ORIGINAL RESEARCH PAPER

Glacial sediments on the outer Chukchi Shelf and Chukchi Borderland in seismic reflection data

Carsten Lehmann[1,3] · Wilfried Jokat[1,3] · Bernard Coakley[2]

Abstract

The up to 900 km broad shelves off East Siberia and northwest off Alaska, including the Chukchi Shelf and Borderland, are characterized by shallow water in the periphery of the Arctic Ocean, north of the Bering Strait. Seafloor investigations revealed the widespread presence of glacial bedforms, implying the former existence of grounded ice in this region. We discuss the erosion and deposition around and beneath ice sheets/shelves using a regional grid of 2D seismic reflection data, acquired in 2011 from R/V Marcus G. Langseth across the outer ~ 75 km of the Chukchi Shelf and the adjacent Chukchi Borderland. A high amplitude glacial base (GB) reflection extends over large parts of the shelf, separating glacial from preglacial strata. We define eleven seismic reflection characters, that we use to infer distinct depositional environments of glacial sediments. Thick well stratified sediments overlying the GB reflection in the south may have been impacted by fewer advance-retreat cycles than those near the northeastern and western shelf breaks. Here, the GB reflection pinches out at the seafloor next to reworked and eroded areas. Numerous meltwater channels, some up to several kilometers wide, together with grounding zone wedges and recessional moraines are hints for ice sheets in the Chukchi Region. These ice sheets built up a huge grounding zone wedge of 48 km × 75 km on the Chukchi Rise. More grounding zone wedges on the western sides of bathymetric highs of the Chukchi Borderland along with mega scale glacial lineations indicate later ice shelf advances from east during the late Quaternary. However, in the absence of deep sediment cores, the timing or origin of the ice grounding events cannot be fully reconstructed.

Keywords Arctic Ocean · Chukchi Borderland · Seismic reflection · Continental Shelf · Glacial sediments

Introduction

Ice sheets and their attached ice shelves play an important role in Earth's climate system (IPCC 2018). The extent and geometry of ancient ice sheets and shelves and their evolution provide important constraints for numerical climate and glacio-isostatic models of the past, present and the future (Stokes et al. 2005; Stokes and Tarasov 2010; Brigham-Grette 2013). Determining the distribution of ice sheets on the continental shelves surrounding the Arctic Ocean is partly made difficult by sea ice cover, which hinders systematic geophysical investigations. This is especially true for the northern Chukchi Sea, a region of rapid ongoing changes in sea ice distribution over an up to 900 km broad, shallow continental shelf. This shelf and the adjacent Chukchi Borderland are of particular interest for regional glaciation studies because they appear to have been covered by an ice sheet-shelf system prior to the Last Glacial Maximum (LGM) (Brigham-Grette 2013; Niessen et al. 2013; Dove et al. 2014).

Previous multibeam bathymetric seafloor mapping has revealed the widespread impact of icebergs/sheets reaching to water depths of 1200 m along the Arctic Ocean's continental margins and across submarine ridges (e.g., Kristoffersen et al. 2004; Gebhardt et al. 2011; Niessen et al. 2013; Dove et al. 2014; Jakobsson 2016). Together with sub-bottom profiler data, they reveal preserved glacial landforms on the seafloor, including Mega-Scale Glacial Lineations

✉ Carsten Lehmann
   clehmann@awi.de

1   Alfred-Wegener-Institute, Helmholtz Centre for Polar
    and Marine Research (AWI), Am Alten Hafen 26,
    27568 Bremerhaven, Germany

2   Geophysical Institute, University of Alaska Fairbanks, 2156
    Koyukuk Drive, Fairbanks, AK 99775, USA

3   Geoscience Department, University of Bremen, Klagenfurter
    Str. 4, 28359 Bremen, Germany

(MSGL), drumlins, ice-marginal Grounding Zone Wedges (GZW), and moraines. All of these are diagnostic features of paleo-ice stream processes (Stokes and Clark 1999; Ottesen et al. 2005; Ottesen and Dowdeswell 2006). Multibeam and sub-bottom profile data, however, have no or limited depth penetration and image only the surface and the very shallow sub-surface of these regions (Dowdeswell et al. 2007; Batchelor et al. 2013b; Dove et al. 2014), which represent for the most part the last ice mass grounding event. Multichannel seismic reflection data can reveal the structure and extent of deeper horizons, and can be used to constrain the geometry and chronology of even older ice sheets/shelves (Dowdeswell et al. 2007).

This paper describes and interprets the geomorphic structures and seismic character of the sediments left behind by ice sheets and ice shelves at the northern part of the Chukchi Shelf and the adjacent Chukchi Borderland in water shallower than 750 m. For this, we use reprocessed 2D seismic reflection data supported by sub-bottom profiler (SBP) data to better resolve the shallow structures.

Study area and previous work

The Chukchi Shelf is an up to ~ 900 km wide continental shelf in the Arctic Ocean, located north of Chukchi Peninsula in Siberia and northwest of Alaska (Fig. 1). From the Bering Strait connecting the Chukchi and Bering seas, the seafloor continuously deepens from less than 50 m to 450–750 m at the northern Chukchi shelf break. This shallow margin is prolonged northwards by the Chukchi Borderland, which comprises the Northwind Ridge, Chukchi Rise, and Chukchi Plateau (Fig. 1). These plateaus rise as much as 3400 m above the deep abyssal plains of the Canada Basin, reaching a minimum water depth of approximately 300 m (Hall et al. 1990). The Chukchi Borderland is considered to consist of high standing continental blocks (Hall et al. 1990; Brumley et al. 2015).

Numerous studies have focused on the impact of ice sheets and ice shelves on the Chukchi margin (e.g., Hunkins et al. 1962; Polyak et al. 2007; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021). Early depth recorder data
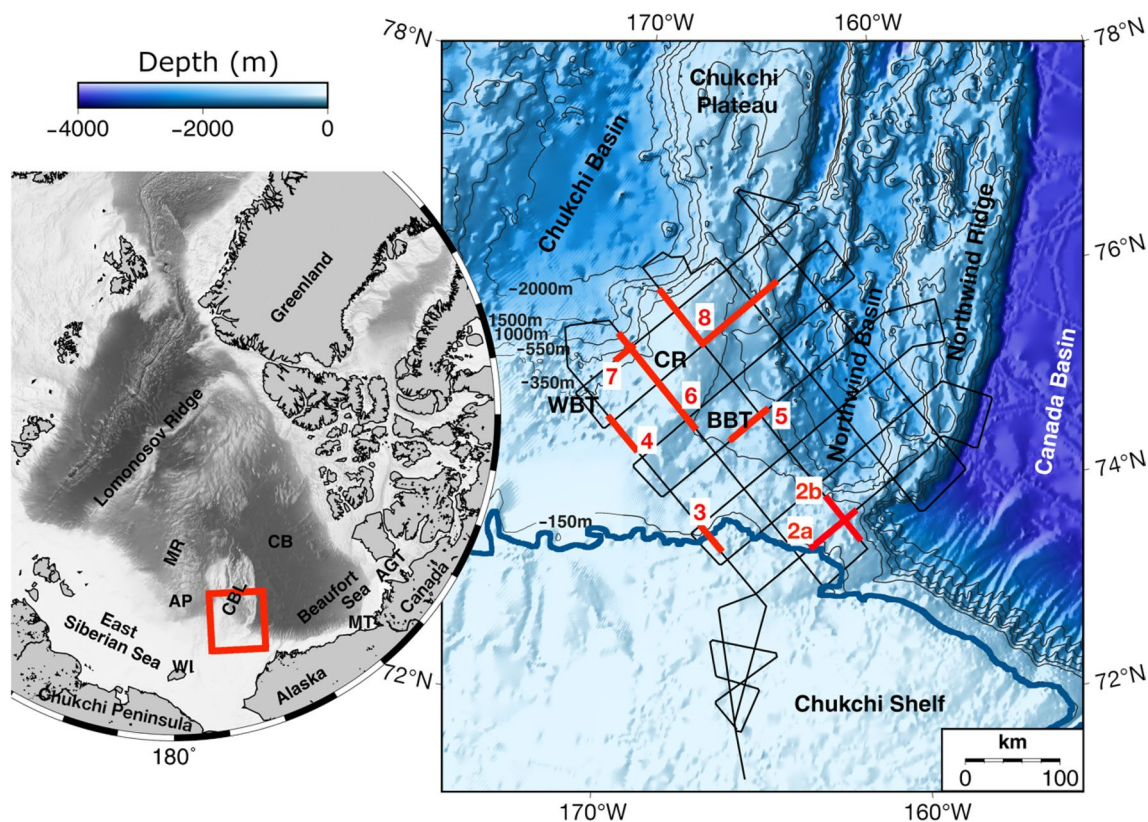

Fig. 1 Study area: Bathymetric map IBCAO v3.0 (Jakobsson et al. 2012) showing the locations of seismic reflection profiles. Locations for Figs. 2, 3, 4, 5, 6, 7, and 8 shown in red. Blue thick line indicates 130 m isobath which is likely the shoreline during the LGM sea-level lowstands (Clark et al. 2009). Massive iceberg scouring occurs between the − 150 and − 350 m contour lines (Dove et al. 2014). The main shelf break depth along the Chukchi Borderland is represented by the − 550 m contour line. *AGT* Amundsen Gulf Trough, *AP* Arlis Plateau, *BBT* Broad Bathymetric Trough, *CB* Canada Basin, *CBL* Chukchi Borderland, *CR* Chukchi Rise, *MR* Mendeleev Ridge, *MT* Mackenzie Trough, *WBT* Western Bathymetric Trough, *WI* Wrangel Island

revealed a very rough seafloor at depths of less than 350 m on the Chukchi Plateau interpreted to be incised by icebergs (Hunkins et al. 1962). Swath bathymetric data from the Chukchi margin show a widespread impact of not only icebergs but also grounded ice sheets/shelves such as glaciogenic bedforms like MSGL and morainic ridges (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021). These bedforms suggest a complex glacial history with origins from an ice shelf emanated from the northwestern margin of the Laurentide Ice Sheet and/or a likely regional ice sheet on the Chukchi Shelf (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021). Multiple indications for ice stream activity were found in glacial eroded bathymetric troughs, namely the Broad Bathymetric Trough (BBT) and the Western Bathymetric Trough (WBT) on the eastern and western flanks of the Chukchi Rise, respectively (Dove et al. 2014; Kim et al. 2021). In deeper water, prograding glacial wedges were identified at the western shelf edges of the Chukchi Rise (Hegewald and Jokat 2013; Ilhan and Coakley 2018; Kim et al. 2021). Indications for a wider glacial history in this region are observed on the East Siberian margin and on the Arlis Plateau (Fig. 1) (Niessen et al. 2013; Jakobsson et al. 2016; Joe et al. 2020) and along the Beaufort-Alaska margin to the east (Engels et al. 2008). It has been suggested that these ice sheets may have been part of an extensive glacial complex associated with a kilometer-thick ice shelf that completely covered the central Arctic Ocean at one point in time (Hughes et al. 1977; Jakobsson et al. 2016). In summary, the current, sparse knowledge on the glacial history of the Chukchi margin provides ample evidence for ice sheet/shelf impact but is not sufficient to understand the extent, timing and interaction(s) of glaciations in this of region.

