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Quaternary Research 63 (2005) 150–160

QUATERNARY RESEARCH

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# Multibeam bathymetric and sediment profiler evidence for ice grounding on the Chukchi Borderland, Arctic Ocean

Martin Jakobsson[a,b,*], James V. Gardner[a], Peter R. Vogt[c], Larry A. Mayer[a], Andrew Armstrong[a], Jan Backman[b], Rick Brennan[a], Brian Calder[a], John K. Hall[a], Barbara Kraft[a]

[a] *Center for Coastal and Ocean Mapping/Joint Hydrographic Center, University of New Hampshire, NH 03824, USA*
[b] *Department of Geology and Geochemistry, Stockholm University, 106 91 Stockholm, Sweden*
[c] *Marine Geosciences Division, US Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375-5320, USA*

Received 28 June 2004

## Abstract

Multibeam bathymetry and 3.5-kHz sub-bottom profiler data collected from the US icebreaker *Healy* in 2003 provide convincing evidence for grounded ice on the Chukchi Borderland off the northern Alaskan margin, Arctic Ocean. The data show parallel, glacially induced seafloor scours, or grooves, and intervening ridges that reach widths of 1000 m (rim to rim) and as much as 40 m relief. Following previous authors, we refer to these features as "megascale glacial lineations (MSGLs)." Additional support for ice grounding is apparent from stratigraphic unconformities, interpreted to have been caused by ice-induced erosion. Most likely, the observed sea-floor features represent evidence for massive ice-shelf grounding. The general ESE/WNW direction of the MSGLs, together with sediment, evidently bulldozed off the Chukchi Plateau, that is mapped on the western (Siberian) side of the plateau, suggests ice flow from the Canada Basin side of Chukchi Borderland. Two separate generations of glacially derived MSGLs are identified on the Chukchi Borderland from the *Healy* geophysical data. The deepest and oldest extensive MSGLs appear to be draped by sediments less than 5 m thick, whereas no sediment drape can be distinguished within the resolution of the sub-bottom profiles on the younger generation.

*Keywords:* Ice grounding; Chukchi Borderland; Multibeam bathymetry; Iceberg scour

## Introduction

A diversity of hypotheses and speculations exists about past glacial conditions in the Arctic Ocean. These vary from sea-ice-free conditions with limited glaciation on surrounding shelves (Olausson, 1985) to huge floating ice shelves, >1 km thick and fed by large ice caps that occupied the surrounding shelves (e.g., Grosswald, 1980; Hughes et al., 1977; Mercer, 1970). Testing these ideas has been difficult because of the lack of geophysical data and sediment cores, reflecting the limited access to the central Arctic Ocean by surface ships. Over the past 10–15 years, however, scientific icebreaker and nuclear submarine expeditions have begun to change that picture. Recent geophysical mapping and coring provide evidence that ice has influenced the seafloor of the Arctic Ocean down to 1 km below present sea-level (Fig. 1). For instance, the sediments on the crest of the Lomonosov Ridge show seafloor scours and stratigraphic unconformities that reflect up to 50 m of erosion (Jakobsson, 1999; Polyak et al., 2001). Polyak et al. (2001) proposed that these features were caused by the action of a grounded shelf ice. An alternative interpretation is provided by Kristoffersen et al. (2004) who argue that the mapped erosion and scours on the Lomonosov Ridge were formed by grounding of armadas of large icebergs during times of disintegration of the Barents–Kara ice sheet. Features

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* Corresponding author. Department of Geology and Geochemistry, Stockholm University, 106 91 Stockholm, Sweden. Fax: +(46) 8 6747897.
*E-mail address:* martin.jakobsson@geo.su.se (M. Jakobsson).

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doi:10.1016/j.yqres.2004.12.004

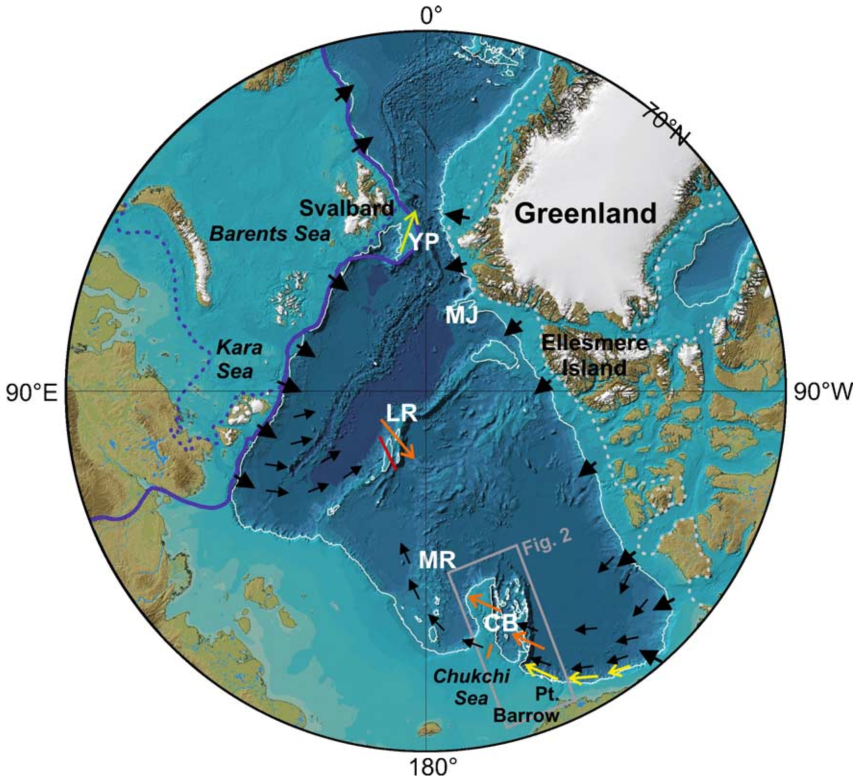

Figure 1. Overview map showing mapped glacigenic features in the Arctic Ocean and inferred directions of ice movement. Physiographic features include Chukchi Borderland (CF), Mendeleev Ridge (MR), Lomonosov Ridge (LR), Morris Jesup Rise (MJ), and Yermak Plateau (YP). Ice directions are: orange = Polyak et al. (2001); red = Jakobsson (2000); yellow = Engels et al. (2003); green = Vogt et al. (1994). Arrows show directions of ice-shelf movement and lines show general orientations of mapped iceberg scours. Black arrows show glacial iceberg directions and sources of late Quaternary sediments (Phillips and Grantz, 2001). White contour is the present 1000 m isobath (Jakobsson et al., 2000). Blue solid line is the outline the ice-sheet extension during marine oxygen isotope stage (MIS) 6 on the Barents and Kara Sea margin (Svendsen et al., 2004). The late Weichselian (MIS 2) limit for the ice sheet extension in the Barents and Kara Sea is shown with a blue dashed line (Svendsen et al., 2004). The Late Wisconsinan (MIS 2) ice sheet extension from Dyke et al. (2002) is shown with a gray dashed line.

