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Short Paper

Iceberg discharge to the Chukchi shelf during the Younger Dryas

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ABSTRACT

The extent of glaciation in northwestern Alaska, the source of sediment supply to the Chukchi shelf and slope, and the movement of sea ice and icebergs across the shelf during the last glacial maximum (LGM) remain poorly constrained. Here we present geophysical and geological data from the outer Chukchi margin that reveal a regionally extensive, heavily ice-scoured surface ~5–8 m below the modern seafloor. Radiocarbon dating of this discrete event yields age estimates between 10,600 and 11,900 ^{14}C yr BP, indicating the discharge event occurred during the Younger Dryas. Based on mineralogy of the ice-rafted debris, the icebergs appear to be sourced from the northwestern Alaskan margin, which places important constraints on the ice extent in northern Alaska during the LGM as well as existing circulation models for the region.

Introduction

Although recent studies of ice grounding have been conducted along the Chukchi borderland and greater Arctic Ocean regions (Polyak, et al., 2001; Jakobsson, et al., 2005), the shallow Chukchi shelf remains relatively unexplored. Numerous questions persist concerning the extent of glaciation in northwestern Alaska during the last glacial maximum (LGM), the source of sediment supply to the Chukchi shelf, and the movement of sea ice and/or icebergs across the shelf. Evidence of iceberg scouring and ice-rafted debris on the outer Chukchi shelf presented here provide an important proxy for deglacial circulation patterns, as well as insight into ice extent across the western Arctic during recent glaciations. Regional ice cover in the Arctic strongly affects albedo, which has climatic feedbacks that can play an important role in oceanic and atmospheric circulation (Aagaard and Carmack, 1989). The question of ice extent during the LGM has particular significance in the coherence of global circulation models for glacial periods, the results of which are strongly influenced by ice-extent input parameters (Smith, et al., 2003; Zweck and Huybrechts, 2005).

Methods

CHIRP subbottom data were acquired aboard the USCGC Healy on the outer Chukchi shelf (Fig. 1) in 2002, using the Scripps Institution of Oceanography EdgeTech X-Star CHIRP subbottom sonar. The subbottom profiles were acquired using a 1- to 6-kHz CHIRP signal with a 50-ms sweep. The core locations are correlated with the subbottom profiles by projecting the core location orthogonally onto the plane of the subbottom profile and this projection distance is noted in each figure. Two-way travel time was converted to depth employing a nominal sound velocity of 1500 m/s in order to correlate the lithostratigraphy with the CHIRP profiles. Swath bathymetry data was collected underway using the hull-mounted Seabeam 2112 aboard the USCGC Healy. Cores were sampled at 20 cm spacing for identification and dating of the foraminifera, as well as examination of the mineralogy in the >150 μm fraction. Abundance peaks in benthic foraminifera were sampled for ^{14}C dating using standard methods at the National Ocean Sciences Accelerator Mass Spectrometer facility at Woods Hole. Radiocarbon dates presented here are uncorrected; however, a reservoir correction of 700–1000 yr may be applicable, but this does not significantly change our interpretation.

Results

CHIRP subbottom data collected along the outer Chukchi shelf (60–100 m water depth; Fig. 1) show evidence of numerous ice scours along a surface as much as 8 m below the modern seafloor. Individual scours are represented by v-shaped incisions, ranging from 50 to 100 m wide and averaging 5 m deep, with some plough marks>8 m deep. Similar ice scour morphology has been identified from glaciated margins worldwide (Davies et al., 1997). Sediment drape above the scour surface is thickest in the western portion of the profiles (~8 m), and systematically diminishes toward the east (Fig. 2). The buildup of sediment to the west mantles a preexisting bathymetric high and records the westward flow of the Beaufort Gyre. The acoustic character below the scour surface is chaotic and generally featureless. In contrast, the scour infill is highly reflective and acoustically laminated at the base, becoming less reflective upsection, especially above the crest of the scours.

