sea-bottom surface is observed. Here, water depths were calculated from the chirp data, assuming a constant tow depth of 20 m.

Reflector 2A can be traced both on the ridge slopes and on the crest, and appears to be continuous in Area 2. Reflector 2B occurs at water depths shallower than 1015 m. An acoustically transparent unit is limited by reflectors 2A and 2B, similar to that occurring between reflectors 1A and 1B in Area 1 (Fig. 2a). Hyperbolae with vertices tangent to reflector 2B are recorded at depths shallower than 1015 m (Fig. 2a), however, generally less regularly spaced

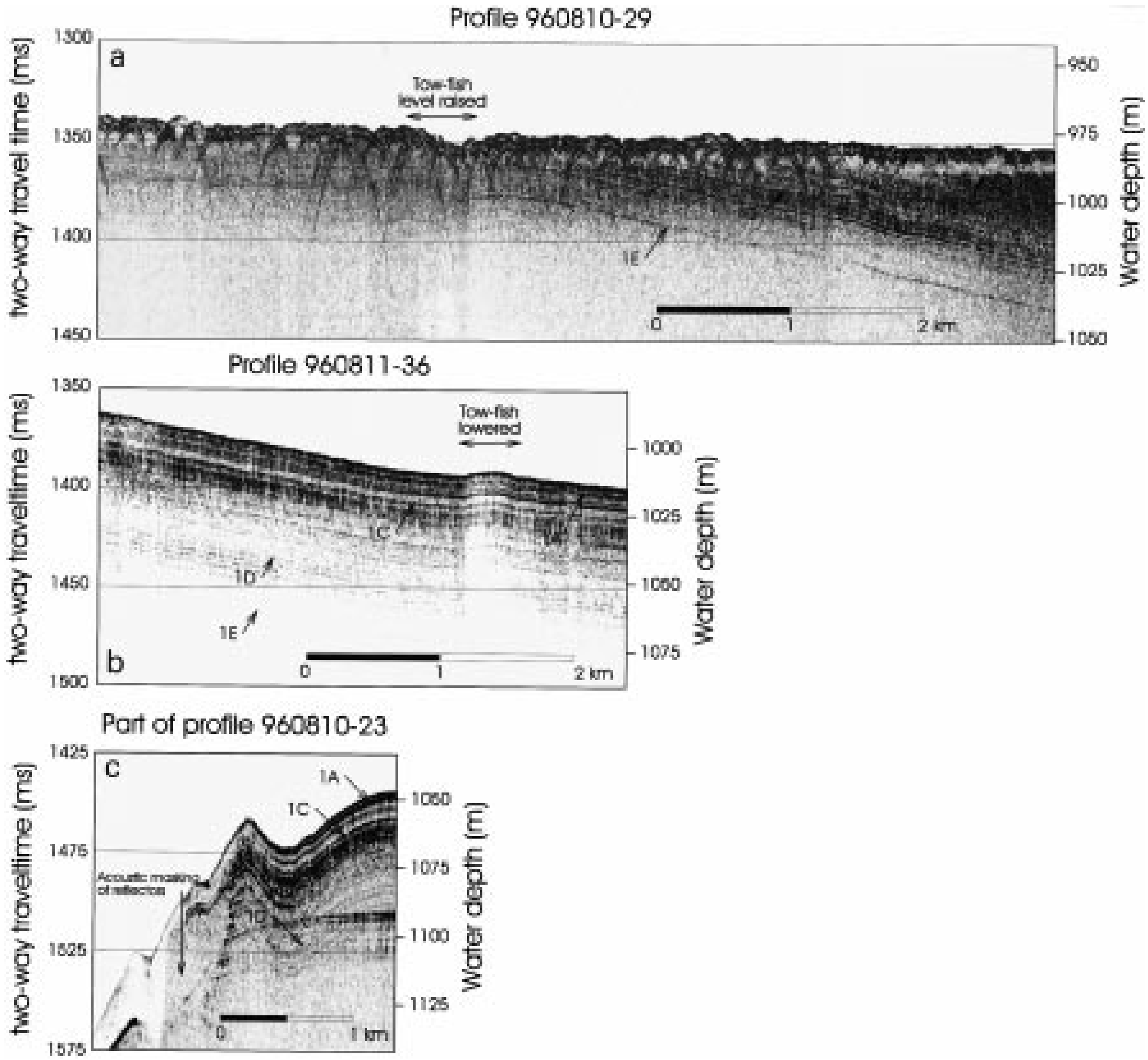

Fig. 2. Chirp sonar records in Area 1. The locations of the profiles are marked by red lines in Fig. 1. Water depths are calculated using a velocity of sound in water of 1450 m/s.

and abundant than the hyperbolae recorded in Area 1 with vertices tangent to reflector 1B. Reflectors 2C and 2D can be recognised and followed from the slope to the ridge crest, although the seismic records are of lower quality compared to those in Area 1. Reflector 2C is not observed in the shallowest parts of Area 2. Reflector 2E probably lies below acoustic penetration in the main part of the profiles and is only vaguely recognised at some locations on the ridge crest in Area 2.

3.5. Area 3

Area 3 is located on a previously unknown bathymetric shoal and on the ridge slope facing the Makarov Basin (Fig. 1). Profiling thus occurred in water depths ranging between 607 and 2042 m. The acoustic signal generally shows a prolonged bottom echo in Area 3, and does not reveal any clear sub-bottom structures; i.e., with little or no penetration. However, vague evidence of acoustically stratified

