Widespread, multi-source glacial erosion on the Chukchi margin, Arctic Ocean

Authors:

*Dayton Dove [a] – British Geological Survey, Murchison House, West Mains Rd, Edinburgh EH9-1JG, UK; (44)131-650-0355; dayt@bgs.ac.uk

Leonid Polyak [b] – Byrd Polar Research Center, Ohio State University, 1090 Carmack Rd., Columbus, OH 43210, USA; (614) 292-2602; polyak.1@osu.edu

Bernard Coakley [c] - University of Alaska Fairbanks, 900 Yukon Drive, Fairbanks, AK 99775, USA; (907) 474-5385; bernard.coakley@gi.alaska.edu

**Corresponding Author*

Abstract

Multibeam bathymetry and subbottom profiler data acquired in 2011 from R/V Marcus Langseth in a broad grid over the Chukchi Sea margin reveal multiple glacigenic features on the top and slopes of the outer Chukchi Shelf/Rise and adjacent Borderland. Glacial lineations record a complex pattern of erosion likely formed by both local glaciation and far-travelled ice shelves/streams sourced from the Laurentide, and possibly East Siberian ice sheets. Multiple till units and stacked debris flows indicate recurrent glacial grounding events. Composite till wedges of several hundred meters thick extend the shelf edge by 10-20 km in places. Distribution of ice-marginal features on the Chukchi Rise suggests stepwise deglacial retreat towards the shelf, backing up the broad bathymetric trough at the eastern side of the Rise. Glacigenic features other than extensive iceberg scouring cannot be identified above 350-m depth, and no glacigenic bedforms are present on the current-swept shallow shelf. Despite the resulting uncertainty with the southern extent of the glaciation, the data suggest a widespread grounded-ice presence on the northern Chukchi Shelf, which makes it an important, previously underestimated component of the Arctic paleo-glacial system.

1. Introduction

Seafloor mapping data from the last two decades indicate the widespread impact of deep-keeled ice from ice sheets/shelves and attendant megabergs on the continental margins and submarine ridges and plateaus in the Arctic Ocean (Polyak et al., 2001, 2007; Kristofersson et al., 2004; Jakobsson et al., 2005, 2008, 2010; Engels et al., 2008; Dowdeswell et al., 2010). Understanding the extent and timing of these past Arctic ice sheets is important for studies of climate sensitivity, boundary conditions for paleoclimate and ocean modeling, and for insight into the response of existing marine glacial systems (such as WAIS, Greenland margins) to climatic warming and sea-level rise (e.g., Truffer and Fahnestock, 2007; Vaughan and Arthern, 2007). However, relevant data from the Arctic remain fragmentary due to the sparse distribution of bathymetric highs in the central Arctic Ocean and the historical presence of perennial sea ice inhibiting data acquisition.

High-resolution geophysical data (swath bathymetry and shallow seismic reflection) can greatly improve our understanding of past marine ice sheets by revealing remarkably well preserved signatures of sub-glacial processes (e.g., Ó Cofaigh et al., 2008; Dowdeswell et al., 2008). Assimilated evidence may include streamlined bedforms (mega-scale glacial lineations (MSGLs) and drumlins), sub-glacial deposits, transverse ridges, and grounding zone wedges on the shelf and bathymetric highs, as well as associated debris flows and fans on the slope. Finding such features however may be difficult due to pervasive iceberg scouring from the most recent deglaciations, which obliterated the potential record of preceding glacial events. In the Arctic Ocean such scouring has been reported from waters typically shallower than 300-400m (e.g., Jakobsson et al., 2008); hence, detailed surveys are needed with a focus on the deeper shelf.

Glacigenic seafloor features in the Arctic Ocean, prominent on elevated portions of the central Lomonosov Ridge and the Chukchi Borderland, have been primarily related to ice arriving from the Barents-Kara and Laurentide ice sheets, respectively (e.g., Jakobsson et al., 2008, 2010). Other expanses of the Arctic Ocean perimeter such as broad and shallow Chukchi and East Siberian shelves have not been considered as significant glaciation centers, except for earlier inferences based on geomorphic features of unconstrained age and simplified paleoglaciologic modeling (Grosswald, 1989; Hughes and Hughes, 1994). In the initial study of the Chukchi Borderland, Polyak et al. (2001) inferred ice expanding from the Chukchi Shelf, but in later studies glacigenic bedforms in this area have been related to ice impinging only from the Laurentide ice sheet, with possibly local small ice cap(s) on the Chukchi Plateau (Jakobsson et al., 2005, 2010; Polyak et al., 2007). This conclusion has been influenced by evidence from the Chukchi Sea coast and Wrangel Island indicating absence of large ice sheets, at least in the Late Pleistocene (Brigham-Grette et al., 2001; Gualtieri et al., 2005). The interpretation was severely impeded by very scarce data coverage of the northern Chukchi Shelf.

Here we present recently acquired multibeam bathymetry and sub-bottom profiling data (Fig. 1) that reveal evidence of widespread glaciation on the northern part of the Chukchi Shelf (Chukchi Rise) and adjacent Borderland. This evidence, together with that presented by Niessen et al. (this issue) from the East Siberian margin, requires reconsidering the Pleistocene glacial history in this part of the Arctic.

2. Study area and methods

The Chukchi Shelf encompasses a broad, predominantly shallow continental margin north of Chukotka and Alaska, with water depths ranging from less than 50m in the south, to 450m-750m at the shelf break around the northward extension known as the Chukchi Rise (Fig. 1b). The Chukchi Borderland is an adjacent fragment of continental crust extending north into the Canada Basin of the Arctic Ocean (Grantz et al., 1998). The Borderland incorporates the Northwind Ridge and the Chukchi Plateau, with depths on the Plateau as shallow as ~300 m.

Late Cenozoic climatic, sea-level, and tectonic changes radically impacted the Chukchi Shelf, a gateway between the Pacific and Arctic oceans that turned into a Beringian land bridge between America and Eurasia during sea-level lowstands. Growth and decay of ice caps on the Chukchi Shelf and Borderland was clearly a major factor of this history. Knowledge of the yet poorly understood limits, provenance, and timing of glacial events on the Chukchi margin is thus important for reconstructing paleoclimatic and sedimentary environments in the Chukchi-Beringian region and adjacent Arctic Ocean.

In 2011, approximately 5,000 km of continuous geophysical data were acquired from the *R/V Maurice G. Langseth* on a broad grid over the Chukchi Rise (northern extension of the Chukchi Shelf) and adjacent portions of Chukchi Plateau, Northwind Ridge, and interspaced deep basins (Fig. 1b). Along with the deep penetrating (kilometre-scale) multi-channel seismic (MCS) and marine gravity data collected to study the tectonism of the Chukchi Borderland, multibeam echo-sounder (MBES) bathymetry and CHIRP sub-bottom profiler data were acquired to investigate seafloor morphology and the shallow subsurface geology of the region. These data provide a comprehensive characterization of bedforms related to the glaciation history of the northern Chukchi margin.

The MBES data were acquired using a 12kHz Kongsberg EM122, well suited for this cruise with surveyed depths ranging from 40m to 4000m, and a swath width of 4-6x water depth. Swath editing and gridding were conducted using MB-System (Caress and Chayes, 2008), and GMT (Wessel and

Smith, 1991), The processed data were gridded to a resolution of 20m. To avoid azimuth biasing, QPS Fledermaus was utilized for data 3D visualization, and ESRI ArcGIS was used for feature mapping.

The sub-bottom data were acquired using a Knudsen 3260 swept frequency (2-6kHz) CHIRP sonar. The Knudsen system applies a matched filter to remove the source signal, and exported SEG-Y data were further post-processed using SIOSEIS (Henkart, 2003). The CHIRP data were imported into Fledermaus for 3D visualization with the MBES data, and SMT Kingdom software was used for seismostratigraphic interpretation. Penetration depths varied from approximately 10 to 100m below seafloor, depending on seafloor morphology and the physical properties of the sediments.

3. Results

Both the MBES and CHIRP data reveal a complex pattern of glacigenic erosion and deposition on the Chukchi margin to nearly 900m water depth (Figs. 2-6). With survey lines spaced approximately 50 km apart, it is typically not possible to trace individual features between lines with the exception of line crossings. However, MBES swath widths on the deeper parts of the shelf are up to 4 km, enabling the identification and interpretation of individual as well as groups of bedforms.