reflecting the action of grounded ice are also mapped on the Chukchi Plateau and the Northwind Ridge (Polyak et al., 2001), the two major topographic highs comprising the Chukchi Borderland (Hall, 1990). Similar glacial features had been previously discovered on the Yermak Plateau off northern Svalbard (Vogt et al., 1994, 1995).

The wide-spread presence of glacially generated features on the Arctic seafloor at water depths up to 1 km have been used to suggest that immense ice shelves existed during at least some Pleistocene glaciations (Polyak et al., 2001). Mercer (1970) pointed out the general similarity in settings between the present-day Arctic Ocean and West Antarctica, where large ice shelves are fed from ice streams and expand into the Weddell and Ross seas. But, with few exceptions, today's small Arctic ice shelves are different from the large Antarctic ice shelves; the former are primarily sustained by basal accretion of sea-ice and surface accumulation, rather than being fed from ice streams that emanate from a large grounded ice cap (Jeffries, 2002). Present climate conditions do not allow basally accreted Arctic ice shelves to grow much thicker than a few tens of meters (Jeffries, 2002). Consequently, to determine the character of the Arctic Ocean during Pleistocene glaciations, we must first determine the spatial extent and thickness of former floating ice shelves.

Here, we present geophysical data that suggest that glacier ice was grounded on the Chukchi Borderland at least once prior to the last glacial maximum (LGM; ~17,000 years ago, Bassinot et al., 1994), possibly during one or more of the glacial maxima from marine oxygen isotope stages (MIS) 6 to 4. Multibeam bathymetry is combined with 3.5-kHz sub-bottom profiles to identify and analyze the size, frequency, and directions of iceberg scours and glacial flutes.

The term *iceberg scour* is henceforth used for seafloor plowmarks caused by grounding of individual icebergs. The term *flutes* or *fluting* refers to sets of streamlined parallel seafloor scours, better described as alternating grooves and ridges, interpreted to have been caused by the plowing action of a larger coherent ice mass with under-ice relief. Such a large ice mass is most likely a grounded but moving ice shelf, or possibly a very large tabular iceberg. Previous studies of large-scale flutes formed by the Laurentide ice sheet (Clark, 1993, 1994) led to the terms *megaflute* for features with lengths of

