

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

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11

## 12 **Abstract**

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

## 26 **1. Introduction**

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

37  
38 High-resolution geophysical data (swath bathymetry and shallow seismic reflection) can greatly  
39 improve our understanding of past marine ice sheets by revealing remarkably well preserved  
40 signatures of sub-glacial processes (e.g., Ó Cofaigh et al., 2008; Dowdeswell et al., 2008).  
41 Assimilated evidence may include streamlined bedforms (mega-scale glacial lineations (MSGs) and  
42 drumlins), sub-glacial deposits, transverse ridges, and grounding zone wedges on the shelf and  
43 bathymetric highs, as well as associated debris flows and fans on the slope. Finding such features  
44 however may be difficult due to pervasive iceberg scouring from the most recent deglaciations,  
45 which obliterated the potential record of preceding glacial events. In the Arctic Ocean such scouring  
46 has been reported from waters typically shallower than 300-400m (e.g., Jakobsson et al., 2008);  
47 hence, detailed surveys are needed with a focus on the deeper shelf.

48  
49 Glacial features in the Arctic Ocean, prominent on elevated portions of the central  
50 Lomonosov Ridge and the Chukchi Borderland, have been primarily related to ice arriving from the  
51 Barents-Kara and Laurentide ice sheets, respectively (e.g., Jakobsson et al., 2008, 2010). Other  
52 expanses of the Arctic Ocean perimeter such as broad and shallow Chukchi and East Siberian shelves  
53 have not been considered as significant glaciation centers, except for earlier inferences based on

54 geomorphic features of unconstrained age and simplified paleoglaciologic modeling (Grosswald,  
55 1989; Hughes and Hughes, 1994). In the initial study of the Chukchi Borderland, Polyak et al. (2001)  
56 inferred ice expanding from the Chukchi Shelf, but in later studies glacial bedforms in this area  
57 have been related to ice impinging only from the Laurentide ice sheet, with possibly local small ice  
58 cap(s) on the Chukchi Plateau (Jakobsson et al., 2005, 2010; Polyak et al., 2007). This conclusion has  
59 been influenced by evidence from the Chukchi Sea coast and Wrangel Island indicating absence of  
60 large ice sheets, at least in the Late Pleistocene (Brigham-Grette et al., 2001; Gualtieri et al., 2005).  
61 The interpretation was severely impeded by very scarce data coverage of the northern Chukchi  
62 Shelf.

63  
64 Here we present recently acquired multibeam bathymetry and sub-bottom profiling data (Fig. 1) that  
65 reveal evidence of widespread glaciation on the northern part of the Chukchi Shelf (Chukchi Rise)  
66 and adjacent Borderland. This evidence, together with that presented by Niessen et al. (this issue)  
67 from the East Siberian margin, requires reconsidering the Pleistocene glacial history in this part of  
68 the Arctic.

## 69 **2. Study area and methods**

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

76  
77 Late Cenozoic climatic, sea-level, and tectonic changes radically impacted the Chukchi Shelf, a  
78 gateway between the Pacific and Arctic oceans that turned into a Beringian land bridge between  
79 America and Eurasia during sea-level lowstands. Growth and decay of ice caps on the Chukchi Shelf  
80 and Borderland was clearly a major factor of this history. Knowledge of the yet poorly understood  
81 limits, provenance, and timing of glacial events on the Chukchi margin is thus important for  
82 reconstructing paleoclimatic and sedimentary environments in the Chukchi-Beringian region and  
83 adjacent Arctic Ocean.

84  
85 In 2011, approximately 5,000 km of continuous geophysical data were acquired from the *R/V*  
86 *Maurice G. Langseth* on a broad grid over the Chukchi Rise (northern extension of the Chukchi Shelf)  
87 and adjacent portions of Chukchi Plateau, Northwind Ridge, and interspaced deep basins (Fig. 1b).  
88 Along with the deep penetrating (kilometre-scale) multi-channel seismic (MCS) and marine gravity  
89 data collected to study the tectonism of the Chukchi Borderland, multibeam echo-sounder (MBES)  
90 bathymetry and CHIRP sub-bottom profiler data were acquired to investigate seafloor morphology  
91 and the shallow subsurface geology of the region. These data provide a comprehensive  
92 characterization of bedforms related to the glaciation history of the northern Chukchi margin.