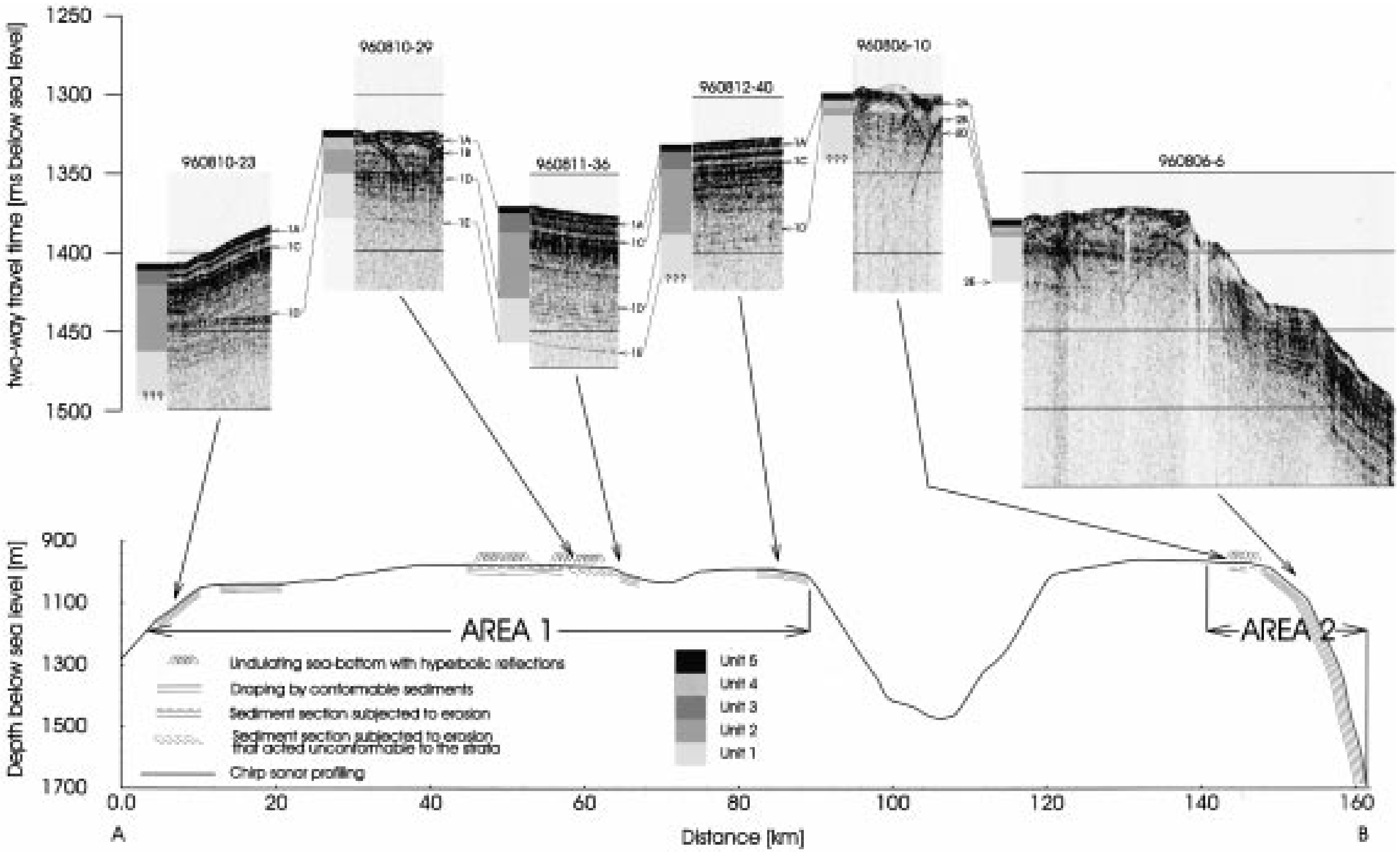

Fig. 3. Correlation of the acoustic stratigraphy from the surveyed areas of the Lomonosov Ridge. Line *A–B* represents the bathymetric profile shown in Fig. 1. The chirp sonar records consist of selected parts from longer profiles marked by red lines in Fig. 1.

sediments draping the slope was observed in a few short segments of some profiles.

4. Correlation and interpretation of the high-resolution seismic stratigraphy

The seismic reflectors, A, B, C, D and E are used for correlation of the acoustic stratigraphy within and between two of the three survey areas. Low penetration in Area 3 prevented correlation between this area and the other two areas. A correlation of acoustic stratigraphies between Area 1 and 2 is suggested in Fig. 3, where stratigraphic units are assigned to seismic sections whose boundaries are defined by reflectors A, B, C, D and E. Five units have been assigned, where Unit 1 is the lowest (oldest) and Unit 5 the uppermost (youngest). A grid survey was made in a limited part of Area 1, which made it possible to create a 3-D model showing the acoustic stratigraphy in detail (Fig. 4a).

Based on seismic reflection profiles across the Lomonosov Ridge, Jokat et al. (1995) subdivided the entire stratigraphic sequence capping the ridge into six seismic units (LR1–LR6) with a total thickness of over 2 km. The high-resolution chirp data presented here probably did not reach below Jokat's uppermost unit, LR6. This unit is about 80–100 m thick, and