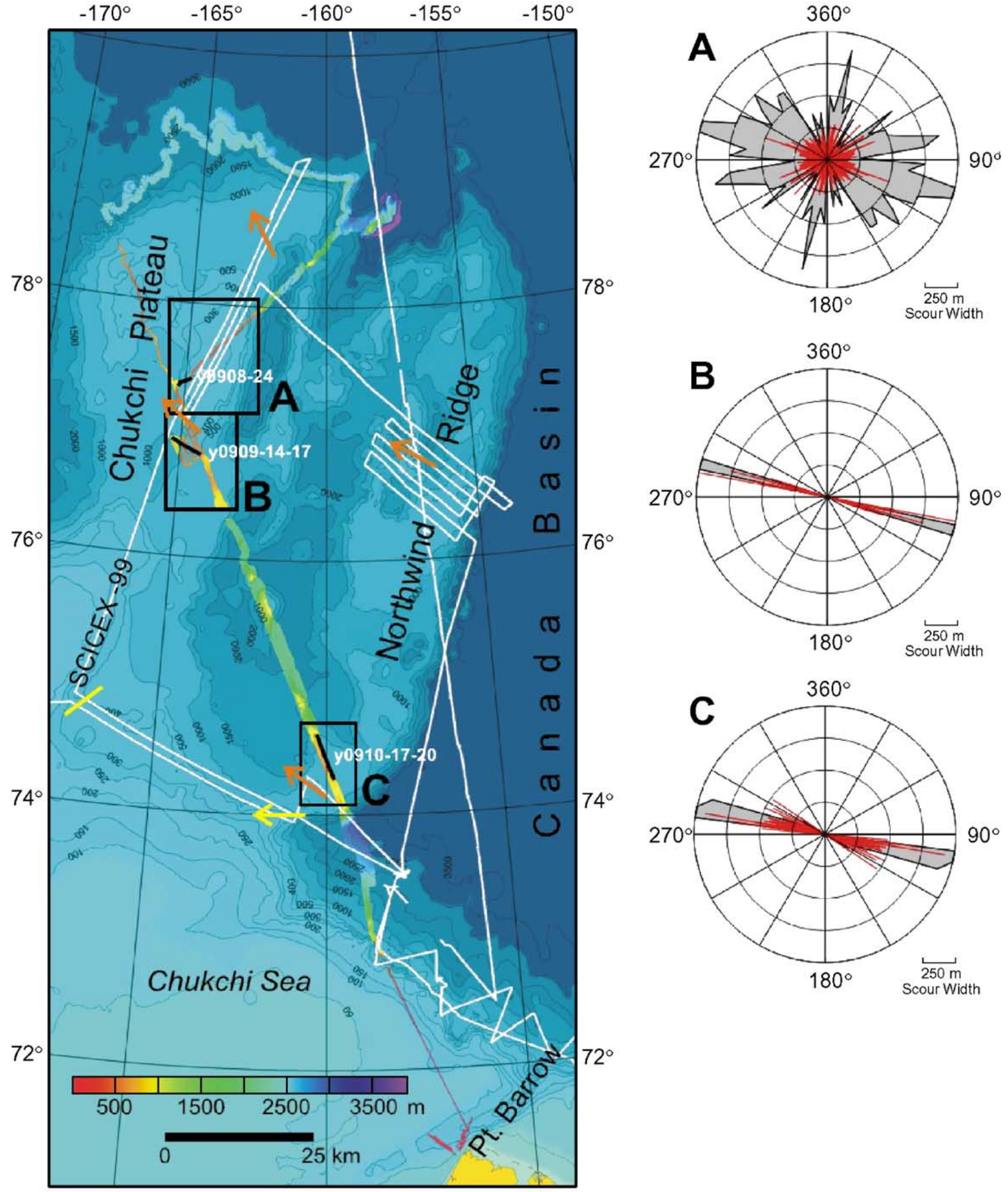

Figure 2. Bathymetry of the Chukchi Borderland. The *Healy* multibeam swath is shown with a rainbow color table to distinguish it from the background bathymetry, which is from Jakobsson et al. (2000). Boxes A, B, and C outline areas discussed in text. The right side rosette diagrams represent directional analysis of glacial scours in Areas A, B, and C. Multibeam and sub-bottom profiles are shown in Figures 3A–C and 4A–C respectively. Ice directions are also inferred on the map from Polyak et al. (2001) for comparison; orange arrows indicate older glacial flutes and yellow a younger generation of flutes (arrows) and iceberg scours (line).

200–2000 m and spacings of 20–400 m, and *megascale glacial lineations* for flutes with lengths of 8–70 km, widths of 200–1300 m, and spacings of 300–5000 m. Following Shipp et al. (1999), and wishing to avoid confusion over terminology, we adopt “megascale glacial lineations” (MSGL) for the large flutes reported in this paper.

## Methods

The new data presented here were collected with a hull-mounted multibeam echo sounder and 3.5-kHz sub-bottom profiler during August 30–September 11, 2003 on the US Coast Guard icebreaker *Healy* (Fig. 2). *Healy* is equipped with a 12-kHz Seabeam 2112 multibeam system and a 3.5-kHz ODEC Bathy 2000 sub-bottom profiling system. Bathymetry was collected in ice conditions up to 8/10 between Point Barrow, Alaska and 79°30′N (Fig. 2). Sub-bottom profiles were recorded only during the second part of the cruise because of hardware problems. About 3000 km of bathymetry was collected, representing a seafloor area of ~12,400 km$^2$, and about 1000 km 3.5-kHz data were collected. The multibeam bathymetry soundings were compiled into digital terrain models (DTM) with a Polar Stereographic projection and grid-cell resolutions that range from 25 to 100 m, depending on the water depth. In general, on the ridge crests, the resolution of the DTMs are 25 to 50 m, which allows features with spatial dimensions larger than between ~50 to 100 m to be resolved. The size and orientation of scours and MSGLs were measured on the DTMs to determine *scour width* (the horizontal distance measured from scour rim to rim) and *scour relief* (the vertical depth from the top of the scour rim to the bottom of the scour). The present water depth at the bottom of the scour is defined as *scour water depth*.

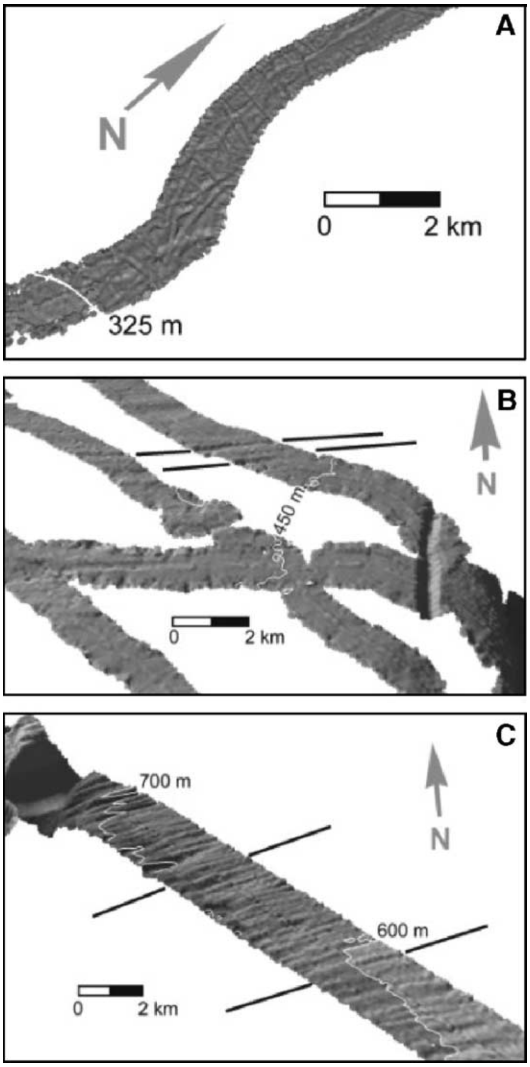

Figure 3. Multibeam DTMs from Areas A, B, and C. The location of the multibeam swaths is shown in Figure 2.

## Results

Three areas from the Chukchi Borderland (Areas A, B and C, Fig. 2) were chosen for discussion because they contain the main characteristics of the scours. Statistics for the scours are summarized in Table 1.

