Last Glacial ice-sheet dynamics offshore NE Greenland – a case study from Store Koldewey Trough

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Abstract

The presence of a grounded Greenland Ice Sheet on the northeastern part of the Greenland continental shelf during the Last Glacial Maximum is supported by ~~N~~new swath bathymetry and high-resolution seismic data, supplemented with multi-proxy analyses of sediment gravity cores from Store Koldewey Trough, NE Greenland.~~,~~ ~~support the presence of a shelf-break terminating Greenland Ice Sheet (GIS) on the northeastern part of the Greenland Margin during the Last Glacial Maximum (LGM).~~ Subglacial till fills the trough, with an overlying drape of maximum 2.5 m thickness of glacier proximal and glacier distal sediment. The presence of mega-scale glacial lineations and a grounding zone wedge in the outer part of the trough, comprising subglacial till, provides evidence of the expansion of fast-flowing, grounded ice, probably originating from the area presently covered with the Storstrømmen ice stream and cutting across Store Koldewey Island and Germania Land. Grounding zone wedges and recessional moraines provide evidence that ~~M~~multiple halts and/or readvances interrupted the deglaciation. The formation of grounding zone wedges took at least 130 years, whilst distances between the recessional moraines indicate that the grounding line locally retreated between 80 to 400 meters/year during the deglaciation. ~~. Two sets of crevasse-squeezed ridges in the outer and middle part of the trough may indicate repeated surging of the GIS during the deglaciation.~~ The complex ~~landform assemblage~~geomorphology in Store Koldewey Trough is attributed to the trough shallowing and narrowing towards the coast. ~~is suggested to reflect a relatively slow and stepwise retreat during the deglaciation. Thus, the ice retreat probably occurred asynchronously relative to other ice streams offshore NE Greenland. Subglacial till fills the trough, with an overlying thin drape of maximum 2.5 m thickness of glacier proximal and glacier distal sediment.~~ At a late stage of the deglaciation, the ice stream retreated across Store Koldewey Island and Germania Land, terminating the sediment input from this sector of the Greenland Ice Sheet to Store Koldewey Trough.

1 Introduction

The Greenland Ice Sheet (GIS) is the second largest ice sheet on Earth storing 2.9 million km^3 of ice (Dahl-Jensen et al., 2009). The GIS has ~~been exposed to~~experienced increasing ice loss during the last decades, contributing 0.6 ± 0.1 mm/yr to global sea-level rise between 2000-2010 (Fürst et al., 2015). About 16% of the GIS are presently drained via marine terminating outlet glaciers in NE Greenland, mostly through the North East Greenland Ice Stream (NEGIS) (Joughin et al. 2000) consisting of three main outlets: 79°-Glacier, Zachariae Isstrøm and Storstrømmen (e.g. Rignot and Kanagaratnam 2006) (Fig. 1). A future warming global climate, which will be particularly strong in the Arctic (Serreze and Francis, 2006), will lead to a reduced sea-ice cover adjacent to the glacier termini and subsequent accelerated melting of the ice sheet in NE Greenland (Bendtsen et al., 2017). Thus, a continuing global warming could cause an instability and possibly irreversible loss of the GIS, which has - together with the West-Antarctic Ice Sheet (WAIS) - been identified as a tipping element~~s~~ in the Earth's climate system (Lenton et al., 2008). A complete meltdown of these ice sheets can potentially lead to a global sea-level rise of 7.3 (GIS) m and 3.2 m (WAIS) (Bamber et al., 2001, 2009), causing severe consequences for coastal societies (IPCC, 2018). However, precise predictions of ~~the~~ future evolvement ~~of a potential decay~~ of the GIS ~~in the future~~ remains difficult (Nick et al., 2013). ~~By getting a~~A better understanding of the development of glaciers in response to past climate changes, e.g. from the Last Glacial Maximum (LGM; c. 24-16 ka BP) ~~and up to~~towards the present, ~~we contribute~~is needed to validat~~e~~ion and improve~~ment~~ ~~of~~ numerical models focusing on present processes, as well as the future development of glaciers and ice sheets.