shows an average seismic velocity of 1800 m/s as determined from refraction data (Jokat et al., 1995). The velocity of 1800 m/s is hence adopted here for estimating the thickness of Units 1–4. However, a velocity of 1600 m/s has been used for Unit 5, inferred from physical property measurements of Lomonosov Ridge cores (Brass et al., in Fütterer, 1992).

The cause of the sub-bottom acoustic reflections in the chirp sonar records must be addressed in order to interpret the erosional/depositional history as depicted from the acoustic results. A relationship exists between the relative abundance of coarse, bedded terrigenous sediment (silt/sand/gravel) and the high-resolution acoustic character (Damuth, 1980). However, silt/sand beds are not solely responsible for reflections in acoustic records. Physical parameters such as changes in density and seismic velocity caused by variations in $CaCO_3$ content, sediment compaction and grain size in the fine sediments can also give rise to acoustic reflections (Embley, 1975). The origin of prolonged echoes with no visible sub-bottom reflections is more complex and uncertain. For this reason, the interpretation of some of the acoustic data collected during the 'Arctic Ocean-96' expedition must await studies of the sediment cores. Diffraction represented by hyperbolic echoes are returned from point sources and areas of irregular or rugged sea-bed morphology (Damuth, 1980). For example, hyperbolic echoes may be returned by erosional furrows, sediment waves and blocks.