### Area A

Area A is located on the northern section of the flat-topped crest of Chukchi Plateau in water depths that range from slightly more than 500 m to less than 300 m below present sea level (Fig. 2). The multibeam bathymetry and sub-bottom profiles reveal a seafloor morphology dominated by scours that at first appear to show an almost random orientation (Fig. 3A). However, a $\chi^2$ test for the presence of a preferred directional trend (e.g., see Davis, 1986) provides that the null hypothesis: that is, there is no preferred direction, can be rejected at a significance level of 1% (on both $N = 5$ and $N = 10$ bins in the range (180°,

Table 1
Statistics of measured seabed scours and MSGLs in Areas A, B, and C (see Fig. 2)

| Area | Scour width (m) | | | Scour relief (m) | | | Scour water depth (m) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min–Max | Mean | Med. | Min–Max | Mean | Med. | Min–Max | Mean | Med. |
| Area A | 97–500 | 177 | 162 | 1–13 | 5 | 5 | 266–393 | 297 | 286 |
| Area B | 240–1000 | 499 | 432 | 2–10 | 7 | 7 | 422–442 | 433 | 433 |
| Area C | 214–913 | 407 | 402 | 4–40 | 12 | 7.5 | 557–760 | 648 | 656 |
| | | | | | | | MIS 2 Scour water depth (m) | | |
| | | | | | | | Min–Max | Mean | Med. |
| | | | | | | | 145–272 | 176 | 165 |
| | | | | | | | 301–321 | 312 | 312 |
| | | | | | | | 436–639 | 527 | 535 |

See Figure 2 for directional analysis. MIS 2 water depths were derived using a sea level 121 m below present for the last glacial maximum (Fairbanks, 1989).

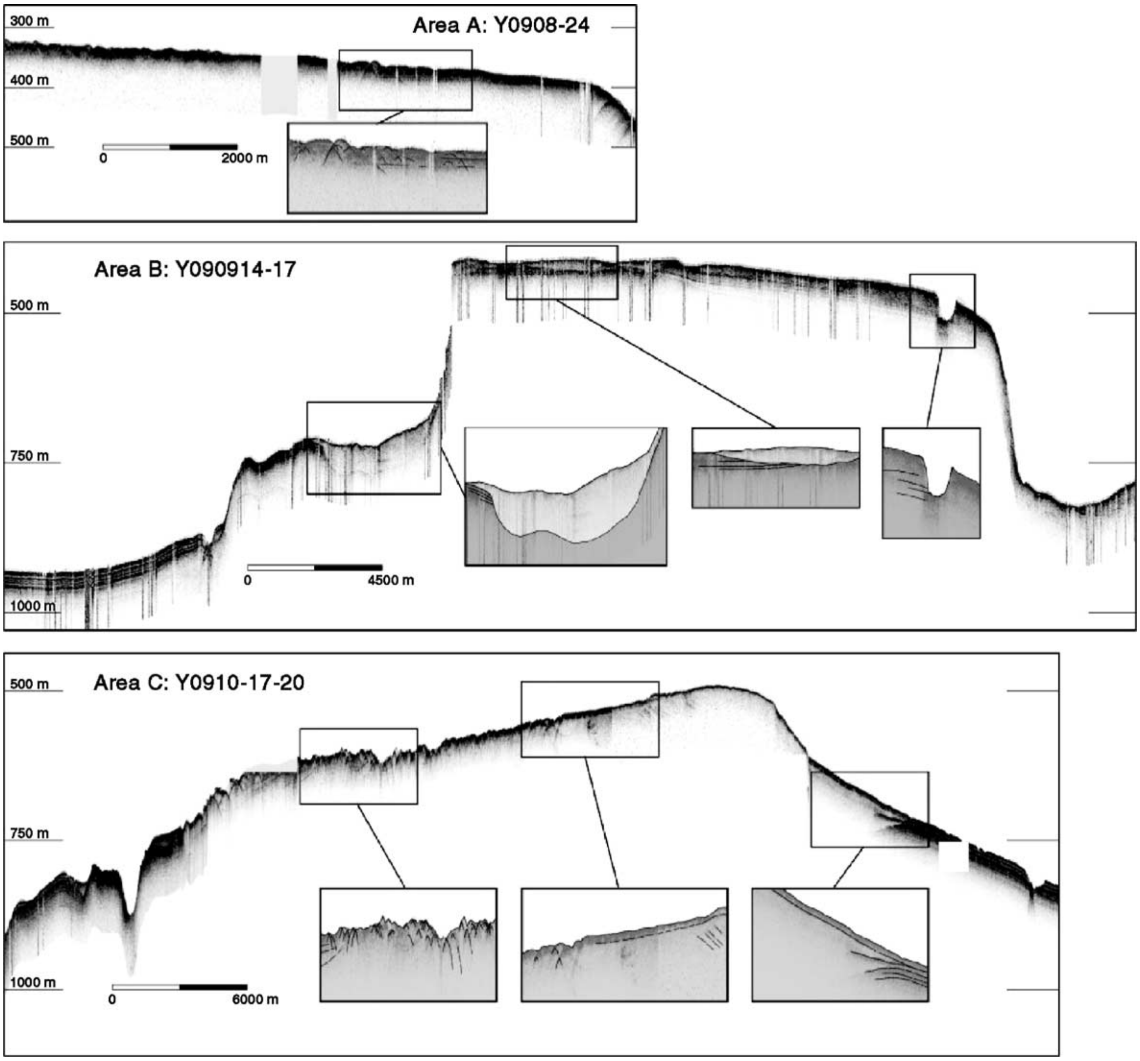

Figure 4. Seismic profiles from Areas A thru C. The locations of the profiles are shown in Figure 2.

360°]). A polar histogram with 5° bins shows two trends in the orientation of scours (Fig. 2A). One trend is statistically well-constrained with an orientation of 014°/194°, whereas the other trend shows a spread of values around a mean orientation between 105°/285°, virtually perpendicular to the first trend. The 014°/194° trend suggests a scour source either from the shallow Chukchi shelf or the central Arctic Ocean. This trend is offset ~36° from the scour orientation mapped by Polyak et al. (2001) in an area where the Chukchi Plateau extends from the shelf at 74°50′N (Figs. 1 and 2). The 105°/285° trend suggests a scour source from either the Canada Basin side of Chukchi Borderland or from the direction of Mendeleev Ridge (see Fig. 1). The widths of the scours range from ~100 to 500 m and scour depths range from ~1 to 13 m (Table 1). The largest scours are located in the deeper portions of Area A and trend 110°/290°.

The 3.5-kHz sub-bottom profiles from Area A show a rough, scoured seafloor with abundant hyperbolae along most of the surface (Fig. 4A). Any sediment drape is not thick enough to be resolved by the sub-bottom profiler.