Data and methods

A regional grid of 5300 km of 2D multi-channel seismic (MCS) profiles were acquired by R/V Marcus G. Langseth (Fig. 1) across the Chukchi Shelf and Chukchi Borderland in 2011 to investigate the tectonic evolution and seismic stratigraphy (Coakley 2011). Additionally, sub-bottom profiler and swath bathymetric data were recorded throughout the entire cruise.

As seismic source, a tuned airgun array of ten Bolt guns with a total volume of 1830 cubic inches (~ 30 l) was used. Its frequency spectrum ranges between 5 and 125 Hz. A 5850 m-long Sentinel™ streamer with 468 hydrophones and 12.5 m hydrophone spacing was used to image the subsurface. Source and streamer were towed at 6 m and 9 m depth, respectively. The shot spacing on most profiles was distance-controlled to 37.5 m. Returning signals were recorded for 10 s at a sampling rate of 2 ms. Satellite differential GPS losses in parts of the survey grid made a distance defined shot interval impossible to achieve on some profiles. On these profiles, the seismic energy was released time-controlled every 12.8 s, which resulted in a shot spacing of approximately 37.5 m.

The MCS data were first processed with 25 m bins by ION Geophysical and interpreted for studying the tectonic evolution of the Chukchi Borderland by Ilhan and Coakley (2018). We reprocessed the seismic profiles to resolve small-scale structures in the shallow parts of the sedimentary column. For the reprocessing, MCS data were common depth point (CDP) sorted into 6.25 m bins resulting in a maximum fold of 78. Seismic data processing included attenuation of random, linear and coherent noise, in particular the seafloor multiple. For noise reduction, we applied bandpass filtering, velocity analysis, noise attenuation (high amplitude noise bursts, etc.), F-K dip multiple filtering (one coherence filter to weaken the multiple and a F-K filter on overcorrected CDP gathers), spherical spreading corrections, stacking and, finally, time migration and a mean filter. A distance of over 200 m between source and first channel combined with a binning of only 6.25 m results in negative interference between the direct wave and the seafloor reflection over shallow areas (< 100 m water depth). Consequently, the seafloor reflection is weak or completely suppressed in the stack, and so we rely on sub-bottom profiler data for our interpretation of shallow structures in these areas. To estimate the shallow sediment thicknesses in meters, we applied a mean velocity of 1.7 km/s for the glacial sediments, based on a model by Hegewald (2012). Water depths were calculated with a mean velocity of 1.5 km/s. Using these velocities, and a peak frequency of 30 Hz for the sediments, the vertical resolution of our seismic data is about 12.5 m at the seafloor and 14 at the base of the shallow sediments we focus on. The seismic data are displayed in Two-Way-Traveltime (TWT) below the sea surface. The available sediment cores in the research area are too short to provide age constraints for the upper pre-glacial sedimentary units.

The sub-bottom profiler (SBP) data were acquired using a Knudsen Chirp 3260 echosounder with a source frequency range of 2–6 kHz. The SBP data penetrated the sediments between 10 and 100 m.

The multibeam bathymetric data were recorded during the cruise using a 12 kHz Kongsberg EM122. After editing and gridding the multibeam data with MB-System (Caress and Chayes 2008) and the Generic Mapping Tool (GMT) (Wessel and Smith 1998), the data were visualized using QGIS.
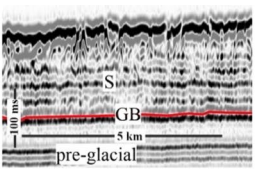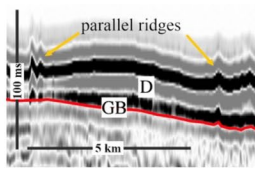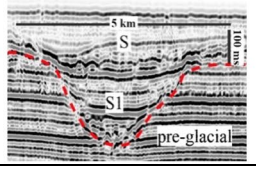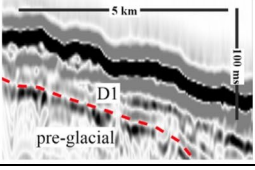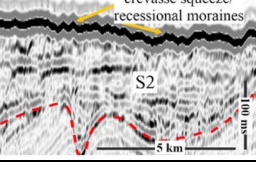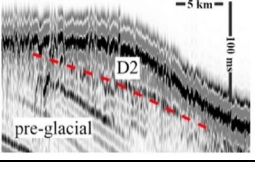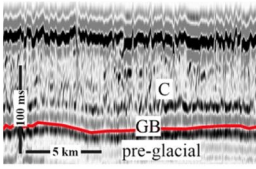
Results

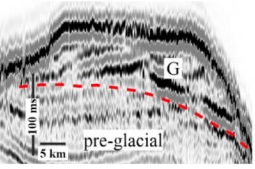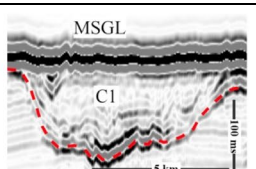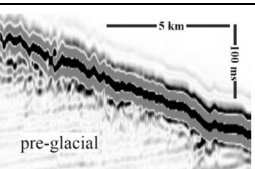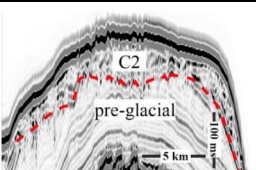As a first step for the subsequent interpretation, we identified and classified sedimentary structures potentially caused by ice sheets or ice streams, and mapped their areal extents

within the study area. The description of analyzed MCS data is split into two areas. The first is located south of ~75° N on the Chukchi Shelf and Northwind Ridge down to water depths of 750 m, the second one north of 75° N on the Chukchi Rise and surrounding shelf breaks. Eleven seismic characters relevant for this study are described in Table 1. Examples are shown in Figs. 2, 3, 4, 5, 6, 7, and 8. The distribution maps of these characters are shown in Figs. 9 and 10. The abbreviations for the characters are chosen after their main reflection pattern and their origin, respectively, similar to Batchelor et al. (2013a, 2013b). Based on the acoustic

reflection pattern, stratified characters are denoted with S, S1, and S2. Chaotic characters are separated into the three categories C, C1, and C2. Predominately (semi-)transparent seismic characters are titled D, D1, and D2. Morphological structures such as a sedimentary wedge on the Chukchi Rise and truncated layers topped by laminated sediments are labelled G and T, respectively. Acoustically well-layered strata below the defined characters are collectively termed 'pre-glacial'. A prominent high amplitude reflection is considered to separate pre-glacial strata from glacial influenced sediments. Here, we name it the glacial base reflection (GB,

Table 1 Classification of seismic characters identified from 2D seismic profiling of the Chukchi Shelf and Chukchi Rise

Seismic Abbreviation		Seismic Example	Character Description	Seismic Abbreviation		Seismic Example	Character Description
stratified	S		stratified, low to medium amplitude, topped by thin transparent layer	(semi-)transparent	D		No internal reflections, partly accumulated to asymmetric wedge
	S1		stratified, high to medium amplitude, infill channels		D1		stratified with lobate-shape geometry, occurs at shelf edges
	S2		Mixture of stratified and chaotic characters, fills channels		D2		No internal reflections, deposited close to truncated areas
chaotic	C		Chaotic, with medium to low amplitude		G		semi-transparent, dipping internal reflections, asymmetric geometry
	C1		Chaotic, medium amplitude, fills large incisions		T		truncated pre-glacial reflectors covered by laminated sediments
	C2		Chaotic character, wedge-like body on a bathymetric high				

Red line represents the glacial base reflection (GB). Where the high amplitude glacial base reflection is absent, the stippled red line indicates the correlated boundary between pre-glacial and glacial sediments. The characters abbreviations are chosen after the predominant seismic reflection pattern of the characters and their, morphology and stratigraphy (see text for more details)
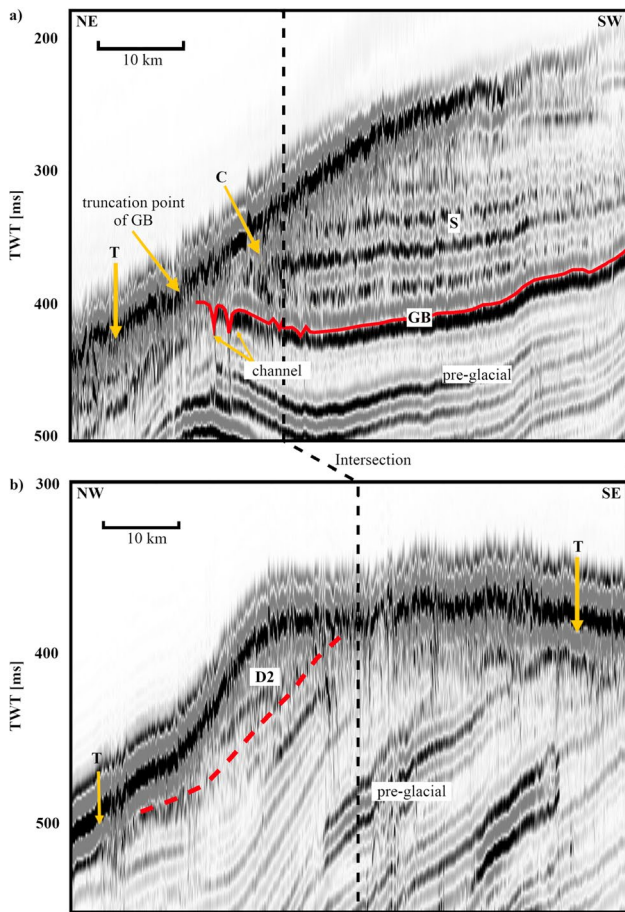
Fig. 2 Two seismic reflection profiles showing the truncated preglacial strata (Character T). Dashed vertical line indicates the intersection point of the two profiles. **A** Stratified sediments (Character S) and chaotic sediments (Character C) over the glacial base reflection (GB); the truncation point of GB is close to the seafloor. **B** Cross-profile of a wedge of sediments of character D2 between two areas with truncated pre-glacial strata (T). The stippled line indicates the base of the wedge. Location is shown in Fig. 1
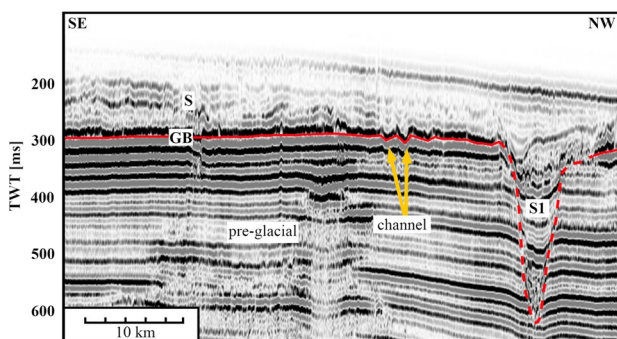

