Extensive local seabed disturbance, erosion and mass wasting on Alpha Ridge, Central Arctic Ocean: possible evidence for an extra-terrestrial impact?

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Sub-bottom sediments within a 200 x 600 km area on the crest and south slope (water depth 1200-2500 meter) of the submarine Alpha Ridge in the central Arctic Ocean have been locally disrupted down to at least 500 meter below the seabed, suffered intensive local current erosion, and abundant mass wasting. There appears to be a westward progression along the ridge from an eastern area of chaotic and eroded sub-bottom sediments to proximal intense erosion of an undisturbed section and a more distal occurrence of mass wasting and minor erosion. As a working hypothesis, we propose that the spectrum and scale of drastic, spatially restricted and apparently geologically short-lived environmental changes are compatible with the effect of a shock wave from the impact of an extra-terrestrial body into the central Arctic Ocean.

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Introduction

Seismic reflection data collected over five years (1967-71) during the drift of U.S ice station *T-3* over the Alpha Ridge in the central Arctic Ocean (Fig. 1) revealed a local area of unusual seabed roughness characterized by hyperbolic echo returns and lateral truncation of acoustic horizons (Hall 1979). The seabed roughness was suggested to indicate a strong palaeo-bottom current event. An increasing inventory of modern multi-channel seismic surveys from the margins of the deep polar basin (Grantz & May 1983; Grantz et al. 1998; Sekretov 2001;

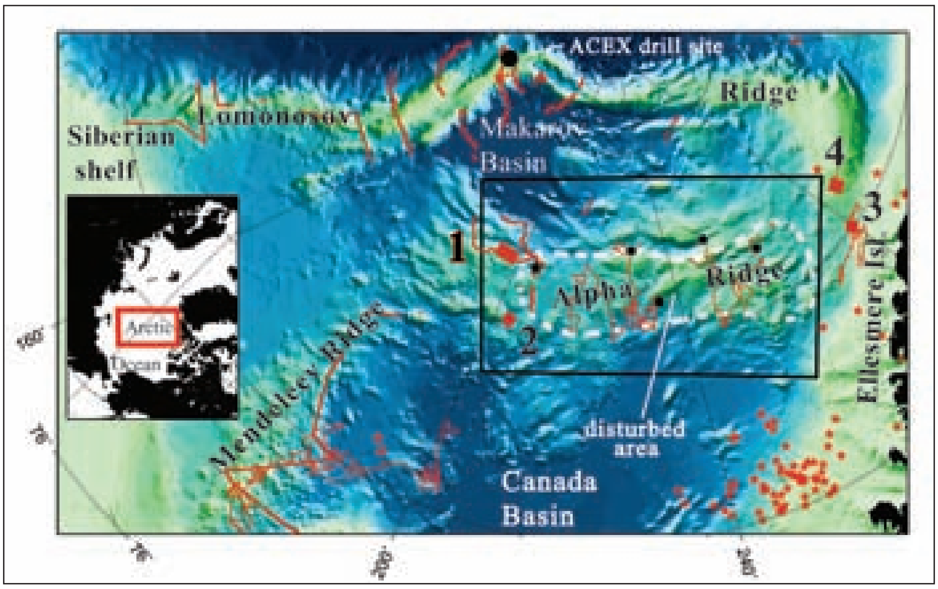

Fig. 1: Bathymetry of the Amerasia Basin of the Arctic Ocean from (http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html) with outline of area of sediment disturbance (white dashes) on Alpha Ridge. Tracks of multichannel seismic lines by icebreakers indicted by thick red lines and drifting ice stations by thin red lines. Sample seismic sections (1-4) of undisturbed stratigraphy are shown in figure 2. Earthquake locations (red stars) are from http://earthquakescanada.nrcan.gc.ca/. Large black dot is location of Arctic Ocean Coring Expedition drill site (Moran et al., 2006), and small black dots show locations where slumped Late Cretaceous material has been recovered in short (3-4 m) cores. Polarstern core (PS51/034-4, Jokat et al. 1999) indicated by black star.