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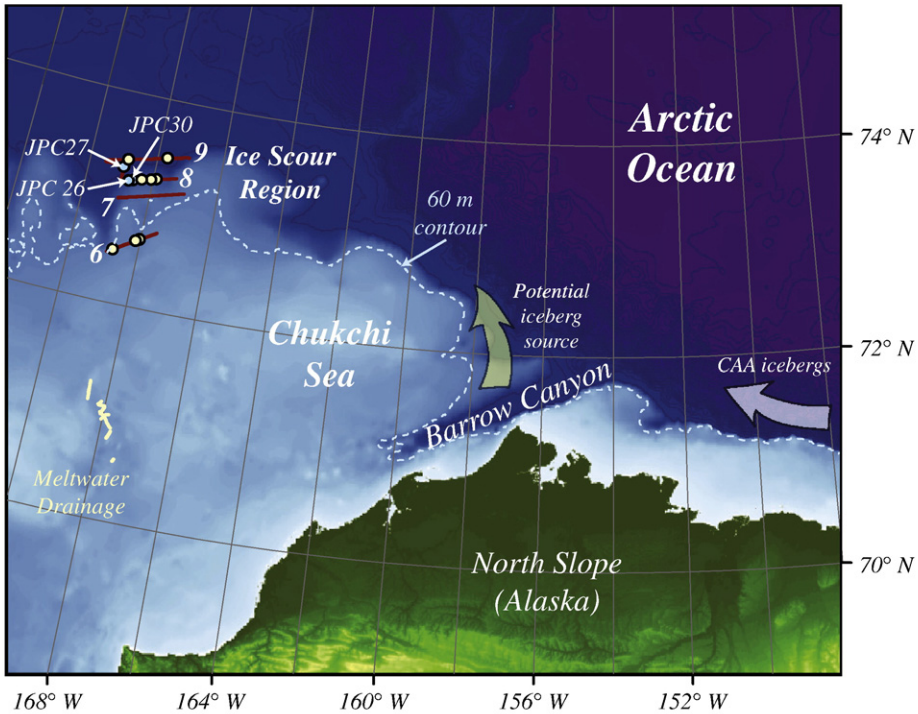

Figure 1. Map of the eastern Chukchi margin showing CHIRP profiles across the ice scour surface and sediment core locations. Profile locations of midshelf meltwater drainage (Hill et al., 2007; Hill and Driscoll, 2008) discussed in the text are shown. At the time of ice scour incision, sea level was ~60 m below present. We suggest Barrow Canyon may have served as an embayment directing iceberg discharge from the Alaskan North Slope to the outer shelf.

In addition to CHIRP subbottom data, we acquired eleven piston cores from the ice-scour region. Although the overall grain size in the cores is dominated by silt, coarsest-grained intervals correlate with high-amplitude reflectors in the base of the ice scour (Fig. 3). Several cores penetrated the base of the ice-scour surface, recovering sediments above and below the erosive horizon (Fig. 3). Despite a relatively small sand fraction, several trends are apparent in the composition. Overall the sand fraction is dominated by quartz, but there appears to be at least two distinct mineralogical zones in the cores. A flooding surface (FS) at 5–6 m depth within the cores separates blueschist minerals (e.g., glaucophane, epidote) in the basal section from authigenic pyrite above, with the upper few meters showing no distinguishing grains (Fig. 3). The foraminifer, *Elphidium excavatum*, which prefers brackish, estuarine environments, is most often observed in the base of the cores, coincident with the zone of metamorphic minerals. The blueschist minerals, in combination with the Elphidium, suggest relatively shallow water conditions, with a terrigenous component that appears to be sourced from the nearby Brooks Range of northern Alaska, where large exposures of blueschist facies bedrock are found (Beikman, 1980; Dusel-Bacon et al., 1989). The FS, associated with rapid sea-level rise, records the transition to more open marine conditions consistent with the presence of authigenic pyrite and decreased Elphidium abundance upsection.

Sufficient biogenic material was recovered from piston cores JPC26, JPC27 and JPC30 for radiocarbon dating. The scour surface represents an erosional event; therefore we acquired samples from horizons directly above and below the surface to constrain the scour timing. Radiocarbon dating from the basal section of JPC27 below the scour surface with high abundance of blueschist minerals yields an age of 12,850 ± 220 ^{14}C yr BP (Fig. 3). Radiocarbon dates from the more reflective, laminated sequence infilling the base of scours yield ages of 10,400 ± 140 and 10,650 ± 170 ^{14}C yr BP (JPC27; Fig. 3). In JPC30, radiocarbon dates from the interval at 6.8 m, which is below the ice-scour surface as projected on the sub-bottom profile, are 11,900 ± 160 ^{14}C yr BP and 11,000 ± 50 ^{14}C yr BP (Fig. 3). Similar to core JPC27, this interval has a high terrigenous component. The radiocarbon age on a mollusk from JPC30 (11,000 ± 50 ^{14}C yr BP, 7.2 m; Fig. 3) also confirms the relative age for the surrounding sediments, but appears chronologically out of context with the other dated samples and may reflect a vital effects difference in radiocarbon fractionation between foraminifera and mollusks. The radiocarbon date of 9830 ± 140 ^{14}C yr BP in JPC26, the most landward core, correlates with the scour surface observed in the CHIRP profile. Given these constraints, the timing for the iceberg discharge event and consequent scour formation is between 10,650 ± 170 and 11,900 ± 160 ^{14}C yr BP.