The reconstruction of the GIS configuration and dynamics from marine-geoscientific data, including maximum extent during the LGM, as well as the timing and dynamics of the deglaciation, have been addressed in multiple studies {Formatting Citation}~~(Andrews et al., 1998; Bennike et al., 2002; Dowdeswell et al., 1994; Funder et al., 2011b; Hogan et al., 2011, 2016, 2020; Hubberten et al., 1995; Ó Cofaigh et al., 2013)~~(e.g. Andrews et al., 1998; Bennike et al., 2002; Dowdeswell et al., 1994, 2014; Funder et al., 2011a~~b~~; Hogan et al., 2011, 2016, 2020; Hubberten et al., 1995; Ó Cofaigh et al., 2013). However, these reconstructions focus primarily on the southern and western sectors offshore Greenland, and reconstructions from offshore northeast Greenland remain sparse (Arndt, 2018; Arndt et al., 2017; Evans et al., 2002; Laberg et al., 2017; Stein et al., 1996; Winkelmann et al., 2010). ~~It has been suggested that the northeastern part of the GIS reached the inner or middle parts of the continental shelf during its maximum extent during the last glacial (Funder et al., 2011b). However, s~~ S~~ubglacial and ice-marginal depositional landforms, including mega-scale glacial lineations and recessional moraines presented in more recent m~~Marine geoscientific studies suggest that the northeastern sector of the GIS extended all the way to the shelf edge during the last glacial based on observations of ~~–~~subglacial and ice-marginal depositional landforms, including mega-scale glacial lineations and terminal moraines (Arndt, 2018; Arndt et al., 2015, 2017; Evans et al., 2009; Laberg et al., 2017; Ó Cofaigh et al., 2004).

Laberg et al. (2017) presented glacial landforms interpreted as retreat moraines ~~i~~on the outermost ~~parts~~shelf of the Store Koldewey Trough (Fig. 1), suggesting a stepwise early deglaciation likely triggered by an increase in ocean temperature. However, an absolute chronology for the deglaciation is still pending. According to Evans et al. (2002), breakup and retreat of the GIS further to the south, outside Kejser Franz Joseph Fjord (for location, see Fig. 1), commenced after c. 15.3 ka BP, with the ice abandoning the mid-shelf before 13 ka BP and the inner shelf being ice free before 9 ka BP. ~~Dating of lake sediments~~Cosmogenic nuclide dating on Store Koldewey Ø, located ~~east~~ west of Store Koldewey Trough (Fig. 1), reveals that the ~~area was deglaciated prior to 11 ka BP (Klug et al., 2009)~~ice retreated from the area ca. 12.7 ka BP (Skov et al., 2020), whereas the ice front rested east of the present coastline of Germania Land until c. 10 ka BP (Landvik, 1994). By 7.5 ka BP the ice front had retreated close to its present position, and after further recession Germania Land became an island about 6 ka BP. Storstrømmen readvanced again c. 1 ka BP, reaching its present position during the Little Ice Age (Weidick et al., 1996).

The overall objective of this paper is to ~~confirm~~provide new knowledge regarding the presence of a shelf-break terminating GIS on the northeastern part of the Greenland Margin by presenting evidence from new acoustic data (multibeam bathymetry and Chirp seismic) and sediment cores. These new data sets expands and complements existing data in one of the largest glacial troughs offshore northeast Greenland, i.e. the Store Koldewey Trough. ~~Furthermore~~More specifically, the aims are to 1) reconstruct the ice dynamics and ice drainage pathways of this sector of the GIS overlying Store Koldewey Trough during the LGM and the deglaciation, and 2) discuss the post-glacial marine environmental conditions of Store Koldewey Trough.~~,~~ ~~one of the largest glacial troughs offshore northeast Greenland.~~

2 Regional setting

The large-scale morphology of the NE Greenland continental shelf is characterized by several large cross-shelf troughs separated by shallower banks and shoals (Fig. 1). The troughs are characteristic features of formerly glaciated continental shelves, interpreted as glacially over-deepened landforms acting as conduits for fast-flowing ice streams eroding into the sub-glacial bed~~rock~~ (e.g. Vorren et al. 1988; Canals et al. 2000; Batchelor and Dowdeswell 2014), whilst inter-trough banks are interpreted to have been covered by slower flowing ice, consequently experiencing less erosion (Klages et al., 2013; Ottesen and Dowdeswell, 2009).