Jokat et al., 1995; Geissler & Jokat, 2004), the Lomonosov Ridge (Jokat et al. 1992; Kristoffersen et al. 2004; Jokat 2005; Kristoffersen & Mikkelsen 2006) and Alpha Ridge (Jokat 2003) indicate subordinate bottom current erosion within the upper ca. 200 m of the stratigraphic section in the Arctic Ocean basin and its margin. This is supported by the results of scientific drilling on Lomonosov Ridge (Fig. 2 and 3 of Moran et al. 2006). New multi-channel seismic reflection data collected by U.S. Coast Guard icebreaker *Healy* in August-September 2005 across the Mendeleev ridge complex show an undisturbed sediment drape, but also local evidence of disrupted stratification. We have re-examined the single channel data from ice station *T-3* used in previous studies as well as hitherto unpublished data from the drift during 1967-1974 and find evidence of a spatially restricted area of massive sea-bed disturbance, erosion and mass wasting.

Data

Single channel seismic data were acquired during the drift of U.S. ice station *T-3* (Radar Target # 3, Fletcher's Ice Island, or Ice Station Bravo) over the Mendeleev and Alpha ridges from 1967 to 1974 using a 9 kJ sparker source (Hunkins & Tiemann 1977). The seismic signals from two single hydrophones were recorded on electro-sensitive dry paper on a drum recorder. Navigation was by Transit satellite fixes. We have enhanced scanned photographic prints and xerox copies of the original paper records to optimize contrast, mute water column noise and adjust horizontal scale. New multi-channel seismic data were acquired in September 2005 from the U.S. Coast Guard icebreaker *Healy* using a 24 channel 300 meter long streamer and a 2 x 4 liter G-gun source. The preliminary processing included editing, band-pass filtering and stacking, assuming a sub-bottom velocity of 2 km/s.

Results: Characteristic features of the sea-bed and sub-bottom sediments in the central Arctic Ocean

The sea bed on the entire Mendeleev Ridge and the western end of Alpha Ridge, as well as near the continental slope north of the Canadian Arctic islands, are parts of a laterally uniform and undisturbed sediment drape which is at least 0.2 s (two-way travel time) thick (Figs. 1 and 2). This continuity of acoustic horizons contrasts with observations from the crest and south slope of the cen-