3.1. Iceberg scoured shallow seabed

Observed both in the MBES and CHIRP data, scours resulting from iceberg keels ploughing through the sedimentary seabed dominate the seafloor above ~350 m water depth (Figs. 2b, 5b), consistent with the depth threshold observed previously in the region (Polyak et al., 2001; Jakobsson et al. 2008). Where present, scouring has eliminated all evidence of previous processes impacting the seafloor. Individual scours are up to 30 m deep, and while superposition is evident, overall scour orientation appears random. Sediment on top of scoured seabed is absent or very thin in deeper waters towards the ~350m trimline, but infills and partially drapes the scours in waters shallower than 130m. This drape is acoustically layered to transparent and has been identified as Holocene marine transgressive sediments pinching out towards the current-swept inner shelf (Keigwin et al., 2006; Polyak et al., 2007; Darby et al., 2009; Hill and Driscoll, 2010). This stratigraphy confirms that preserved scouring occurred during the last deglaciation. Associated with the scouring, CHIRP data frequently reveal a thin (~5m) unit of acoustically homogenous, unstratified sediment with a strong basal reflector, likely indicating a till-like unit generated by iceberg turbation (e.g., Dowdeswell et al., 1994).

Below the iceberg scouring trimline, a discontinuous, thin (<10m) drape of acoustically layered sediment is present at the seabed, likely representing sediment re-deposited by currents from the shelf (Figs. 3b, 6a)(Darby et al., 2009).

Acoustically well-layered, frequently dipping and apparently structurally controlled strata (collectively termed ‘pre-glacial’) are sometimes observed below iceberg scoured seabed. Below the iceberg scouring trimline these pre-glacial strata may be observed at seabed or under glacigenic sediment (Figs. 4, 5a,c, 6a) (see also Hegewald and Jokat, 2013).

3.2. Glacigenic features on the outer shelf and borderland

3.2.1 Tills and till-like sediments

Chaotic to transparent, unstratified deposits of varying thickness (up to 20 m) are observed extensively across the Chukchi margin (Figs. 3b, 4, 5a,c, 6a). The strong basal reflector is frequently flat but in places exhibits high relief, suggestive of erosion. MSGL fields and ridge features are observed on top of these deposits in multiple locations. Along with the seismic character, this identifies these deposits as subglacial tills (e.g., Stewart and Stoker., 1990; Ó Cofaigh et al., 2005). The interpretation is further supported by the recovery of glacial diamictons in sediment cores on the ramp to the Northwind Ridge (Fig. 7) (Polyak et al. 2007).

Several locations bear the evidence of multiple till units indicating multiple glacial episodes affecting the region (Fig. 4, 5a, 6a). Due to the limited penetration of the CHIRP and not always strong basal reflector, we may not always see the base of the till units. This limits our understanding of the spatial patterns and timing of processes that led to till formation.

At the shelf margin, the till is persistent on both sides of the Chukchi Rise between the 350 m contour and the shelf break, where till commonly forms prograding, cross-sectional wedges (Fig. 5a,c). Such depositional till wedges, which effectively extend the continental shelf, are a characteristic feature of glaciated continental margins (e.g., Dahlgren et al., 2005). Around the Chukchi Rise till wedges extend the shelf edge by as much as 10-20 km and reach up to >300 meters in thickness as seen on deep seismic records (Fig. 5) (Hegewald, 2012; Hegewald and Jokat, 2013).

3.2.2 Mega-Scale Glacial Lineations

Linear to curvilinear sets of parallel grooves and ridges are frequently observed in water depths ranging from ~350 to 900 m (Figs. 2-4). Inboard of the shelf break, they occur in the broad bathymetric trough on the eastern side of the Chukchi Rise (Fig. 7). Both the lower depth limit, and orientation of the lineations vary on a regional scale. Individual lineations are commonly 5 km in length with a vertical relief of ~5 m, though some can be up to 15 km long and 20 m high (Fig. 4). As survey lines are spaced approximately 50 km apart, we mostly observe only the partial extent of the lineations. For those mapped in full, length-to-width ratios exceed 10:1. The seabed relief of these features is occasionally dampened by the presence of the thin hemi-pelagic sediment drape, in particular in the broad bathymetric trough east of the Chukchi Rise (Fig. 3).

The morphology and pattern of these bedforms indicates they are mega-scale glacial lineations (MSGLs), which have been identified from multiple sites on previously glaciated seafloor in the Arctic (e.g., Jakobsson et al., 2008; Dowdeswell et al., 2010), Antarctic (Ó Cofaigh et al., 2002), and mid-latitudes (Todd and Shaw, 2012). The presence of MSGLs is generally recognized as evidence of coherent, fast-flowing grounded ice, frequently associated with ice streaming (Stokes and Clark, 2001; King et al., 2009). The MSGLs are also observed in the CHIRP data lying on till or pre-glacial strata, in places causing acoustic diffraction (Figs. 2c, 3b, 4). In several locations we also observe what may be buried MSGLs, where a rugged erosional boundary is overlain by till, likely indicating multiple episodes of glacial erosion.

Most MSGLs observed fall into two general orientations: (1) E-W (W-E) to SE-NW (NW-SE), and (2) more SW-NE (NE-SW) trending (Fig. 7). There is no apparent relationship between orientation and depth, though such a comparison is biased by the highly variable regional bathymetry. The group (1) MSGLs occur at or near the shelf break on the northeastern edge of the Chukchi Rise and on adjacent parts of the Chukchi Plateau and Northwind Ridge. The group (2) MSGLs are primarily observed in the broad bathymetric trough on the eastern side of the Chukchi Rise, but also on the western edge of the Rise, northern part of Northwind Ridge, and an isolated high within the Northwind Basin.

At one site on the eastern side of the Chukchi Rise we observe the partial extent of three larger (up to 15 km by 2.5 km, with 40 m relief) streamlined bedforms, possibly drumlins, parallel in orientation to adjacent MGSL (Fig. 3). Perpendicular to these features are multiple, closely and regularly spaced, low relief (2-5m) ridges similar to ribbed moraines, which are of disputed origin. Like MSGLs and Drumlins, ribbed moraines may provide evidence of fast flowing ice (Dunlop and Clark, 2006). Alternatively, they have been hypothesized to result from differential stresses at the base of frozen-bed, ~stable ice masses (Kleman and Hätterstrand. . Due to the limited number, and as we only observe the partial extent of two of the drumlinized features, we do not infer flow direction on the basis of their morphology (Clark et al., 2009). The bedform in Fig. (3a) would actually suggest flow generally to the south, however the bedform in Fig. (3b) shows a sedimentary tail suggesting northerly flow. Apart from this ambiguity, it is clear that these large bedforms have been streamlined in an orientation consistent with the adjacent MSGLs.

Isolated deep-keeled iceberg scours sometimes occur in waters greater than 350m along with MSGLs (Fig.2b). We differentiate these features from the MSGLs as they exhibit one or several of the following characteristics: individual occurrence, a curved path, a raised rim of the scour, and a scaphiform (scoop shaped) profile. Where they occur in sparse aggregations, scours are not parallel in orientation and thus not suggestive of a coherent ice-mass grounding.

3.2.3 Ice Marginal Features

A diverse suite of bedforms observed in the MBES and CHIRP data, predominately between 350 m and 550 m water depth, can be interpreted as ice-marginal in origin (Figs. 4,5). Broadly grouped, the most common are narrow to broad (100-800 m wide) ridges of curvilinear to sinuous shape frequently occurring at or near the shelf break. In the CHIRP data these ridges often appear as symmetric or asymmetric ridges and wedges (5-50 m thick). They may have a strong basal reflector indicative of a depositional origin, or appear contiguous with the underlying till. In most places there are several, sub-parallel ridges interspaced with hummocky seabed. Some ridges are long and continuous; where discontinuous, they are component parts of a longer, continuous band of similar bedforms. We interpret these features to be moraines (e.g. Bradwell et al., 2007; Ó Cofaigh et al., 2008; Dowdeswell et al., 2008). Near the shelf break they often form a morainic belt, delimiting a temporarily halted, seaward extent of grounded ice similar to grounding zone wedges (GZWs) described on glaciated margins elsewhere (Fig. 5) (Rüther et al., 2011; Dowdeswell and Fugelli, 2012). The bathymetry of the GZWs is characterized by hummocky to ridge-like relief, though our data coverage is insufficient to map the extent of these features. The shelf-break located till wedges and MSGLs provide evidence that grounded ice reached the shelf edge (up to or seaward of the GZWs), and the GZWs likely represent later glacial still-stands, during step-wise retreat.