The east coast of Greenland is presently largely influenced by the southward flowing East Greenland Current carrying cold, ~~and~~ fresh surface Polar Water and sea ice from the Arctic Ocean together with warmer modified Atlantic Intermediate Water (Aagaard and Coachman, 1968; Hopkins, 1991). An increased inflow of warm Atlantic Intermediate Water into East Greenland troughs and fjords is ~~thought~~ proposed to influence the submarine melt rates, causing an instability at the grounding line of marine terminating outlet glaciers (Khan et al., 2014; Mayer et al., 2018), e.g. the 79º-Glacier (Straneo and Heimbach, 2013; Wilson and Straneo, 2015).

Store Koldewey Trough is a NW-SE oriented cross-shelf trough located at ~76º N offshore northeast Greenland (Fig. 1). The trough is ~210 km long, 30-40 km wide and~~,~~ up to 400 m deep. It is divided into an inner-, middle- and outer shelf (Fig. 1C), with~~has~~ a sinuous centerline terminating at the shelf edge. A bathymetric profile along the axis of Store Koldewey Trough reveals that it differs from most troughs offshore northeast Greenland, ~~it is a seaward deepening trough~~because it deepens towards the shelf break (Fig. 1B). In addition, Store Koldewey Trough is the only trough on the NE Greenland continental shelf without a fjord continuation; it terminates near Germania Land and the island Store Koldewey to the west (Fig. 1A).

The ice stream Storstrømmen, located west of the study area (Fig. 1), has presently a floating ice tongue with a 20 km wide calving front (Khan et al., 2014). It surged around 1910 and 1978 (Mouginot et al., 2018). Similar to surging glaciers on Svalbard (e.g. Dowdeswell et al., 1991), Storstrømmen undergoes a slow initiation and termination with a long active surge phase lasting 10 years (Mouginot et al., 2018). The bed topography beneath the ice stream has a reverse slope, resulting in accumulation of subglacial water creating favorable conditions for surges (Mouginot et al., 2018), as well as episodic~~ally~~ calving events (Hill et al., 2018).

~~Gneisses from the Caledonian fold belt of East Greenland as well as Mesozoic and Cenozoic marine deposits dominate the bedrock geology of the drainage area of Storstrømmen (Henriksen and Higgins, 2009; Koch, 1916).~~

Laberg et al. (2017) identified an assemblage of glacigenic landforms ~~i~~on the outer ~~part~~ shelf of Store Koldewey Trough, including mega-scale glacial lineations and rhombohedral- and transverse ridges with variable dimensions. From the landform assemblage, it was inferred that grounded ice expanded to the shelf edge during the last glacial. Four prominent transverse ridges located on the outer, middle and inner shelf were interpreted as grounding-zone wedges deposited in front of the GIS during temporary stillstand and/or readvances during the last deglaciation (see labels A-D in Fig. 1B, C). Similar landform assemblages are also identified in other troughs along the northeastern continental shelf of Greenland (Arndt, 2018; Arndt et al., 2015) as well as on other formerly glaciated continental shelves (e.g. Ottesen et al. 2005; Winsborrow et al. 2010; Jakobsson et al. 2012a; Bjarnadóttir et al. 2013; Andreassen et al. 2014; Batchelor and Dowdeswell 2014).

3 Material and methods

Acoustic data, including swath bathymetry and high-resolution seismic data, as well as four sediment gravity cores were collected during cruises arranged within the TUNU-program (Christiansen, 2012) using *R/V Helmer Hanssen* of UiT The Arctic University of Norway in 2013, 2015 and 2017.