93  
94 The MBES data were acquired using a 12kHz Kongsberg EM122, well suited for this cruise with  
95 surveyed depths ranging from 40m to 4000m, and a swath width of 4-6x water depth. Swath editing  
96 and gridding were conducted using MB-System (Caress and Chayes, 2008), and GMT (Wessel and

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

100

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

### 107 **3. Results**

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

#### 113 **3.1. Iceberg scoured shallow seabed**

114 Observed both in the MBES and CHIRP data, scours resulting from iceberg keels ploughing through  
115 the sedimentary seabed dominate the seafloor above ~350 m water depth (Figs. 2b, 5b), consistent  
116 with the depth threshold observed previously in the region (Polyak et al., 2001; Jakobsson et al.  
117 2008). Where present, scouring has eliminated all evidence of previous processes impacting the  
118 seafloor. Individual scours are up to 30 m deep, and while superposition is evident, overall scour  
119 orientation appears random. Sediment on top of scoured seabed is absent or very thin in deeper  
120 waters towards the ~350m trimline, but infills and partially drapes the scours in waters shallower  
121 than 130m. This drape is acoustically layered to transparent and has been identified as Holocene  
122 marine transgressive sediments pinching out towards the current-swept inner shelf (Keigwin et al.,  
123 2006; Polyak et al., 2007; Darby et al., 2009; Hill and Driscoll, 2010). This stratigraphy confirms that  
124 preserved scouring occurred during the last deglaciation. Associated with the scouring, CHIRP data  
125 frequently reveal a thin (~5m) unit of acoustically homogenous, unstratified sediment with a strong  
126 basal reflector, likely indicating a till-like unit generated by iceberg turbation (e.g., Dowdeswell et al.,  
127 1994).

128

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

132

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

137

## 138 **3.2. Glacigenic features on the outer shelf and borderland**

### 139 **3.2.1 Tills and till-like sediments**

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

147  
148 Several locations bear the evidence of multiple till units indicating multiple glacial episodes affecting  
149 the region (Fig. 4, 5a, 6a). Due to the limited penetration of the CHIRP and not always strong basal  
150 reflector, we may not always see the base of the till units. This limits our understanding of the  
151 spatial patterns and timing of processes that led to till formation.

152  
153 At the shelf margin, the till is persistent on both sides of the Chukchi Rise between the 350 m  
154 contour and the shelf break, where till commonly forms prograding, cross-sectional wedges (Fig.  
155 5a,c). Such depositional till wedges, which effectively extend the continental shelf, are a  
156 characteristic feature of glaciated continental margins (e.g., Dahlgren et al., 2005). Around the  
157 Chukchi Rise till wedges extend the shelf edge by as much as 10-20 km and reach up to >300 meters  
158 in thickness as seen on deep seismic records (Fig. 5) (Hegewald, 2012; Hegewald and Jokat, 2013).

### 159 **3.2.2 Mega-Scale Glacial Lineations**

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

169  
170 The morphology and pattern of these bedforms indicates they are mega-scale glacial lineations  
171 (MSGs), which have been identified from multiple sites on previously glaciated seafloor in the Arctic  
172 (e.g., Jakobsson et al., 2008; Dowdeswell et al., 2010), Antarctic (Ó Cofaigh et al., 2002), and mid-  
173 latitudes (Todd and Shaw, 2012). The presence of MSGs is generally recognized as evidence of  
174 coherent, fast-flowing grounded ice, frequently associated with ice streaming (Stokes and Clark,  
175 2001; King et al., 2009). The MSGs are also observed in the CHIRP data lying on till or pre-glacial  
176 strata, in places causing acoustic diffraction (Figs. 2c, 3b, 4). In several locations we also observe  
177 what may be buried MSGs, where a rugged erosional boundary is overlain by till, likely indicating  
178 multiple episodes of glacial erosion.