Discussion

There is little to no evidence of ice disturbance in the sediments above the scour surface, which suggests these features were formed by a single, unrepeated event. Sea level at this time would have been ~50–60 m lower than present, (Bard et al., 1988; Keigwin et al., 2006; Hill and Driscoll, 2008) indicating a paleo water depth of 10–40 m for the scour surface. If the scour depressions were derived from grounded sea ice, we would expect repeated scouring of the seafloor as the sea ice surges and retreats seasonally. This should create a stratigraphic record with ice scours present throughout the sediment column, exhibiting scours at various depths or a more chaotic acoustic character of nested scours; a scenario that is not observed in the data. Additionally, the individual ice scour dimensions observed here are much larger than that observed from modern sea ice gouges on the Chukchi and Beaufort shelves, which average 1 m or less in depth, with maximum incision of 3–4 m (Barnes et al., 1984; Phillips et al., 1988; Héquette et al., 1995). Therefore, we suggest the regional scour surface was formed by discharge of a large number of icebergs over a relatively short period of time, rather than seasonal or multiyear sea-ice movement, followed by generally iceberg-free conditions. There appear to be small quantities of sediment at the base of the ice scours with grain size > 250 µm, indicating the possible presence of ice-rafted debris (IRD). These deposits may be analogous to the Heinrich layers of the North Atlantic, which record large outbursts of icebergs during deglaciation (Heinrich, 1988). Evidence from the Chukchi