Superimposed sets of low relief, sub-parallel, linear to sinuous ridges occur on the eastern edge of the Chukchi Rise inboard of the proposed maximum grounded-ice extent, in places intersecting larger ~linear ridges (Fig. 6).The smaller ridges are approximately four meters in height, while the larger ~linear ridges are 10-30 m. The cross-cutting pattern of the smaller ridges ranges from sub-rectilinear to dendritic in plan-view. Though data coverage over these bedforms is limited, they are tentatively interpreted as either superimposed recessional moraines or basal crevasse-filled ridges.

On the Chukchi Plateau, MBES data reveal crescentic ridges overridden and partially drumlinized by E-W oriented MSGLs (Fig. 2c). CHIRP data show the bedforms to be wedge shaped and overlapping one-another from west to east. We tentatively interpret these peculiar features, clearly not associated with preglacial bedrock, as moraines formed by a grounded ice front retreating eastwards. Underlying, and overriding MSGLs probably indicate ice stream re-advance(s). Ridges and barchan-shaped bedforms overridden and partially drumlinized by W to NW trending MSGLs have also been found ~10 km to the north (Mayer et al., 2010) and on the northern part of Northwind Ridge (Jakobsson et al., 2008).

3.3. Debris Flows

On the continental slope and adjacent basins around the Chukchi margin, CHIRP data regularly reveal debris lobes indicating episodes of increased sediment delivery to the shelf edge, characteristic of glaciated contintental margins (Fig. 5a) (e.g., Dowdeswell et al., 2002; King et al., 1998). Debris flows are easily distinguishable from encompassing hemipelagic sediments by their unstratified acoustic character. Down-slope, individual lobes vary in thickness, and are up to 50 m thick. Across-slope the flows are lenticular and occur at several, regionally consistent stratigraphic levels, separated and overlain by packages of well-layered hemiplegic sediments. A lobe cored on the ramp to the Northwind Ridge (Fig. 7) consisted of gray, fine, faintly laminated mud interpreted as glacio-turbidites (Polyak et al., 2007). While the exact depositional processes and ages of these deposits are yet to be constrained, they clearly indicate that grounded ice delivered large amounts of sediment to the slope along the Chukchi margin.

3.4. Buried Channels

A network of buried erosional channels (Figs. 5a,c, 7) can be recognized on the shelf and near the shelf break, similar to those reported from the adjacent shelf south of the study area (Fig. 1b-dark pink tracks)(Hill et al., 2007; Hill and Driscoll, 2008). The channels are mostly less than 50 m deep, though larger channels reach up to ~350 m deep as confirmed by the deeper penetrating multi-channel seismic data. The larger channels are also up to 12 km wide, though some degree of crossing obliquity is likely. Within the broad bathymetric trough east of the Chukchi Rise, one of the buried valleys occurs where the seabed is ~360 m deep, far deeper than the sea-level lowstands of Pleistocene glacial periods, precluding a purely fluvial origin.

As described by Klaucke and Hesse (1996), similar channels may have formed by the turbidity, or ‘fluvial’ submarine currents associated with a submarine glacial drainage system. Alternatively the channels on both the shallow, and deeper shelf may be tunnel valleys, which are eroded by over-pressurized subglacial meltwater (e.g. Stewart and Lonergan, 2011).

Incised channels are also observed sub-parallel to the shelf break at the northwestern edge of the Chukchi Rise. Seismic evidence confirms they are erosional rather than slump related features (Fig. 5). The location and orientation of these features indicates that they may have been eroded by a glacial mass flowing along the shelf edge.

4. Discussion

The diverse suite of subglacial and ice marginal bedforms occurring in complex configurations across the Chukchi Margin, along with the till deposits and glacigenic debris flows on the slope, provides compelling evidence for the broad distribution of grounded-ice in the region, operating under varying flow regimes (Fig. 7).

The orientation of group (1) E-W (W-E) to SE-NW (NW-SE) trending MSGLs and their occurrence on the eastern side of the survey area are consistent with earlier interpretations suggesting that eroding ice arrived from the northwestern sector of the Laurentide ice sheet via the northern Alaska margin (Polyak et al., 2001, 2007; Jakobsson et al., 2005, 2008, 2010; Engels et al., 2008).

The group (2) SW-NE (NE-SW) oriented MSGLs indicate a more complex picture with likely multiple sources of ice. Whereas the Laurentide attributed group (1) MSGLs of the Northwind Ridge and Chukchi Plateau occur at localized bathymetric highs, the group (2) MSGLs observed to the east of the Chukchi Rise occur in a broad bathymetric trough, similar to the ice streams of the Western Antarctic and the Barents-Kara ice sheet (e.g., Ó Cofaigh et al., 2008; Winsborrow et al., 2010). While only a few are observed, elongated drumlin-like bedforms and associated ribbed-moraines found in the trough (Fig. 3) along with a consistently thick package of till provide further evidence of extensive ice streaming north-eastwards from the northern Chukchi Shelf.

Two other generations of group (2) MSGLs on the western edge of the Chukchi Rise and on some local highs on and near the Northwind Ridge are too sparse in the existing data to provide a conclusive interpretation. One possibility is that the eroding ice for all of the areas with group (2) MSGLs arrived from the East Siberian margin, where evidence for a widespead glaciation is emerging (Stein et al., 2010; Niessen et al., this issue). More data from the margin west of the Chukchi Rise is needed to test this hypothesis.

The presence of moraines and GZWs near the shelf break to the east and west of the Chukchi Rise, along with the till wedges extending the shelf and debris flows on the slopes provide further evidence of extensive grounded ice delivering glacigenic sedments to the margin all around the Chukchi Rise. Large prograding till wedges, extending the shelf edge (Fig. 5) (Hegewald, 2012; Hegewald and Jokat, 2013), indicate large volumes of sediment redeposited by glaciers on the upper slope .The distribution of these features further east and west of the Chukchi Rise yet needs to be surveyed.

The overall smooth slope bathymetry west of the Northwind Ridge, in contrast to strongly canyonized slope further to the east (Fig. 1b), may be related to glacially redeposited sediment masses. If true, this change in relief may indicate the eastern boundary of the margin affected by glaciers advancing to the shelf edge. If the broad bathymetric trough east of the Chukchi Rise served to focus glacial drainage from the Chukchi Shelf, the Northwind Basin should contain a significant accumulation of glacigenic debris, though due to the confining nature of the regional bathymetry we do not expect to observe the splayed morphology typical of trough-mouth fans (e.g. Pedrosa et al., 2011). While this requires further investigation with deeper penetrating seismic data, the CHIRP data reveal glacigenic debris extending to at least 100 m thickness at the base of slope, suggesting the Northwind Basin has served as a significant depocenter.

The overall pattern of moraines on the shelf primarily indicates up-slope retreat of the grounded-ice mass after the advance phase(s), onto the Chukchi Rise, and back up the broad bathymetric trough to the east of the Rise (Fig. 7). The dense aggregations of superimposed, cross-cutting ridges on the northeast of the Rise may be recessional moraines or crevasse-filled ridges (Fig. 6). If recessional moraines, they suggest stepwise retreat towards the inner shelf. Alternatively, to preserve crevasse-filled ridges with cross-cutting relationships, a surging glacial system is inferred. During a period of stagnation sediments infill basal crevasses, and then gradually melt out between phases of surging (Ottensen and Dowdeswell, 2009; Rea and Evans, 2011).

In the northeast of the Chukchi Rise, group (2) MSGLs are found to be perpendicular to group (1) MSGLs over a stretch of ~25 km. This configuration may have resulted from flow switching and episodic retreat (e.g., Ó Cofaigh et al., 2008; Graham et al., 2010), though more likely resulted from ice impinging on the area from different ice sources, during separate glacial episodes. A relatively uniform bathymetry on the outer shelf provides no justification for switching flow direction so dramatically over so short a distance. Likewise, in several locations moraines exhibit sub-parallel relationships with nearby MSGLs. In the far west of the survey area, this configuration is also best reconciled by invoking separate ice sources (Such as from the East Siberian Shelf).

Deeply incised, buried channels observed on the Chukchi Shelf provide further evidence of glaciation (Figs. 5, 7). While the valleys on the shelf south of the study area (Fig. 1b-dark pink tracks) were interpreted by Hill and Driscoll (2008) to result from meltwater discharge from Alaska-based glaciers, their broad distribution and common co-occurrence with glacially impacted areas suggests a possible subglacial origin (Stewart and Lonergan, 2011). Channels mapped at greater water depths on the outer shelf may have also been formed by submarine turbidity or ‘fluvial’ currents in a proglacial environment (Klaucke and Heese, 1996). As eroded channel depths of up to ~350m, and widths of up to 12km can be accounted for with both the submarine channel and tunnel valley models, further data is required to better understand the connectivity and origin of these features.

