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Seismic constraints for ice sheets along the northern margin of Beringia

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ABSTRACT

Beringia today is a partly submerged Arctic region bordered by the Lena River in East Siberia and the Mackenzie River in North America. Whilst emergent at times of eustatic sea-level fall, the northern Beringian Margin was affected by the repeated growth and decay of regional ice sheets. The size and dynamism of these ice sheets are a subject of some debate that can be addressed using geophysical data, which reveal widespread evidence for glacial processes on the continental shelves. We use published and reprocessed 2D multichannel seismic reflection data from the northern margins of Beringia between 147° E to 149° W to investigate their glacially deposited sediments in detail. Deposition of up to 450 m of sediments caused the shelf break to migrate basinward by up to 13 km between 165° E and 161° W. On the Kucherov Terrace (175° E to 176° W) the data show evidence for erosion by grounded ice in water depths of 1200 m. Deposits in the Northwind Basin, between 165° W and 161° W, are separated by continuous reflections indicating at least 3–5 glacial advances. However, the continental slopes of the western East Siberian Sea and the Beaufort Sea lack the thick glacial deposits found in the intervening region. Overall, the volume of glacial deposited sediments along the margins of Beringia are significantly smaller than the reported amounts along the Norwegian and Greenland margins. Therefore, we suggest a less dynamic and fewer number of glaciations of Beringia compared to other glaciated margins during the Quaternary.

1. Introduction

During Pleistocene sea-level lowstands controlled by continent-wide glaciations, a large portion of the up to 900 km wide shelf north of the Bering Strait between East Siberia and Alaska became emergent (Elias and Brigham-Grette, 2013). This area is part of a region named Beringia (Fig. 1). Onshore geological investigations suggest that Beringia has not hosted large ice sheets like those on Greenland or the marine-based Kara-Barents ice sheet during the Quaternary (Brigham-Grette and Gualtieri, 2004; Elias and Brigham-Grette, 2013). Instead, a widespread mountain glaciation in East Siberia and Alaska was assumed from the presence of moraines and the lack of evidence for glacio-isostatic rebound along the coasts (Barr and Clark, 2012; Brigham-Grette and Gualtieri, 2004; Glushkova, 2011; Kaufman et al., 2011). Additionally, cored evidence for continuous deposition in lake El'gygytgyn over the last 2.8 Myr (Fig. 1) support models that no large ice sheets existed onshore East Siberia (Melles et al., 2012).

The offshore sedimentary record of its northern continental margin supports a contrasting scenario. Geophysical data from the northern margin of Beringia provide reliable information that the outer continental margins of the East Siberian and Chukchi seas host widespread glacial seafloor features on the continental shelf (e.g., mega-scale glacial lineations, grounding zone wedges), and slope (glacial debris flows in water depths shallower than 1200 m) (Dove et al., 2014; Hegewald and Jokat, 2013b; Kim et al., 2021; Lehmann et al., 2022; Niessen et al., 2013). Further, glacial sediments raise evidence for larger glaciations prior to the Late Pleistocene are found on the New Siberian Islands and Wrangel Island (Gualtieri et al., 2005; Nikolskiy et al., 2017). The widespread presence and great variety of glacial features indicate the action of a regional marine-based ice sheet in the area of the Beringian continental margin (Dove et al., 2014; Niessen et al., 2013). Additionally, three bathymetric troughs likely eroded by ice streams (the DeLong Trough, the Western Bathymetric Trough and the Broad Bathymetric Trough (Fig. 1, top panel 1–3) are found along the northern continental shelf of Beringia (Dove et al., 2014; Kim et al., 2021; O'Regan et al., 2017). However, the exact timing, geometries and dynamics of these ice sheets are at present unknown.

Grounded ice sheets have shaped the continental shelves and

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delivered large amounts of sediments to the continental slopes of most high latitude continental margins (Berger and Jokat, 2008; Dahlgren et al., 2005; Laberg et al., 2012; Nielsen et al., 2005). In seismic reflection data, glacial deposits on continental slopes appear as chaotic or opaque wedges separated by thinner acoustically stratified units (Laberg and Vorren, 1996; Ó Cofaigh et al., 2003). These patterns are the consequence of episodic delivery of unsorted glacially transported sediments, interspersed with interglacial periods of hemipelagic sedimentation (Ó Cofaigh et al., 2003). The volume of glacially transported sediments varies with different ice flow velocities along such margins (Dahlgren et al., 2002; Dowdeswell et al., 2002; Rydningen et al., 2015). The largest quantities of such sediments are delivered by fast flowing ice-streams to be deposited in trough mouth fans at the mouths of deep glacially scoured cross-shelf troughs (Batchelor and Dowdeswell, 2014; Vorren and Laberg, 1997; Vorren et al., 1989). In contrast, between ice streams the flow rate is one to two orders of magnitude slower leading to a relative dearth of glacially transported sediments on the continental slope (Dowdeswell et al., 2002). Glacially transported material forms prograding wedges that relocate shelf breaks towards the ocean. For example, the continental margins of East Greenland and Scandinavia have prograded basinwards by up to 80 and 150 km, respectively (Berger and Jokat, 2008; Rise et al., 2005; Vorren et al., 1998). Furthermore, Ó Cofaigh et al. (2003) stated that trough mouth fans require a wide continental shelf with abundant and erodible sediments and low gradient (<1°) continental slopes. However, along the northern rims of Beringia, wedges of chaotic strata overlying stratified, prograding sediment horizons have so far only been described at a few locations (Dove et al., 2014; Hegewald and Jokat, 2013a; Kim et al., 2021).

The objective of this paper is to review the accessible seismic data base to find evidence for: i) glacial sediments on the continental margin, and from this, ii) the existence and possible extent of former ice sheets and/or ice shelves along the continental margins from the Laptev Sea to the Beaufort Sea. For this, we use reprocessed 2D multichannel seismic data from the outer Chukchi Shelf and Chukchi Borderland as well as published seismic reflection data (Niessen et al., 2013; Nikishin et al., 2017; Triezenberg et al., 2016) along the continental margin of Beringia to identify and describe glacial deposits. Afterwards, we compare these deposits with glacial deposits along the Norwegian and East Greenland margins.