The swath bathymetry data were~~as~~ acquired using hull-mounted Kongsberg Maritime Simrad EM 300 and 302 multibeam echo sounders in 2013/2015 and 2017, respectively. Sound velocity profiles for the water column were derived from CTD (conductivity-temperature-depth) ~~measurements~~ casts prior to and during the bathymetric surveys. High-resolution seismic profiles were acquired with a hull-mounted EdgeTech 3300-HM (Chirp) sub-bottom profiler simultaneously with the swath bathymetry data, using a pulse frequency of 2-8 kHz. Visualization and interpretation of the chirp and multibeam bathymetry data were performed using Petrel 2018 and Global Mapper 19.

The sediment volumes of the grounding zone wedges were calculated as box volumes, using a mean thickness and length, obtained from the acoustic data. With the Chirp sub-bottom profiles being unable to penetrate to a basal reflector, a flat base beneath the proximal side of the grounding zone wedges was assumed. Due to the limited data coverage, the calculations were further simplified by calculating the volume per 1-m grounding line width (m^3/m).

The sediment gravity cores (HH17-1326, HH17-1328, HH17-1331 and HH17-1333) were retrieved from 294 to 345 m water depth along a transect extending from inner to middle Store Koldewey Trough using a 6 m long steel barrel (Fig. 1; Table 1). Coring sites were chosen with the purpose of penetrating a stratigraphic sequence including subglacial and glacimarine deposits.

Prior to opening, the physical properties of the sediments were measured using the GEOTEK Multi Sensor Core Logger, with a 10 mm step size and 10 s measuring time. The cores were stored for one day in the laboratory prior to the measurements to allow the sediments to adjust to room temperature as temperature changes can affect the physical properties (Weber et al., 1997). After splitting, color images were acquired with a Jai L-107CC 3 CCD RGB Line Scan Camera installed on an Avaatech XRF core scanner. Furthermore, X-radiographs were taken with a GEOTEK MSCL-XCT X-ray core imaging system. ~~X-Ray Fluorescence (XRF) core scanning for qualitative element-geochemical analyses using an Avaatech XRF Core Scanner was performed. The data acquisition was carried out in 10 mm measurement steps in two runs with a 12 mm cross-core slit size and following settings; 1) 10 kV, 1000 µA, 10 sec counting time and no filter; 2) 30 kV, 2000 µ, 10 sec counting time and Pd-thick filter. XRF return values for Ca, Fe and Ti divided over the sum of the most abundant elements (Al, Si, K, Ca, Ti, Fe and Rb) were chosen for further interpretation, recording the relative variations in marine carbonate/detrial input and terrigenous sediment delivery. In addition, a~~A systematic description of the sediment surface was carried out and colors were determined visually using the Munsell Soil Color Chart (Munsell, 2000). ~~Shear strength of the sediments were estimated using the fall-cone test (Hansbo, 1957).~~ The cores contained insufficient amounts of dateable material for a chronology to be established.

Grain-size analyses were performed using a Beckman Coulter LS 13 320 laser particle size analyzer, measuring the range from 0.04 µm to 2000 µm. Particles larger than 2000 µm were removed by a sieve and are presented as clasts in the lithological logs. Prior to the analyses, chemical treatment of the samples using HCl and H_2O_2 ~~were~~ was conducted to remove carbonates and organic content, respectively. Distilled water was added to the samples before being shaken for 24 hours. Furthermore, two drops of Calgon solution were added to the samples before being placed in an ultrasound bath for five minutes in order to disintegrate ~~flocculation~~ aggregates of particles. Each sample was analyzed three times and the particle size statistics were calculated using GRADISTAT v. 8.0 (Blott and Pye, 2001).

4 Results

4.1 Lithostratigraphy of the uppermost trough strata

Five lithofacies are defined based on the lithological composition, sedimentary structures~~,~~ and physical properties ~~and sediment geochemistry~~ (Fig. 2 and 3). The properties of the different facies are summarized in Table 2.