The origin of the incised valleys observed near the northwestern shelf break also needs to be clarified. The evidence for a glaciation center on the East Siberian margin (Niessen et al., this issue) indicates that these features may have been eroded by an along-shelf glacial flow path.

The southern extent of glaciation towards the inner Chukchi Shelf may not be possible to identify on the sea floor because of a pervasive iceberg scouring at shallower depths. A large, mostly buried sediment ridge in the northern Bering Sea southeast of Chukotka (Fig. 1a) has been interpreted as a morainic ridge (Grim and McManus, 1970), and was encountered by the Langseth-2011 crossing. As suggested by Brigham-Grette et al. (2001), this ridge might mark the southern limit of the maximal glaciation of the Chukchi region, tentatively dated by Amino Acid Racemization of mollusk shells to a stadial within Marine Isotope Stage (MIS) 5, broadly around ca. 100 ka. A similar age has been inferred for glacial erosion on the Arlis Plateau north of the East Siberian shelf (Stein et al., 2010; Niessen et al., this issue) and a slightly older age, ca. 135 ka estimated from uranium-thorium dating, for glacial advance on the New Siberian islands (Basilyan et al., 2010) (Fig. 1a). This combination of paleoglaciological evidence, although fragmentary and only tentatively dated, offers a possibility that a very large ice sheet existed on the Chukchi-East Siberian margin at the end of middle Pleistocene or beginning of early Pleistocene.

Some inferences of the age of glacial events at the Chukchi margin can be made from existing sediment cores and seismostratigraphic correlations. Core stratigraphy from the ramp to the Northwind Ridge (Fig. 7) constrains the age of the last erosional event associated with the Laurentide-sourced ice to the penultimate glaciation, estimated Marine Isotope Stage (MIS) 4 (Polyak et al., 2007), consistent with the inferred age of the older ice advance from the NW sector of the Laurentide ice sheet through the Mackenzie Trough (Batchelor et al., 2013). A younger erosional age of the Last Glacial Maximum (MIS 2) has been obtained only for the shelf-proximal area with water depths <350 m. The new data indicate that the source of this, relatively thin ice was the outer Chukchi Shelf. We note that these ages constrain only the last phase of glacial activity at a given seafloor site. They do not preclude older grounding events, obliterated by later impacts, nor the occurrence of younger ice shelves that were too thin to reach the sea floor.

The initiation age of glacial impact on seabed at the Chukchi margin is not yet possible to constrain, but the large thickness of glacigenic accumulations at the shelf edge indicates a long history of their formation (Fig. 5) (Hegewald, 2012; Hegewald and Jokat, 2013). Sediment-core data throughout the western Arctic Ocean indicate a sharp increase in glacial, iceberg-rafted material at the beginning of Middle Pleistocene, around MIS 16 (ca. 0.7 Ma) (Polyak et al., 2009, 2013; Stein et al., 2010; Polyak and Jakobsson, 2011). This increase is especially pronounced in cores from the Northwind Ridge and shows a lower content of detrital carbonates, characteristic of the North American provenance, than younger iceberg-rafted peaks, thus indicating a possibility of the Chukchi Shelf source.

5. Conclusions

Marine Geophysical data collected by the *R/V Marcus G. Langseth* from the northern Chukchi margin greatly expand our knowledge on the Quaternary history of the Chukchi-Beringian region. These data allow us to identify a multitude of diverse glacigenic features both on, and below the seafloor, covering the outer Chukchi Shelf, Chukchi Rise, and the adjacent part of the borderland. The perimeter of Chukchi Rise and Plateau provides an especially representative record of glacial impact. Identifying glacigenic features on the shallow, current-swept shelf is inhibited by intensive iceberg scouring, complicating reconstruction of glacial history in this area.

An association of directional bedforms, such as Mega Scale Glacial Lineations (MSGLs) and transverse morainic ridges, depicts grounded ice streaming from the northern Chukchi Shelf towards the edges. This picture is especially compelling in a broad bathymetric trough at the eastern side of the Chukchi Rise, where a combination of glacigenic bedforms and the overall trough morphology resembles cross-shelf troughs of the West Antarctic and the Barents-Kara seas that served as outlets for large ice streams (e.g., Ó Cofaigh et al., 2008; Winsborrow et al., 2010). Composite, prograding till wedges of several hundred meters thickness extend the Chukchi Shelf edge, similar to, though not as large (10-20 km wide vs. 50-100 km) as those along the northwestern European margin(Dahlgren et al., 2005). Along with the regional pattern of MSGLs, the composite till wedges, multiple erosional surfaces in till and pre-glacial strata, and stacked till units, bear evidence of several glacial events impacting the Chukchi margin, from multiple ice sources.

In combination with already known and newly emerging results from the adjacent areas such as East Siberian and Beaufort Sea shelves (e.g., Engels et al., 2008; Niessen et al., this issue), the *Langseth-2011* data provide a new understanding for the glacial history of the Chukchi-Beringian region. Orientation of directional bedforms and the general configuration of the mapped features suggests ice impinged on the area from three ice sheet sources: Northwestern sector of the Laurentide ice sheet, Chukchi Shelf, and possibly East Siberian Shelf. These features may represent different glacial events as indicated by limited sediment-core data and seismostratigraphic correlations, with a likely LGM impact on the Chukchi Rise and older glacial grounding on the borderland further east and north. The new picture emerging from marine geophysical data raises further questions about the extent interaction of different Arctic ice masses, the glacio-isostatic history of Beringia, and the implications for oceanic and atmospheric circulation, especially the Arctic-Pacific connection.

Acknowledgments

We thank the crew of the *R/V Marcus G. Langseth*; Melissa Meiner-Johnson, Grant Cain, Emily Decker, Rachel Gray, Karina Monson, and Margot Swank for ship-board processing of MBES data; Paul Henkart for discussions on CHIRP processing; and Ibrahim Ilhan for providing plots of the co-registered MCS data. We thank the two anonymous reviewers and guest editors Ólafur Ingólfsson and Martin Jakobbson for helpful comments which improved the manuscript. Dayton Dove publishes with the permission of the Executive Director, British Geological Survey (NERC). Leonid Polyak is supported by NSF grant ARC-0806999, and Bernard Coakley by NSF grant ARC-0909568.

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Figure Captions

Figure 1. A) Arctic Ocean bathymetry. Dotted blue lines represent the recently mapped, glacially impacted areas of the outer-East Siberian Shelf (Niessen et al., this issue), the southwestern limit of glaciation on the New Siberian islands (Basilyan et al., 2010), and a buried morainic ridge in the northern Bering Sea (Grim and McManuns, 1970). Regional Bathymetry: IBCAO v. 3.0 (Jakobsson et al., 2012). B) Survey location map of the Chukchi Margin showing relevant high-resolution geophysical data which has been used to study the glacial geomorphology of the region. Black lines (this study): RV Langseth 11'; Orange lines: SCICEX-USS Hawkbill - 98', 99'; Light pink lines: CCOM-USCG Healy - 03',04', 07'; Dark pink: USCG Healy - 02'; Green lines: HOTRAX- USCG Healy - 05'; Blue lines: RV Polarstern 08'. Locations for Figs. 2-6 shown in red.

Figure 2. Data examples showing glacigenic erosional features. A) Multibeam bathymetry data showing mega scale glacial lineations (MSGLs) on glacially peneplaned bathymetric high. B) Multibeam bathymetry data showing MSGLs and iceberg scours in bathymetric trough east of Chukchi Rise. C) Multibeam bathymetry and CHIRP data showing MSGLs and partially drumlinzed morainic wedges on the Chukchi Plateau. Locations of Figs 2a-c shown on Fig. 1b.