2. Data and methods

The R/V Marcus G. Langseth acquired a regional 2D seismic grid

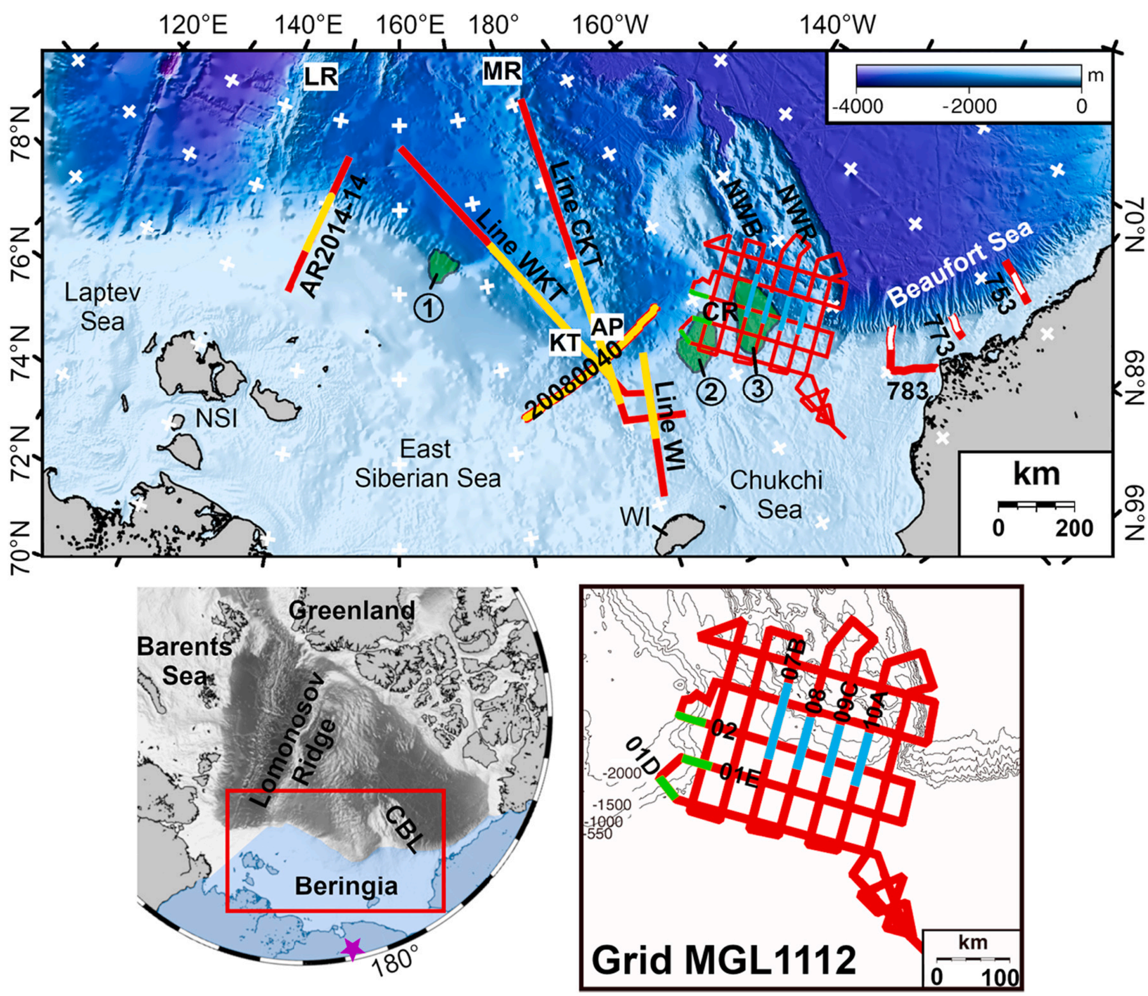

Fig. 1. Top panel: Overview of used seismic profiles. Bathymetric background map: IBCAO v4 (Jakobsson et al., 2020). Red lines: seismic profiles used in this study. Yellow lines: sections shown in Fig. 2 (East Siberian Sea), Light green lines: sections shown in Fig. 3 (Western Chukchi Rise), Light blue lines: sections used in Fig. 4 (Northwind Basin), White Lines: sections used in Fig. 5 (Beaufort Sea), Green areas: 1 – DeLong Trough, 2 – Western Bathymetric Trough, 3 – Broad Bathymetric Trough. Lower left panel: Overview Arctic Ocean and Beringia (transparent blue area). Purple Star: Lake El'gygytgyn. Lower right panel: Zoom of seismic profiles MGL1112. Abbreviations: AP – Arlis Plateau, CR – Chukchi Rise, CBL – Chukchi Borderland, KT- Kucherov Terrace, LR – Lomonosov Ridge, MR – Mendeleev Ridge, NWB – Northwind Basin, NWR – Northwind Ridge, NSI – New Siberian Islands, WI – Wrangel Island. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1, in total 5300 km) across the Chukchi Shelf and Borderland (Coakley, 2011a, 2011b; Ilhan and Coakley, 2018) in 2011. Details of this cruise can be found in Ilhan and Coakley (2018) and Lehmann et al. (2022). The multichannel seismic data (MCS) were originally processed in 25 m bins by ION Geophysical (Ilhan and Coakley, 2018). We reprocessed the data with a 6.25 m binning to achieve better resolution of shallow and small-scale structures by using the closer hydrophone spacing. The reprocessing is described in detail in Lehmann et al. (2022).

In addition to the reprocessed profiles, we use the few previously-published seismic profiles that enable us to image the continental slopes from ~147°E in the East Siberian Sea to ~149°W in the Beaufort Sea (a distance of ~1800 km) (Fig. 1). The profiles are of variable resolution; in some older ones, shallow acoustic sequences are difficult to interpret. We split the study area into four parts (East Siberian Margin, Chukchi Rise, Northwind Basin, Beaufort Sea; Figs. 2 – 5). For the East Siberian Margin (Fig. 2), we rely on seismic reflection data published by Nikishin et al. (2017) and Niessen et al. (2013). The reprocessed MCS profiles across the western Chukchi Rise and the Northwind Basin are shown in Fig. 3 and Fig. 4, respectively. Line drawings from the Beaufort Sea (Fig. 5) are based on published MCS data of the L-9-77-AR cruise (Triezenberg et al., 2016).

3. Results

We identified acoustically chaotic sequences and prograding wedges in all four sub-regions. These sediments are highlighted with light blue fill in Figs. 2-5. Acoustically well-layered strata below the chaotic layers and wedges are filled in light gray in the figures. Individual reflectors highlighted with colored lines in the line drawings are adopted from the original interpretations.

3.1. East Siberian Margin (147°E – 175°W)

In the western East Siberian Sea sector (147°E to 165°E), no large-scale erosion is imaged on the continental shelf in the available MCS data (Fig. 2a). In addition, the upper sedimentary units on the slope are well stratified and show no extensive shelf progradation consisting of chaotic sediments (Fig. 2a). The slope angle is ~0.8°.

Further east, from ~170° E to ~175°W, the shallow shelf of the East Siberian Sea hosts chaotic layered sediments with a maximum thickness of 150 m (200 ms TWT) (Fig. 2 b, c, d). On profile WKT, a layer of chaotic sediments with a maximum thickness of ~90 m (100 ms TWT) covers the shelf and slope in water depths <1200 m (Fig. 2b). This sediment layer is on profile AWI-20080040 (Fig. 2d) over the eastern Kucherov Terrace, in contrast, up to ~325 m (380 ms TWT) thick. The development of this wedge shape relocated the shelf break outwards by ~13 km towards the Kucherov Terrace (Fig. 2d). A small terrace is present at a water depth of ~650 m (Fig. 2d) on profile AWI-20080040. On the western Kucherov Terrace in water depths below ~1200 m (1600 ms), the seafloor and the underlying reflections are flat and undisturbed (Fig. 2b). However, at the northern and eastern flanks of the Kucherov Terraces, the MCS data image chaotic sediments in water depths of 1500 m (2 s TWT, Fig. 2c) and 2750 m (3 s TWT, Fig. 2d), respectively.

On profile WI (Figs. 1, 2e), located between the Kucherov Terrace and the Chukchi Borderland, chaotic sediments have led to shelf progradation by ~6 km. The slope angle is ~1.5° (Fig. 2e). The chaotic unit is up to ~200 m (230 ms TWT) thick (Fig. 2e). A terrace of ~5 km width, with a rough seafloor, can be observed in water depths of ~450 m (600 ms TWT) (Fig. 2e).

3.2. Western Chukchi Rise (175°W – 168°W)

Seismic profiles across the western flank of the Chukchi Rise show well layered strata to be truncated on the shelf, but to be covered by chaotic deposits and prograding chaotic sequences beyond the shelf break (Fig. 3). The accumulation of chaotic seismic units on the slope has led to progradation of the shelf break by ~6 km at 168°W (Fig. 3a; profile 01D), ~10 km on profile 01E at 170°W (Fig. 3b; profile 01E) and ~3 km on profile 02 at 172°W. The prograding wedge on profile 01D (Fig. 3a) reaches a maximum thickness of ~450 m (530 ms TWT). The thickness decreases eastward to ~380 m (450 ms TWT) on profile 01E (Fig. 3b) and just ~140 m (160 ms TWT) on profile 02 (Fig. 3c). Along with the decreasing thickness, the slope angle increases from west (~1.7°, Fig. 3a) to east (~3°, Fig. 3c).