4.1.1 Facies 5 - Diamicton (Dmm)

The lowermost facies in all four cores comprises a very dark gray, massive, matrix-supported diamicton with a sandy mud matrix and high amounts of randomly oriented clasts ~~of various origin~~ (Fig. 2 and 3; Table 2). The upper boundary is sharp and bioturbation is absent. ~~Both t~~The magnetic susceptibility ~~and Ca/Sum ratio~~ varies~~y~~ between each core, with the highest in HH17-1326 and lowest in HH17-1328. Wet bulk density ~~and shear strength values are~~is generally high, suggesting over-consolidation of the sediments.

Based on the ~~poorly sorted nature~~ diamictic composition of these deposits, the high amounts of clasts, absence of bioturbation and a considerable consolidation of the sediments we suggest that the facies represents diamictic subglacial debris/basal till deposited at the base of an ice stream from the GIS (compare with Evans et al. 2006). ~~The facies is recognized in the seismostratigraphy as an acoustically transparent unit (Fig. 7).~~

4.1.2 Facies 4 – Interlaminated glacimarine sediments (Fl)

Facies 4 is present in the two ~~westernmost~~ cores on the inner shelf; HH17-1326 and HH17-1328, with thicknesses of 12 cm and 35 cm, respectively (Fig. 2 and 3, Table 2). The facies consists of dark gray laminated mud with fine sandy layers. Bioturbation and clasts are absent. The upper unit boundary is gradational and defined by the onset of dropstone deposition. Wet bulk density is medium, whilst the ~~shear strength and~~ magnetic susceptibility variesy with a decrease in HH17-1326 and an increase in HH17-1328 relative to the underlying unit. ~~The measured increase in the shear strength in core HH17-1328 is likely a result of influence of the sandy laminae, causing too high values (Hansbo, 1957). Ti/Sum and Fe/Sum ratios correlate with the sediment grain-size, with higher Fe and Ti content within the sand and mud laminae, respectively.~~

The facies is interpreted to contain glacier-proximal glacimarine sediments deposited from suspension settling, where the stratification of the sediments reflects variations in the current strength of the water masses emanating from the ice margin.~~deposited as emanating subglacial meltwater at the grounding line generates two coupled density currents: suspension plumes transporting fine-grained sediments and high-density underflows (hyperpycnal flows; Mulder et al. 2003) carrying coarser sediments.~~ The lack of clasts interpreted as ice-rafted debris (IRD) in ice-proximal settings may have several explanations, which will be discussed further below (see chapter 5.2).~~;~~ ~~i) the time of deposition may represent a period with an extensive sea-ice cover preventing icebergs to drift over the area (Jennings and Weiner, 1996; Moon et al., 2015; Vorren and Plassen, 2002), ii) the sediments may be deposited in a sub-shelf environment proximal to the grounding line (Jennings et al., 2019) or iii) as a result of a high flux of sediment-laden glacial meltwater masking the amount of iceberg rafted debris (Boulton, 1990).~~

4.1.3 Facies 3 – Interlaminated glacimarine sediments with occasional IRD (Fl (d))

Facies 3 occurs in all sediment cores, and~~. I~~it consists of dark gray laminated mud with fine sandy layers and clasts (Fig. 2 and 3; Table 2). The clasts, interpreted as IRD, appear in massive diamict layers. The unit is 9-23 cm thick and has a sharp or gradational lower boundary overlying either facies 5 or 4, respectively, whilst the upper boundary is gradational. The unit has similar properties as facies 4, with medium-high wet bulk density. ~~and varying shear strength.~~ However, the magnetic susceptibility varies between the cores.