Fig. 3 Seismic reflection data of the Chukchi Shelf showing a large channel incised into pre-glacial strata and infilled with stratified sediments of character S1. Location is shown in Fig. 1. Red line: glacial base reflection (GB). Dashed red line: boundary between channel fill and pre-glacial sediments
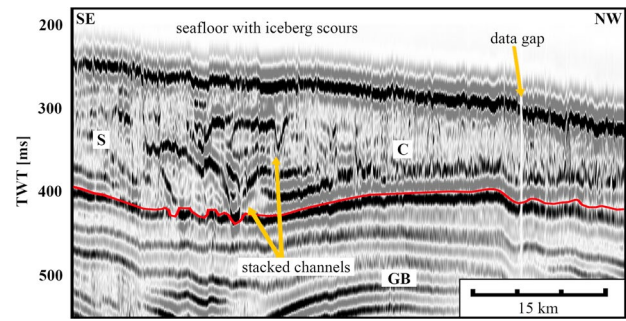

Fig. 4 Seismic reflection data showing vertically-stacked channels separating horizontal layers of chaotic and stratified sediments (Characters C and S). Location is shown in Fig. 1. Red line: glacial base reflection (GB)

see more details in the next sections). An age for the top of the pre-glacial sediments is not available because available sediment cores do not penetrate pre-glacial strata.

Chukchi Shelf and slope

A prominent smooth, continuous, high amplitude GB reflection is present in MCS data at 250–400 ms TWT south of 73° N to 1000 ms TWT on a profile east of the Chukchi Rise (Figs. 2a, 3, 4, 5, 9a). On all other profiles the GB reflection pinches out at the seafloor in water depths of 300–350 m (400–450 ms TWT; for example, at the "truncation point" labelled in Fig. 2a). This reflection marks the transition from deeper, well stratified deposits, marked by medium-to-high amplitude reflections, to shallower and apparently more irregular strata. In general, the GB reflection is covered by sediments of stratified character S, chaotic character C and transparent character D with varying thickness of up to ~210 m (250 ms TWT) (Fig. 9b–d). Their distribution is described in detail in the next paragraphs.

In the southern part of the study area, with water depths shallower than the truncation depth, the GB reflection is overlain by stratified sediments (Character S) (Fig. 9b). Large incisions observed at the base of these sediments are up to 6 km wide and cut up to ~210 m (250 ms TWT) deep into the pre-glacial sediments. These incisions are filled with stratified sediments of character S1 (Fig. 3).

Towards the outer shelf, the acoustically stratified character S changes to a chaotic character C. This transition appears over a short distance on a seismic dip profile towards the Northwind Ridge (Fig. 2a). Furthermore, the layer comprising of characters S and C thins towards the northeast and disappears where the GB reflection is cut at or close to the seafloor (Figs. 2a, 9c). Further downslope, pre-glacial deposits are truncated and covered by a thin, laminated drape (Fig. 2a, b; character T). Several areas of truncated pre-glacial sediments, indicated by character T (Fig. 9f), as
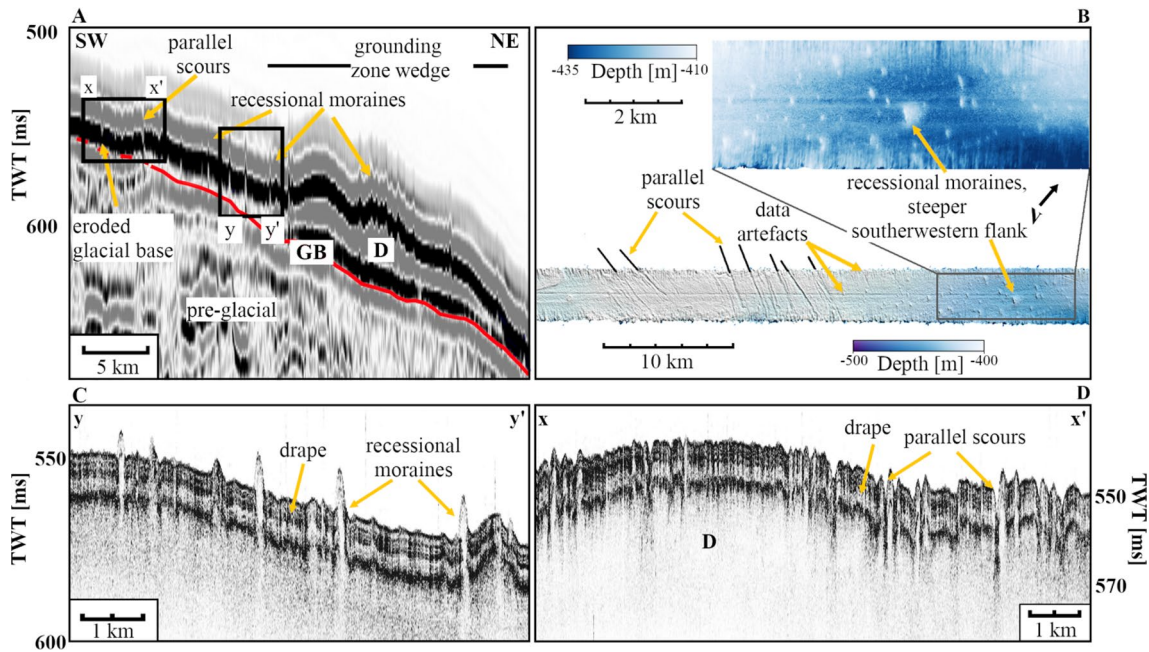
Fig. 5 Ridges, scours and GZW of and in transparent sediments (D) in the BBT. **A** Seismic reflection data showing accumulation of sediments with character D above glacial base (GB). **B** Multibeam bathymetric data showing the seafloor positions of the ridges and scours. **C** SBP data showing parallel ridges topping sediments with character D. **D** SBP data showing parallel scours in layer of sediment layers with character D. Location is shown in Fig. 1

Fig. 6 Seismic reflection data from the Chukchi Rise. Top: seismic profile of a line crossing the Chukchi Rise. Bottom: interpreted seismic profile showing distribution of the sediments with characters C1, D1 and G on top of partly eroded pre-glacial strata. Dashed red line indicates the boundary between glacial and pre-glacial sediments. Dashed black line represents maximum water depth ~ 350 m for random orientated iceberg scours (Dove et al. 2014). Location is shown in Fig. 1
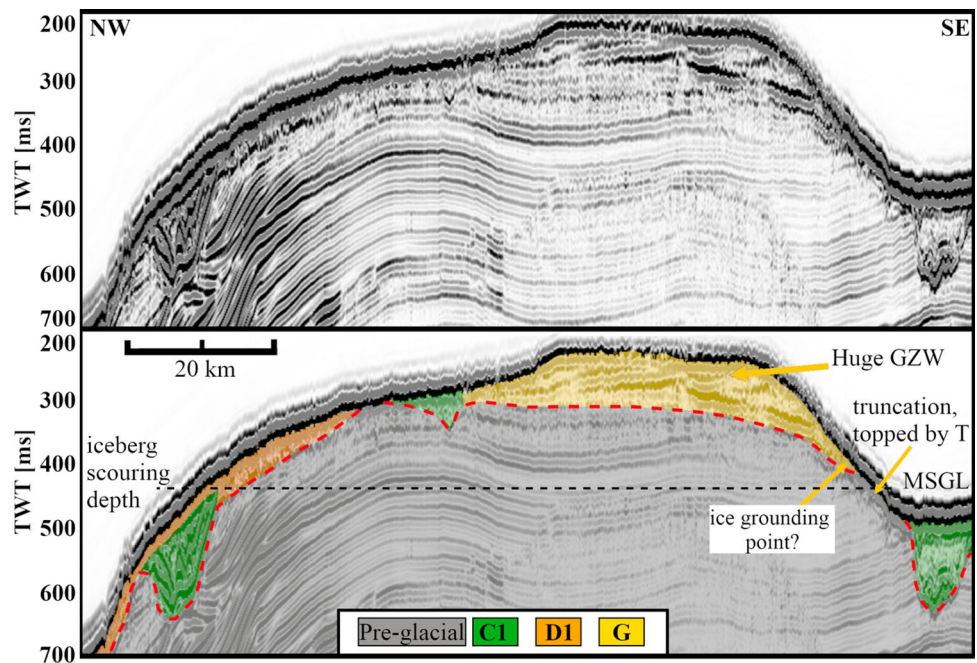
well as truncated stratified glacial sediments (Fig. 2a), are observed in the study region in present day water depths of 150–750 m.

To the west, the transition between stratified glacial sediments S and chaotic sediments C takes place after a 20 km wide series of vertically-stacked incisions (Fig. 4). The deepest buried channels eroded the pre-glacial strata, resulting in a sediment layer covering the GB that is up to ~ 42 m (50 ms TWT) thicker than that of the surrounding areas. Further, many smaller incisions are found in the study area,
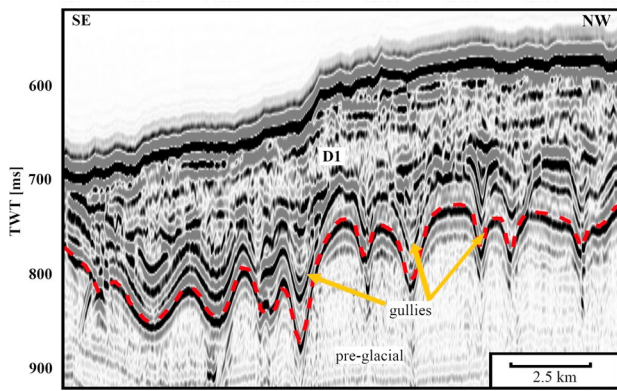
Fig. 7 Seismic reflection data showing several channels cutting into pre-glacial strata. Channels are filled with sediments of character D1. Dashed red line indicates the boundary between glacial and pre-glacial sediments. Location is shown in Fig. 1

cutting into packages of sediments with characters S and C (Fig. 2a). These channels are up to 1 km wide and ~ 50 m (60 ms TWT) deep (Figs. 2a, 3, 4).