179  
180 Most MSGs observed fall into two general orientations: (1) E-W (W-E) to SE-NW (NW-SE), and (2)  
181 more SW-NE (NE-SW) trending (Fig. 7). There is no apparent relationship between orientation and

182 depth, though such a comparison is biased by the highly variable regional bathymetry. The group (1)  
183 MSGs occur at or near the shelf break on the northeastern edge of the Chukchi Rise and on  
184 adjacent parts of the Chukchi Plateau and Northwind Ridge. The group (2) MSGs are primarily  
185 observed in the broad bathymetric trough on the eastern side of the Chukchi Rise, but also on the  
186 western edge of the Rise, northern part of Northwind Ridge, and an isolated high within the  
187 Northwind Basin.

188

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

201

202

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

### 208 **3.2.3 Ice Marginal Features**

209 A diverse suite of bedforms observed in the MBES and CHIRP data, predominately between 350 m  
210 and 550 m water depth, can be interpreted as ice-marginal in origin (Figs. 4,5). Broadly grouped, the  
211 most common are narrow to broad (100-800 m wide) ridges of curvilinear to sinuous shape  
212 frequently occurring at or near the shelf break. In the CHIRP data these ridges often appear as  
213 symmetric or asymmetric ridges and wedges (5-50 m thick). They may have a strong basal reflector  
214 indicative of a depositional origin, or appear contiguous with the underlying till. In most places there  
215 are several, sub-parallel ridges interspaced with hummocky seabed. Some ridges are long and  
216 continuous; where discontinuous, they are component parts of a longer, continuous band of similar  
217 bedforms. We interpret these features to be moraines (e.g. Bradwell et al., 2007; Ó Cofaigh et al.,  
218 2008; Dowdeswell et al., 2008). Near the shelf break they often form a morainic belt, delimiting a  
219 temporarily halted, seaward extent of grounded ice similar to grounding zone wedges (GZWs)  
220 described on glaciated margins elsewhere (Fig. 5) (Rüther et al., 2011; Dowdeswell and Fugelli,  
221 2012). The bathymetry of the GZWs is characterized by hummocky to ridge-like relief, though our  
222 data coverage is insufficient to map the extent of these features. The shelf-break located till wedges  
223 and MSGs provide evidence that grounded ice reached the shelf edge (up to or seaward of the  
224 GZWs), and the GZWs likely represent later glacial still-stands, during step-wise retreat.

225

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

232

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

241

### 242 **3.3. Debris Flows**

243 On the continental slope and adjacent basins around the Chukchi margin, CHIRP data regularly  
244 reveal debris lobes indicating episodes of increased sediment delivery to the shelf edge,  
245 characteristic of glaciated continental margins (Fig. 5a) (e.g., Dowdeswell et al., 2002; King et al.,  
246 1998). Debris flows are easily distinguishable from encompassing hemipelagic sediments by their  
247 unstratified acoustic character. Down-slope, individual lobes vary in thickness, and are up to 50 m  
248 thick. Across-slope the flows are lenticular and occur at several, regionally consistent stratigraphic  
249 levels, separated and overlain by packages of well-layered hemipelagic sediments. A lobe cored on  
250 the ramp to the Northwind Ridge (Fig. 7) consisted of gray, fine, faintly laminated mud interpreted  
251 as glacio-turbidites (Polyak et al., 2007). While the exact depositional processes and ages of these  
252 deposits are yet to be constrained, they clearly indicate that grounded ice delivered large amounts  
253 of sediment to the slope along the Chukchi margin.

254

### 255 **3.4. Buried Channels**

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

264

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

269

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

274

#### 275 **4. Discussion**

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

280

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

285

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

294

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

301

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

309

310 The overall smooth slope bathymetry west of the Northwind Ridge, in contrast to strongly  
311 canyonized slope further to the east (Fig. 1b), may be related to glacially redeposited sediment  
312 masses. If true, this change in relief may indicate the eastern boundary of the margin affected by  
313 glaciers advancing to the shelf edge. If the broad bathymetric trough east of the Chukchi Rise served



314 to focus glacial drainage from the Chukchi Shelf, the Northwind Basin should contain a significant  
315 accumulation of glacial debris, though due to the confining nature of the regional bathymetry we  
316 do not expect to observe the splayed morphology typical of trough-mouth fans (e.g. Pedrosa et al.,  
317 2011). While this requires further investigation with deeper penetrating seismic data, the CHIRP data  
318 reveal glacial debris extending to at least 100 m thickness at the base of slope, suggesting the  
319 Northwind Basin has served as a significant depocenter.