Facies 3 is interpreted to represent a glacier-proximal setting with glacimarine sediments containing IRD deposited ~~rapidly in periods of high calving rates (e.g. Ó Cofaigh and Dowdeswell 2001)~~in episodic calving events. The sediments are thought to have been deposited in ~~more~~ open marine conditions, ~~with more intense iceberg rafting compared to facies 4, possibly~~ reflecting an outer ice-proximal setting where the ice front has retreated and IRD becomes a more dominant component on the expense of suspension settling, compared to facies 4. ~~(cf. Boulton 1990).~~

4.1.4 Facies 2 – Massive glacimarine sediments (Fm)

Massive olive gray to dark gray mud with little to moderate bioturbation and rare clasts composes facies 2. The facies is 10-80 cm thick and occurs in all four sediment cores (Fig. 2 and 3; Table 2). Both the lower and upper unit boundaries are gradational. The physical properties, including wet bulk density and~~,~~ magnetic susceptibility ~~and shear strength~~ vary slightly within the facies and between the ~~studied sediment~~ cores.

The facies is interpreted to reflect suspension settling in an ice-distal glacimarine environment with limited iceberg or sea-ice rafting~~ (Boulton and Deynoux, 1981)~~. With increased distance from the grounding line, deposition from turbid meltwater plumes typically grade into more massive, bioturbated mud (Ó Cofaigh and Dowdeswell, 2001). ~~However, it~~It ~~could also be speculated that there was a permanent sea ice cover during the deposition of this facies.~~ The rare amount of IRD within the massive mud may be a consequence of warm surface water during the Early Holocene causing prolonged open water conditions and reduced ice rafting on the shelf (Müller et al., 2012; Syring et al., 2020).

4.1.5 Facies 1 – Massive glacimarine sediments with IRD (Fm (d))

The uppermost facies in all of the studied cores consists of massive mud with clast-containing intervals~~ containing clasts~~, the latter interpreted to be IRD (Fig. 2 and 3; Table 2). ~~The s~~Sediment color alternates between brown to dark grayish brown, as well as olive gray to dark olive gray. Facies 1 is generally coarser than facies 2.~~, with a p~~Peaks in the magnetic susceptibility~~ and decreases in Ti/Sum ratios~~ correspond~~ing~~ to the depth with highest abundance of coarser material. ~~The Ca/Sum ratios increase towards the top of the facies. Both t~~The wet bulk density ~~and shear strength are~~is similar to the underlying facies 2.

Facies 1 is interpreted to have been deposited in a similar environment as facies 2. Deposition of IRD can occur from dropping and dumping (see Vorren et al., 1983), i.e. dumping from a single iceberg or ice flow may be misinterpreted as enhanced iceberg rafting. However, since we identify increased amounts of IRD in all four cores we are confident that facies 1 reflects increased ice rafting at a regional scale, most probably related to the Neoglacial cooling trend (cf. Syring et al., 2020). ~~However, the enhanced presence of clasts indicates an increased influence of drifting icebergs and/or sea-ice.~~

4.2 Submarine landforms: glacial – deglacial ice-sheet dynamics

The swath bathymetry data from the middle and outer shelf~~part~~ of Store Koldewey Trough reveal glacigenic landforms interpreted to reflect various stages of ice-sheet extent, flow dynamics and retreat patterns. This is based on an entirely new data set from the middle shelf, in addition to including and expanding the data set described by ~~(~~Laberg et al.~~,~~ (2017) from the outer shelf (Fig. 5). The addition of the new data set led to minor re-interpretations of landforms on the western part of the data set from ~~(~~Laberg et al.~~,~~ (2017) (see subchapter *4.2.4. Curvilinear ridges – Saw-tooth recessional moraines*).

4.2.1 Streamlined landforms – ~~m~~Mega-scale glacial lineations~~ (MSGL)~~

Streamlined, trough-parallel grooves and ridges occur in the middle and outer ~~trough~~ shelf (Fig. 4, 5 and 6A), terminating close to the shelf edge. Individual ridges have widths of 150-500 m and reliefs between 4-8 m (Table 3). They occur in clusters with spacing from 200 to 700 m. The grooves and ridges are partly eroded and/or overprinted by other landforms, ~~which makes it difficult to measure their lengths~~making the determination of their maximum lengths challenging. ~~However, they appear to be~~Their minimum lengths range from ~~>~~1.5 to >9km ~~long with elongation~~and their length/width ratios ~~of the ridges~~ generally exceed~~ing~~ 10:1. ~~The landforms occur in clusters with spacing from 200 to 700 m.~~ High-resolution seismic data ~~show~~ reveal that the ridges are acoustically transparent (Fig. 7F), i.e. that their acoustic properties are ~~a property that is~~ characteristic for basal till (e.g. Ó Cofaigh et al., 2007)~~ (Fig. 7F)~~.