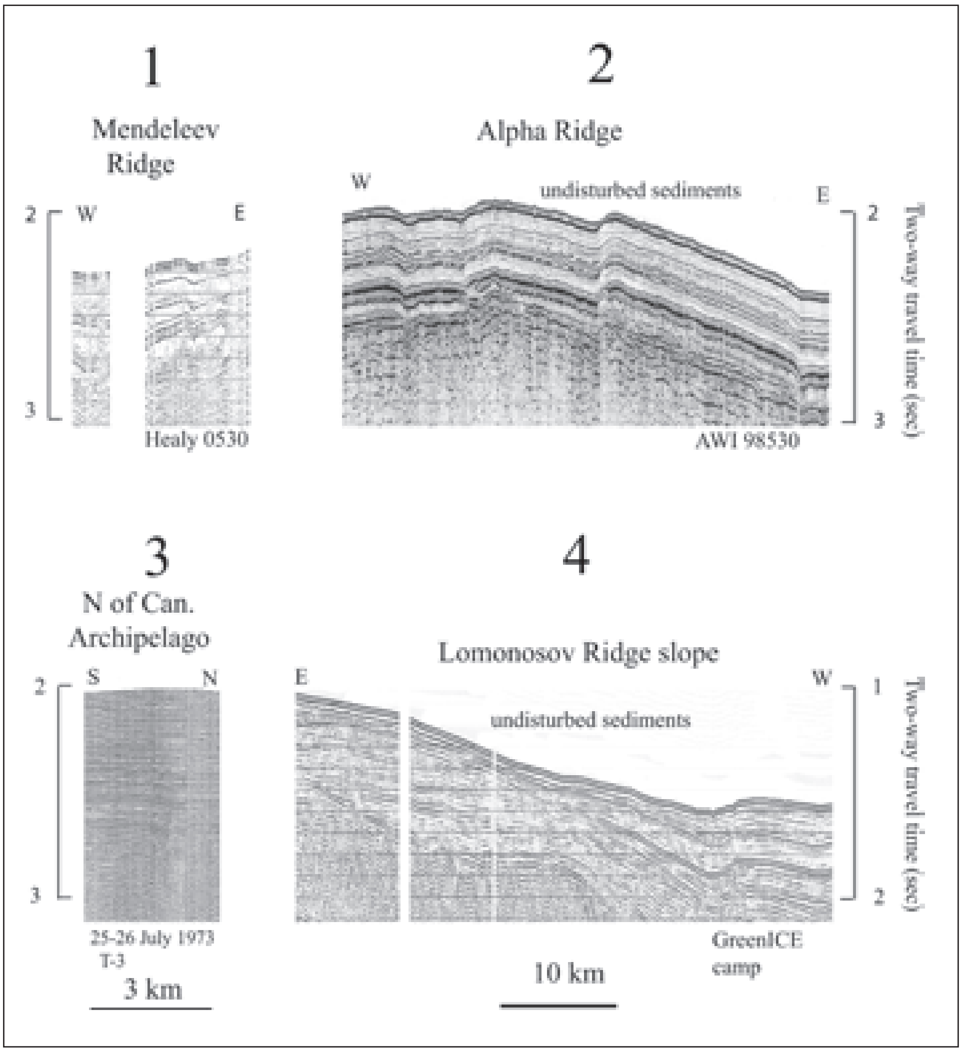

Fig. 2: Seismic sections representing undisturbed stratigraphy on the Alpha Ridge and environs. Line AWI 98530 from Jokat (2003), T3-*data from Hunkins & Tiemann (1977), and the GreenICE camp from Kristoffersen & Mikkelsen (2006). Note different length scale for profile 3. Profile locations shown in Fig. 1.*