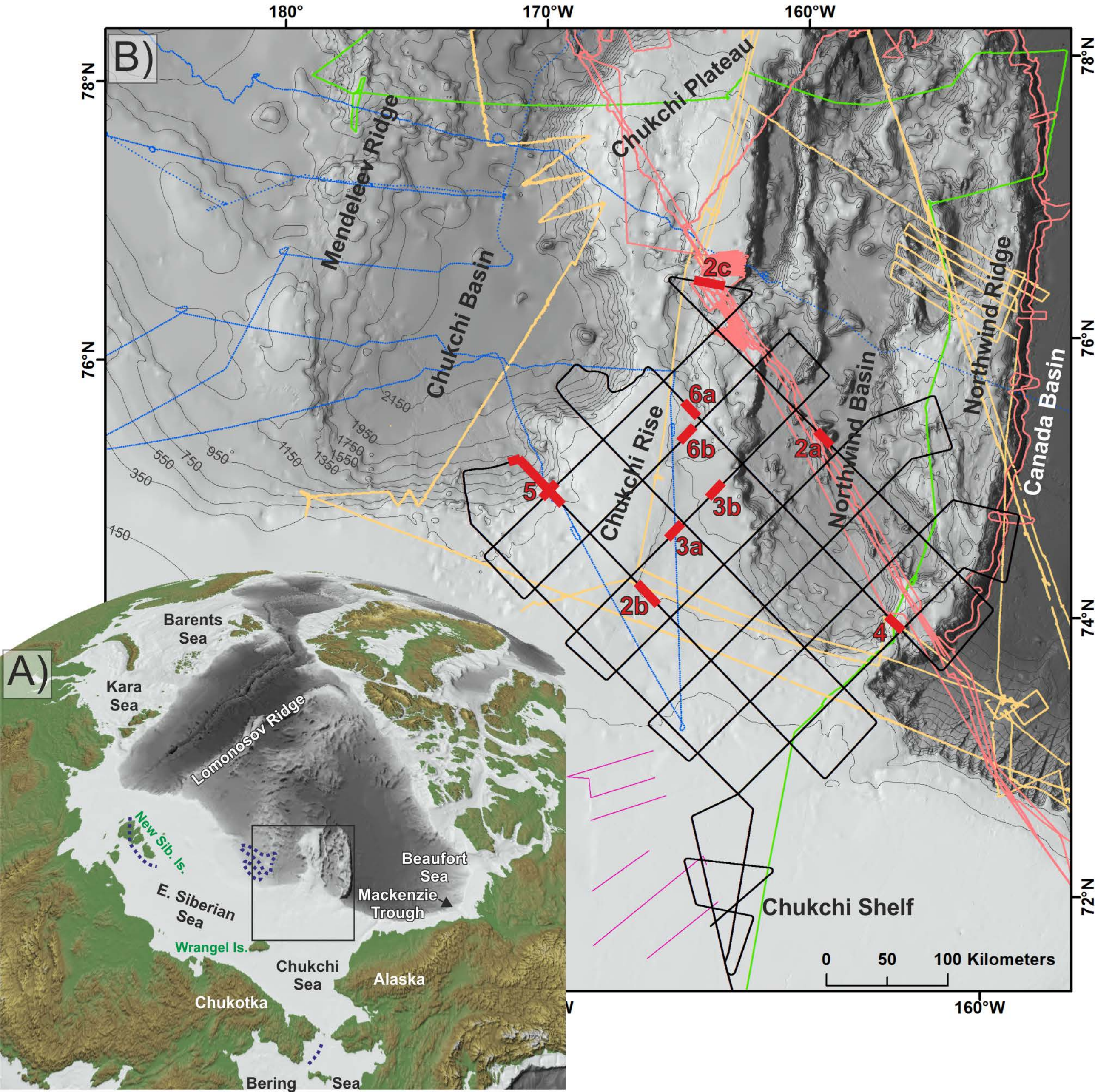
Figure 3. MSGLs, drumlinized bedforms, and ribbed moraines in the broad bathymetric trough east of the Chukchi Rise (Fig. 1). A) Multibeam bathymetry data show the consistently aligned streamlined bedforms indicating flow along an ~N/S orientation. B) Corresponding sections of multibeam bathymetry andand CHIRP data showing further streamlined bedforms. Note that the drumlinized feature here is slightly oblique to the MSGLs, and the thin hemipelagic drape dampens the seabed relief of the MSGLs and ribbed moraines. Figure locations shown on Fig. 1b.

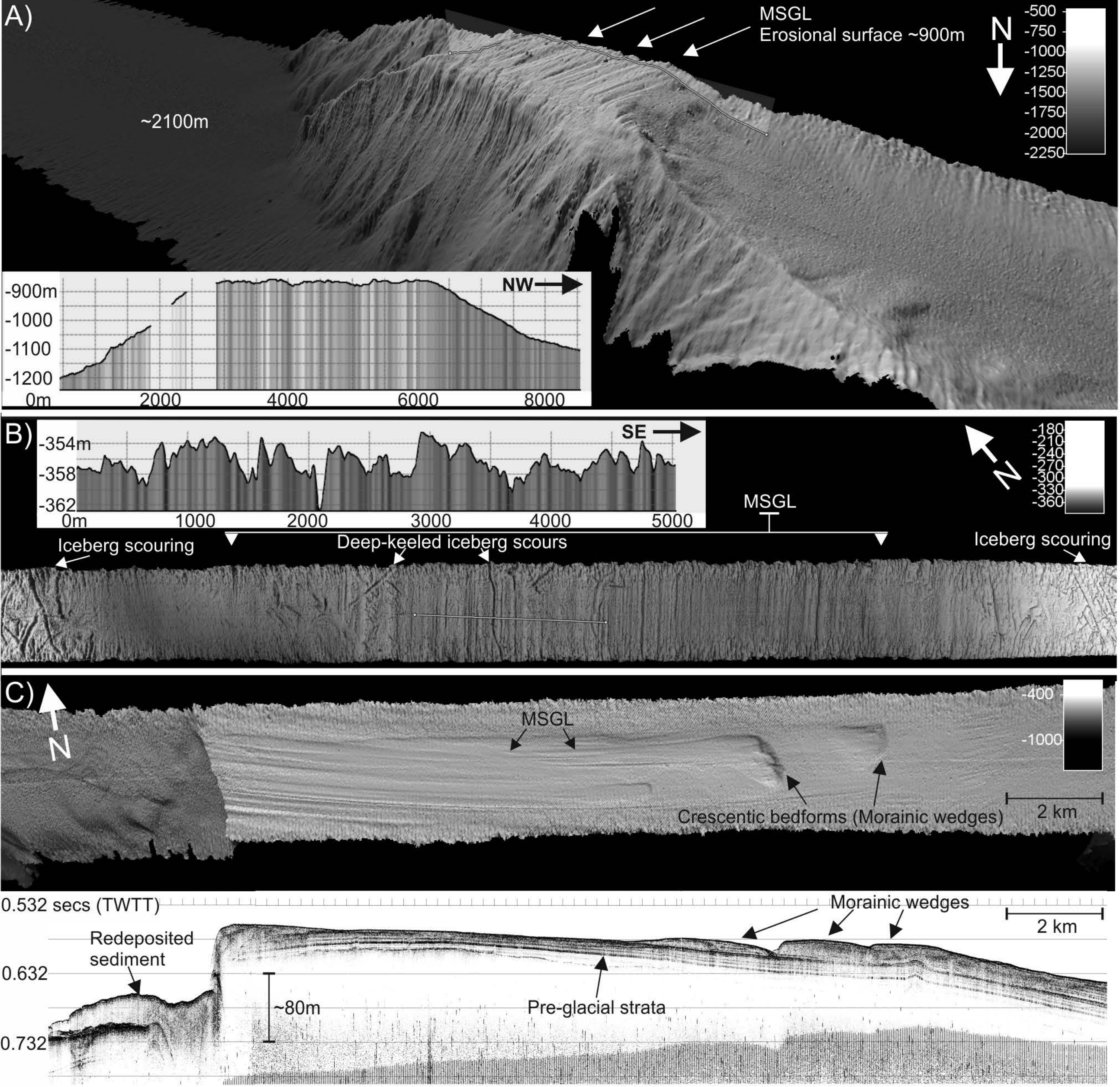
Figure 4.Multibeam bathymetry and CHIRP data show mega scale glacial lineations (MSGLs) and till units on an eroded section on the ramp to the Northwind Ridge (Fig. 1). The MSGLs have a relief of up to 20 m. Moraines around the till lens, indicating ice recession up-slope, to the North. CHIRP data reveals evidence of multiple episodes of glacial erosion and respective till units. Sediment-core data indicate the age of the upper till unit as the Last Glacial Maximum (Polyak et al., 2007). Figure location shown on Fig. 1b.