Acoustically transparent sediments (D) (Table 1) occur as a drape over the GB reflection in a larger area between Chukchi Rise and Northwind Ridge at depths of 280–750 m (375 ms TWT and 1000 ms TWT) (Fig. 9d). The sediments reach a maximum thickness of ~ 25 m (30 ms TWT) in a

20 km-wide wedge-like accumulation (Fig. 5a). Several ridges with widths of 100–500 m are located on top of this wedge (Fig. 5a–c). SBP data reveal the ridges to have maximum heights of 21 m (~ 25 ms TWT). Multibeam data (Fig. 5b) show an assemblage of ridges with slightly steeper southwestern flanks, orientated parallel to each other, at the seafloor. More ridges are observed in water depths between 400 and 510 m (540 ms TWT and 680 ms TWT). The ridge crests trend 107° (ESE). In water depth of 335 m (550 ms TWT), character D and the top of the pre-glacial sediments are grooved by two sets of linear scours aligned approximately east–west (Fig. 5a, b, d). Sediments of character D are buried by a layer of laminated reflections of ~ 8 m (10 ms TWT) thickness (Fig. 5c, d).

Chukchi Rise

On the western side of the Chukchi Rise (Fig. 1, approx. 170° W), where a strong GB reflection is absent, a layer with lobate-shaped acoustically stratified character D1 (Table 1) overlies truncated, stratified reflections in a basinward prograding wedge-like form (Fig. 6). This package has a maximum thickness of ~ 100 m (120 ms TWT) (Fig. 9e). Below this layer, a cluster of incised channels is observed at the shelf break west of the Chukchi Rise (Fig. 7). Spaced
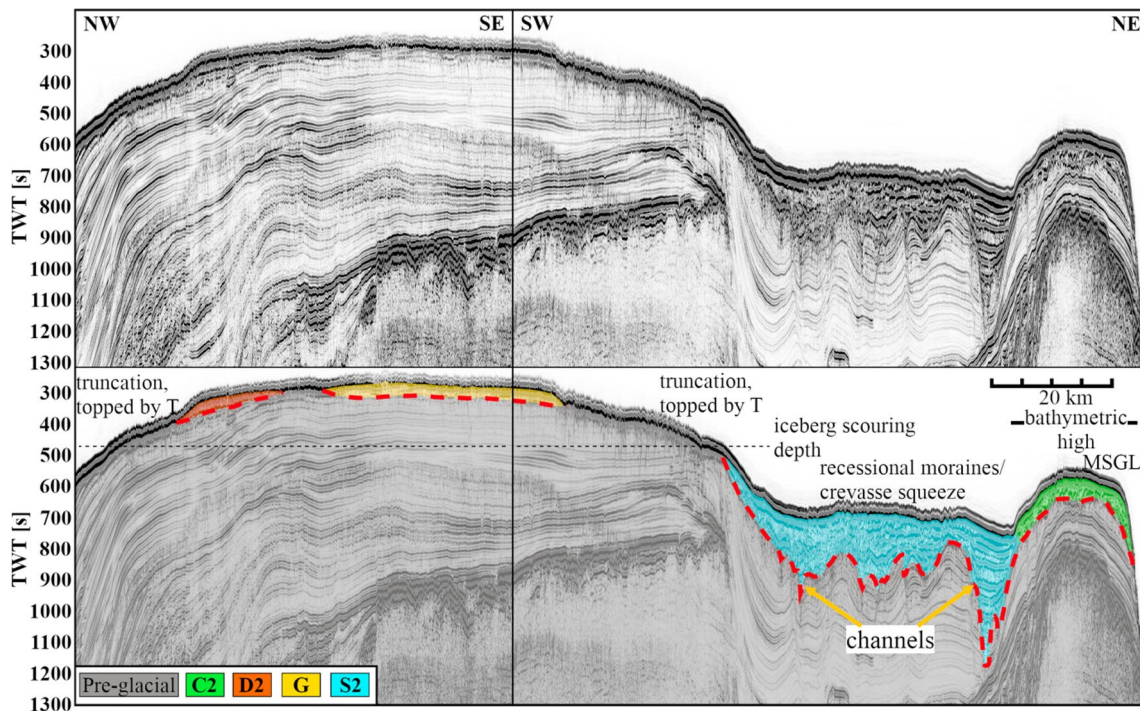
Fig. 8 Seismic reflection data from northwestern Chukchi Rise. Top: seismic profile, Bottom: interpreted profile, showing the distributions of the seismic characters C2, D2, G and S2 on pre-glacial strata. Dashed red line indicates the boundary between glacial and pre-gla-cial sediments. Dashed black line indicates the maximum depth of random orientated iceberg scours at ~ 350 m water depth (Dove et al. 2014). Location is shown in Fig. 1
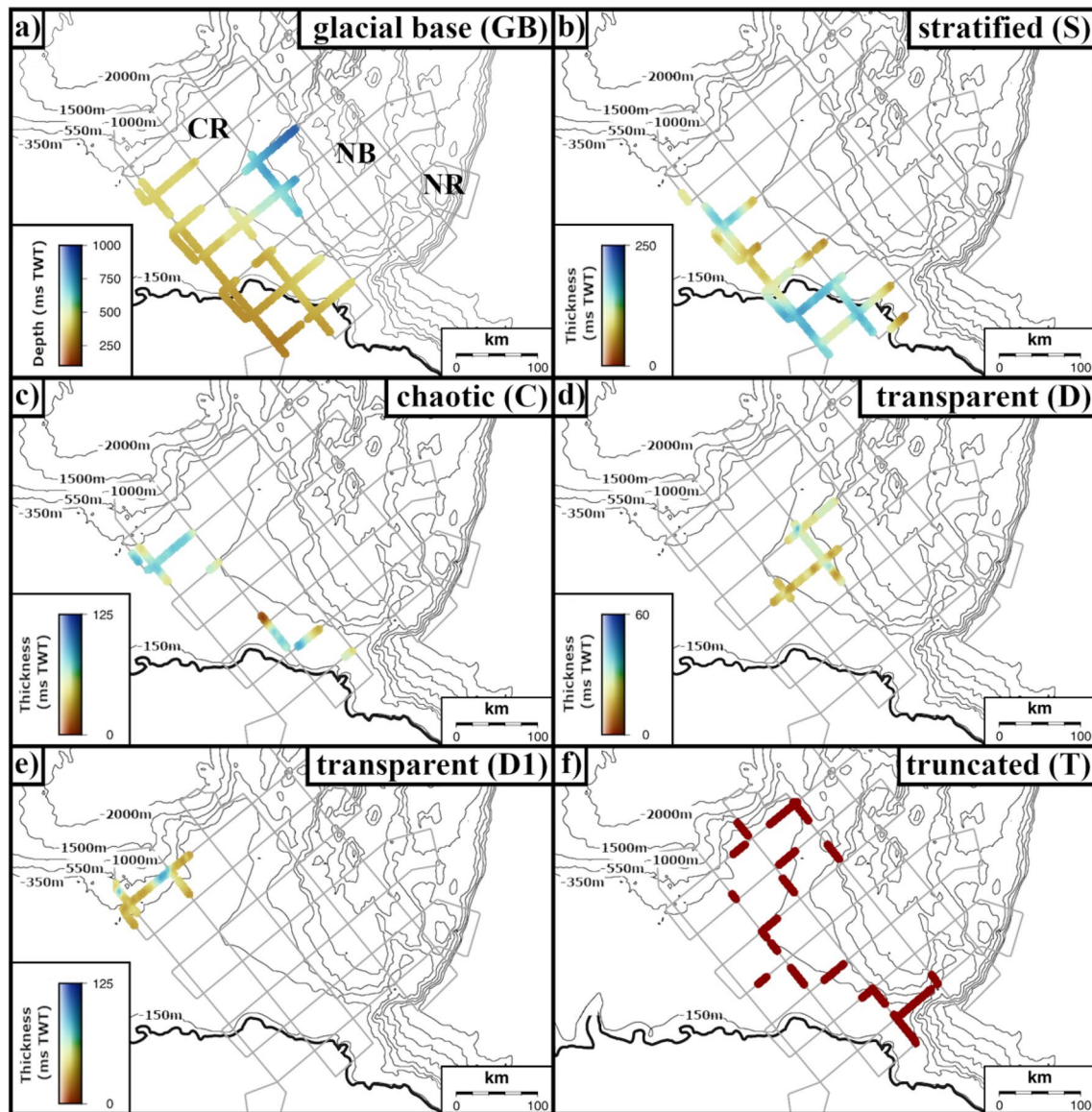
Fig. 9 Maps of the distribution and thickness of **a** the glacial base GB, **b** Character S, **c** Character C, **d** Character D, **e** Character D1, and **f** Character T. Light gray lines represent seismic profiles. Black line represents the 130 m contour line which is considered as shoreline during the last glacial maximum (Clark et al. 2009). *CR* Chukchi Rise, *NB* Northwind Basin, *NR* Northwind Ridge

1–3 km apart from each other, they reach widths of up to 1 km and depths of ~ 65 m (75 ms TWT).

Sediments with a transparent acoustic character (D2, Table 1) appear in a large patch on the western side of the Chukchi Rise (Fig. 8, #5 in Fig. 10b). This patch has an asymmetric shape with a steeper flank at the shelf break and a shallower distal flank. Its thickness reaches up to ~ 50 m (~ 60 ms TWT). On the crossline, this accumulation extends for 39 km NE and SW (#5 in Fig. 10b). Further to the east, a second accumulation of character D2 is observed at the transition between the Northwind Ridge and Northwind Basin (Fig. 2b, #2 in Fig. 10b). This accumulation displays a shallow southeastern side and a steeper northwestern flank closer to the basin, is around 15 km wide, and up to ~ 70 m (80 ms TWT) high. To the southeast and northwest, seismic data show areas with truncated underlying reflections covered by a drape (T) (Fig. 2b). Four smaller patches with a maximum height of ~ 25 m (30 ms TWT) occur north and east of Chukchi Rise and on the Northwind Ridge (Fig. 10b, #1–6).