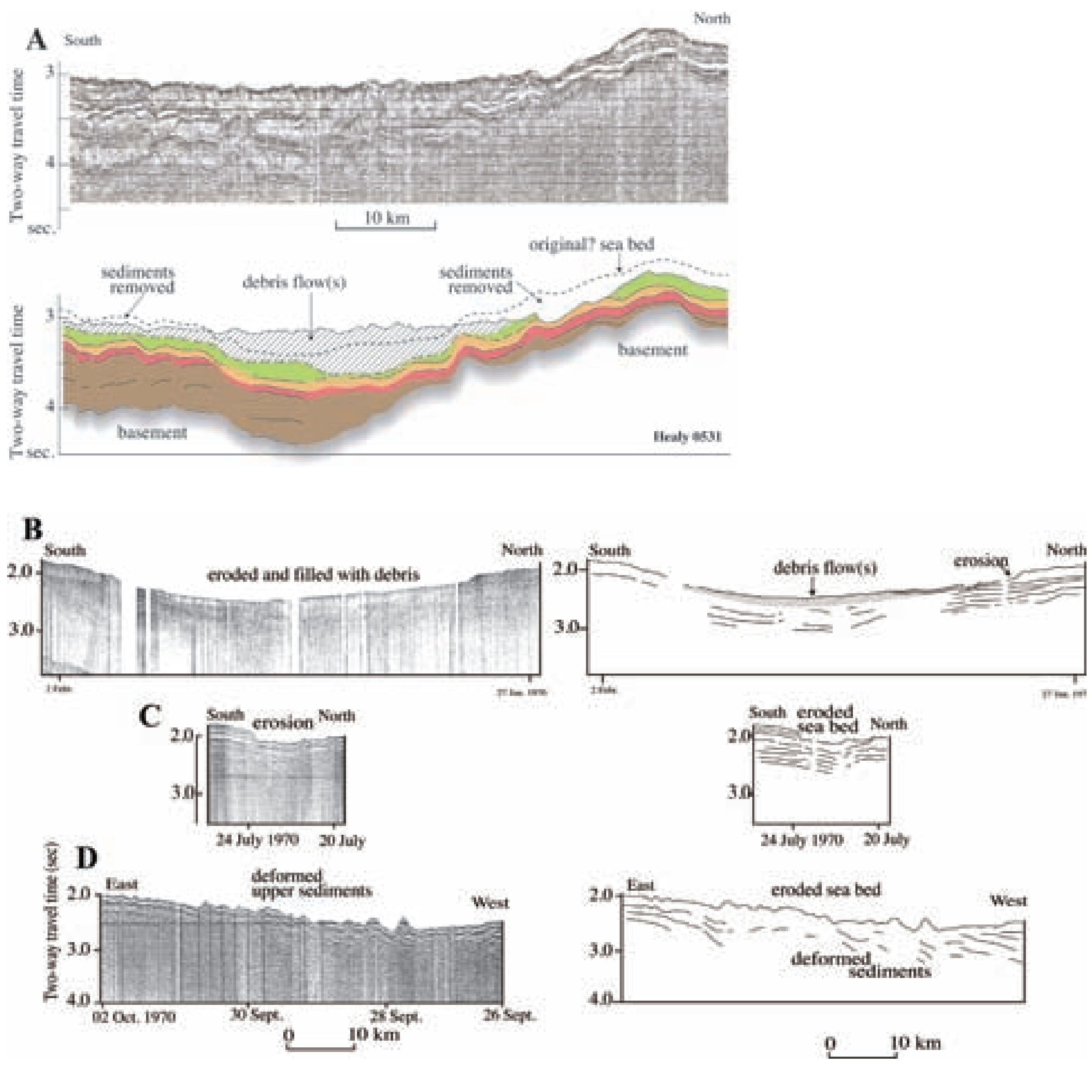

Fig. 3a. Multi-channel seismic section over the crest of Alpha Ridge acquired from U.S. Coast Guard icebreaker Healy *in 2005. Profile locations are shown in Figure 4. The colour scheme in the line drawing is keyed to the acoustic stratigraphic correlation shown in Fig. 5. Fig. 3b. Analogue seismic data acquired during the drift of ice station* T3 *in 1970 and recorded directly on a drum covered by electrosensitive paper. Profile locations are shown in Figure 4.*

tral part of Alpha Ridge (Figs. 1, 3-5). An area at about 84.7°N, 206°E (Figs. 3a and 4, profile A) is characterized by irregular short sub-bottom reflection segments with random apparent dip directions in the upper 0.2 s two-way travel time (TWT) of the sedimentary section extending to 0.5 s TWT sub-bottom in the central part of the line. Below the disturbed zone, acoustic horizons are piecewise coherent except below the central part. The seabed is irregular on the high ground in profile A (Fig. 3a) and the thickness of sub-bottom deposits (0.2-0.4 s TWT) is less than half the thickness of the undisturbed stratified section below the adjacent flanks of Alpha Ridge to the north and south (Fig. 4 and 5).

The area east of the Healy track (Fig. 4, east of 210° E) has so far only been accessed by drifting ice stations (Hall 1979). The quality of the analog seismic reflection records are much lower than modern multi-channel data, but clearly shows an irregular sea bed associated with completely disrupted sub-bottom stratification and the upper sediments are missing (Figs. 3b and 4, profiles B-D). Chaotic sub-bottom reflections are most