4.1. Unit 1

The boundaries of Unit 1 are defined by reflectors E and D, and have a maximum thickness of approximately 26 m on the ridge slopes. On the most shallow part of the ridge crest, in both Area 1 and 2, the top of the unit has been subjected to erosion, causing both angular unconformities and disconformities. The erosional surface is indicated by reflector B, which is especially pronounced in profile 960810-29 (Fig. 2a). Unit 1 shows a regular acoustic stratification, representing sedimentation in a low energy environment over the crest and flanks of the ridge. The cause of the impedance variations giving rise to the laminated stratigraphy will remain unknown until suitable core material becomes available for analysis of sediment physical properties. It appears tenable to suggest, however, that the reflections are caused by variations in coarse fraction (silt/sand and gravel).

4.2. Unit 2

The boundaries of Unit 2 are defined by reflectors D and C, and have a maximum thickness of approximately 39 m. The acoustic characteristics of Unit 2 are similar to those of Unit 1, suggesting near identical conditions during deposition. The event that eroded Unit 1 also affected Unit 2, truncating the strata unconformably on the shallowest part of the ridge (Fig. 2a).

4.3. Unit 3

The boundaries of Unit 3 are defined by reflectors C and A, where B can not be recognized. The unit

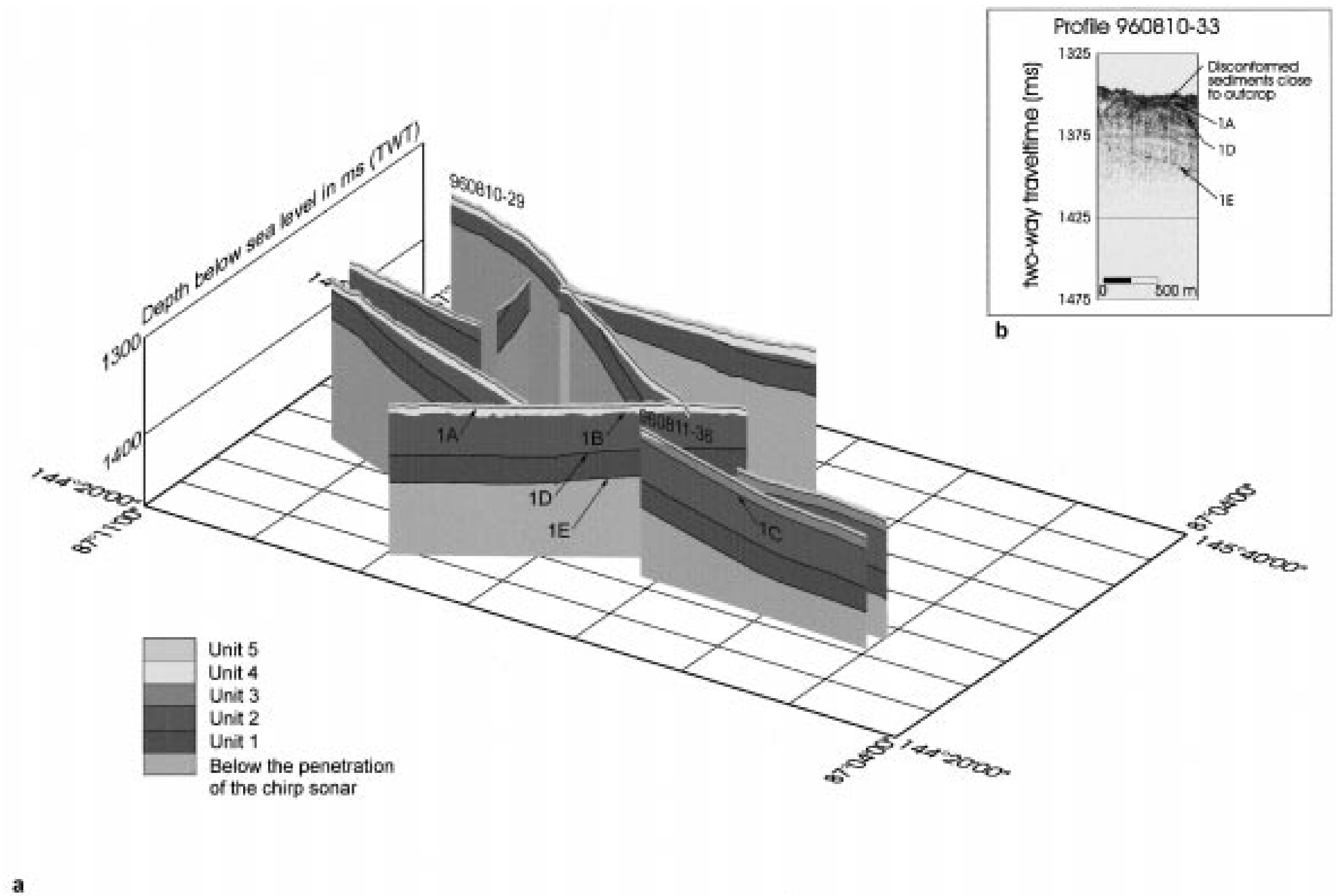

Fig. 4. (a) A 3-D model showing the interpretation of the acoustic stratigraphy in Area 1. The locations of profiles 960810-29 and 960811-36 are indicated in Fig. 1. The arrow shows a location where Unit 4 appears to be absent and the underlying unconformable sediments are close to outcrop. (b) The chirp sonar profile showing that the acoustically transparent to semi-transparent Unit 4 is absent and the underlying unconformable sediments are close to outcrop. The location of this profile is indicated by the arrow in (a).

has been eroded and is missing on the ridge crest. The thickness reaches a maximum of approximately 10 m on the upper gentle slopes in both areas where the unit is unaffected by erosion (Fig. 2b, c). It probably represents sedimentary depositional conditions similar to those which prevailed during the formation of Units 1 and 2.