3.3. Northwind Basin (165° W – 161° W)

Seismic data image basins on the outer Chukchi Shelf east of the Chukchi Rise. The basins are floored by preglacial strata and filled with chaotic sediments (Fig. 4a, b). The basins are 32 km to 44 km wide (Fig. 4a, b) and the thickness of their fill ranges between 425 m (500 ms TWT) and ~220 m (250 ms TWT) on profile 07B and 08 (Fig. 4a, b), respectively. The underlying well stratified sequences both up- and downslope of these basins are truncated and covered by chaotic sediments (Fig. 4, zoom 4b).

The structure of the continental slope to the Northwind Basin changes from east to west. On profile 07B, no prograding chaotic sequences are observed beyond the shelf break to the Northwind Basin (Fig. 4a). Instead, a thick wedge-shaped unit with chaotic seismic character is visible in the Northwind Basin (Fig. 4a). The wedge extends for ~62 km into the basin and onlaps an exposed basement high at CDP 1600 (Fig. 4a). The chaotic reflection character in this wedge is crossed by two relatively continuous reflections, dividing it into 3 different units (Fig. 4a, zoom). The lowermost unit (blue fill in Fig. 4a, zoom) is wedge-shaped, and can be further subdivided by two semi-continuous reflections (white stippled lines). The wedge is thickest in the southwest, up to ~360 m (420 ms TWT), and thins towards the northeast to ~70 m (85 ms TWT). The continental slope on profile 07B has an angle of 11.5° (Fig. 4a).

Similar to profile 07B (Fig. 4a), prograding chaotic sequences are absent on the step-like slope to the Northwind Basin on profile 08 (Fig. 4b). The upper slope is steep, with an angle of 8.1° (Fig. 4b). A small basin ~300 m below the shelf break is filled with ~250 m (300 ms TWT) of chaotic sediments. Downslope of the small basin, the continental slope is covered by ~130 m (150 ms TWT) of chaotic deposits (Fig. 4b).

The margin of the Northwind Basin is less steep in the east than in the west. Here, on the two eastern profiles 09C at ~162°W and 10 at ~161°W, prograding chaotic sequences have widened the shelf by 2 km and 1 km, respectively (Fig. 4c, d). The continental margin of profile 9C (Fig. 4c) is divided into two parts by a spike-like elevation of underlying stratified material that forms a step in the seafloor at CDP 6800 (Fig. 4c). The maximum thicknesses of chaotic deposits of profile 09C are ~340 m (400 ms TWT) on the upper slope and ~280 m (330 ms TWT) on the lower slope (Fig. 4c). On profile 10, chaotic sediments reach a maximum thickness of 255 m (300 ms TWT; profile 10), thinning basinward over a distance of 12.5 km to ~65 m (75 ms TWT) (Fig. 4d). Slope angles on profile 09C are 1.5° on the upper part of the slope and ~0.4° further down. The slope angle on profile 10 is ~1.2° (Fig. 4d).

3.4. Beaufort Margin (161° W – 149° W)

Typical prograding chaotic sequences of the kind described previously are absent along the Alaskan-Beaufort Margin between 160°W and 149°W (Fig. 5). Instead, well stratified reflections lie parallel to the dipping seafloor on the upper part of the slope close to the shelf break (Fig. 5b). On profile 753, a ~200 m (250 TWT) thick disturbed sediment layer below a rough seafloor is present on the slope (Fig. 5c).

On the western profiles (Fig. 5a, b), a planar terrace with slope angle lower to the wider slope is imaged which is absent from the eastern profile (753; Fig. 5c). This terrace is up to 35 km wide and located at a depth of 250 m to ~500 m. Stratified reflections are partly truncated on

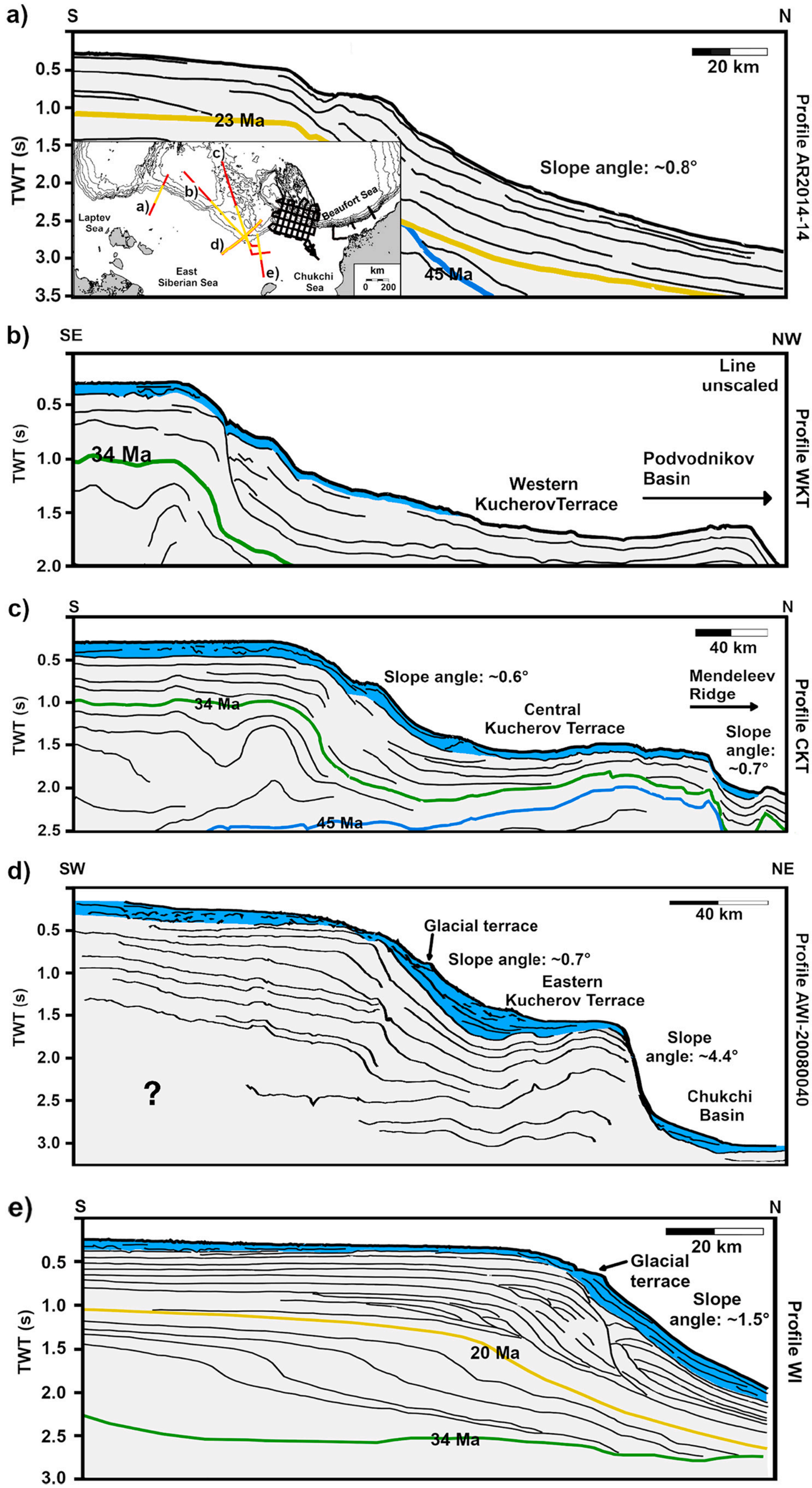

Fig. 2. Line drawings of seismic profiles in western East Siberian Sea. a) profile AR2014–14 just east of Lomonosov Ridge (Nikishin et al., 2017), b) across western Kucherov Terrace (Composite profile, unscaled, (Nikishin et al., 2017)), c) across the central and northern flank of the Kucherov Terrace (composite profile, Nikishin et al. (2017)), d) eastern Kucherov Terrace (AWI20080040), e) from Wrangel island to Chukchi Basin (Nikishin et al., 2017)). Blue: glacial sediments, light gray: preglacial. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