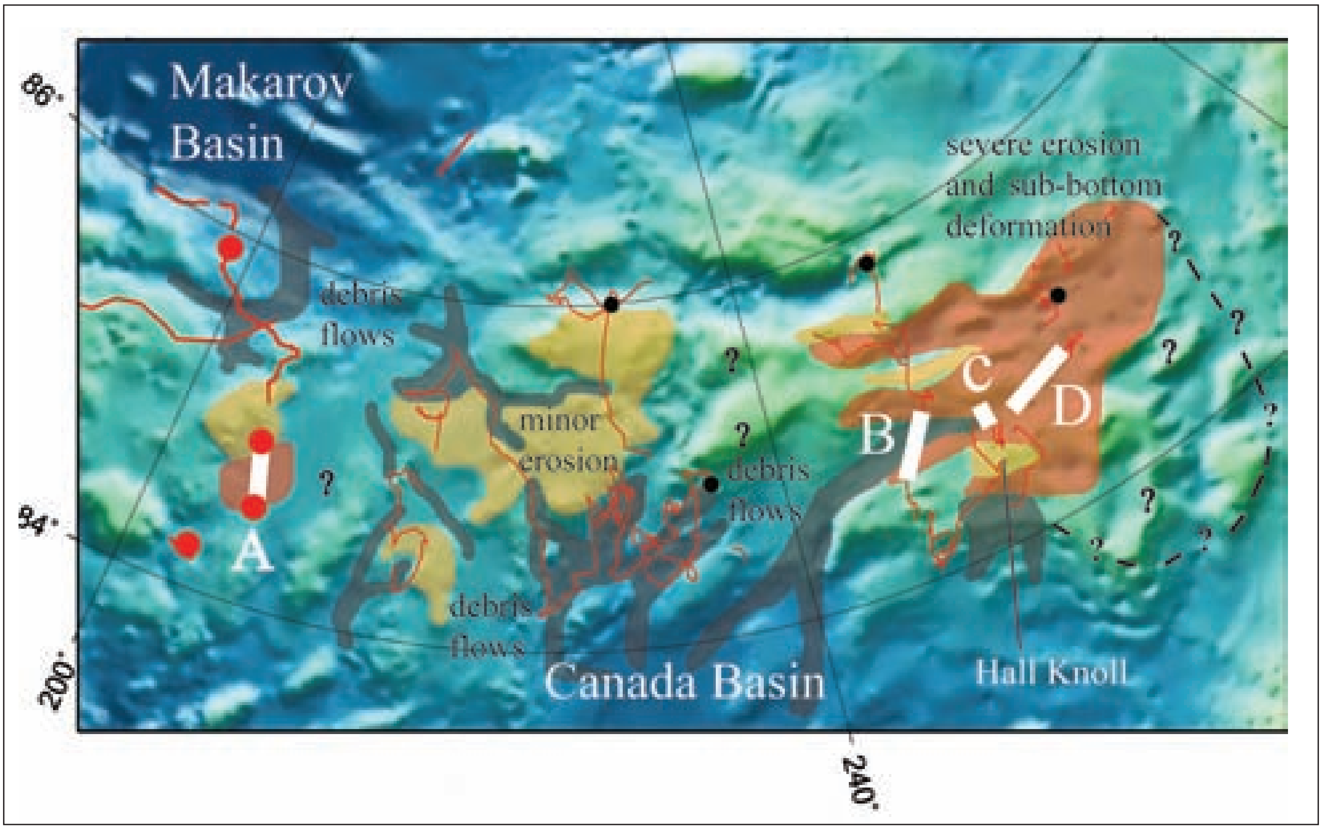

Fig. 4. Outline of areas of sub-bottom, depth-limited sediment deformation and heavy erosion (brown), minor seabed erosion (violet), and debris flows (dark grey). Most disrupted sub-bottom sediments are at location of profiles A and D. The seismic data coverage is shown by red tracks and the position of sample seismic profiles (Fig. 3, A-D) are indicated by white bars. Red dots show locations of representative acoustic sections correlated in Fig. 5.