4.4. Unit 4

The boundaries of Unit 4 are defined by reflectors B and A. The unit occurs only in water depths shallower than 986 m in Area 1 and shallower than 1015 m in Area 2. The unit is acoustically semi-transparent to transparent and internal reflectors can not be distinguished. The lower boundary, defined by reflector B (1B and 2B), is interpreted as the base of the erosional event that influenced Units 1–3. The thickness of the acoustically semi-transparent to transparent unit is generally less than 5 m in both Area 1 and 2. The unit appears to wedge out at depth in Area 1 (986 m) but seems to end more abruptly at 1015 m in Area 2. However, the acoustic data are not sufficient to cover the lateral extent of the unit in either Area 1 or 2; thus, its termination remains uncertain. Unit 4 is missing in Area 1 in profile 960810-33 where the underlying sediments of Units 1–2 are close to outcrop (Fig. 4a, b). The hyperbolae recorded at the upper boundary of the unit, with vertices tangent to reflector A, probably characterise an irregular morphology. It is speculated that the formation of Unit 4 is related to the erosion that affected Units 1–3.

4.5. Unit 5

Unit 5 is defined by reflector A and the sea-bottom and is estimated to have a thickness of approximately 3 m. It is considered to represent the youngest unit in the acoustic stratigraphy and appears to be continuously present on the ridge slopes and crests of Area 1 and 2. The formation of Unit 5, therefore, is considered to reflect a change in sedimentary environment, from erosion to deposition at depths shallower than 986 m in Area 1 and 1015 m in Area 2. The irregular sea-bottom topography, which is clearly distinguished in the chirp records in Area 1 and 2, may reflect the draping of an irregular topography of Unit 4, an irregular sea-bed (top Unit 5), or a combination of both. The irregularities of uppermost Unit 5 (present sea-bed) may have been caused by sediment waves or erosional furrows. However, the acoustic data are not conclusive.