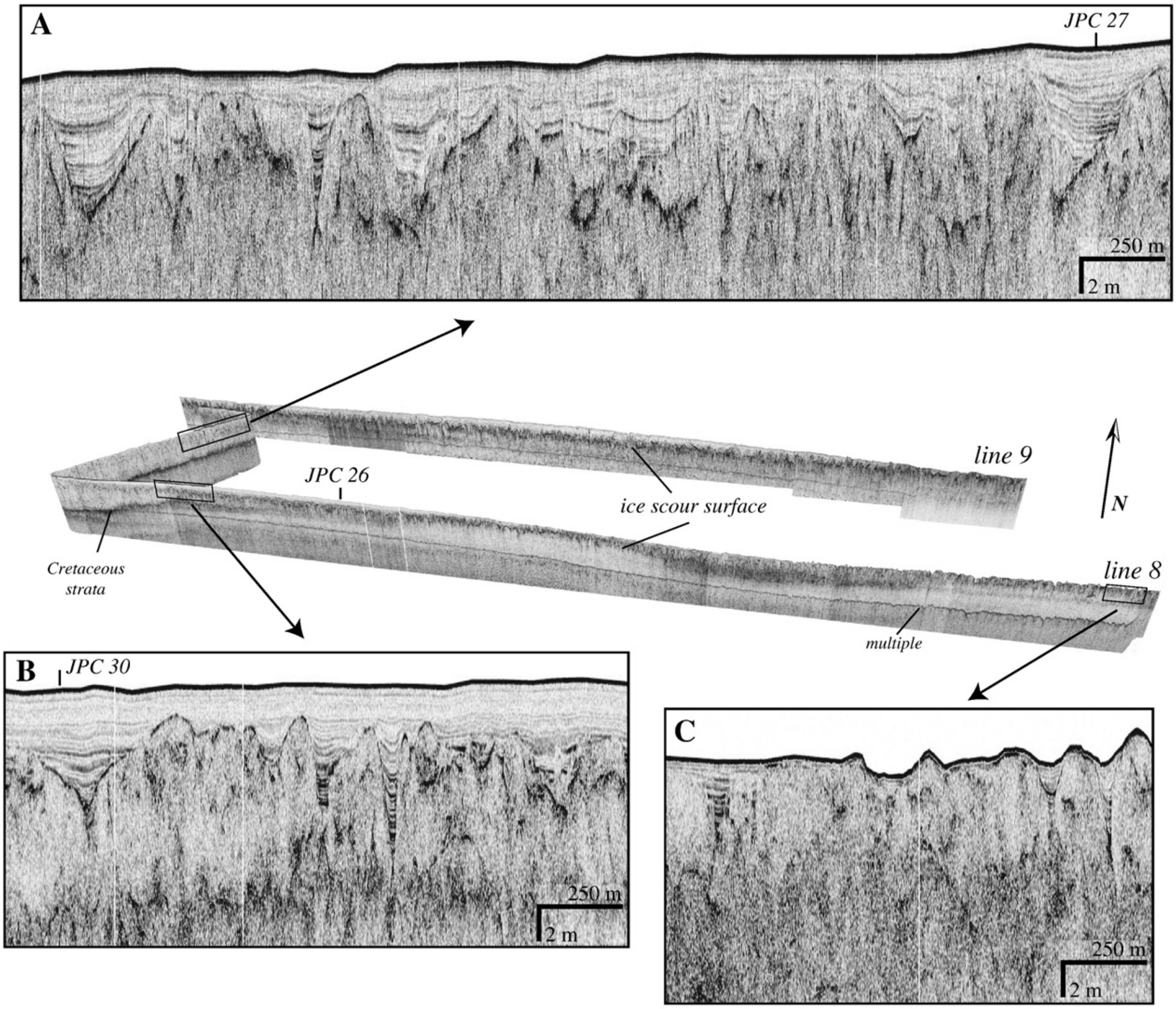

Figure 2. 3-D perspective view of CHIRP profiles across the ice scour region. Sediment cover is thickest in the western portion of the profiles. Boxes A, B and C show insets. The ice scour morphology has a distinctive v-shaped morphology, with elevated ridges on either side, infilled with highly reflective, acoustically laminated sediment. Above the localized scour infill the acoustic character becomes more transparent. Box C, in the eastern region, shows very little sediment cover. Profile locations are shown in Figure 1.

margin of massive discharge and channel scouring, derived from glacial meltwater drainage during deglaciation, suggests that ice extent across the northern Brooks Range may have been greater than previously recognized (Hill et al., 2007). Breaching of possible ice-dammed lakes in the region would have created large outburst floods that may have been a conduit for high-volume meltwater and iceberg discharge (Hill and Driscoll, 2008). Radiocarbon dating of the oldest material above and the youngest material beneath the scour surface indicates that the iceberg discharge event occurred during the Younger Dryas. Heinrich-type events have been observed elsewhere during this same time period (~10,500 to 11,000 ^{14}C yr BP) (Bond et al., 1993). Heinrich events generally occur during cold stadial periods and have been frequently invoked for climatic forcing through freshwater input and disruption of thermohaline circulation (Broeker, 1994; Clark et al., 2001).

One of the primary western outlets for ice streams and icebergs emanating from the large Pleistocene ice sheets across North America during deglaciation was through the dolostone-rich Banks Island and Victoria Island regions of northern Canada, as well as the Mackenzie River Valley (Dyke et al., 2002; Stokes et al., 2005). Consequently, most IRD deposits in the western Arctic basin exhibit carbonate-rich facies diagnostic of the Canadian Arctic Archipelago (CAA) (Bischof et al., 1996) These late-stage icebergs on the Chukchi shelf may have been sourced from glaciated regions of Canada; however, a distinct absence of detrital carbonate in the sediment cores suggests provenance from a less carbonate-rich region, most likely west of the Mackenzie River district. The clockwise circulation of the Beaufort Gyre in the western Arctic and the Transpolar Drift, which directs the eastern basin flow northward from the Siberian shelves to the Fram Strait, would inhibit icebergs released from the Siberian margin from reaching this part of the Chukchi shelf. Therefore, the Chukchi shelf icebergs may have been sourced instead from the Alaskan margin.