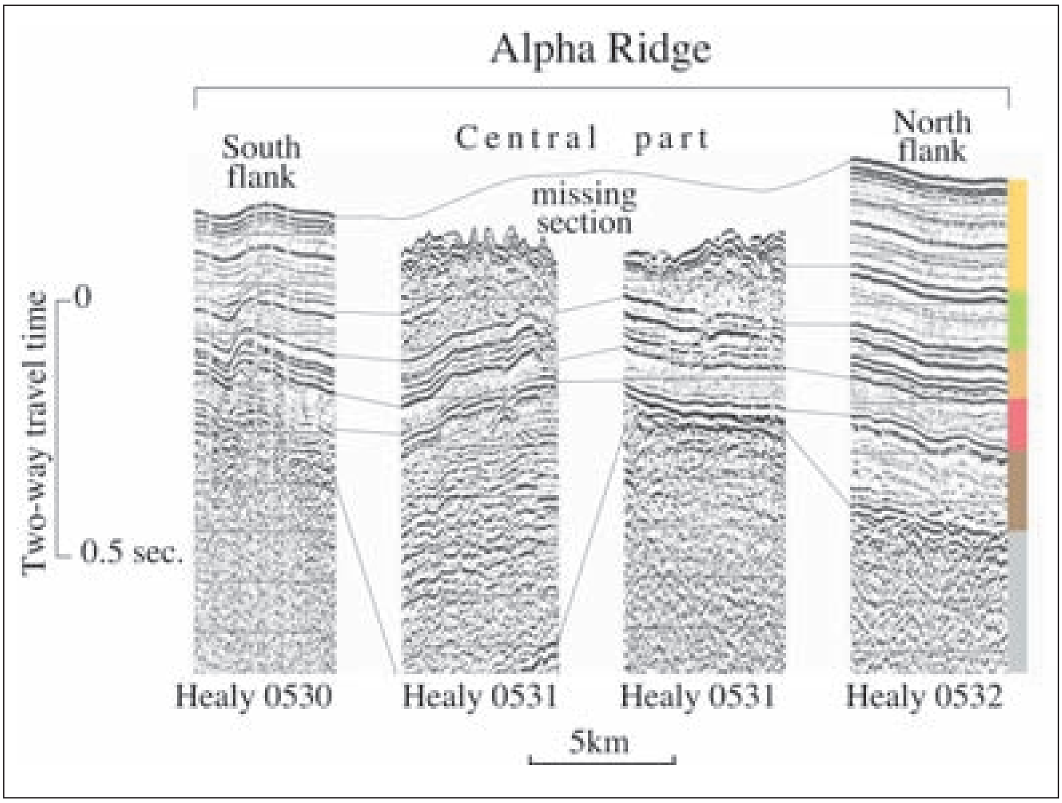

Fig. 5. Correlation of acoustic stratigraphy across Alpha Ridge. Location of sample sections marked by red dots in Fig. 4.

dramatically expressed in an area centred at about 84.5° N, 255° E (Figs. 3b and 4, profile D). Immediately to the west, the sub-bottom stratification is truncated and over 0.1 s of section is missing (Figs. 3b, profile C). Continuing down slope farther to the west, more than 0.1 s of section is lacking and the void partially filled with acoustically non-stratified material (Figs. 3b and 4, profile B). Farther along the southern slope of Alpha Ridge about 250 km to the west are numerous cases where a confined, acoustically transparent or incoherent unit with lens-shaped cross-section lies within bathymetric lows. The unit either partially infills missing stratigraphy or overlies laterally intact acoustic layering.

Interpretation

The acoustically well stratified deep sea sediment cover on Alpha Ridge shows several separate types of disturbance within a spatially confined area; 1) local complete disruption of sub-bottom stratal continuity, 2) local areas where the upper part of the stratigraphy is missing, and 3) numerous acoustically incoherent lenses overlying intact stratigraphy or partially filling a void where part of the section is missing.

The seabed is uneven and a 40 km wide chaotic pattern extends to about 500 m sub-bottom at 84.7°N, 206°E (Figs. 3a and 4, profile A). The depth extent of disrupted stratigraphy shallows towards north and south. Acoustic stratification below the disturbed zone is interrupted by flexures or offsets at the southern end of the profile A and stratal continuity is partially lost at depth below the central part of profile. We define acoustic basement as the base of the stratified section, although intra-basement reflections are frequent (Fig. 3a). Figure 5 represents a tentative correlation of the acoustic stratification across Alpha Ridge. The reflection pattern in the undisturbed stratigraphic section on the northern slope (Fig. 5, line Healy 0532) of the ridge includes two single cycle distinct reflections above a more than 0.1 s TWT thick band of strong reflectors at about 0.35 s TWT below the seabed (Fig. 5). Another bright single reflection is present below the reflective band. This characteristic pattern is similar to a slightly more attenuated acoustic section on the southern flank (Fig. 5, section Healy 0530). This correlation implies that up to 0.2 s TWT of sediments are missing on top of the ridge and part of the chaotic reflection zone in the central part of profile A includes an extra volume of material (Fig. 3a). We interpret the zone of chaotic reflections in profile A to represent debris flows proximal to an upslope source as well as sediments deformed *in situ*. Although, the missing upper sediments on the shallowest part of the ridge may have sourced debris flows, a lack of distinct scars in the seabed appears more indicative of erosion by a strong bottom current event.

Mass wasting may have been induced by a basement tectonic event as indicated by the presence of vertically displaced blocks with partially preserved internal stratal continuity below the peripheral areas of the chaotic zone (Fig. 3a, profile A). However, near complete disruption at depth below the central part of the disturbed zone is suggestive of a more complex situation

Outcrop of acoustic layering at the seabed (Fig. 3b, profiles B and C) may be due to: 1) a lateral transition from deposition to non-deposition/erosion caused by gradients in persistent bottom currents, 2) erosion of intact stratigraphy by a strong bottom current event, or 3) sediment removal by mass wasting. Lateral truncation of the uppermost part of the section in profiles B and C (Fig. 3b) is abrupt and not tapered as would be the case in the presence of a lateral gradient in bottom current velocity (Faugères et al. 1999). Hall Knoll (Fig. 4) is flanked by truncated strata on all sides and constitutes an erosional remanent (Fig. 3b, profile C). We argue that sediments of an intact stratigraphic section appear to have been removed by a locally intense bottom current event with velocities far beyond the range of geostrophic bottom currents (Fig. 3b, profile C). The erosion scars are partially infilled down-slope, and lack of internal acoustic stratification in the fill may result from a debris-like character or rapid resedimentation (Fig. 3b, profile B).