5. Discussion

Previous investigations show indications of erosion at several locations in the ridge stratigraphy (Fig. 5). The LOREX data revealed evidence of recent erosion of the ridge sea-bed. The ‘Arctic Ocean-91’ seismic profile AW1-91091 shows laterally limited surface erosion of the ridge flanks (Fig. 5; Jokat et al., 1992). Parasound data from the ‘Arctic Ocean-91’ expedition (Fütterer, 1992), and seismic profile AWI-91090 (Jokat et al., 1992) shows sections of the Lomonosov Ridge with relatively undisturbed stratigraphies near the sea-bed surface (Fig. 5).

The ‘Arctic Ocean-96’ high-resolution chirp sonar data provide evidence of erosional events that acted in limited areas on the shallow parts of the Lomonosov Ridge (Figs. 4 and 5). The erosion affecting the sediment stratigraphy resulted in partly unconformable layering, and more than 50 m of stratigraphic section is estimated to be missing in the most eroded parts. Three alternative scenarios, aiming to explain the most likely cause(s) of this erosion, are suggested.

(1) One explanation of the missing stratigraphic section, and thus to the cause of the erosion, may be gravitational mass wasting. However, several significant factors arguing against large-scale mass wasting, in the form of slide(s), are present in the Lomonosov Ridge chirp sonar records. There are no slide scars present in the records and there are no obvious signs of mass wasting down-slope of the eroded areas. Furthermore, the eroded areas are chiefly located on the relatively flat ridge crest, and the erosional surface is mainly unconformable to the eroded strata, suggesting that no layer can have acted as a gliding plane (Fig. 2a). This does not exclude small-scale mass flow events in the form of turbidity currents and/or debris flows, which may have contributed to the erosion.

(2) A second explanation is the possibility of a grounded ice-sheet on the Lomonosov Ridge crest.