Based on the spatial distribution, dimensions and orientations, we interpret the grooves and ridges as mega-scale glacial lineations~~ (MSGLs)~~ formed subglacially at the base of a fast-flowing, grounded ice stream (Clark, 1993; King et al., 2009; Spagnolo et al., 2014) draining the GIS towards the shelf break. Similar landforms have been described on the seafloor of other formerly glaciated margins where they have been interpreted to indicate the presence of grounded ice streams (e.g. Canals et al. 2000; Ottesen et al. 2005; Evans et al. 2009; Rydningen et al. 2013; Andreassen et al. 2014; Hogan et al. 2016; Arndt 2018).

4.2.2 Large transverse ridges - Grounding zone wedges

Four prominent bathymetric sills interpreted as grounding zone wedges *A*-*D* by Laberg et al. (2017) are present within the trough (Fig. 1B, C and7). These authors presented acoustic data from wedges *A* and *B*, while the data from our study provides new information about wedge *C*. The wedges are 35-100 m high, 3.5-10 km wide and are spaced 45-60 km apart (Table 3). Sediment volumes per meter grounding line width are approximately 130 000 m^3, 738 000 m^3 and 150 000 m^3 for wedges *A*, *B* and *C*, respectively. The cross-trough extent of the grounding zone wedges exceeds the multibeam data coverage. Smaller ridges overprint the grounding zone wedges (Fig. 4, 5 and 6~~A~~). The base of the wedges is not possible to identify from our high-resolution Chirp profiles, but 2-D seismic profiles described by Petersen et al. (2015) reveal a thick Neogene sedimentary succession offshore NE Greenland, thus ruling out that these features are bedrock sills. As such, ~~T~~these large landforms are interpreted to be ~~produced by~~ accumulations of sediments deposited at the ice stream`s grounding line, recording the temporary position of the grounding line during stillstand and/or readvance during a late phase of the last glacial in conformity with ~~(~~Laberg et al.~~,~~ (2017).

4.2.3 Small transverse ridges – Transverse recessional moraines ~~and crevasse-squeeze ridges~~

~~The most prominent characteristic of the seafloor throughout Store Koldewey Trough is the high number of small ridges~~Multiple straight to slightly curvilinear transverse/semi-transverse ridges are visible on the seafloor of Store Koldewey Trough (Fig. 4, 5, 6 and 7). ~~These ridges are one order of magnitude smaller than the grounding-zone wedges and occur in two forms; (1) as curvilinear to straight transverse/semi-transverse ridges, or (2) as rhombohedral ridge patterns.~~ The ridges are up to 2200 m wide, have reliefs <50 m and have a spacing of 50-500 m (Table 3). Some of the ridges superimpose others, implying several generations of ridge formation~~s~~. There are two generations of ridges on the outer shelf (between grounding zone wedges *A* and *B*), where the first generation is spaced ~80 m apart, whilst the superimposing ridges are larger and mostly spaced 200-400 m apart. The spacing of ridges on the middle shelf is commonly 100-200 m.~~The transverse ridges located southeast seaward of grounding zone wedge *C* appear to be spaced further apart and/or are less well preserved.~~

We interpret the curvilinear to straight ridges as recessional moraines formed at the grounding line during ~~slow~~ overall retreat with repeated stillstand and/or small readvances (cf. Dowdeswell et al., 2008; Ó Cofaigh et al., 2008). ~~The rhombohedral network of ridges are interpreted to be crevasse-squeeze ridges that formed from soft sediments squeezed into basal crevasses of the ice stream during and after its transition from fast flow to stagnation, often associated with glacial surges (Boulton et al., 1996; Dowdeswell and Ottesen, 2016; Evans and Rea, 1999; Sharp, 1985; Solheim, 1991).~~ The ridge-like features identified on the sub-bottom profiles are acoustically transparent suggesting a diamictic composition (Stewart and Stoker, 1990) (Fig. 7).