On the Chukchi Rise, an up to ~ 145 m (170 ms TWT) thick semi-transparent sedimentary wedge with dipping internal reflections (Character G) overlies stratified, partly truncated pre-glacial sediments (Figs. 6, 8). The
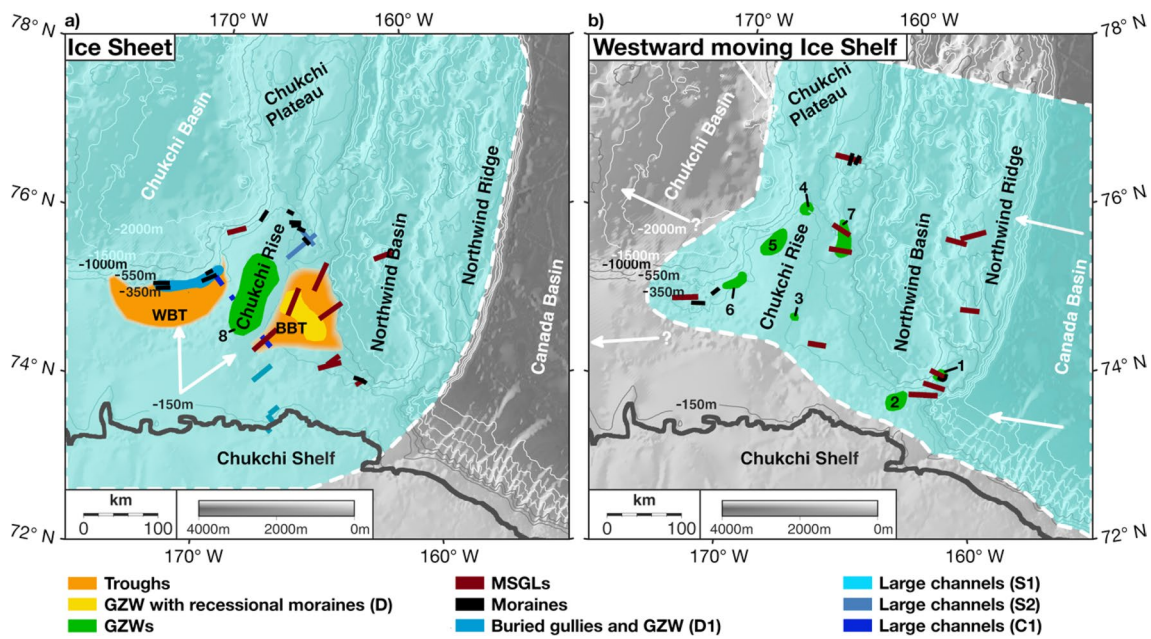
Fig. 10 Glacial features in the MGL1112 data (Dove et al. 2014, this study) consistent with: **a** an ice sheet on the Chukchi Shelf, **b** westward along slope advances of grounded ice shelves during succeed-ing glaciations. Numbers are GZWs (see text for deatails). Arrows indicate inferred ice movement direction. *BBT* Broad Bathymetric Trough, *WBT* Western Bathymetric Trough

area covered by this wedge is 48 km wide and 75 km long (Fig. 10a). Reflections within the wedge appear to dip east-ward and westward. The wedge has a shorter, steeper west-ern flank and a more gently dipping, longer eastern flank. Both flanks are marked by truncated horizontal stratified reflections covered with transparent sediments of character T (Figs. 6, 8).

East and west of the Chukchi Rise, seismic data show three incisions, two with a width of 8 km and depth of ~85 m (100 ms TWT), one with a width of ~5 km and a depth of ~42 m (50 ms TWT). All are filled with sedi-ments showing a chaotic character C1. The channels are incised into the underlying pre-glacial strata (Fig. 6).

Partly stratified to chaotic sediments (Character S2) are present north of Chukchi Rise in large incisions (Fig. 8). The overall width of this area is ~45 km. The incisions cut up to ~380 m (400 ms TWT) into the underlying strata. While the character in the deepest incision has a more stratified pattern, in all other channels the sediments are less stratified and partly chaotic (Fig. 8). The seafloor above the channels shows superimposed, low relief ridges (Fig. 8).

Acoustically chaotic sediments (Character C2) occur on top of elevated pre-glacial strata on a bathymetric high, northeast of the incisions filled with sediments of character S2 (Fig. 8). The maximum thickness of this layer is ~100 m (~120 ms TWT). It is lenticular, with a NE–SW extent of ~20 km and a NW–SE extent of ~15 km. Below it, the top pre-glacial strata show an irregular surface.

Interpretation and discussion

Previous studies of multibeam and SBP data in our research area have focused entirely on seafloor structures which were formed by glacial processes (Polyak et al. 2001, 2007; Jakobsson et al. 2005, 2008; Dove et al. 2014; Kim et al. 2021). Fortunately, the seismic data allow a clear distinc-tion between the glacial influenced and pre-glacial units in our research area. The up to 10 m deep gravity/piston cores provide vague information on the underlying glacial or non-glacial sediments (Polyak et al. 2007; Park et al. 2017). Therefore, we base our interpretation of glacially influenced sediments and landforms on comparisons to similar features imaged in other glaciated regions which have been better sampled (e.g., Sættem et al. 1992; Kehew et al. 2012; Dow-deswell et al. 2016).

Glacial landforms and bedforms

Glacial base reflection (GB)

We infer the GB reflection (Fig. 2a, 3, 4, 5; GB) to mark the base of glacial erosion. The higher reflection amplitude compared to over- and underlying reflections indicates a change of the physical properties similar to an unconformity described in the Barents Sea (Sættem et al. 1992; Solheim et al. 1996; Bellwald et al. 2019). Here, this unconformity divides glacially over-compacted pre-glacial sedimentary rocks from unlithified, rapidly deposited glacial sediments

(Sættem et al. 1992; Solheim et al. 1996; Bellwald et al. 2019). Its occurrence across the outer shelf (Fig. 9a) and the strong impedance contrast to well stratified pre-glacial sediments suggests that the GB unconformity was formed at the base of an erosive ice sheet.

We favor the interpretation that the GB unconformity and sediments overlying it (Figs. 2a, 3, 4) are products of several glacial advances and retreats as it is observed in the Barents Sea (e.g., Sættem et al. 1992; King 1993; Batchelor et al. 2013b). The GB overlies basins filled with glacially redeposited sediments on the outer shelf east of the Chukchi Rise (Hegewald and Jokat 2013; Ilhan and Coakley 2018). These filled basins indicate that a glacial advance preceded the formation of the GB. The truncation of the GB along the outer shelf, together with the underlying pre-glacial and overlying glacial sediments, indicates erosion by at least one later glacial event.

Stratified sediments

By analogy to the Barents Sea (Sættem et al. 1992; Solheim et al. 1996), the up to 210 m thick stratified sediments (Character S) overlying the GB reflection are interpreted to be an alternation of glacial and interglacial sediments (Figs. 2a, 3, 4). This interpretation is supported by analysis of shallow sediment cores on the Chukchi Shelf, which contain interglacial and glacial sediments (Polyak et al. 2007). The preserved stratification indicates that these areas were not strongly affected by subsequent glacial advances (Polyak et al. 2008).

Chaotic sediments

The chaotic (character C) sediments covering GB (Figs. 2, 4, 9c) were probably reworked after deposition by grounded ice of a subsequent glaciation. This is supported by the presence of reworked sediments in sediment cores from the ramp between the outer Chukchi Shelf and the Northwind Ridge (Polyak et al. 2007). Over this ramp to the Northwind Ridge (Fig. 2a), the abrupt transition between sediments with characters S and C and their truncation at the seafloor indicates extensive reworking of stratified sediments and subsequent erosion of both units by grounded ice (Fig. 4, 9c) (Dowdeswell et al. 2004; Cofaigh et al. 2005).

Truncation of pre-glacial sediments

The occurrence of character T sediments on top of pre-glacial strata (Fig. 9f) is the result of the erosion and deposition of sediments by grounded ice, followed by hemipelagic sedimentation. In our survey area, this hemipelagic drape is found below a water depth of ~350 m with varying thicknesses and postdates the most recent glacial grounding event(s) (Dove et al. 2014; Kim et al. 2021). In general, the erosion by grounded ice is present in water depths between 150 m (Fig. 2a) and 750 m on the outer Chukchi Shelf and Borderland (Fig. 9f) (Polyak et al. 2001, 2007; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021).

(Semi-)transparent sediments

A layer of acoustically transparent sediments (Character D) of up to 25 m thickness occurs east of the Chukchi Rise in water depths between 280 and 750 m (Fig. 9d). Due to its thickness and lack of internal reflections, we interpret this layer to consist of subglacial till. Till has been described as acoustically semi-transparent to transparent (Ó Cofaigh et al. 2005). Similar till layers occur in other formerly glaciated high-latitude regions (e.g., Ó Cofaigh et al. 2005; Batchelor et al. 2013a; Dowdeswell et al. 2016). Further, a wedge of transparent glacial till (Character D) within the BBT east of the Chukchi Rise is due to its shape interpreted as a GZW (Figs. 5a, 10a) (Batchelor and Dowdeswell 2015).

The set of ridges in the BBT (Fig. 5a, b, d), which are 100–500 m wide and up to ~20 m (25 ms TWT) high, is interpreted as hitherto unknown recessional moraines. Similar recessional moraines are found in bathymetric data in several areas in the Chukchi Region (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021) and on other former glaciated margins (e.g., Ottesen and Dowdeswell 2009; Winkelmann et al. 2010; Burton et al. 2016). These moraines are interpreted as the products of minor ice re-advances during a period of overall ice retreat (Ottesen and Dowdeswell 2006). The steeper upslope flank representing the ice proximal side suggests a southward retreat, towards the Chukchi Shelf (Winkelmann et al. 2010). This is supported by the orientations of nearby MSGL (Dove et al. 2014).

Furthermore, the sets of east–west directed parallel grooves in the BBT cut into sediments of character D at the seabed (Fig. 5a, b, d) are comparable to many MSGL in the Chukchi Region (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014; Kim et al. 2021). MSGL are formed by deformation of soft sediments at the base of fast flowing ice sheets/streams (Spagnolo et al. 2014). Usually, these landforms appear as linear to curvilinear sediment ridges, each several tens of kilometers long and a few meters deep, which align with the direction of past ice flow (Clark 1993; Spagnolo et al. 2014). Due to the limited data coverage, it is not possible to estimate the lengths of the grooves (Fig. 5b), leaving open the possibility of a formation by the deep keels of large icebergs, as has been suggested for the Lomonosov Ridge between ~85 and ~86° N (Kristoffersen et al. 2004; Dowdeswell et al. 2007).