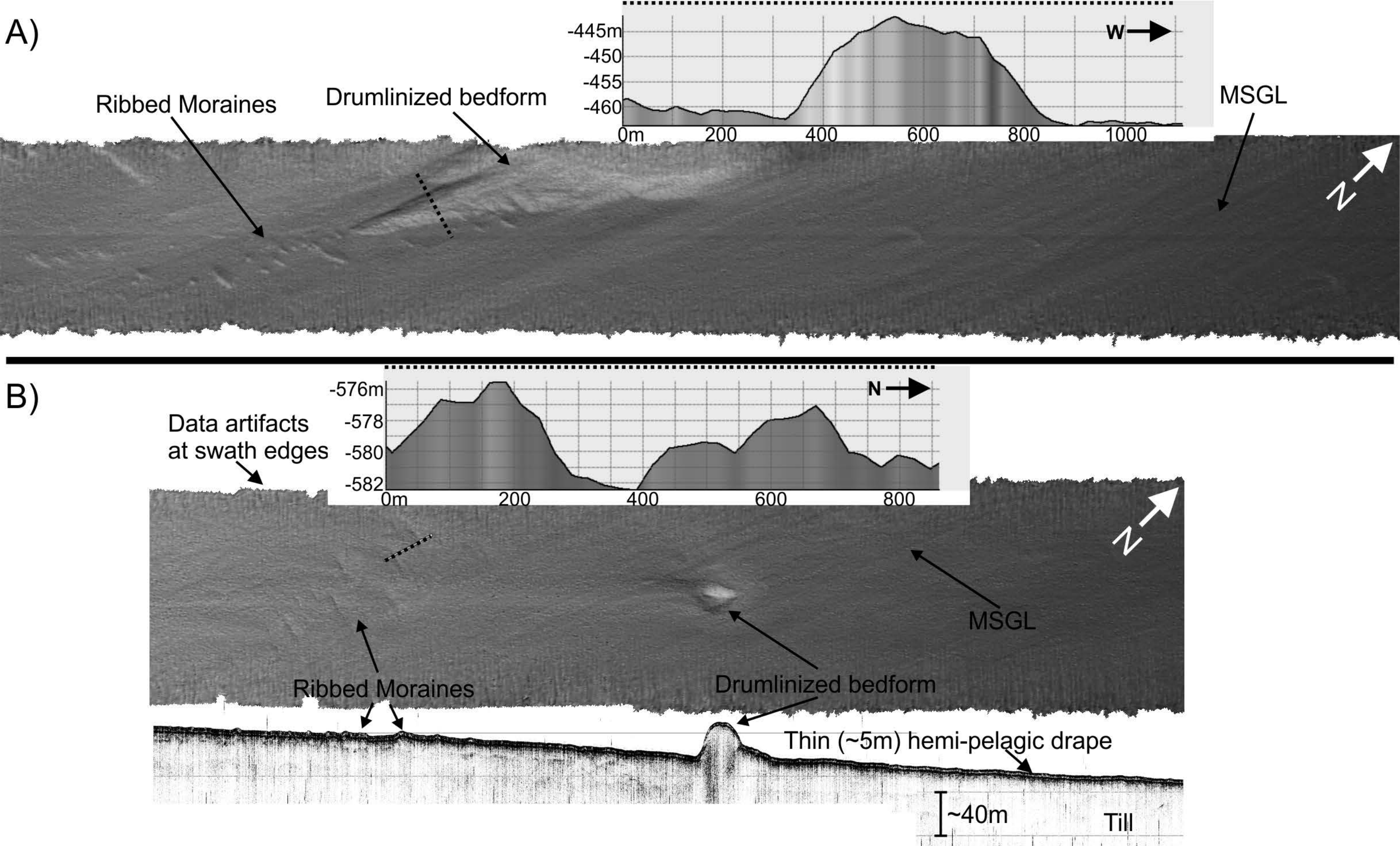
Figure 5. CHIRP (A), multibeam bathymetry (B), and Multi-channel seismic (MCS) (C) data reveal a succession of glacigenic features near shelf break and down slope. Panels A) and B) show the seabed and cross-sectional expression of grounding zone wedges (GZWs). Panel B) shows multiple till wedges (also GZWs) extending the shelf break. C) Deeper penetrating MCS data (near-trace record) reveal the thick package of glacigenic sediments along the margin and glacially incised valleys. Figure location shown on Fig. 1b.

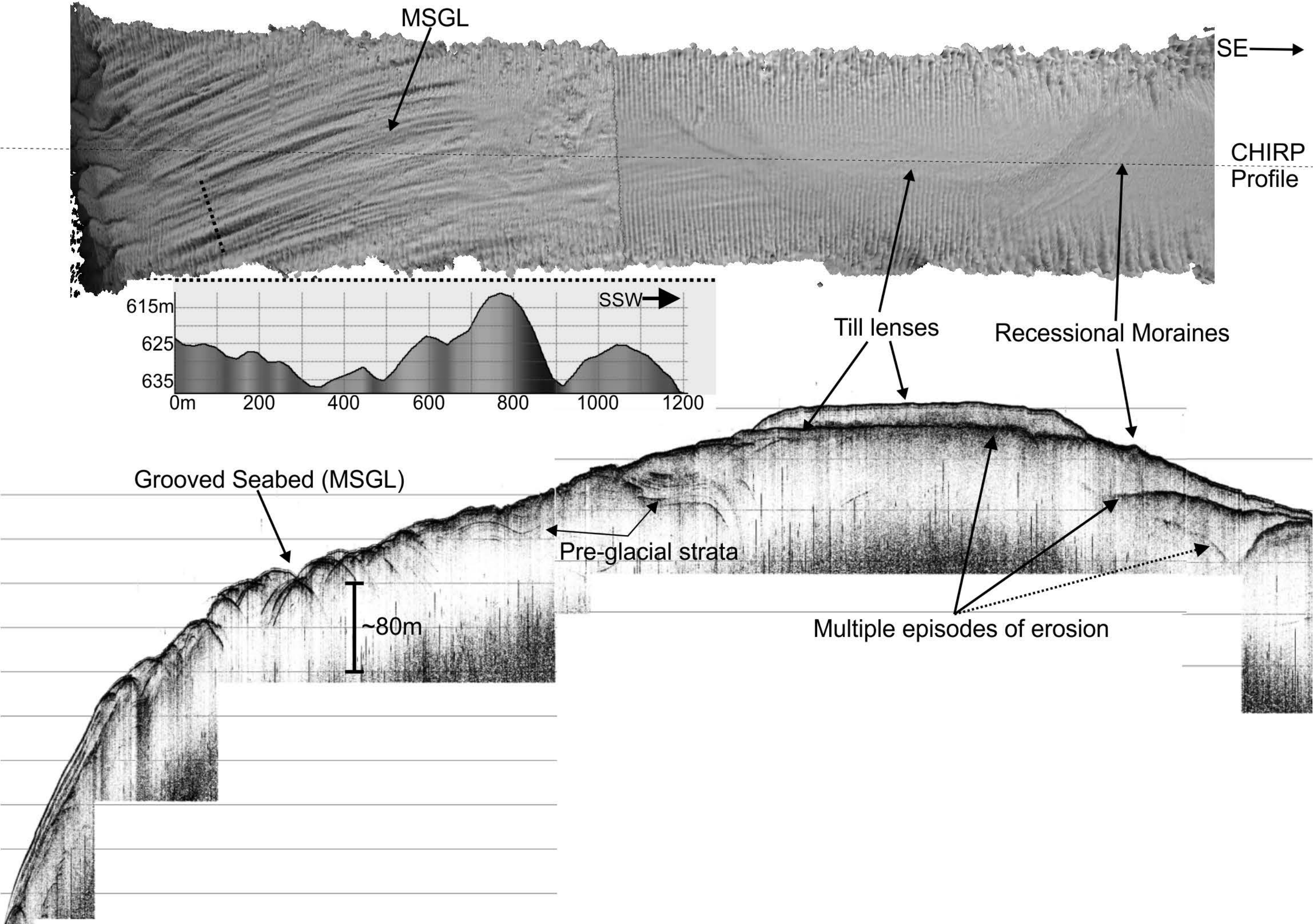
Figure 6. Ice-marginal features in the northeast of the Chukchi Rise (Fig. 1). A) Corresponding sections of multibeam bathymetry and CHIRP data reveal superimposed, low-relief ridges, and cross-cutting larger ridges. B) Further superimposed ridges may be recessional moraines, or crevasse-filled ridges. Figure locations shown on Fig. 1b.