It is somewhat difficult to understand how continental ice in eastern Alaska might be transferred to the marine environment due to the lack of coastal embayments in the region. West of the Mackenzie valley, the largest embayment on the margin is the Barrow Canyon (Fig. 1). Sea level during the ice scour event would have been ~50–60 m below present (Bard et al., 1988; Keigwin et al., 2006; Hill and Driscoll, 2007), at this depth most of the canyon would remain flooded (Fig. 1). CHIRP seismic profiles on the upper slope of Barrow Canyon (~145 m to > 220 m WD) show evidence of a buried ice-scour surface very similar to the surface observed on the outer shelf. As these scours are at much greater depths in the canyon than those observed on the outer shelf, we interpret these features to be related to earlier phases of deglaciation, during a period when sea level was lower. The presence of iceberg scours in the Barrow Canyon supports our hypothesis that this was an important conduit for iceberg discharge.

Another scour field of LGM age has been identified on the Chukchi borderland (Polyak et al., 2001; Jakobsson et al., 2005; Polyak et al.,

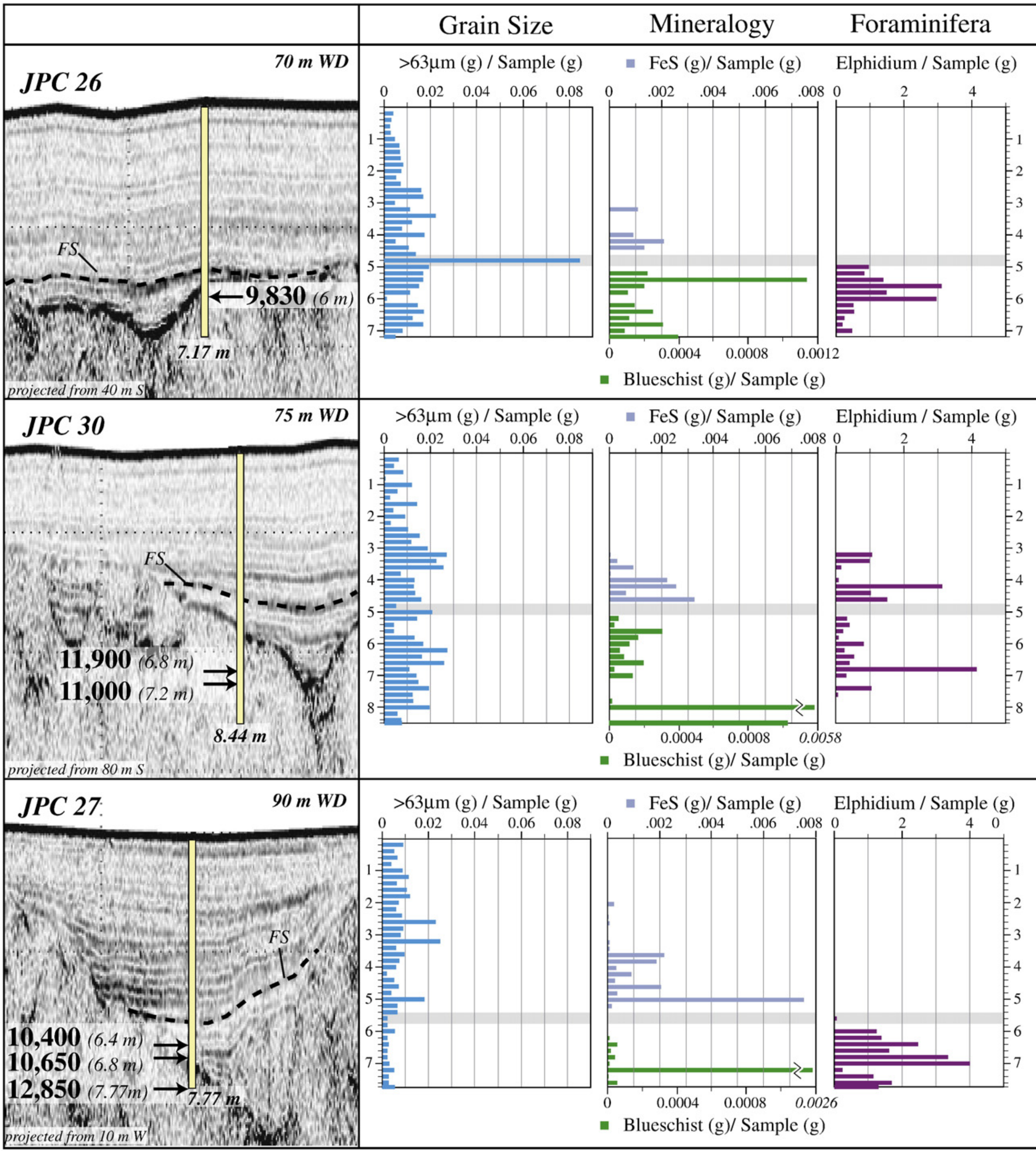

Figure 3. Sediment core locations projected onto the CHIRP profiles, along with sediment analyses (each plot is scaled to the length of the core). Radiocarbon dates were collected (shown in bold) above and below the scour surface to constrain the age of the ice-scour event to between 10,600 and 11,900 ^{14}C yr BP. Sediment composition exhibits a marked transition from blueschist minerals near the scour surface to pyrite precipitation above. Note the break in scale for high abundances of blueschist minerals in JPC27 and JPC30. The