Tunnel valleys

Large channels incising pre-glacial sediments and filled with various seismic characters (Character S1, S2, C1) (Figs. 3, 6, 8) can be interpreted in different ways. These channels are comparable in size and geometry to channels found incised by as much as 50 m into Cretaceous strata on the southern inner Chukchi Shelf in modern water depths of up to 60 m (Hill et al. 2007; Hill and Driscoll 2008). These channels have been interpreted as products of fluvial erosion by Alaskan rivers flowing across the shelf during sea level lowstands with periods of higher meltwater drainage during the late LGM (Hill et al. 2007; Hill and Driscoll 2008). However, the channels on the outer shelf are located at water depths of up to 360 m (Fig. 10a), which is below the level of regional lowstands during glacial times (Clark et al. 2009; Miller et al. 2020). The deep incision of these channels into pre-glacial sediments (Figs. 3, 6, 8) is more consistent with the action of a subglacial drainage system, like those reported for other glaciated regions (e.g., Kehew et al. 2012; Stewart et al. 2013; Graham et al. 2016). Therefore, we interpret these channels as subglacial tunnel valleys formed by catastrophic outbursts from subglacial meltwater lakes or steady-state subglacial meltwater drainage (Kehew et al. 2012; Huuse and Kristensen 2016). This interpretation is supported by the presence of overlying glacial landforms like MSGL (Fig. 6) and as ice marginal crevasse squeeze/recessional moraines interpreted from superimposed, low relief ridges (Fig. 8) (Dove et al. 2014). Multiple smaller tunnel valleys with widths of up to 1 km and depths of up to ~50 m (60 ms TWT) can be observed in areas covered by stratified sediments of character S and C in the southwest of the research region (Figs. 2a, 3, 4). The wide distribution of tunnel valleys suggests a widespread subglacial drainage system. The vertically-stacked configuration of tunnel valleys at the western transition to areas with sediments with a chaotic character C (Fig. 4) indicates that this system was intermittently active during several glacial periods (Walder and Fowler 1994; Kehew et al. 2012). The direction of meltwater flow cannot be determined from our widely spaced seismic profiles.

Gullies

The channels at the western shelf break (up 1 km and 65 m) filled with character D1 sediments (Figs. 7, 10) can be interpreted as buried gullies as they are comparable to gullies at other high latitude shelf breaks occupied by paleo-ice streams (Gales et al. 2013; Batchelor et al. 2014 and references therein). The sediments (Character D1) filling the gullies (Fig. 6) were previously interpreted as a GZW from the imaging of hummocky terrain in multibeam data and transparent glacial till in SBP data (Dove et al. 2014; Kim

et al. 2021). Their burial by glacial sediments indicates development together with the first ice sheet advance to the paleo-shelf break by the release of sediment-laden meltwater (Polyak et al. 2001; Cofaigh et al. 2003; Engels et al. 2008; Gales et al. 2013). Other gullies related to different glacial cycles are found in multibeam and SBP data along the western Chukchi Rise by Kim et al. (2021).

Grounding zone wedges

Grounding zone wedges (GZW) on the outer Chukchi Shelf are reported so far in multibeam and SBP data on the western flank of the Chukchi Rise (Dove et al. 2014; Kim et al. 2021). GZWs are the result of high sedimentation rates during long-lived still stands of the grounding zones of ice sheets, which produce wedge shaped bodies of seismically chaotic to transparent appearance (Ottesen and Dowdeswell 2009; Dowdeswell and Fugelli 2012; Batchelor and Dowdeswell 2015). Truncations within the GZW are caused by modifications of the sediments during fluctuations of the grounding zone position (Dowdeswell and Fugelli 2012). In this section, we discuss eight hitherto unknown GZWs found in our seismic data (Figs. 2b, 5, 6, 8, Numbers 1–8 in Fig. 10).

Six asymmetric GZWs (Fig. 10b; # 1–6) with a transparent character D2 topping pre-glacial strata (Figs. 2b, 8) occur on the west-facing flanks of eroded bathymetric highs like the Northwind Ridge (Fig. 10b). Such GZWs are known to build up behind topographic highs acting as pinning point for the grounding zone of an ice stream (Batchelor and Dowdeswell 2015). Thus, we interpret GZWs #1–6 as remnants of the widespread grounding of westward moving ice from the Northwind Ridge to the Chukchi Rise.

Likewise, we interpret the layer of chaotic sediments with character C2 as a GZW (Figs. 8, 10b; #7), due to its internal structure, its thickness of ~100 m (120 ms TWT) and its setting covering eroded pre-glacial strata on top of a bathymetric high northeast of the Chukchi Rise (Figs. 8, 10b). Similar GZWs are also found on the Greenland Shelf on topographic highs that acted as pinning points for ice streams (Dowdeswell and Fugelli 2012). The action of a paleo ice stream or ice shelf in this area is indicated by MSGL on the shallow slope towards the Northwind Basin (Dove et al. 2014), and crevasse squeeze/recessional moraines on its western side (Fig. 8) (Dove et al. 2014).

A further GZW (GZW #8) is interpreted from a wedge of semi-transparent sediments of character G with internal dipping reflections, situated on the Chukchi Rise (Figs. 6, 8; #8 in Fig. 10a). The interpretation is based on the wedge's asymmetry, with its steeper western and gentler eastern side, its dipping internal reflections, and the truncation of underlying reflections at its base (Dowdeswell and Fugelli 2012). The westward dip of the internal reflections

indicates the eastward glacial retreat (Fig. 6). The dimensions of the Chukchi Rise GZW (48 km × 75 km, ~ 145 m thick) (Fig. 10a) are larger than most known high latitude GZWs, which usually are less than 15 km wide and only 50–100 m thick (Dowdeswell and Fugelli 2012; Batchelor and Dowdeswell 2015). Therefore, the GZW #8 might be the result of an amalgamation of multiple GZWs of successive ice sheets (Rüther et al. 2011), an unusually long-lived still stand of a single ice sheet-shelf system (Batchelor and Dowdeswell 2015) or as a lateral GZW formed at the boundary to an ice free or slow-moving ice zone on the Chukchi Rise adjacent to an ice stream in the BBT (Batchelor et al. 2013a; Batchelor and Dowdeswell 2015). However, without any age constraints and a denser seismic network, the GZW formation remains speculative.

Implications for glaciation history of the Chukchi margin

Grounded ice

Several observations described in the previous chapter indicate on East Siberian Shelf various morphological features, which indicate different glacial processes.

The GB unconformity identified over a large part of the study area (Fig. 9a) suggests the existence of a grounded ice sheet at least on the outer Chukchi Shelf and the adjacent Chukchi Borderland. Considering the extensive overlying deposits increasing in thickness to 210 m southwards (Figs. 3, 9b) leads us to assume that the GB unconformity was formed during the early or middle Quaternary. This inference is consistent with the interpretation of seismostratigraphic data from the Chukchi Rise (Kim et al. 2021) and the terrestrial evidence for the absence of an expansive Late Quaternary glaciation in Beringia (Brigham-Grette 2001, 2013; Gualtieri et al. 2005). The resolution of the MCS data does not allow us to identify individual glacial events in sediments overlying the GB unconformity. Higher-resolution seismostratigraphic data from the Chukchi Rise indicate at least four glacial advances ranging in estimated age from the middle to late Pleistocene (Kim et al. 2021). The ice sheet(s) inferred from the marine data produced north- to northeastwards-flowing ice streams, which advanced and retreated through the bathymetric troughs on the eastern and western flanks of the Chukchi Rise (Fig. 10a) (Dove et al. 2014; Kim et al. 2021). This is indicated by GZWs, drumlins, recessional moraines and MSGL formed in diamictons (Fig. 5a, b, d). Truncations of pre-glacial strata observed in these areas (e.g., Fig. 6) are similar to glacial erosion features in seismostratigraphic records from other formerly glaciated margins, including glacial trough edges (e.g. Bellec et al. 2016). The combined distribution of the glacial unconformity and geomorphic features indicative of the

northwards flowing ice stream (Fig. 10a) is consistent with a proposed East Siberian Ice Sheet (Niessen et al. 2013), or alternatively with an ice sheet centered on the Chukchi Shelf (Dove et al. 2014 and this study; Kim et al. 2021). However, the full extent of such an ice sheet cannot be resolved with the existing data, especially due to the lack of data from the Chukchi Shelf further south.

In addition to the local Chukchi Ice Sheet, glacial impacts could be related to grounded ice shelves transgressing from the Laurentide Ice Sheet across the outer Chukchi Shelf and Borderland. Those are indicated by the large eroded areas including the truncation of the GB reflection (Fig. 9c, f) as well as multiple glacial bedforms like west-striking MSGL and moraines (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014). Along with grounding zone wedges on the western flanks of local topographic highs down to water depths of 600–700 m (Fig. 10b), westward to northwestward ice flow directions are indicated. Therefore, the ice shelves apparently must have originated from the Laurentide Ice Sheet. However, N-S trending MSGL in water depths of 360–380 m on the western flank of the Chukchi Rise associated with one of the last two grounding events in the western Chukchi Region, are difficult to reconcile with a westward moving ice shelf (Kim et al. 2021).

The last grounded ice shelf may have existed during the LGM along the entire Alaskan-Beaufort margin and across the Chukchi Borderland in present-day water depths between 150 and 450 m (Fig. 10b). Evidence for erosion in water depths deeper than 150 m from our eastern study area (Fig. 9f) and along the Alaskan Beaufort margin (Engels et al. 2008) along with the recovery of LGM (~ 20 ka) dated sediments from the Chukchi Region support such an interpretation (Polyak et al. 2007; Park et al. 2017). Polyak et al. (2007) recovered diamicton from east–west striking MSGL in water depths of ~ 450 m on the Northwind Ridge and (Park et al. 2017) found glaciomarine sediments related to a nearby ice shelf in the bathymetric trough east of the Chukchi Rise. However, the preservation of MSGL in water depths of 580 m on the Northwind Ridge, which are dated to marine isotope stage 4/5 (71–123 kyr) (Polyak et al. 2007) as well as preserved NE-SW trending MSGL on the Chukchi margin (Fig. 10 and Dove et al. 2014; Jakobsson et al. 2014; Kim et al. 2021), preclude the existence of a thicker ice shelf during the LGM. This complies with the absence of large grounded ice masses on the Chukchi and East Siberian shelves and restricts the presence of grounded ice during the LGM to the outer shelf areas and the Chukchi Borderland.

Pan-Arctic ice?