### Area B

Area B is located immediately south of Area A and covers a central portion of Chukchi Plateau with water depths ranging from deeper than 1000 m to slightly shallower than 350 m. The scours in this area are wider and more deeply incised than those found in the shallower Area A. The scours range in width from 240 m to as much as 1000 m with a mean of 500 m (Table 1). The scour orientations are tightly grouped at 105°/285°, parallel to the mean trend of the larger group of scours observed in Area A (Fig. 2), which again suggests a scour source from either the Canada Basin side of Chukchi Borderland or from the direction of Mendeleev Ridge. A structural basin in the Chukchi Plateau that trends nearly north–south extends along the western section of Area B (this basin is delineated by the 1000-m isobath in Figures 2 and 5). A trough occurs

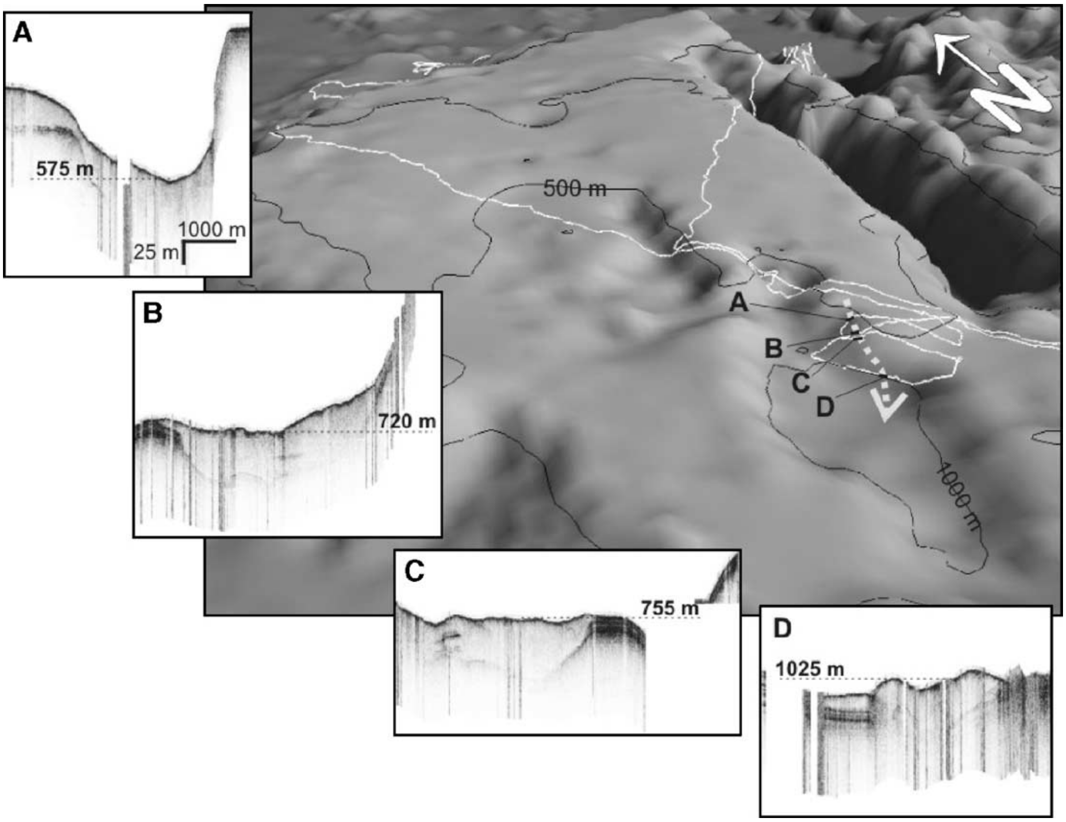

Figure 5. Perspective view of the Chukchi Plateau derived from IBCAO bathymetry with the *Healy* cruise track draped on the seafloor in white. The location of the trough that traverses diagonally across the basin margin in Area B is indicated with a white dashed arrow. Sub-bottom profiles (A–D) cross this trough at four locations. The sub-bottom profiles show a progression from erosion of the trough walls and partial infilling at the shallower end to erosion of the walls and complete filling to overflowing at the deeper end.

along the steep northeastern margin of this basin. This trough traverses diagonally across the steep margin to the bottom of the structural basin (Fig. 5). The trough is more than 2000 m wide and four sub-bottom profiles cross the floor of the trough at depths from 575 to 1025 m (Fig. 5). The sequence of sub-bottom profiles shows a progression, from shallowest to deepest, of erosion of the adjacent walls and partial infilling of the trough, through complete filling, to overflowing of the trough at the deeper end (Fig. 5). This suggests sediment that has been transported south and west off the plateau and into the trough.

The crest of Chukchi Plateau has an acoustically stratified, gently dipping section ~10 to 15 m below the surface (Fig. 4B). This unit is unconformably overlain by surficial lenses of acoustically transparent material. The lenses occur more commonly on the northwestern section of the profiles and especially at the northwestern-most edge of the plateau, just east of the steep margin with the trough described above (Figs. 4B and 5). The acoustically transparent lenses range from 10 to 15 m thick and vary in lateral extent from 250 to >1000 m along the sub-bottom profiles.

A U-shaped, evidently erosional trough, 25 to 45 m deep and 300 to 600 m wide, incises the southeast edge of the plateau, making an angle of 80° with the seabed scours (Figs. 3B and 4B). The trough can be followed for about 6 km on the multibeam bathymetry as the floor of the trough varies in water depth from 505 m in the northeast to 575 m in the southwest. This feature appears to end near its southwestern mapped limit but probably extends beyond the multibeam swath to the northeast. The U-shaped trough was excluded from the scour statistics assembled in Table 1 because of its anomalous nature in Area B. However, the feature's dimensions are compatible with some of the larger scours in Area C (Table 1).

### *Area C*

Area C is on the southeastern section of Northwind Ridge (Fig. 2). The mapped portion of the ridge crest ranges in water depths from 550 to 760 m. Large scours with widths exceeding 900 m cross the ridge crest with an orientation constrained around a mean of 98°/278° (Table 1; Figs. 3C and 4C), almost identical to that found for the larger scours in Areas A and B. Our only seismic profile across Area C shows ice scours on the surface of the ridge from the summit to depths of 710 m (present sea level) on both the northwest and the southeast sides but the scours of greatest width and relief occur on the northwest side. A thin (<5 m) acoustically transparent drape blankets all but the shallowest crest of Northwind Ridge in this area (Fig. 4C).