Sediment disturbance appears most severe in the eastern part of the area at about 84.5°N, 255°E (Fig. 3b, profile D). The seabed is uneven and sub-bottom reflections vary from completely incoherent in the eastern part of profile D to continuous 15 km to the west (Fig. 3b, profile C). Sub-bottom penetration of the *T3* seismic sparker system was more than 0.5 s TWT as seen on neighbouring profiles, but the energy appears insufficient to assess the depth extent of the disrupted stratigraphy (Figs. 3b and 4, profile D). We suggest that disruption of the sediments is most likely due to energy transfer from above the sediment column rather than from the underlying basement.

Discussion

The seismic records from Alpha Ridge show evidence of: 1) very strong erosion of the sub-bottom sediments in a restricted area; 2) extensive mass wasting and 3) severe sediment deformation as well as tectonic movement of basement blocks. Measured present day bottom current velocities are 4-6 cm/s (Hunkins et al. 1969). Basin-scale thermo-haline circulation and bottom current intensities are primarily related to basin geometry and meridional heat transport by tele-connection with lower latitude water masses; constraints which change on a plate tectonic time scale and which are modulated by global climatic events. Sediment deposition in an abyssal realm of moderate relief is generally characterized by persistent lateral continuity except in the presence of significant bottom currents or major basement topography. Gradients in geostrophic, contour-following bottom currents attenuate sediment deposition or erode at the perimeter of a ridge crest or form moats at the foot of steep obstacles to flow. Steeper slopes support greater isopycnal gradients and faster currents (Bowden 1960; Bird et al. 1982). Erosion on the flanks of Hall Knoll involves more than 0.1 s TWT (>100 m) of section (Fig. 3b, profiles B and C) and the short lateral distance between no erosion and severe erosion argues against sediment removal by a steady-state bottom current. Tidal interaction with bottom topography may induce strong local amplification of bottom currents (Hunkins 1986), but is not relevant for the area in question (Kowalik & Proshutinsky 1993; Padman & Erofeeva 2004).

The apparent relative abundance of debris flows within a 150 x 150 km area centred at 85°N, 225°E (Fig. 4) may be a function of data coverage; more mass flows could be present on the southern slope of Alpha Ridge between 200° and 270°E. Sediment stability is a balance between the slope parallel component of gravity and the resistive forces from sediment shear strength. Instability may be generated by footwall erosion by bottom currents or different types of loading events such as sea level changes, earthquakes (Kvalstad et al. 2005) or an external pressure pulse. Sea level changes have a basin-wide effect, while dynamic loading from a point source is site specific. The Alpha Ridge appears aseismic (Fig. 1 - *http://earthquakescanada.nrcan.gc.ca*) relative to a detection threshold of about magnitude 4 and our time scale of half century of observations. However, infrequent earthquakes may occur as we observe vertically displaced blocks of sediments with intact internal acoustic stratification (Figs. 3a and 4, profile A southern part). Offsets are smoothed by overlying syn- or post-tectonic mass flow deposits.

Our observations of several independent processes; intensive local erosion of sub-bottom sediments, extensive mass wasting, sediment deformation and evidence of basement tectonics pose two principal questions; i) are these disturbances coupled to the same event(s), and ii) what is the cause? Firstly, we note an apparent westward progression from the most intense sediment deformation at 84.5°N, 255°E (Figs. 3b and 4, profile D) to adjacent sediment removal by strong local currents (Figs. 3b and 4, profile B and C), and on to an area where abundant mass flows have been triggered (Fig. 4). Secondly, erosion of the upper sediments on Alpha Ridge appears to be a unique local feature within the Arctic Ocean basins and also has the character of a short lived local event since we have no evidence of constructive current-controlled deposition in adjoining areas. Basement tectonics may trigger sediment instabilities and generate mass wasting, both of which are short lived events. However, the latter processes are not known to generate bottom currents of the intensity required here.