Geoscientific data as sediment cores and acoustic data show extensive and widespread glacial erosion and bedforms on the Chukchi margin and the adjacent East Siberian and

Beaufort margins in water depths shallower than 1200 m (Polyak et al. 2007; Jakobsson et al. 2008, 2014; Niessen et al. 2013; Dove et al. 2014; Kim et al. 2021). Those glacial features rise the question if they were caused by local ice sheet-shelf systems or in part caused by a 1 km-thick pan-Arctic ice shelf (Mercer 1970; Grosswald and Hughes 2002; Jakobsson et al. 2016). This ice shelf is suggested to have moved westward across the Chukchi Borderland (Jakobsson et al. 2016). Bedforms as MSGL are reported in up to 1200 m water depth from multiple locations in and around the Chukchi Region (Polyak et al. 2007; Jakobsson et al. 2008, 2014; Niessen et al. 2013; Dove et al. 2014; Kim et al. 2021). Based on their shelf to basinward orientation, these features are interpreted as remnants of a local ice sheet-shelf systems in the Chukchi Region (Polyak et al. 2001; Dove et al. 2014; Kim et al. 2021). In addition, our data show no evidence for extensive erosion below 750 m on the Chukchi margin (Fig. 9) that can be expected from a moving pan-Arctic ice shelf. Erosion is only reported in a small area on the central Northwind Ridge to depths of 900 m, shallowing southwards to 550–750 m and northwards to 620 m (Jakobsson et al. 2008). Other large-scale erosional features which would be comparable to the glacially flat-topped Lomonosov Ridge are not known to date in water depths below 750 m on the Northwind Ridge and Chukchi Plateau (Jakobsson et al. 2008; Dove et al. 2014). Beyond this, while our data set reveals glacio-morphological features supporting the existence of more localized ice sheets/shelves, they do not support a constantly 1 km-thick, westward moving pan-Arctic ice sheet/shelf system in the Chukchi Region. Shallower ice shelves moving westward across the Chukchi margin, however, seem likely to have existed during the Quaternary glaciations.

Conclusions

Regional MCS supported by SBP and bathymetric data collected by the R/V Marcus G. Langseth in 2011 allow a first view of the thickness and distribution of glacially modified sediments overlying eroded pre-glacial strata along the outer Chukchi Shelf and Chukchi Borderland region. Although the data coverage is sparse, we found a variety of geomorphological features in the seismic data that are directly comparable to other glaciated continental shelves. Contrasting orientations of widespread MSGL and recessional moraines, as well as the widespread presence of GZWs, are consistent with multiple glacial cycles and ice sheet/shelf sources. However, in water depths shallower than 350 m, intense iceberg scouring has wiped out seafloor geomorphological features that might have been used for more precise reconstructions of ice sheet/shelf extents. Our main findings are:

1. A glacial unconformity is present over large parts of the Chukchi Shelf and within a bathymetric trough east of the Chukchi Rise. Along with north–south trending seafloor features, like MSGL and drumlins, it provides evidence for a grounded ice sheet-shelf system. Such a system developed likely during several glaciations. Recessional moraines as well as grounding zone wedges within bathymetric troughs east and west of the Chukchi Rise indicate a phase of still stand and minor re-advances during the southward retreat of an ice margin in this region.

2. The erosion of the glacial base reflection, reworked glacial/interglacial sediments and westward directed glacial bedforms indicate that a later erosional ice shelf advanced from the east, probably from the Laurentide Ice Sheet. The preservation of north/northwestward pointing seafloor features in greater water depths indicates that the ice shelf was thinner than previous ice advances from the Chukchi Shelf.

3. A huge, 48 km wide and 75 km long, grounding zone wedge with a thickness of up to ~ 145 m on the Chukchi Rise may have formed over the course of several glacial cycles, during an unusually long stillstand of an ice stream/shelf of one glacial advance or as a lateral moraine adjacent to a trough.

4. Tunnel valleys with a width of up to 12 km and depths of up to 380 m, several smaller tunnel valleys distributed over the research area and gullies at the western shelf edge with a width of up to 1 km and a depth of up 65 m are imaged. All those suggest the existence of large subglacial drainage systems which directed large amounts of meltwater, partly during several glaciations.

Owing to few sediment core data, the complex erosion history, and sparse seismic data coverage, a reliable correlation of glacial morphological features to specific glacial cycles is not yet possible. Discussion about the extent and timing of ice sheets/shelves in the Chukchi Region, including during the LGM, continues.

Data availability All cruise data are archived by Rolling Deck to Repository (R2R) under https://doi.org/10.7284/903767.

References

Batchelor C, Dowdeswell JA (2015) Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins. Mar Geol. https://doi.org/10.1016/j.margeo.2015.02.001

Batchelor C, Dowdeswell J, Pietras J (2013a) Variable history of Quaternary ice-sheet advance across the Beaufort Sea Margin, Arctic Ocean. Geology 41:131–134. https://doi.org/10.1130/G33669.1

Batchelor C, Dowdeswell JA, Pietras JT (2013b) Seismic stratigraphy, sedimentary architecture and palaeo-glaciology of the Mackenzie Trough: evidence for two Quaternary ice advances and limited fan development on the western Canadian Beaufort Sea margin. Quat Sci Rev 65:73–87. https://doi.org/10.1016/j.quascirev.2013.01.021

Batchelor C, Dowdeswell JA, Pietras JT (2014) Evidence for multiple Quaternary ice advances and fan development from the Amundsen Gulf cross-shelf trough and slope, Canadian Beaufort Sea margin. Mar Pet Geol 52:125–143. https://doi.org/10.1016/j.marpetgeo.2013.11.005

Bellec VK, Plassen L, Rise L, Dowdeswell JA (2016) Malangsdjupet: a cross-shelf trough on the North Norwegian margin. Geol Soc Lond Mem 46(1):169–170. https://doi.org/10.1144/m46.30

Bellwald B, Planke S, Lebedeva-Ivanova N, Piasecka ED, Andreassen K (2019) High-resolution landform assemblage along a buried glacio-erosive surface in the SW Barents Sea revealed by P-Cable 3D seismic data. Geomorphology 332:33–50. https://doi.org/10.1016/j.geomorph.2019.01.019

Brigham-Grette J (2001) New perspectives on Beringian Quaternary paleogeography, stratigraphy, and glacial history. Quat Sci Rev 20(1–3):15–24. https://doi.org/10.1016/S0277-3791(00)00134-7

Brigham-Grette J (2013) Palaeoclimate: a fresh look at Arctic ice sheets. Nat Geosci 6(10):807–808. https://doi.org/10.1038/ngeo1960

Brumley K, Miller EL, Konstantinou A, Grove M, Meisling KE, Mayer LA (2015) First bedrock samples dredged from submarine outcrops in the Chukchi Borderland, Arctic Ocean. Geosphere 11(1):76–92. https://doi.org/10.1130/ges01044.1

Burton DJ, Dowdeswell JA, Hogan KA, Noormets R (2016) Little Ice Age terminal and retreat moraines in Kollerfjorden, NW Spitsbergen. Geol Soc Lond Mem 46(1):71–72. https://doi.org/10.1144/m46.35

Caress D, Chayes D (2008) MB-System: open source software for the processing and display of swath mapping sonar data. http://www.mbari.org/data/mbsystem/

Clark CD (1993) Mega-scale glacial lineations and cross-cutting ice-flow landforms. Earth Surf Process Landf 18(1):1–29. https://doi.org/10.1002/esp.3290180102

Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, Mitrovica JX, Hostetler SW, McCabe AM (2009) The last glacial maximum. Science 325(5941):710–714. https://doi.org/10.1126/science.1172873

Coakley B (2011) MGL1112 cruise, RV Marcus G. Langseth. https://doi.org/10.7284/903767. https://www.rvdata.us/search/cruise/MGL1112

Dove D, Polyak L, Coakley B (2014) Widespread, multi-source glacial erosion on the Chukchi margin, Arctic Ocean. Quat Sci Rev 92:112–122. https://doi.org/10.1016/j.quascirev.2013.07.016

Dowdeswell J, Fugelli E (2012) The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. Geol Soc Am Bull 124(11–12):1750–1761. https://doi.org/10.1130/B30628.1

Dowdeswell JA, Cofaigh CO, Pudsey CJ (2004) Thickness and extent of the subglacial till layer beneath an Antarctic paleo–ice stream. Geology 32(1):13–16. https://doi.org/10.1130/g19864.1

Dowdeswell JA, Ottesen D, Rise L, Craig J (2007) Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence. Geology 35(4):359–362. https://doi.org/10.1130/g23200a.1

Dowdeswell JA, Canals M, Jakobsson M, Todd BJ, Dowdeswell EK, Hogan K (2016) Atlas of submarine glacial landforms: modern, quaternary and ancient. Geological Society of London, London. https://doi.org/10.1144/M46

Engels JL, Edwards MH, Polyak L, Johnson PD (2008) Seafloor evidence for ice shelf flow across the Alaska–Beaufort margin of the Arctic Ocean. Earth Surf Process Landf 33(7):1047–1063. https://doi.org/10.1002/esp.1601

Gales JA, Forwick M, Laberg JS, Vorren TO, Larter RD, Graham AGC, Baeten NJ, Amundsen HB (2013) Arctic and Antarctic submarine gullies—a comparison of high latitude continental margins. Geomorphology 201:449–461. https://doi.org/10.1016/j.geomorph.2013.07.018

Gebhardt C, Jokat W, Niessen F, Matthiessen J, Geissler WH, Schenke HW (2011) Ice sheet grounding and iceberg plow marks on the northern and central Yermak Plateau revealed by geophysical data. Quat Sci Rev 30:1726–1738. https://doi.org/10.1016/j.quascirev.2011.03.016

Graham AGC, Jakobsson M, Nitsche FO, Larter RD, Anderson JB, Hillenbrand C-D, Gohl K, Klages JP, Smith JA, Jenkins A (2016) Submarine glacial-landform distribution across the West Antarctic margin, from grounding line to slope: the Pine Island-Thwaites ice-stream system. Geol Soc Lond Mem 46(1):493–500. https://doi.org/10.1144/m46.173

Grosswald M, Hughes T (2002) The Russian component of an Arctic Ice Sheet during the LGM. Quat Sci Rev 21:121–146. https://doi.org/10.1016/S0277-3791(01)00078-6

Gualtieri LYN, Vartanyan SL, Brigham-Grette J, Anderson PM (2005) Evidence for an ice-free Wrangel Island, northeast Siberia during the Last Glacial Maximum. Boreas 34(3):264–273. https://doi.org/10.1111/j.1502-3885.2005.tb01100.x

Hall JK, Grantz A, Johnson L, Sweeney JF (1990) Chukchi borderland. In: Grantz A, Johnson GL, Sweeney JF (eds) The Arctic Ocean region. Geological Society of America, Boulder. https://doi.org/10.1130/dnag-gna-l.337