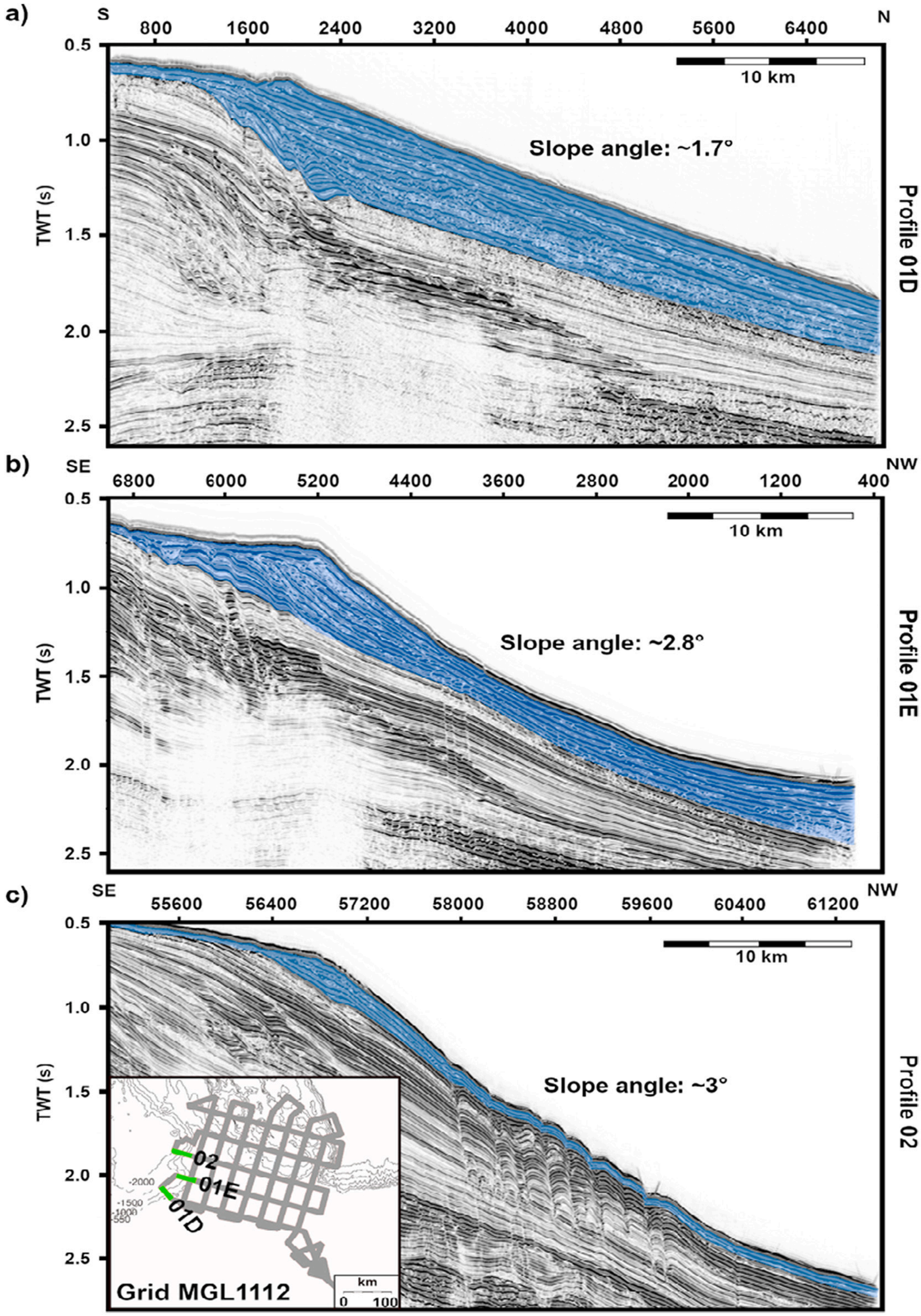

Fig. 3. Seismic profiles of the western flank of the Chukchi Rise with glacial deposited material in blue. Profiles A) 01D, b) 01E, c) 02 from southwest to northeast (see locations in inlet map). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

this terrace (Fig. 5a). A rough seafloor is present in water depths of 300 m (400 ms TWT) (Profile 773; Fig. 5b). Further, the terrace on this profile is covered by an acoustically transparent layer of 40 m thickness. This layer also forms a smaller 2.5 km wide bench on the slope beyond the shelf break (Fig. 5b).

4. Discussion

During Quaternary times, almost all of the continental margins surrounding the northern North Atlantic, Baffin Bay, and the Arctic Ocean were strongly modified by processes related to the Northern Hemisphere glaciations (Batchelor et al., 2019 and references therein). Whilst it is in general well accepted that those parts of Beringia that are situated