320

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

329

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

338

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

348

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

352

353 The southern extent of glaciation towards the inner Chukchi Shelf may not be possible to identify on  
354 the sea floor because of a pervasive iceberg scouring at shallower depths. A large, mostly buried  
355 sediment ridge in the northern Bering Sea southeast of Chukotka (Fig. 1a) has been interpreted as a  
356 morainic ridge (Grim and McManus, 1970), and was encountered by the Langseth-2011 crossing. As  
357 suggested by Brigham-Grette et al. (2001), this ridge might mark the southern limit of the maximal  
358 glaciation of the Chukchi region, tentatively dated by Amino Acid Racemization of mollusk shells to a

359 stadial within Marine Isotope Stage (MIS) 5, broadly around ca. 100 ka. A similar age has been  
360 inferred for glacial erosion on the Arlis Plateau north of the East Siberian shelf (Stein et al., 2010;  
361 Niessen et al., this issue) and a slightly older age, ca. 135 ka estimated from uranium-thorium dating,  
362 for glacial advance on the New Siberian islands (Basilyan et al., 2010) (Fig. 1a). This combination of  
363 paleoglaciological evidence, although fragmentary and only tentatively dated, offers a possibility  
364 that a very large ice sheet existed on the Chukchi-East Siberian margin at the end of middle  
365 Pleistocene or beginning of early Pleistocene.

366

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

378

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

## 387 **5. Conclusions**

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

395

396 An association of directional bedforms, such as Mega Scale Glacial Lineations (MSGs) and  
397 transverse morainic ridges, depicts grounded ice streaming from the northern Chukchi Shelf towards  
398 the edges. This picture is especially compelling in a broad bathymetric trough at the eastern side of  
399 the Chukchi Rise, where a combination of glacial bedforms and the overall trough morphology  
400 resembles cross-shelf troughs of the West Antarctic and the Barents-Kara seas that served as outlets  
401 for large ice streams (e.g., Ó Cofaigh et al., 2008; Winsborrow et al., 2010). Composite, prograding

402 till wedges of several hundred meters thickness extend the Chukchi Shelf edge, similar to, though  
403 not as large (10-20 km wide vs. 50-100 km) as those along the northwestern European  
404 margin(Dahlgren et al., 2005). Along with the regional pattern of MSGs, the composite till wedges,  
405 multiple erosional surfaces in till and pre-glacial strata, and stacked till units, bear evidence of  
406 several glacial events impacting the Chukchi margin, from multiple ice sources.

407

408 In combination with already known and newly emerging results from the adjacent areas such as East  
409 Siberian and Beaufort Sea shelves (e.g., Engels et al., 2008; Niessen et al., this issue), the *Langseth-*  
410 *2011* data provide a new understanding for the glacial history of the Chukchi-Beringian region.

411 Orientation of directional bedforms and the general configuration of the mapped features suggests  
412 ice impinged on the area from three ice sheet sources: Northwestern sector of the Laurentide ice  
413 sheet, Chukchi Shelf, and possibly East Siberian Shelf. These features may represent different glacial  
414 events as indicated by limited sediment-core data and seismostratigraphic correlations, with a likely  
415 LGM impact on the Chukchi Rise and older glacial grounding on the borderland further east and  
416 north. The new picture emerging from marine geophysical data raises further questions about the  
417 extent interaction of different Arctic ice masses, the glacio-isostatic history of Beringia, and the  
418 implications for oceanic and atmospheric circulation, especially the Arctic-Pacific connection.

419

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589

590

591

## 592 **Figure Captions**

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

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

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

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

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

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

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