Hegewald A (2012) The Chukchi Region—tectonic and seminentary evolution. Jena, Friedrich-Schiller-Universität. PhD:130. https://epic.awi.de/id/eprint/31499

Hegewald A, Jokat W (2013) Tectonic and sedimentary structures in the northern Chukchi region, Arctic Ocean. J Geophys Res Solid Earth 118(7):3285–3296. https://doi.org/10.1002/jgrb.50282

Hill J, Driscoll N (2008) Paleodrainage on the Chukchi shelf reveals sea level history and meltwater discharge. Mar Geol 254:129–151. https://doi.org/10.1016/j.margeo.2008.05.018

Hill J, Driscoll N, Brigham-Grette J, Donnelly J, Gayes P, Keigwin L (2007) New evidence for high discharge to the Chukchi shelf since the Last Glacial Maximum. Quat Res 68:271–279. https://doi.org/10.1016/j.yqres.2007.04.004

Hughes T, Denton GH, Grosswald MG (1977) Was there a late-Würm Arctic Ice Sheet? Nature 266(5603):596–602. https://doi.org/10.1038/266596a0

Hunkins K, Herron T, Kutschale H, Peter G (1962) Geophysical studies of the Chukchi Cap, Arctic Ocean. J Geophys Res 67(1):235–247. https://doi.org/10.1029/JZ067i001p00235

Huuse M, Kristensen TB (2016) Pleistocene tunnel valleys in the North Sea Basin. Geol So Lond Mem 46(1):207–208. https://doi.org/10.1144/m46.129

Ilhan I, Coakley BJ (2018) Meso–Cenozoic evolution of the southwestern Chukchi Borderland, Arctic Ocean. Mar Pet Geol 95:100–109. https://doi.org/10.1016/j.marpetgeo.2018.04.014

IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds.) Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 616. https://doi.org/10.1017/9781009157940

Jakobsson M (2016) Submarine glacial landform distribution in the central Arctic Ocean shelf–slope–basin system. Geol Soc Lond Mem 46(1):469–492. https://doi.org/10.1144/m46.179

Jakobsson M, Gardner J, Vogt P, Mayer L, Armstrong A, Backman J et al (2005) Multibeam bathymetric and sediment profiler evidence for ice grounding on the Chukchi Borderland, Arctic Ocean. Quat Res 63:150–160. https://doi.org/10.1016/j.yqres.2004.12.004

Jakobsson M, Polyak L, Edwards M, Kleman J, Coakley B (2008) Glacial geomorphology of the Central Arctic Ocean: the Chukchi Borderland and the Lomonosov Ridge. Earth Surf Process Landf 33(4):526–545. https://doi.org/10.1002/esp.1667

Jakobsson M, Mayer L, Coakley B, Dowdeswell JA, Forbes S, Fridman B et al (2012) The international bathymetric chart of the Arctic Ocean (IBCAO) version 3.0. Geophys Res Lett. https://doi.org/10.1029/2012GL052219

Jakobsson M, Andreassen K, Bjarnadóttir LR, Dove D, Dowdeswell JA, England JH et al (2014) Arctic Ocean glacial history. Quat Sci Rev 92:40–67. https://doi.org/10.1016/j.quascirev.2013.07.033

Jakobsson M, Nilsson J, Anderson L, Backman J, Björk G, Cronin TM, Kirchner N, Koshurnikov A, Mayer L, Noormets R, O'Regan M, Semiletov I (2016) Evidence for an ice shelf covering the central Arctic Ocean during the penultimate glaciation. Nat Commun 7(1):10365. https://doi.org/10.1038/ncomms10365

Joe YJ, Polyak L, Schreck M, Niessen F, Yoon SH, Kong GS, Nam S-I (2020) Late quaternary depositional and glacial history of the Arliss Plateau off the East Siberian margin in the western Arctic Ocean. Quat Sci Rev 228:106099. https://doi.org/10.1016/j.quascirev.2019.106099

Kehew AE, Piotrowski JA, Jørgensen F (2012) Tunnel valleys: concepts and controversies—a review. Earth Sci Rev 113(1):33–58. https://doi.org/10.1016/j.earscirev.2012.02.002

Kim S, Polyak L, Joe YJ, Niessen F, Kim HJ, Choi Y, Kang SG, Hong JK, Nam SI, Jin YK (2021) Seismostratigraphic and geomorphic evidence for the glacial history of the northwestern Chukchi margin, Arctic Ocean. J Geophys Res Earth Surf. https://doi.org/10.1029/2020JF006030

King LH (1993) Till in the marine environment. J Quat Sci 8(4):347–358. https://doi.org/10.1002/jqs.3390080406

Kristoffersen Y, Coakley B, Jokat W, Edwards M, Brekke H, Gjengedal J (2004) Seabed erosion on the Lomonosov Ridge, central Arctic Ocean: a tale of deep draft icebergs in the Eurasia Basin and the influence of Atlantic water inflow on iceberg motion? Paleoceanography. https://doi.org/10.1029/2003pa000985

Mercer JH (1970) A former ice sheet in the Arctic Ocean? Palaeogeogr Palaeoclimatol Palaeoecol 8(1):19–27. https://doi.org/10.1016/0031-0182(70)90076-3

Miller KG, Browning JV, Schmelz WJ, Kopp RE, Mountain GS, Wright JD (2020) Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. Sci Adv 6(20):eaaz1346. https://doi.org/10.1126/sciadv.aaz1346

Niessen F, Hong JK, Hegewald A, Matthiessen J, Stein R, Kim H, Jensen L, Jokat W, Nam SI, Kang S-H (2013) Repeated Pleistocene glaciation of the East Siberian continental margin. Nat Geosci 6(10):842–846. https://doi.org/10.1038/ngeo1904

Ó Cofaigh C, Taylor J, Dowdeswell JA, Pudsey CJ (2003) Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation. Boreas 32(1):37–55. https://doi.org/10.1080/03009480310001858

Ó Cofaigh C, Dowdeswell JA, Allen CS, Hiemstra JF, Pudsey CJ, Evans J, Evans DJA (2005) Flow dynamics and till genesis associated with a marine-based Antarctic palaeo-ice stream. Quat Sci Rev 24(5):709–740. https://doi.org/10.1016/j.quascirev.2004.10.006

Ottesen D, Dowdeswell J (2006) Assemblages of submarine landforms produced by tidewater glaciers in Svalbard. J Geophys Res Earth Surf. https://doi.org/10.1029/2005JF000330

Ottesen D, Dowdeswell JA (2009) An inter-ice-stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. Bull Geol Soc Am 121(11–12):1647–1665. https://doi.org/10.1130/B26467.1

Ottesen D, Dowdeswell J, Rise L (2005) Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian-Svalbard margin (57–80 N). GSA Bull 117(7–8):1033–1050. https://doi.org/10.1130/B25577.1

Park K, Ohkushi KI, Cho HG, Khim B-K (2017) Lithostratigraphy and paleoceanography in the Chukchi Rise of the western Arctic Ocean since the last glacial period. Polar Sci 11:42–53. https://doi.org/10.1016/j.polar.2017.01.002

Polyak L, Edwards M, Coakley B, Jakobsson M (2001) Ice shelves in the Pleistocene Arctic Ocean inferred from deep-sea bedforms. Nature 410:453–457. https://doi.org/10.1038/35068536

Polyak L, Darby DA, Bischof JF, Jakobsson M (2007) Stratigraphic constraints on late Pleistocene glacial erosion and deglaciation of the Chukchi margin, Arctic Ocean. Quat Res 67(2):234–245. https://doi.org/10.1016/j.yqres.2006.08.001

Polyak L, Niessen F, Gataullin V, Gainanov V (2008) The eastern extent of the Barents–Kara ice sheet during the last glacial maximum based on seismic-reflection data from the eastern Kara Sea. Polar Res 27(2):162–174. https://doi.org/10.3402/polar.v27i2.6174

Rüther DC, Mattingsdal R, Andreassen K, Forwick M, Husum K (2011) Seismic architecture and sedimentology of a major grounding zone system deposited by the Bjørnøyrenna Ice Stream during Late Weichselian deglaciation. Quat Sci Rev 30(19):2776–2792. https://doi.org/10.1016/j.quascirev.2011.06.011

Sættem J, Poole DAR, Ellingsen L, Sejrup HP (1992) Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea. Mar Geol 103(1):15–51. https://doi.org/10.1016/0025-3227(92)90007-5

Solheim A, Andersen ES, Elverhøi A, Fiedler A (1996) Late Cenozoic depositional history of the western Svalbard continental shelf, controlled by subsidence and climate. Glob Planet Change 12(1):135–148. https://doi.org/10.1016/0921-8181(95)00016-X

Spagnolo M, Clark CD, Ely JC, Stokes CR, Anderson JB, Andreassen K, Graham AG, King EC (2014) Size, shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset. Earth Surf Process Landf 39(11):1432–1448. https://doi.org/10.1002/esp.3532

Stewart MA, Lonergan L, Hampson G (2013) 3D seismic analysis of buried tunnel valleys in the central North Sea: morphology, cross-cutting generations and glacial history. Quat Sci Rev 72:1–17. https://doi.org/10.1016/j.quascirev.2013.03.016

Stokes CR, Clark CD (1999) Geomorphological criteria for identifying Pleistocene ice streams. Ann Glaciol 28:67–74. https://doi.org/10.3189/172756499781821625

Stokes CR, Tarasov L (2010) Ice streaming in the Laurentide ice sheet: a first comparison between data-calibrated numerical model output and geological evidence. Geophys Res Lett 37(1):L01501. https://doi.org/10.1029/2009GL040990

Stokes CR, Clark CD, Darby DA, Hodgson DA (2005) Late Pleistocene ice export events into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago. Glob Planet Change 49(3):139–162. https://doi.org/10.1016/j.gloplacha.2005.06.001

Walder JS, Fowler A (1994) Channelized subglacial drainage over a deformable bed. J Glaciol 40(134):3–15. https://doi.org/10.3189/S0022143000003750

Wessel P, Smith WHF (1998) New, improved version of generic mapping tools released. Eos Trans Am Geophys Union 79(47):579–579. https://doi.org/10.1029/98EO00426

Winkelmann D, Jokat W, Jensen L, Schenke H-W (2010) Submarine end moraines on the continental shelf off NE Greenland—implications for lateglacial dynamics. Quat Sci Rev 29(9):1069–1077. https://doi.org/10.1016/j.quascirev.2010.02.002

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.