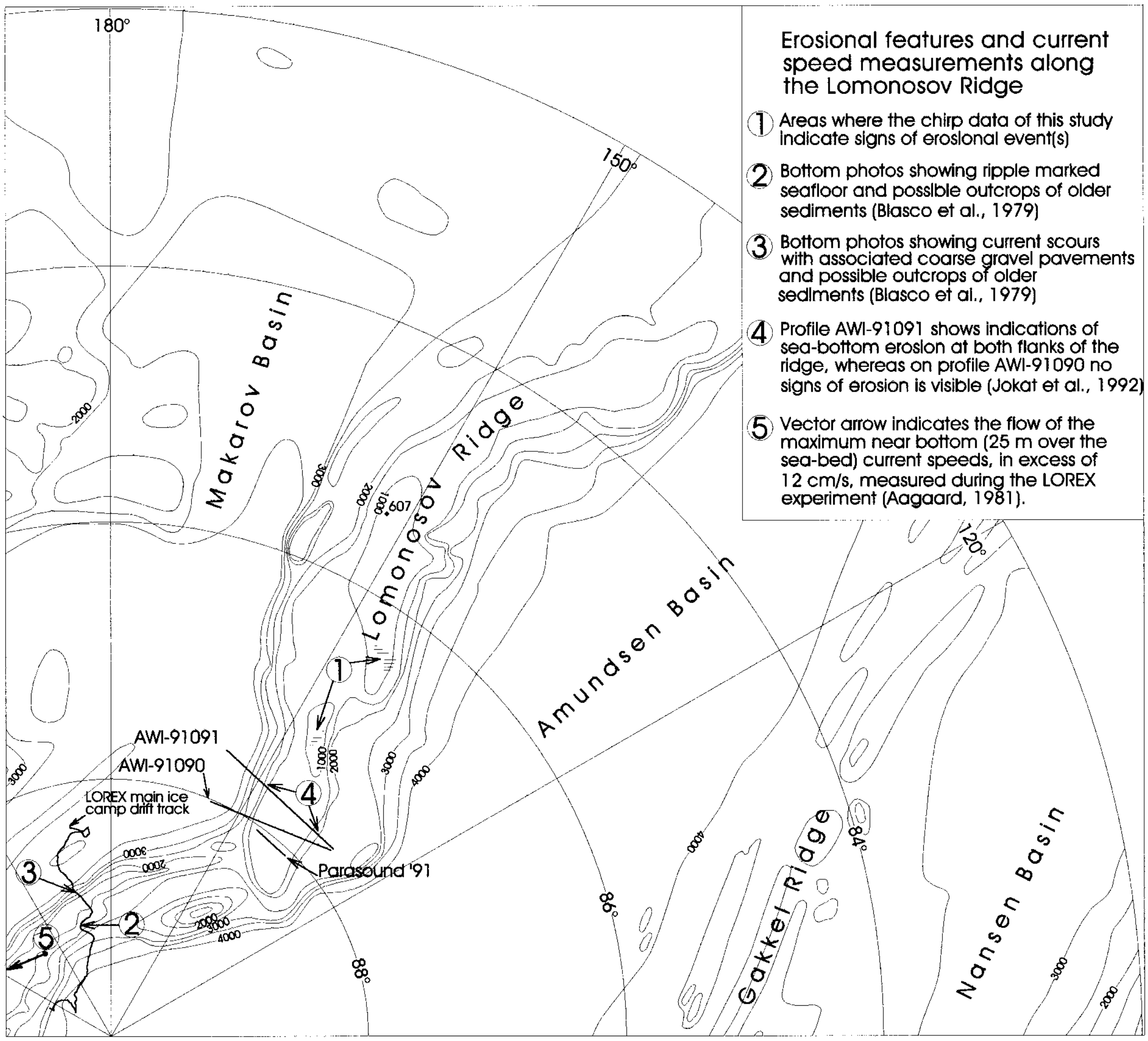

Fig. 5. Previous investigations presenting evidence of erosion on the Lomonosov Ridge. The LOREX experiment measured maximum currents speeds in excess of 12 cm/s at location no. 5.

The existence of a large continuous late Weichselian ice-sheet in the Arctic that behaved as a single dynamic system composed of terrestrial and marine grounded ice and shelf ice has been hypothesized by, e.g., Hughes et al. (1977) and Grosswald (1980). It follows that the grounded ice on the Lomonosov Ridge must have reached a depth below present sea level of 986 m in Area 1 and 1015 m in Area 2 (uncorrected for glacio-isostatic and sea-level changes during glacial maxima). These depths are below the deepest iceberg ploughmarks of 850 m (below present sea level) recorded in the Arctic (Vogt et al., 1994). Vogt also suggested that the ice shelves calving the icebergs may be somewhat thinner than the deepest ploughmarks, implying that the ploughmarks originated from unusual capsizing events. The presence of undisturbed sediment sections between 986 and 1015 m may imply a different cause than grounded ice for the observed erosion or, on the other hand, grounding occurring at different depths (perhaps at separate occasions), or tectonic uplift of the undisturbed areas between 986 and 1015 m following the grounding event(s). In the case of grounding, the ice-sheet/icebergs would pre-date the late Weichselian due to the deposition of Unit 1 (approximately 3 m) and the Holocene sedimentation rates of ca. 1 cm/kyr found on the Lomonosov Ridge (Stein et al., 1994). The deepest ice-sheet grounding recorded from the Arctic so far is from 556 m water depth (ODP Site 910) on the Yermak Plateau (Myhre et al., 1995; see also Vogt et al., 1994). This grounding event has been proposed to have occurred prior to 660 ka (Flower, 1997).