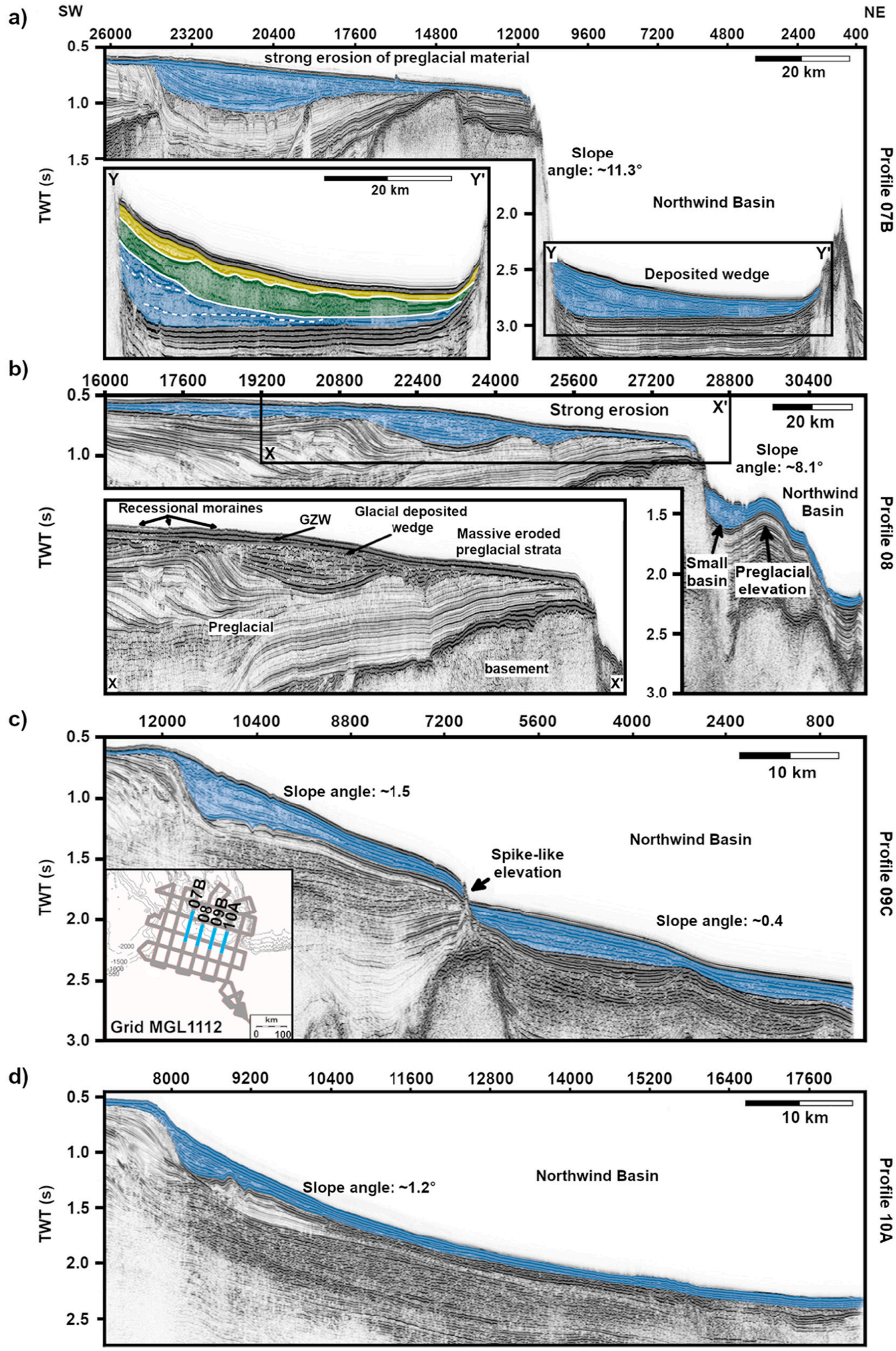

Fig. 4. Four seismic profiles with glacial material shaded in blue. Profiles a) 07, b) 08, c) 09 and d) 10 from west to east along the slope towards the Northwind Basin (see locations in inlet map). Zoom in a) shows sedimentary units: blue colour: units 1 to 3, green: unit 4 and yellow: unit 5. Zoom in b) shows basins filled with glacial sediments and eroded preglacial sediments covered by glacial sediments and landforms (Lehmann et al., 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

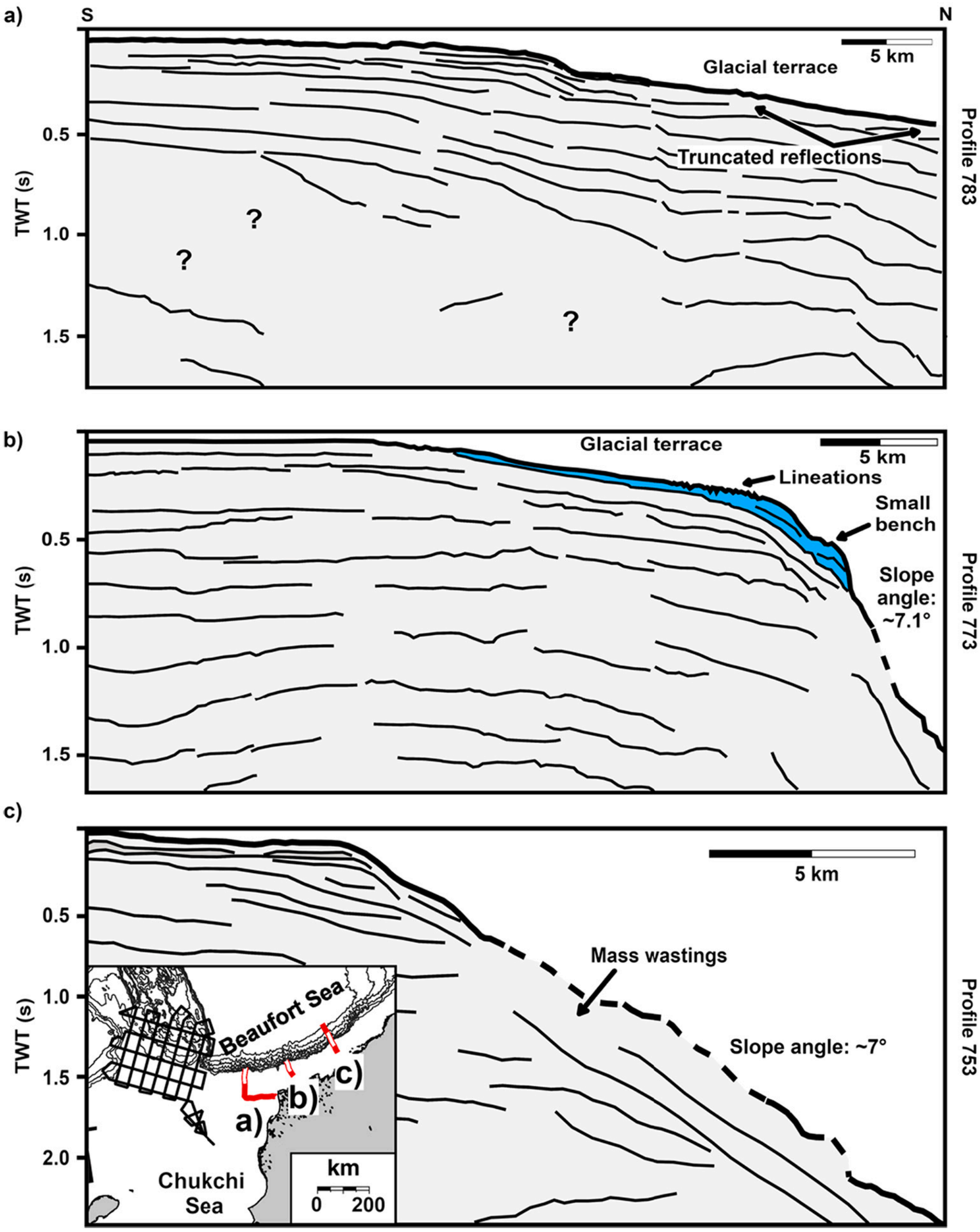

Fig. 5. Sketches of the Beaufort continental margin. A) profile 783 shows a glacial terrace, b) profile 773, glacial terrace is covered by a layer of transparent sediments (blue), c) profile 753 with a thick layer of mass-wastings (see locations in inlet map). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

onshore today did not host major ice sheets during the Quaternary (Elias and Brigham-Grette, 2013; Glushkova, 2011; Kaufman et al., 2011), the of up to 900 km wide shelf regions have been suggested to have hosted a large ice sheet before the LGM (Dove et al., 2014; Kim et al., 2021; Lehmann et al., 2022; Niessen et al., 2013). To assess the significance of this so-called East Siberian Ice Sheet, we first discuss the available observations of its products from the Beringian Margin. Afterwards, we compare those products with those of the better-known ice sheets of the northern hemisphere, using examples from East Greenland and Norway.

4.1. Glacial deposits at the Beringian Margin

Glacially reworked sediments and broad glacially scoured troughs are typical observations that provide information about the extent of glacial erosion from formerly glaciated shelf regions (e.g., Dowdeswell et al., 2002; Dowdeswell et al., 2016; Laberg et al., 2012; Nielsen et al., 2005; Vorren et al., 1989). These sediments show a chaotic to transparent reflection pattern in a stratigraphic position above an erosive unconformity in acoustic data (Sættem et al., 1992). Along the Beringian Margin glacially reworked sediments were recovered in piston cores on the Northwind Ridge (Dipre et al., 2018; Polyak et al., 2007) and on the slope of the Arlis Plateau (Joe et al., 2020). Therefore, we interpret the upper chaotic sequences and prograding sequences along the Beringian Margin to be of glacial origin. Such sediments are imaged in seismic and sediment echosounder data covering not only the East Siberian Shelf (Fig. 2b, c, d, e), but also wide areas of the outer Chukchi Shelf (Dove et al., 2014; Kim et al., 2021; Lehmann et al., 2022). Reworked glacial sediments are not imaged in seismic data at ~147°E (Fig. 2a) and further west (Nikishin et al., 2017; Weigelt et al., 2014). This is supported by geological investigations which suggests that the Laptev Sea and western East Siberian continental shelf and margin (Fig. 2a) remained free of large ice sheets throughout the Cenozoic northern hemisphere glaciations (Batchelor et al., 2019; Kleiber and Niessen, 1999; Romanovskii and Hubberten, 2001; Svendsen et al., 2004). Based on the location of the glacially eroded DeLong trough at ~165°E (Fig. 6) (O'Regan et al., 2017) and glacial deposits on the New Siberian Islands (Nikolskiy et al., 2017), we assume that pre-LGM ice sheets developed northeast of the New Siberian Islands. The absence of extensive glacial deposits on profile 2014–14 (Fig. 2a) limits the maximum ice sheets extension along the Beringian Margin to the region east of this profile and west of the DeLong trough. This enables us to extend Niessen et al. (2013) estimate of the ice sheet limit slightly by ~70 km further to the Laptev Sea (Fig. 6).