grey bar indicates a flooding surface that separates the two mineralogical zones. The flooding surface correlates with a sea level rise and the transition from estuarine to open marine conditions. Elphidium, which prefer brackish environments, are most abundant in the basal section of each core. JPC30 has some additional Elphidium above the basal flooding surface, as there appears to be a second flooding surface in that region.

2007). This outer region has scours with scales similar to that observed on the shelf and estimates of their orientations suggest the icebergs may have been sourced from the shallow Chukchi shelf (Jakobsson et al., 2005). Examining these features, Polyak et al. (2001) postulated the presence of Chukchi shelf ice may have deflected westward-flowing ice streams emanating from the Alaska/Canada margin. Polyak et al. (2007) also noted a distinct absence of carbonate-rich IRD in Chukchi borderland sediments prior to 13,000 cal yr BP. In the eastern region, where there is little to no sediment cover above the scour surface, swath bathymetry data coregistered with the Chirp profiles suggest a WNW iceberg trajectory (Fig. 4). This trend is consistent with iceberg discharge from the Beaufort margin, either Barrow Canyon or the Mackenzie region, flowing along the shoreline. The absence of the carbonate-rich IRD in both outer shelf and borderland sediments during deglaciation is more consistent with a proximal iceberg source (e.g., northwestern Alaska) and explains the deflection of the CAA-sourced icebergs seaward as suggested by Polyak et al. (2007).

Given the scour-forming icebergs on the outer shelf were sourced from the northwest Alaskan margin, this raises important questions