As a working hypothesis we argue that the spatially confined zone of intensely disturbed sub-bottom sediments was most likely created by a local, short-lived pressure event which induced jets of fast bottom flow, numerous dynamically triggered debris flows and induced basement faulting. Impact of an extra-terrestrial object in the Arctic Ocean over the Alpha Ridge in water depths of 1200-2000 meters would have sufficient energy to cause disruption and redistribution of the upper several hundred meters of sediments below the seabed (Artemieva & Shuvalov 2002). Simple calculations using the web-based tool published by Collins et al. (2005) suggest that an object of diameter 1 km or less hitting the atmosphere at a very low angle and relatively slow speed would favour generation of an elongated ellipse of projectile fragments impacting the surface of the Arctic Ocean. The true outline of the most intensely deformed zone is unknown and may not necessarily represent a conventional crater. Darby (1998) has reported on mysterious iron-nickel-zinc spherules observed as ice-rafted debris in short cores from the central Arctic Ocean, but the age of the spherules is in question.

The *Eltanin* impact site (~5000 m water depth) located on Late Cretaceous oceanic crust in the Bellingshausen Sea is presently the only known impact location in the deep ocean. Basement here is covered with less than 100 m of sediments (Gersonde et al. 1997), and direct comparison of seismic images is not possible. The sediment section outside a crater is commonly characterized by well-defined acoustic stratification changing laterally at the crater rim into an upper incoherent lens underlain by partly intact stratigraphic continuity (Morgan & Warner 1999; Kirschner et al. 1992).

Timing of a possible impact in the central Arctic Ocean

About 95 sediment cores (Clark et al. 1980; Minicucci & Clark 1983) have been raised during the drift of *T-3* from areas on Alpha Ridge where the seismic evidence presented here shows that sediment removal has taken place. The stratigraphic ranges covered in these up to 5.5 m long cores suggest continuous sedimentation from the Pliocene on (Clark 1996), but may be much younger (Backman et al. 2004). A 6 m sediment core (Fig. 1, black star) recovered from R/V Polarstern indicates continuous sedimentation (Jokat et al. 1999) over perhaps the last million years (R. Stein, pers. comm). The thickness of post-impact sediments draped over an eroded substratum appears to be below the resolution in the seismic data (<15 m), but is apparently greater than the interval recovered by the longest available sediment cores (max. 6 m). Four cores which have captured intact stratigraphic intervals of Upper Cretaceous–Lower Cenozoic silicious ooze and black mud within Pleistocene and younger sediments (Clark 1977; Mudie & Blasco 1985) are all located on graben-bounding faults or on steep slopes (Figs. 1 and

4, black dots). The older sediments likely represent parts of blocks of material emplaced by slumping and covered by later sedimentation (Clark 1977). All Late Cretaceous-early Cenozoic cores are within or in the vicinity of the extensive mass flows reported here (Fig. 4). We suggest these older sediments became exposed as a result of mass wasting triggered by an impact. The impact event may be of Plio-Pleistocene age.

An impact on the Alpha Ridge would be about 300 km from the northern shores of Arctic Canada and 1800 km from the shores of eastern Siberia. Sea ice may or may not have been present. A major part of the circum-arctic shores has subsequently been covered by Pleistocene and younger glacial advances and any evidence of a tsunami would most likely be obliterated except in eastern Siberia.

Conclusions

Deposits within a 200 x 600 km area on Alpha Ridge, central Arctic Ocean have been locally disrupted down to at least 500 m below the seafloor, and have undergone intensive local erosion and extensive mass wasting. We note that: 1) tectonic events normally involve displacement of basement blocks and overlying intact stratigraphic sections bounded by narrow faults and not continuous lateral deformation over tens of kilometres as observed here, 2) basement tectonics may trigger mass wasting, but do not generate bottom currents, and 3) abyssal bottom currents are part of the basin-scale thermo-haline circulation and may be locally intensified, but disruption of stratigraphic continuity is limited to the deepest erosion level. Our working hypothesis is that the spectrum and scale of the observed disturbances are best explained as the effect of a shock wave generated by the impact of an extra terrestrial object.

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