(3) Current controlled erosion represents a third option. During the LOREX experiment maximum current speeds in excess of 12 cm/s were measured from the top of the Amundsen Basin flank (Fig. 5) (Aagaard, 1981). Near bottom currents varied periodically and indicated, together with sea water temperature profiles, a flow of cold water diagonally across the ridge sinking adiabatically into the Makarov Basin and producing a down slope current along the Makarov flank (Aagaard, 1981; Pounder, 1986). It is difficult to estimate the bottom current velocity that would be required to erode the Lomonosov Ridge sediments. The grain size composition and consolidation of the ridge sediments has only been studied within the depth range of conventional piston coring. The upper sediment sections consist predominately of normally consolidated fine-grained silty clays with intervals that have a sand component and occasional larger dropstones (Morris et al., 1985; Brass et al., in Fütterer, 1992). However, recent current action of the ridge sea-bed is evident from LOREX photographs showing ripple marks, scouring and clean, coarse gravel pavements (Blasco et al., 1979) (Fig. 5). If the extensive erosion of Units 1–3 is current controlled, this implies different oceanographic conditions allowing higher current velocities over the ridge crest than present, which permits sediment deposition (Unit 5). Strong paleo-bottom current activity on the crest of the Alpha Cordillera and in the Mendeleyev Abyssal Plain has been suggested by Hall (1979) inferred from buried sediment waves and other evidence. The sediment waves across the Alpha Cordillera were postulated by the same author to result from a drastic change in sedimentary regime which occurred for a certain period prior to the development of the present permanent sea-ice cover. Morris and Clark (1986) suggested that during periods of increased glacial ice influx into the Arctic Ocean system there was reduced current activity in the bottom and intermediate water masses relative to periods when little glacial ice was present, that is, during prominent interglacials or during pre-glacial times. If assuming that the erosion was current induced, it may follow that Unit 4 may represent a lag deposit. Sedimentary furrows in the form of longitudinal beds formed in fine-grained, cohesive sediments have been observed in the deep-sea where bottom currents often flow in one direction at 5 to 20+ cm/s (Flood, 1983). Measurements of the present current velocity across the Lomonosov Ridge near the North Pole are within this range (Aagaard, 1981). The irregular sea-bed morphology observed in uppermost Unit 5, represented by hyperbolic reflections, are thus compatible with current induced furrows. The surface of Unit 4 is also clearly irregular (Fig. 2a), which may have contributed to or accentuated the sea-bed topography, or alternatively, the sea-bed undulations may simply reflect draping of the irregular surface of Unit 4. However, the problem in explaining the undisturbed sections observed between 986 and 1015 m, and thus the limited areas of paleo-current activities, remains to be answered. Detailed bathymetric mapping (for example with a multibeam system) of the eroded areas and neighbouring regions might reveal key features and thus the answer to this enigma.

6. Conclusions

Results from the ‘Arctic Ocean-96’ chirp sonar data are presented and five seismic units are defined. The data reveal evidence of substantial erosion that acted in laterally limited areas on shallow parts of the investigated ridge segment. More than 50 m of sediment stratigraphy is missing in the most eroded parts. The observation of erosion of Lomonosov Ridge sediments bear witness of a dynamic sedimentary environment. Three possible explanations for the erosional event(s) are discussed: (1) large-scale gravitational mass wasting, (2) grounded ice-sheets in the central Arctic at 1 km water depth, and (3) current controlled erosion. Mass wasting is considered less tenable because of lack of, for example, slide scars in the seismic records. The present data are not conclusive with respect to which of the two remaining explanations is the most likely one. The extensive erosion may have occurred during period(s) with different oceanographic conditions in the central Arctic Ocean leading to vigorous paleo-currents flowing over the Lomonosov Ridge crest. In that case, the acoustically semi-transparent to transparent Unit 4 is proposed to consist of a lag deposit from which the finer materials have been winnowed. On the other hand, the near horizontal erosional truncation is compatible with erosion by floating ice which may locally have grounded on the ridge. Moreover, the transparent nature of Unit 4 suggests a structureless deposit which is compatible with ice keel turbates, diamicts related to draft of icebergs (Vorren et al., 1983). In that case, this would be the deepest known record of ice grounding (ca. 1 km below present sea level).

Furthermore, *Oden* echo sounding data has been used together with data from the US Navy SCICEX program in order to update existing bathymetric charts in the 'Arctic Ocean-96' working area. The update shows a narrower ridge crest with a different outline than previously published charts. A minimum depth of 607 m was recorded where previous maps indicated 1000–1500 m. This is the shallowest depth of the Lomonosov Ridge recorded (in the public domain) in the central Arctic Ocean.

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