The thin scoured section abruptly changes down-slope to a 30-m-thick, acoustically stratified, section at water depths greater than 760 m (Fig. 4C).

## Discussion

### *Modern arctic ocean icebergs*

Present circum-Arctic glaciers that produce icebergs with a potential to reach the Chukchi Borderland include glaciers of the high Arctic islands in the Canadian Arctic Archipelago (see Koerner, 2002). The drift track of Fletcher Ice Island T3, which likely originated from the Yelverton Bay ice-shelf of Ellesmere Island (Crary, 1960), crossed Area A as well as the area near 74°50′N where ice scours were discovered during the SCICEX mapping project (Polyak et al., 2001). T3 was ~14 km long, 8 km wide, and 60 m thick when the camp was originally established on the ice island near the North Pole (Hunkins and Tiemann, 1977). Even if the potential drift paths of icebergs from present glaciers of the Canadian Archipelago, including the Ellesmere Island ice shelves, cross the Chukchi Borderland, these glaciers are not currently capable of producing icebergs thick enough to ground in the present 300 to 500 m water depths of Area A (Jeffries, 2002). In contrast, Northern Greenland's largest glaciers drain into the Arctic Ocean through outlet glaciers and form floating ice shelves that range from 120 m to nearly 800 m thick at the grounding line (Rignot et al., 1997). However, calved icebergs that escape the narrow fjords of Greenland's outlet glaciers would be thinner than their mother outlet glaciers at the grounding line. In addition, the northern Greenland continental shelf area west of about 40°W will, given present conditions, prevent icebergs thicker than 300 m from escaping into the deep Arctic Ocean because of bathymetric sills shallower than 300 m (Jakobsson et al., 2000).

### *Interpretation and comparison to previously mapped glacigenic features*

The lack of present sources of >300 m thick icebergs that could make their way to ground on Chukchi Borderland indicates that the iceberg scours in Area A are relict features from glacial periods or early stages of deglaciations. Measured scour sizes, directional trends, and the absence of acoustically measurable sediment drape (within the ~0.5-m resolution of the sub-bottom profiler system) imply that the majority of the mapped scours in Area A probably were generated by individual icebergs during the last glaciation. A ~121-m lower eustatic sea level during the last glacial maximum (Fairbanks, 1989) puts the iceberg scour water depths at about 176 m in Area A (Table 1). Whereas individual iceberg scours can explain the smaller features in Area A, they may not explain the larger features that are located in more than 300 m present water depth and are similar in size and direction to the larger scours seen in Areas B and C. These larger scours of Areas B and C are parallel to each other, with a general orientation of ESE/WNW (Figs. 2 and 3).

The type of glacier ice that grounded on Chukchi Borderland and caused the large parallel scours, or lineations, may be addressed by comparing their dimensions with previous studies of under-ice topography of large icebergs, floating ice shelves, and the morphology of glacially scoured or molded seabeds from other areas. Large icebergs may have significant drafts. For example, those produced from the glaciers calving into the Scoresby Sund fjord complex in Eastern Greenland frequently scour the seafloor to water depths as deep as 550 m and occasionally deeper (Dowdeswell et al., 1993). These icebergs commonly leave irregular, generally curving plowmarks with widths from between a few meters to occasionally over 20 m (Dowdeswell et al., 1993). The large scours from the Chukchi Borderland are significantly wider (Table 1), paralleling and mostly adjoining one another, with a "fluted" appearance, suggesting they were produced by a large coherently moving ice mass rather than by many individual icebergs moving independently. The seafloor scour morphology resembles what is known from subaerial morphology (e.g., Clark, 1993, 1994) and from multibeam seafloor mapping of areas where large fast-flowing ice streams have moved over and remolded underlying sediments. Similar but smaller (in spacing and relief) lineated seafloor fabric has been reported, for example by Barnes (1987), Solheim et al. (1990), and Josenhans and Zevenhuizen (1990). Larger-scale examples include those mapped in Marguerite Bay on the continental shelf west of the Antarctic Peninsula (Dowdeswell et al., 2004), the Ross Sea between the ice-shelf edge and the continental margin (Shipp et al., 1999), and the mid-Norwegian continental margin (Ottesen et al., 2002). The features in Marguerite Bay are 130 to 400 m wide and have 2 to 6 m of relief. Following Clark (1993, 1994) and Shipp et al. (1999), Dowdeswell et al. (2004) referred to the large-scale lineation fabric as "megascale glacial lineations." The megascale glacial lineations on the mid-Norwegian shelf are described as a series of streamlined parallel ridges and depressions with spacing between ridge tops of 400 to 500 m and a maximum ridge height of 10 m (Ottesen et al., 2002). Very similar but Holocene-aged MSGLs (300–650 m in width) were mapped by Shipp et al. (1999) in the Ross Sea. By comparison, the mean scour width in our areas B and C combined is 453 m and the mean relief is 9.5 m (Table 2), comparable to the dimensions of MSGLs in Marguerite Bay, the Ross Sea, and the mid-Norwegian continental shelf. However, the paleo-ice streams responsible for creating the latter MSGLs were largely confined to bathymetric troughs, whereas the parallel scours of the Chukchi Borderland occur on the relatively flat Chukchi Plateau and Northwind Ridge crest.

Table 2

Comparison of megascale glaciation lineation (MSGL) dimensions on the Chukchi Borderland (Areas B and C) with scours/lineations mapped on the Yermak Plateau (Vogt et al., 1994, 1995) and under-ice topography measured on the Ross Ice Shelf, Antarctica (Shabtaie and Bentley, 1982)

| Area | Ice thickness (m) | Ice underside undulation wavelength (m) | Bottom undulation relief (m) |
|---|---|---|---|
| Ross Ice Sheet (Shabtaie and Bentley, 1982) | 350–390 | 1200 (mean) | 24–40 |
| | Scour water depth—130 m | Mapped undulation wavelength (m) | Mapped undulation relief (m) |
| Yermak Plateau | 340–765 | 300–1500, 585 (mean) | 2–14, 5 (mean) |
| Chukchi Borderland (this study; Area B and C) | 292–630 | 240–1000, 453 (mean) | 2–40, 9.5 (mean) |

The scour depth reported for Yermak Plateau and Chukchi Borderland is estimated using a eustatic sea level 130 m below present to relate to MIS 6 conditions (Shackleton, 1987).