Further verification of the estimated extent of the ice sheet is difficult at present, for various reasons. Firstly, widespread and long-lived subaerial erosion of much of the shelf region (blue stipple in Fig. 6) during the LGM, which was accompanied by eustatic sea-level fall of 130 m (Miller et al., 2020). This erosion, along with the marine transgression(s) and post transgressive sediments, has likely removed much of the evidence of pre-LGM glaciations (Hill et al., 2007). Secondly, the existing geophysical database of the Beringian Shelf is sparse and focused on deeper sedimentary and tectonic structures, so that shallow reflections are not well imaged in seismic data. Furthermore, the remaining interpretable features, like erosional surfaces, moraines, and drainage channels that were probably incised by meltwater, are either undated or dated to the LGM (Hill and Driscoll, 2008, 2010; Jakobsson et al., 2017; Lehmann et al., 2022). Thirdly, iceberg scouring during the LGM has extensively eroded the margins of Beringia to present-day water depths of ~350 m (Fig. 6, white hatched area), eliminating seafloor evidence for previous glaciations (Dove et al., 2014; Hill et al., 2007; Jakobsson et al., 2014; Polyak et al., 2007).

The thicknesses of glacial deposits vary along the continental slope

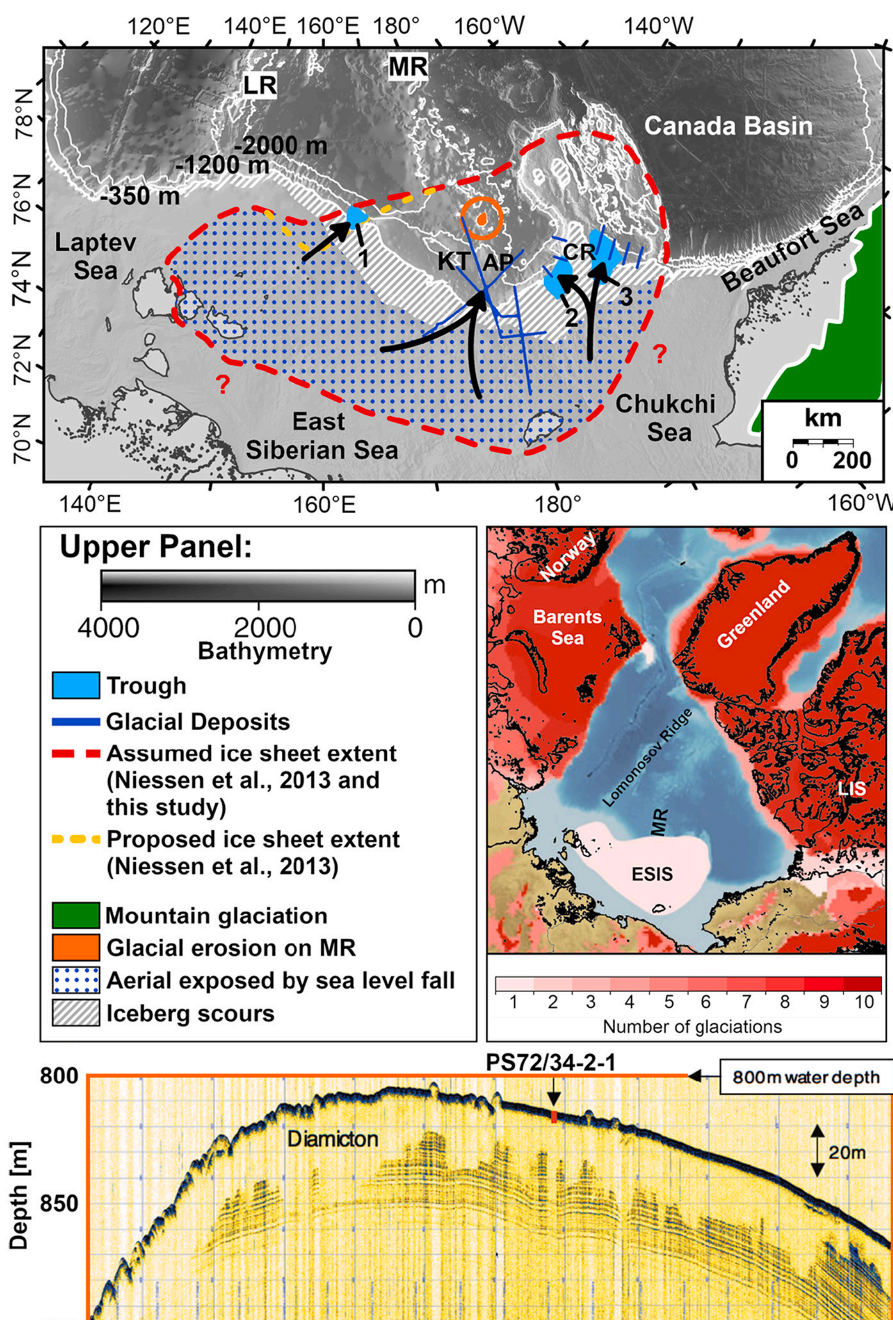

Fig. 6. Upper panel: suggested maximum ice sheet extent on the Beringian Margin (Niessen et al., 2013). Bathymetric map from Jakobsson et al. (2020), 1) DeLong Trough, 2) Western Bathymetric Trough, 3) Broad Bathymetric Trough. Central right panel: maximum ice sheet extensions and number of regionally glaciations in the Northern Hemisphere regardless of time (modified from Batchelor et al., 2019), lower panel: sub-bottom profiler section showing glacial eosion and diamiton on the southern Mendeleev Ridge (modified from Stein et al., 2010). Abbreviations: ESIS – East Siberian Ice Sheet, LIS – Laurentide Ice Sheet, LR – Lomonosov Ridge, MR – Mendeleev Ridge.

between the DeLong Trough at 165°E in the East Siberian Sea and the Northwind Ridge at 161°W (Table 1). This variation can be interpreted in terms of variable ice flow velocities along the shelf edge causing fan and inter-fan areas (Dowdeswell et al., 2002). The limited available acoustic data of the trough mouth fan at the head of the DeLong trough suggest a glacial sediment thickness of at least 65 m (O'Regan et al., 2017).The thickest deposits occur on the eastern Kucherov Terrace at ~178° E as well as east and west of the Chukchi Rise between 170°W and 172°W and between 165°W and 163°W (Table 1) at the head of the suggested Western Bathymetric Trough and Broad Bathymetric Trough (Fig. 6; upper panel) (Dove et al., 2014; Kim et al., 2021). As ice flow patterns are controlled by subglacial topography (Siegert and Dowdeswell, 1996; Winsborrow et al., 2010), it seems likely that the Chukchi Rise affected the routing of the ice streams that would have scoured these glacial troughs.