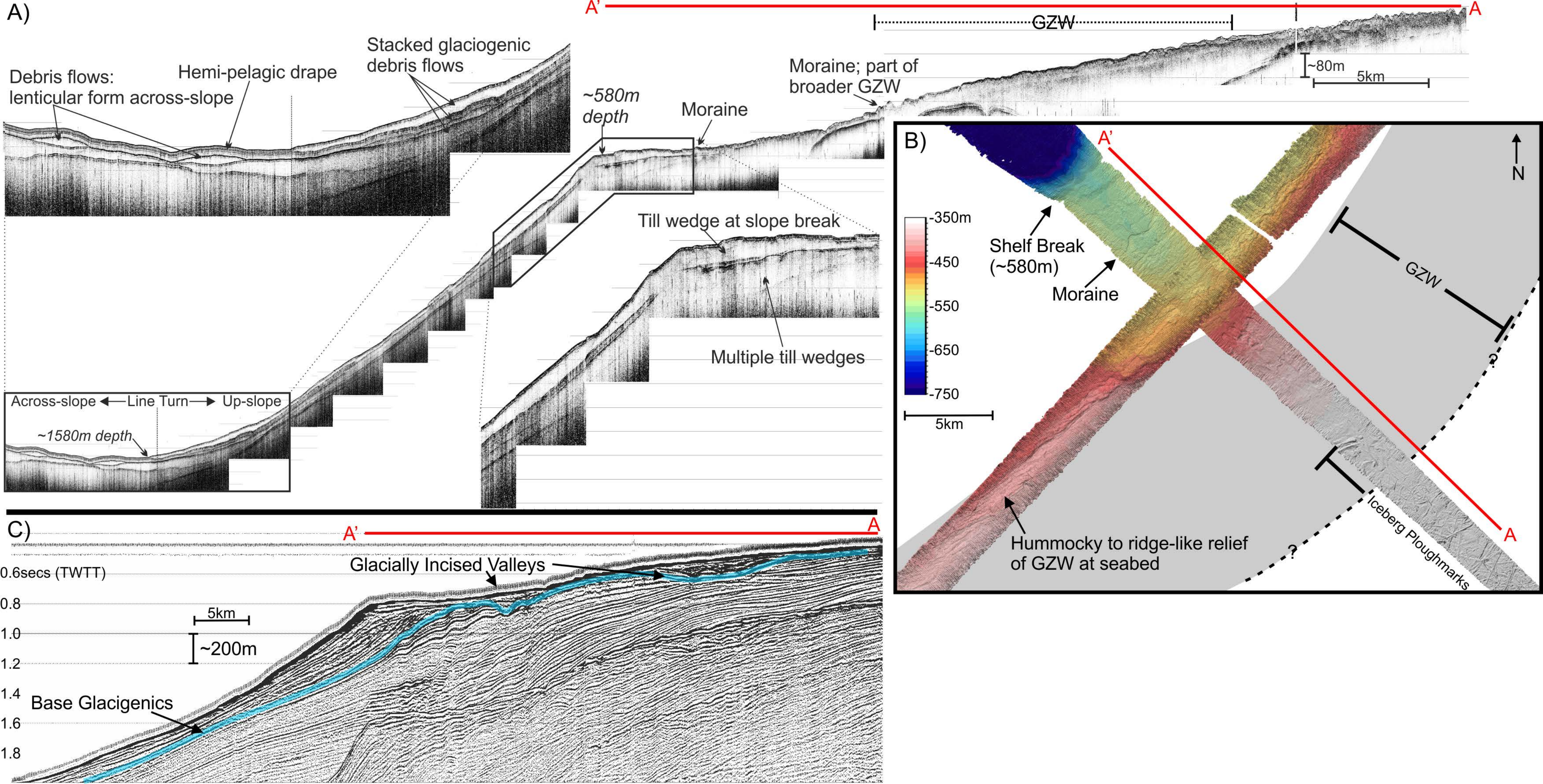
Figure 7. Interpreted Map: Red arrows show orientations of observed mega scale glacial lineations (MSGLs). Interpreted glacial flow lines associated with Chukchi-sourced ice shown in white, Laurentide-sourced ice in orange.


B)
180°
170°W
160°W
78°N
76°N
74°N
72°N
Mendeleev Ridge
Chukchi Basin
Chukchi Plateau
Chukchi Rise
Northwind Basin
Northwind Ridge
Canada Basin
Chukchi Shelf
2c
6a
6b
2a
5
3b
3a
2b
4
2150
1950
1750
1550
1350
1150
950
750
550
350
150
0
50
100 Kilometers
A)
Barents Sea
Kara Sea
Lomonosov Ridge
New Sib. Is.
E. Siberian Sea
Wrangel Is.
Chukchi Sea
Chukotka
Alaska
Beaufort Sea
Mackenzie Trough
Bering Sea

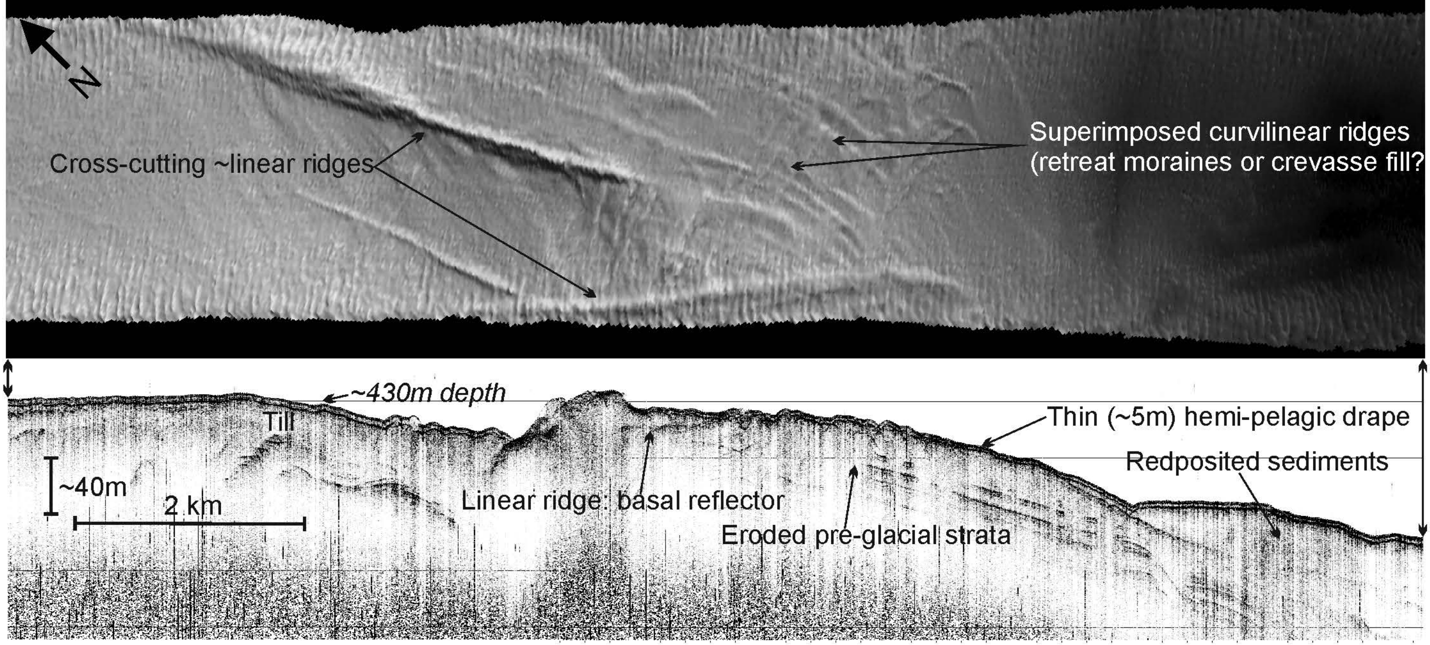

A)
MSGL
Erosional surface ~900m
N
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
~2100m
NW
-900m
-1000
-1100
-1200
0m
2000
4000
6000
8000
B)
SE
-354m
-358
-362
0m
1000
2000
3000
4000
5000
-180
-210
-240
-270
-300
-330
-360
N
MSGL
Iceberg scouring
Deep-keeled iceberg scours
Iceberg scouring
C)
N
MSGL
-400
-1000
Crescentic bedforms (Morainic wedges)
2 km
0.532 secs (TWTT)
Morainic wedges
2 km
Redeposited sediment
0.632
~80m
Pre-glacial strata
0.732