Although iceberg plowmarks are readily attributed to iceberg keels dragging through the seafloor sediment, the nature and origin of parallel scours such as presented in this and other publications are not well understood. As suggested by Vogt et al. (1994, 1995), an ocean choked by icebergs would force all the icebergs to move in approximately the same direction. Catastrophically, rapid disintegration of a large floating ice-shelf, perhaps larger versions of the recent (1995 and 2002) rapid (days) disintegration of the Larsen A and B ice shelves off the Antarctic Peninsula (MacAyeal et al., 2003), might thus produce an iceberg jam, carving parallel scours in the seabed. This is a plausible mechanism behind the ice grounding on the Chukchi Borderland that must be considered. The parallel scours may also have been produced by relief on the undersides of intact ice shelves in motion. In this case, the scour relief must be related to the ice-shelf underside relief. Parallel scours could be produced by random, unlineated roughness, in the manner of scratches made in wood by a moving sheet of sandpaper or a wide plow moving through a field. The scour marks would then have been made predominately by those protrusions (bosses) with the greatest relief. Modern ice shelves exhibit a variety of structural complexities, e.g., rift zones, surface and bottom crevasses, corrugations, ridge/troughs (Shabtaie and Bentley, 1982), many of which could be associated with ice bottom relief and therefore capable of leaving their traces on the seafloor where such ice shelves ground. The few existing data on extant large ice shelves (all in Antarctica) suggest that ice-shelf underside relief is of the ridge and furrow type, with the undulations more or less parallel to past glacier flow direction. Shabtaie and Bentley (1982) used radio-echo sounding to measure underice relief along a small part of the western Ross Ice Shelf. Their measurements indicate that the Ross Ice Shelf has a relatively regularly undulating underside, with a relief ~25–40 m and a mean wavelength of 1200 m where the shelf is 350 to 390 m thick (Table 2). Although this wavelength exceeds the widest measured scours on the Chukchi Borderland, to a first order the under-ice topography measured by Shabtaie and Bentley (1982) is comparable in width and relief to the scours we report here (Tables 1 and 2), suggesting that the scours may have been produced by under-ice relief of past Arctic ice shelves.

In applying these mostly Antarctic findings to the Arctic MSGLs, we remain uncertain as to whether the parallel scours were formed by huge (many kilometers wide) tabular icebergs, calved from Canadian or Eurasian ice shelves, that were then carried intact into the Arctic Ocean interior, or whether the scours were formed by ice shelves growing outwards from the Canadian and West Siberian shelves far enough to ground on the Chukchi Rise, Yermak Plateau, and Lomonosov Ridge. In the former case, the under-ice relief was a relic of glacier kinematics and the observed parallel scours in the seabed comprise a record of the direction these undulations were dragged during the grounding process across the shallow plateaus and ridges. The ice grounding in this case would not necessarily have occurred in a direction that paralleled the undulations. Alternatively, the parallel scours may have been created by undulations generated when thick ice shelves grew out towards and across bathymetric highs. We favor the latter interpretation because both on the Chukchi Plateau (Fig. 4C) and on the Yermak Plateau (Vogt et al., 1994, 1995), prominent parallel scours occur on the flanks of the shallowest portions of the rise, but appear absent on the rise tops, perhaps because of hard, less erodible substrate on the crest, as in parts of the Ross Sea, Antarctica (see Fig. 8 of Shipp et al., 1999). However, we think it is more likely that the rise crests were “ice rises” (comparable to Roosevelt or Berkner Islands in the Antarctic) with fully grounded glacier ice (e.g., “D” in Fig. 1 of Vogt et al., 1995), stationary or moved slowly in a radial direction. The ice was only slightly grounded but moving on the flanks (i.e., an area of “ice rumples” as defined by Swithinbank et al., 1988), producing the observed parallel scours. At greater water depths, the shelf ice was fully afloat, leaving no marks on the seafloor.

## *Glacier source and timing*

Coherent sets of evenly spaced, parallel, streamlined, low-relief lineations that extend to 700 m present water depth on the Northwind Ridge of the Chukchi Borderland were described from the SCICEX interferometric swath bathymetry and sidescan mapping, and referred to as “flutes” (Polyak et al., 2001). The SCICEX track is south of Area C on the Northwind Ridge and the orientation of the low-relief lineations there closely matches the orientation of the parallel scours in Areas A, B, and C (Figs. 1 and 2). Polyak et al. (2001) hypothesized from the SCICEX results that a major ice-shelf that originated from eastern Alaska or the western part of the Canadian Arctic Archipelago overran the Chukchi Borderland to ground and create the features they described as low-relief lineations. We suggest that all the mapped larger scours that occur in sets parallel to each other in Areas A, B, and C are flutes (MSGLs) that have been formed by a large, spatially coherent ice mass such as a grounded ice-shelf. However, on the basis of available data sets, we cannot exclude the possibility of an "iceberg jam" carving parallel scours in the seabed. This was recently proposed by Kristoffersen et al. (2004) as a likely explanation to the features first mapped by Jakobsson (1999) on the Lomonosov Ridge.

Recent analysis of SCICEX sidescan data identified bedforms along the Alaskan margin that were interpreted to be caused by grounding glacier ice (Edwards et al., 2003). The bedforms appear as margin-parallel lineations on the Alaskan continental slope and are interpreted to have been formed by a floating ice-shelf or densely packed armadas of tabular icebergs that moved and carved their path from the Canadian Arctic Archipelago towards the Chukchi Borderland (Engels et al., 2003). Provenance studies based on ice-rafted glacial erratics in sediment cores indicate that as much as 70% of the glacial erratics in the southern Amerasian Basin consist of dolostones and limestones that originated from the Canadian Arctic Islands (Phillips and Grantz, 2001), thus supporting the interpretation that the glacier source responsible for the grounding on the Chukchi Borderland is located in this part of the Arctic.