Sediments transported by ice streams are present in basins in the Broad Bathymetric Trough at the eastern flank of the Chukchi Rise (Fig. 4a, b) and as a sedimentary wedge in the western Northwind Basin (Fig. 4a). This wedge developed at the foot of the slope because the slope gradients of ~11.5° and ~ 8° were too steep to accumulate progradational strata between ~165°W and ~163°W (Fig. 4 a, b) (Ó Cofaigh et al., 2003). This is comparable with an immature high gradient trough mouth fan with sigmoid slope with gradients >4° (Dahlgren et al., 2005; Rydningen et al., 2015). The sedimentary wedge is characterized by mainly chaotic reflections and subdivided by two continuous reflections into three main units, of which the lowermost unit may possibly be divisible by two further semi-continuous reflections (Fig. 4a, zoom: yellow, green and blue areas). The continuous reflections are indications for the presence of hemipelagic sediments accumulated during interglacials (Ó Cofaigh et al., 2003) and so indicate a minimum of three and as many as five major ice streams advances through the Broad Bathymetric Trough. At least four glacial advances are assumed by seismostratigraphic studies of deposits at the head of the Western Bathymetric Trough (Kim et al., 2021). Diamictons on the western slope of the Kucherov Terrace also suggest at least five major glacial advances (Niessen et al., 2013). The suggested number of glacial advances supports a multi-cyclic glaciation history of the northern Beringian Margin (Dove et al., 2014; Kim et al., 2021; Lehmann et al., 2022; Niessen et al., 2013).

The thickest glacial deposits occur between the shelf break and seafloor elevations formed by preglacial deposits on the central profiles 08 and 09C across the slope to the Northwind Basin (162°W – 163°W) (Fig. 4b, c). Both seafloor elevations acted as barriers to glacial transportation, explaining the contrasting thicknesses of glacial material up- and downslope of the elevations (Fig. 4b, c). Similar observations have been made along the East Greenland Margin, where glacial deposits are thicker upslope of a basement high (1000 m) and thinner downslope of it (400 m) (Berger and Jokat, 2008).

The small terraces with rough seafloor at ~650 m and ~450 m below sea level, basinwards of the East Siberian shelf break at 178°E and 180° (Fig. 2d, e), are interpreted to mark maximum grounding depths of ice masses (Niessen et al., 2013). The terraces are topped by small retreat moraines, similar to those previously observed along the Beringian Margin (Dove et al., 2014; Jakobsson et al., 2016; Jakobsson et al., 2008; Kim et al., 2021; Niessen et al., 2013). These moraines indicate upslope retreat of the ice sheet. Earlier ice advances eroded both the Kucherov Terrace and a more northerly located part of the Mendeleev Ridge to water depths of ~1200 m and ~900 m, respectively (Niessen et al., 2013; Stein et al., 2010; Fig. 2, Fig. 6 lower panel).

Glacial erosion and sediments as imaged in Fig. 5 were interpreted along the Beaufort Margin towards the Chukchi Borderland as the result of a margin parallel advancing ice shelf sourced from the Laurentide Ice Sheet (Engels et al., 2008; Jakobsson et al., 2008; Polyak et al., 2007). Based on these interpretations and the absence of thick glacial deposits on the slope (Fig. 5), it is possible that an ice sheet on the Beringian Margin extended only as far as the Northwind Ridge. However, glacial debris from a more extensive ice sheet on the Chukchi Shelf could have bypassed the slope by turbidity currents into the deep Canada Basin facilitated by slope gradients in places exceeding 10° east of 161°W (Engels et al., 2008; Ó Cofaigh et al., 2003; Piper and Normark, 2009). This process is indicated by the abundance numerous canyons at the slope of the Beaufort Margin (Engels et al., 2008). In addition, along the Beaufort Margin at the base of the slope and in the adjacent Canada Basin (Fig. 5c) the products of large mass wasting events are imaged (Dinter et al., 1990; Grantz et al., 1979). They affected >200 m of Upper Quaternary sedimentary cover and may have displaced glacially deposited material downslope (Dinter et al., 1990; Grantz et al., 1979). However, transparent sedimentary unit and erosion of preglacial sediments might also be the result of strong currents (Corlett and Pickart, 2017; Darby et al., 2009). Our database is not sufficient to investigate

Table 1
Glacial sediments sequences found along the Beringian, Norwegian and East Greenland continental margins. The absence of propagation and slope angle measurements for profile WKT are related to the absence of a scale bar in the original figure. TMF: trough mouth fan.

Region	Profile	Basinward propagation [km]	Thickness glacial sediment [m]	Slope angle [°]	References
East Siberian Margin (147°E – 175°W)	AR2014–14	–	–	0.8	Fig. 2a
	DeLong Trough	–	>65	1.2	(O'Regan et al., 2017)
	WKT	Not determinable	90	Not determinable	Fig. 2b
	CKT	10	140	0.6	Fig. 2c
	20080040	13	325	0.7 upper part, 4.4 lower part	Fig. 2d
	WI	6	200	1.5	Fig. 2e
Western Chukchi Rise (175° W – 168° W)	01D	6	450	1.7	Fig. 3a
	01E	10	380	2.8	Fig. 3b
	02	3	140	3	Fig. 3c
Northwind Basin (165° W – 161° W)	07B	–	360	11.5	Fig. 4a
	08	–	250	8.1	Fig. 4b
	09C	2	340	1.5 upper part, 0.4 lower part	Fig. 4c
	10A	1	255	1.2	Fig. 4d
Beaufort Margin (161° W – 149° W)	783	Slope not displayed	–	Slope not displayed	Fig. 5a
	773	–	–	7.1	Fig. 5b
	753	–	–	7	Fig. 5c
Norwegian Margin	Lofoten Margin	–	–	>10	(Taylor et al., 2000)
	Bear Island TMF	120	3500	0.8	(Laberg and Vorren, 1996)
Greenland Margin	Scoresby Sound TMF	45	2000	2.1	(Vanneste et al., 1995)

these possibilities for the Beaufort Sea in detail.

4.2. Comparisons to the Greenland and Norwegian continental shelves

Geophysical and sediment core data clearly show that the northern margin of Beringia was glaciated at some time during the Quaternary (Dove et al., 2014; Jakobsson et al., 2014; Kim et al., 2021; Niessen et al., 2013; O'Regan et al., 2017; Polyak et al., 2007). However, the morphology shaped by glaciation in this region have yet to be compared to that of the better known glacially overprinted shelves from the East Greenland and Norwegian continental margins.

The ice sheets that affected the Norwegian and Greenland continental margins nucleated on the onshore mountain ranges with present-day elevations of up to 3700 m in Greenland and 2500 m in Norway. The mountain ranges of northern Alaska and East Siberia are similarly high, reaching 2750 m and 3000 m, respectively. However, geological and geomorphological studies onshore of East Siberia and Alaska excluded an extensive ice sheet in these regions during the Quaternary (Barr and Clark, 2012; Elias and Brigham-Grette, 2013; Glushkova, 2011; Kaufman et al., 2011). This is based partly on sedimentary deposits in Lake El'gygytygn in East Siberia, which have been continuous since 2.8 Myr (Melles et al., 2012), and partly on moraines and glacial sediments, which show that the maximum extent of the glaciers was confined to the mountain ranges of East Siberia and Alaska (Barr and Clark, 2012; Glushkova, 2011; Kaufman et al., 2011; Fig. 6). All these studies show that an onshore source area is missing in Beringia to provide massive ice volume for the development of large-scale ice streams to the northern shelf areas, and in turn glacially eroded large-scale cross-shelf troughs.