A)
-445m
-450
-455
-460
0m
200
400
600
800
1000
W
Ribbed Moraines
Drumlinized bedform
MSGL
N
B)
-576m
-578
-580
-582
0m
200
400
600
800
N
Data artifacts at swath edges
N
MSGL
Ribbed Moraines
Drumlinized bedform
Thin (~5m) hemi-pelagic drape
~40m
Till

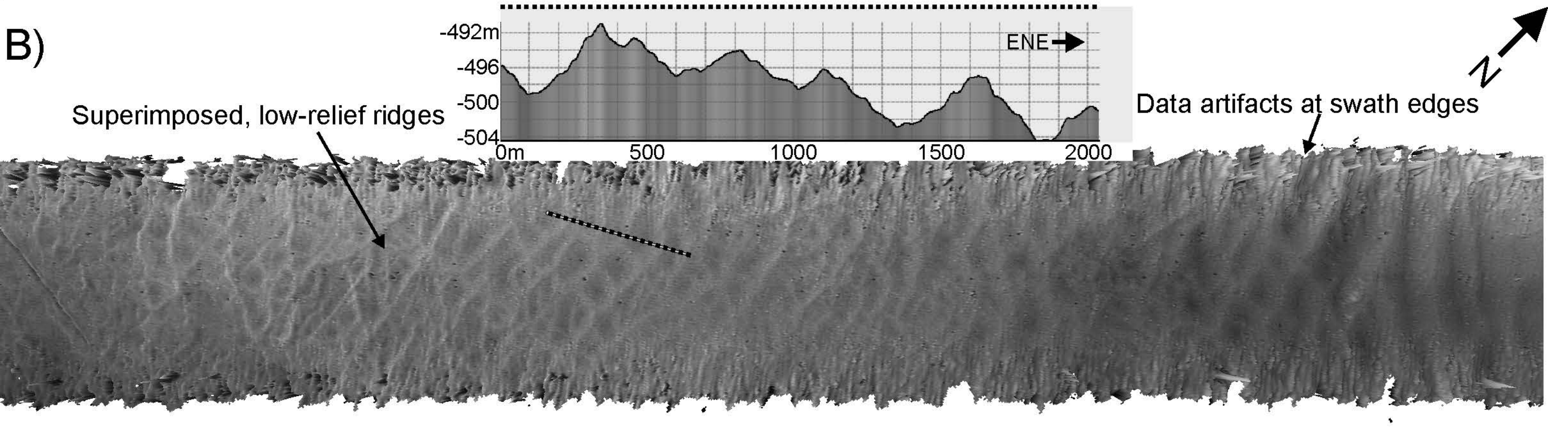

MSGL
SE
CHIRP Profile
615m
625
635
SSW
0m
200
400
600
800
1000
1200
Till lenses
Recessional Moraines
Grooved Seabed (MSGL)
Pre-glacial strata
~80m
Multiple episodes of erosion

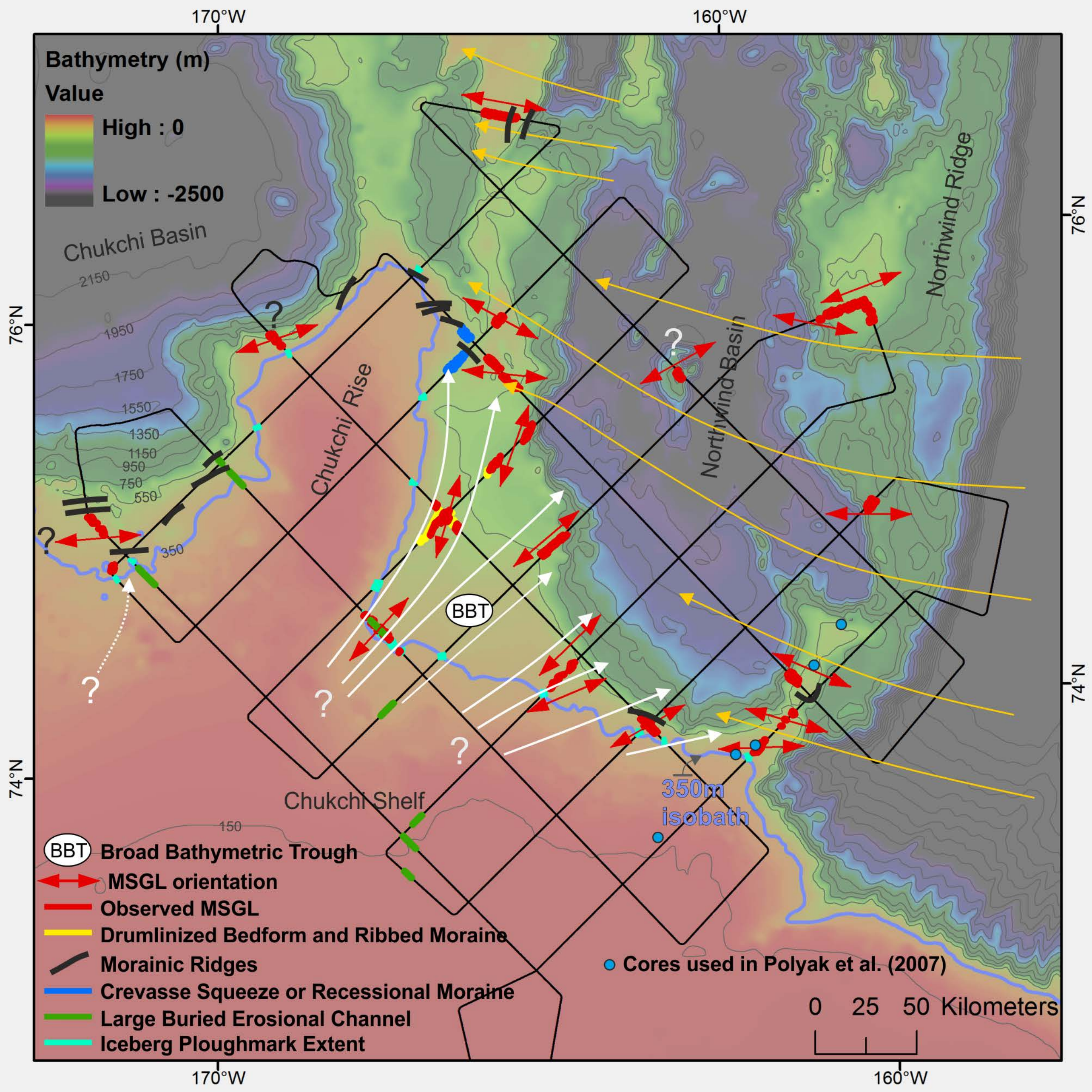

A)
A'
A
GZW
~80m
5km
Debris flows:
lenticular form across-slope
Hemi-pelagic drape
Stacked glaciogenic debris flows
~580m depth
Moraine
Moraine; part of broader GZW
Till wedge at slope break
Multiple till wedges
Across-slope ◄ Line Turn ► Up-slope
~1580m depth
B)
A'
A
N
-350m
-450
-550
-650
-750
5km
Shelf Break (~580m)
Moraine
GZW
?
Iceberg Ploughmarks
Hummocky to ridge-like relief of GZW at seabed
C)
A'
A
0.6secs (TWTT)
0.8
1.0
1.2
1.4
1.6
1.8
5km
~200m
Glacially Incised Valleys
Base Glacigenics

A)


N
Cross-cutting ~linear ridges
Superimposed curvilinear ridges
(retreat moraines or crevasse fill?
~430m depth
Till
Thin (~5m) hemi-pelagic drape
Redposited sediments
~40m
2 km
Linear ridge: basal reflector
Eroded pre-glacial strata

B)


-492m
-496
-500
-504
0m
500
1000
1500
2000
ENE
N
Superimposed, low-relief ridges
Data artifacts at swath edges


170°W
160°W
Bathymetry (m)
Value
High : 0
Low : -2500
Chukchi Basin
2150
1950
1750
1550
1350
1150
950
750
550
350
150
Chukchi Rise
Northwind Basin
Northwind Ridge
Chukchi Shelf
BBT
350m isobath
76°N
74°N
?
BBT Broad Bathymetric Trough
MSGL orientation
Observed MSGL
Drumlinized Bedform and Ribbed Moraine
Morainic Ridges
Crevasse Squeeze or Recessional Moraine
Large Buried Erosional Channel
Iceberg Ploughmark Extent
Cores used in Polyak et al. (2007)
0 25 50 Kilometers