When did the ice-shelf and iceberg grounding occur on the Chukchi Borderland? The sediment drape, less than 5 m thick, that blankets the megaflutes in Area C (Fig. 4C) suggests that the flutes there are older than the shallower and smaller-sized scours in Area A. We cannot resolve a sediment drape on our 3.5-kHz profiles from the MSGLs in Areas A and B, but due to their similarity to features in Area C (i.e., size and directional trend), we assume that all these flute-like lineations are of similar morphological genesis, albeit possibly of different ages. In other words, at least two separate generations of glacially derived features appear to be present on the Chukchi Borderland. The post-MSGL sediment thickness in Area C resembles that in the ice-eroded areas of the Lomonosov Ridge crest in the central Arctic Ocean. There, the bottom of the overlying drape is dated to MIS 5.5, suggesting that the last major ice grounding occurred during MIS 6 (185,000 to 130,000 yr ago, Bassinot et al., 1994) (Jakobsson et al., 2001). It is difficult to speculate on the age of the large MSGLs in the Chukchi Borderland solely from the thickness of the sediment drape derived from the seismic data because of the large uncertainty in sedimentation rates. However, sediment cores that were retrieved by the USGS in 1991 from the ice-grounded areas of southern Northwind Ridge and the adjacent Chukchi Shelf contain two episodes of glacial seafloor erosion (Polyak et al., 2003; Polyak, L., personal communication, 2004). The older episode is found only in cores located deeper than 450 m, and the post-erosional deposition is estimated to have begun sometime between MIS 4 and MIS 6 (Polyak, L., personal communication, 2004). The younger and shallower erosion episode is estimated to have occurred during the last glacial maximum (MIS 2, Polyak, L., personal communication, 2004).

Our seismic data provide additional support for the hypothesis of a glacial-age ice-shelf that moved from the Canada Basin and grounded on the Chukchi Borderland. The seismic profiles acquired from the Chukchi Plateau, particularly those in Area B, show acoustically transparent lenses of sediment that fill large, shallow scour depressions (Fig. 4B). These lenses are more common on the northwestern section of the profiles and especially at the northwestern-most edge of the plateau just in front of the steep margin with the sediment-filled trough. The sediment lenses may have formed in conjunction with an ice rise located on the highest parts of the Chukchi Plateau, which acted as a source for glacigenic mudflows through the influence of subglacial meltwater. The lenses may, alternatively, consist of diamicton that resulted from ice plowing over the plateau seabed. The truncated strata apparent in the seismic profiles from both Areas B and C provide additional support for an erosional force that has bulldozed off the uppermost strata of the Chukchi Plateau and Northwind Ridge crest. The sediment-filled trough in the steep margin of Area B appears to have acted as a conduit for such sediment that has been scraped off the top of the Chukchi Plateau and deposited in the trough and transported towards the basin floor (Fig. 5). Together, the presence of the sediment lenses concentrated on the northwestern section of the Chukchi Plateau, the sediment fill in the trough, and the directions of the mapped MSGLs suggest a motion of the grounding ice towards the northwest, consistent with an ice-shelf origin in eastern Alaska or/and the western part of the Canadian Arctic Archipelago—most probably from ice streams emanating from McClure Strait and Amundsen Gulf.

## Conclusions

Recent multibeam bathymetry and 3.5-kHz sub-bottom profiles imaged glacial features on the Chukchi Borderland seafloor in the form of iceberg plowmarks, streamlined (fluted) parallel scours and ridges, referred to here as "megascale glacial lineations (MSGL)," as well as stratigraphic unconformities interpreted to have been caused by extensive ice erosion. The size, distribution, and general ESE/WNW trend of the mapped megascale fluting morphology suggest that massive and thick glacier ice flowed over the Chukchi Borderland from the Canada Basin side and grounded in water depths as deep as 760 m below present sea level. If this ice was in the form of a coherent ice shelf, then it is likely that local ice rises with fully grounded glacier ice were formed on the shallowest areas of the borderland. Two separate generations of glacially derived features are seen in the geophysical data; a thin (less than 5 m) sediment drape distinguishes the older and more extensive MSGLs from the younger and shallower-water lineations and from iceberg plowmarks, on which the subsequently draped sediment cover is too thin to measure acoustically. We conclude that our new geophysical data together with results from previous studies of sediment provenances (Phillips and Grantz, 2001), seafloor glacial morphology (e.g., Polyak et al., 2001), and sediment cores from ice-grounded areas of the Northwind Ridge (Polyak et al., 2003; Polyak, L., personal communication, 2004) point to thick floating glacier ice that emanated from northeastern Alaskan margin or the Canadian Arctic Archipelago (most likely through McClure Strait or/and Amundsen Gulf) on one or several occasions between MIS 4 and MIS 6. However, from the available data sets, we cannot with any certainty differentiate if the larger features mapped on the Chukchi Borderland were caused by a large thick ice-shelf or icebergs with deep drafts moving coherently in an ocean choked with icebergs. The shallower and younger generation of MSGLs may have been formed during the latest glaciation.

## Acknowledgments

We gratefully acknowledge NOAA Grant NA97OG0241 for supporting the research efforts of the members of the Joint Hydrographic Center and the NOAA Ocean Exploration Program for platform support. We also thank the Captain and crew of icebreaker *Healy* for their superior service during the cruise, as well as Dale Chayes and the cruise science party members that are not authors. Members of the *Healy* science team (besides authors 1, 3-7 and 9) included Jessica Abrams, Diane Bentley, Kathleen Crane, Joan Gardner, Alan Hayashida, Kevin Kelly, Naja Mikkelsen, Morten Solvsten, and Jeremy Weirich. Professor Charles Bentley provided valuable discussions on ice rumples and relief of ice-shelf undersides and Professor Leonid Polyak gave insightful comments on an early draft of this manuscript. The 3rd author was supported by the Office of Naval Research. We thank the two anonymous reviewers who provided valuable comments on the manuscript.

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