As the onshore geology reports its absence, the today's outer shelf areas and continental margins of Beringia are left as a host for ice sheets. The northern Beringian Shelf is up to 900 km wide which exceeds the maximum 300 km and 250 km widths of the continental shelves of East Greenland and Norway (excluding the epicontinental Barents Sea), respectively (Arndt et al., 2015; Nielsen et al., 2005). Water depths across the Beringian Shelf range from <50 m on the inner shelf to present-day shelf breaks in water depths of 100–200 m in the Beaufort Sea to ~300–750 m along the rest of the Beringian Margin. The shelf break is deeper than its counterparts off East Greenland (142 m - 500 m) and Norway (50 m to 350 m south of 64°N, up to 400 m northwards) (Nielsen et al., 2005; Rise et al., 2005). Along the Norwegian and East Greenland margins, a number of deep glacial troughs are observed to cross the continental shelves with water depths as deep as 1000 m separated by shallow banks with water depths <100 m (Batchelor and Dowdeswell, 2014; Nielsen et al., 2005; Vorren et al., 1989). Some of these troughs are in part over-deepened on the inner shelf compared to the trough mouth (Batchelor and Dowdeswell, 2014; Nielsen et al., 2005). In contrast, only three troughs have been discovered along the northern Beringian Margin (Dove et al., 2014; Kim et al., 2021; O'Regan et al., 2017). A maximum depth of 140 m is reported for the DeLong Trough northeast of the New Siberian Islands (O'Regan et al., 2017). The dimensions of the two glacial troughs on the flanks of the Chukchi Rise are not fully mapped and not precisely known, but are likely in a depth range of tens of meters. The major troughs of the East Greenland and Norwegian shelves are often associated with fjord systems at the coasts, and straits between islands of the Canadian Archipelago (Batchelor and Dowdeswell, 2014). These associations are not observed along the shores of Beringia (Fig. 6). Trough depths are controlled by the intensity, duration and frequency of cross-shelf glaciations (Batchelor and Dowdeswell, 2014). Greenland and Norway have both experienced more than ten ice sheet advances during the Quaternary alone (central right panel Fig. 6; Batchelor et al., 2019 and references therein). Owing to the lack of sediment cores, it is unknown how many shelf glaciations occurred on the Beringian Shelf during the lifetime of the East Siberian Ice Sheet. Imaging of diamictons separated by laminated hemipelagic sediments in the Northwind Basin (Fig. 4a), at the flank of the Chukchi Rise (Kim et al., 2021) and in the vicinity of the Arlis Plateau (Niessen et al., 2013), indicate the occurrence of at least 3–5 major shelf glaciations. If this number is regionally applicable, it suggests that the less pronounced overdeepening of the Beringian troughs may be attributable to a relatively stable and/or short-lived ice sheet, or alternatively to an ice sheet with a relatively stable northern edge.

Tidewater glaciers and/or small ice caps calving into the adjacent ocean have existed since 44 Myrs in Greenland and and since ~15–14 Myrs the northern Barents Sea (Knies and Gaina, 2008; Tripati and Darby, 2018). This is assumed from ice rafted detritus pulses in sediment cores drilled in and south of the Fram Strait (Knies and Gaina, 2008; Tripati and Darby, 2018). However, the onset of continental-scale glaciation of Greenland is reported at around 3.5 Ma (Jansen et al., 2000) while the glacially-induced progradation of the East Greenland continental shelf already started at around 15 Ma (Berger and Jokat, 2008). Along the Norwegian Margin, ice sheets first reached the shelf break at 2.7 Ma (Jansen et al., 2000; Rise et al., 2005). According to the sedimentary record as observed in one sediment core retrieved in the Canada Basin, the oldest known glaciation of the Beringian Margin is associated with MIS 12 (478–424) (Dong et al., 2017). This considerably later than the onset of the Northern Hemisphere Glaciation.

If ice streams delivered large quantities of sediment to the continental margins, trough mouth fans formed (Batchelor and Dowdeswell, 2014; Dowdeswell et al., 2002; Ó Cofaigh et al., 2003; Vorren et al., 1998). The trough mouth fans of East Greenland and Norway locally prograded the shelves (Batchelor and Dowdeswell, 2014; Dahlgren et al., 2005; Vorren et al., 1998). This is partly evident from seawards-convex bathymetric contour segments (Batchelor and Dowdeswell, 2014). Examples of such fans can be observed off Scoresby Sound and Bear Island Trough, where the fan shows basinward prograding sequences of 45 km and 120 km, respectively. The sediments have accumulated to thicknesses of 2 km and 3.5 km, respectively (Laberg and Vorren, 1996; Vanneste et al., 1995; Vorren et al., 1998). Along the Beringian Margin, in contrast, we found such propagating sequences only reach a maximum of 10 km for a maximum sediment thickness of 450 m at the head of the suggested Western Bathymetric Trough (Table 1) (Kim et al., 2021). These observations strongly support the hypothesis of a shorter-lived or less dynamic ice sheet or ice sheet edge.

Undoubtedly, glacial prograding sequences between the Northwind Ridge at ~161° W and the DeLong Trough at ~165°E record the sediment cross-shelf transport of an ice sheet on this part of the Beringian Margin (Fig. 6). As discussed before, the absence of voluminous glacially transported sediments suggests that the East Siberian Ice Sheet(s) did not reach the shelf edge west of 165°E (Fig. 6; DeLong trough). However, further east it remains possible that an ice margin advanced at least to the western Beaufort Shelf. If this was the case, the ice sheet margin may have been slow-moving and, therefore, delivered relatively insignificant quantities of sediment to the slope. Those were not deposited but instead transported further into the basin by turbidity flows down the steep continental slope. This would be a comparable scenario to that for the continental margin west of the Lofoten Islands, whose formerly glaciated shelf is located close to a steep continental slope with numerous canyons (Taylor et al., 2000). Here, the Eurasian Ice Sheet repeatedly reached the shelf edge but transported only small amounts of sediment to the slope, which were directly transported further into the deep sea (Taylor et al., 2000). A recent study reported that a grounded, westward flowing ice shelf in western Alaska caused isostatic depression during MIS 5 (130–70 ka) (Farquharson et al., 2018). However, it could also have been partly caused by a northeastward out-phase advance of an ice sheet, which might have existed at the same time, from a more westerly Beringian Margin into the Beaufort Sea.

Our study reveals quite puzzling observations regarding the thickness variations of glacial deposits and the extent of ice sheets along the nearly 1800 km Beringian Margin. Clearly, a denser network of acoustic and sediments core data is needed to better understand the more local variations visible in the sparse geophysical data. This study could be helpful in identifying specific areas for more focused geoscience research.

5. Conclusion

From our compilation of already published and new seismic data along the Beringian continental margin we conclude that:

- The strongest impact of ice sheet(s) occurs along the continental margin of Beringia from the Northwind Ridge to the Kucherov Terrace, as indicated by the distribution and thickness of glacially deposited sediments. The adjacent Beaufort Margin and the western East Siberian continental margin were either not glaciated during glacial cycles or experienced less intense cyclicity. More data, especially along the East Siberian Margin, are necessary to more precisely constrain the ice sheet's geometry.
- The largest depocenters for glacial sediments are located upslope of the eastern Kucherov Terrace, in the western Northwind Basin, and at the flank of the western Chukchi Plateau. This distribution reflects the locations of fast flowing ice and ice streams.
- Erosion by grounded ice is only observed down to water depths of at maximum 1200 m on the western Kucherov Terrace.
- The influence of ice sheets on Beringia is comparable to that on other glaciated margins in terms of the variety of products. However, in contrast to the Norwegian and Greenland margins, glacially products like troughs and prograding sequences are generally less developed in our research area. This indicates the action of an ice sheet, that was less dynamic and/or shorter-lived than its Greenland and Eurasian counterparts.

A more detailed ice sheet reconstruction and grounding history on the northern rim of Beringia must await the availability of a better geoscientific database and sediment core data to provide age control on it.

Declaration of Competing Interest

None.

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