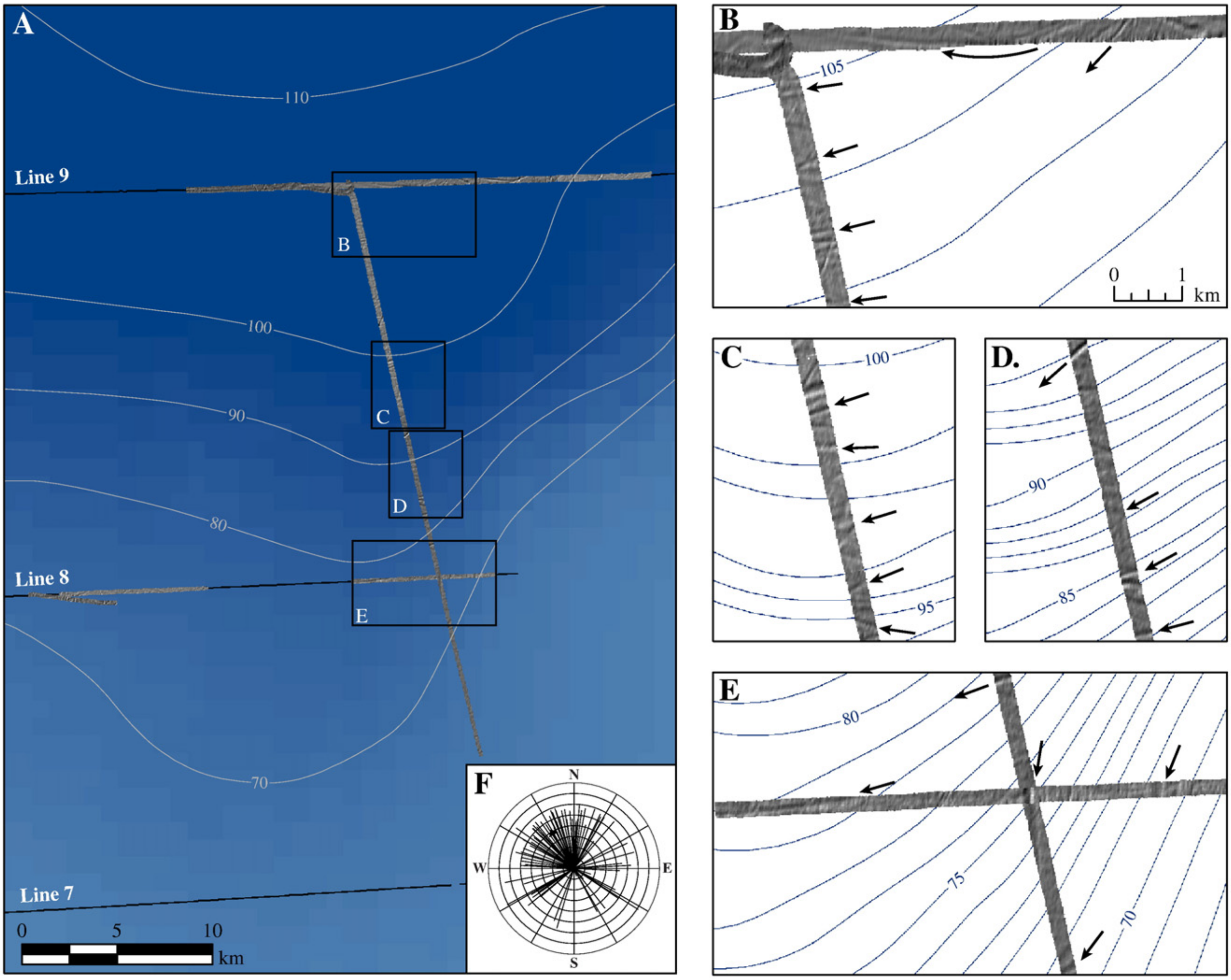

Figure 4. (A) Shaded relief imagery of swath bathymetry data across the ice scour region on the outer Chukchi shelf. Lines 7, 8 and 9 indicate the ship tracks for the Chirp subbottom data shown in Figure 2. (B–E) Arrows point to examples of the iceberg scours, which appear to be oriented along the general bathymetric contours of the outer shelf. (F) Rose diagram showing measured azimuths of iceberg scours. The mean azimuth (239°) is shown in bold.

about the mapped extent of continental glaciation in northern Alaska during the LGM. Compared with much larger scours observed in the greater Arctic basin, (Polyak et al., 2001; Jakobsson et al., 2005) the iceberg scours on the outer shelf are relatively small and do not indicate extremely large volumes of ice on the margin. It is unclear when the ice buildup was initiated, whether it was during marine oxygen isotope stage 3 or 4, a period interpreted to be fairly arid, or perhaps during waning stages of glaciation when the moisture supply would have increased. Climate records indicate an increase in effective moisture ~12,500 ^{14}C yr BP (Mann et al., 2002), which appears to correlate with glacial readvance in the Brooks Range between 13,000 and 11,500 ^{14}C yr BP (Hamilton, 1986).

Conclusions

Previous authors have argued for extremely limited glaciation across the Brooks Range, restricted primarily to montane glaciers in the eastern region (Hamilton, 1986; Kauffman and Manley, 2004). Many of these arguments are based on field observations of glacial geomorphology and biogenic proxies; however, very few studies have been conducted in northwestern Alaska and recent evidence has begun to suggest there may have been more variability in this region than previously recognized. Large meltwater-discharge channels present on the mid Chukchi shelf appear to link up with drainage patterns sourced from the northwest Alaskan margin (Hill and Driscoll, 2008; Hill et al., 2007) (Fig. 1) and a very large progradational wedge on the continental slope entering the Arctic Basin (Grantz et al., 1986). Furthermore, these channels appear to have been incised during the most recent period of sea-level rise and may record catastrophic drainage that was coincident with the iceberg-discharge event. High sedimentation rates on the shelf from 11 ka to 7 ka, are also consistent with glacial drainage from the margin (Keigwin et al., 2006; Hill and Driscoll, 2008; Hill et al., 2007). Additional investigation of the northwestern Alaskan margin, both on and offshore, will help illuminate the complex glacial history and provide insight into Arctic ice-sheet dynamics and their role in global climate interactions.

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