~~4.2.4 Multi-keel iceberg ploughmarks~~ 4.2.4 Curvilinear ridges - Saw-tooth recessional moraines

~~Linear to c~~Clusters of curvilinear ~~depressions with berm ridges along their lateral margins~~ridges occur ~~in clusters, characterizinge the seafloor east~~ both landward~~proximal~~ and seaward of grounding zone wedge *B*, and seaward of grounding zone wedge *C* (Fig. 4, 5, 6B,~~ E~~ and 7D, E). ~~The depressions are flat-bottomed and occur often in groups~~~~In planview the curvilinear~~ These ridges ~~often~~ occur often closely spaced, exhibiting a saw-tooth pattern in plan view. Many of the features continue as long moraine ridges oriented sub-parallel ~~with~~to the ice-flow direction. Bifurcations and cross-cutting patterns occur. Individual ~~depressions with associated~~ ridges are up to 1.3 km long, 170-1100 m wide and have a relief of 5-30 m (Table 3). ~~They are predominantly orientated parallel to the trough axis.~~ They are typically asymmetrical with a steeper ice distal slope and a more gentle ice proximal slope (Fig. 6E). The ~~depressions~~ saw-tooth ridges partly superpose and ~~thereby obscure reworked~~modify the underlying transverse ridges ~~and~~ creatinge ~~a~~ chaotic seafloor patterns.~~.~~ Furthermore, grounding zone wedge *B* partly covers some saw-tooth ridges.

We interpret the saw-tooth ridges as recessional- moraines that formed by a combination of push- and squeeze processes, recording an active ice retreat punctuated by periodic advances~~-~~. The formation of these distinctive landforms is inferred to be dependent on the topography, where down-ice widening, in this case of the trough, causes increased transverse stress leading to longitudinal crevasses initiating an irregular ice front~~)~~. Similar saw-tooth like moraines have been observed in e.g. Norway (Burki et al., 2009; Matthews et al., 1979), Barents Sea (Hogan et al., 2010; Kurjanski et al., 2019), Iceland (Chandler et al., 2016; Evans et al., 2016) and Arctic Canada (Andrews and Smithson, 1966). The landforms were previously interpreted as rhombohedral ridges by ~~(~~Laberg et al.~~,~~ (2017) on the western part of the data set from the outer shelf, however, we found the saw-tooth-like morphology incompatible with the geometric ridge networks of rhombohedral ridges (cf. Bennett et al., 1996).

~~We interpret these landforms as plough marks generated from grounded icebergs with multiple keels. The groups with parallell ploughmarks are comparable to the features suggested to be a result of multi-keeled icebergs in e.g. West-Antarctica (Wise et al., 2017) and northern Barents Sea (Andreassen et al., 2014). However, the ploughmarks in this study are one magnitude shorter and corrugation ridges within the furrows appear to be absent. We suggest both the uniform orientation and limited length of the ploughmarks to be a result of the presence of an ice melange limiting iceberg drift, similar to the observations of similar landforms by Kristoffersen et al. (2004) in the Arctic Ocean.~~

~~4.2.5~~ 4.2.5 Straight incisions - Channels

Two straight incisions that are U-shaped in cross section, 150-300 m wide and with incision depths of 3-10 m are identified along the northern and southern trough sidewalls (Fig. 4; Table 3). The incisions are oriented parallel to the recessional moraines and continue beyond the extent of the swath bathymetry data set. They cut into the mega-scale glacial lineations and the acoustically transparent sediments interpreted as basal till (see below for description and interpretation of the latter). The landforms are interpreted as channels formed during deglaciation and are probably related to erosion by meltwater. ~~as the ice sheet disintegrates and produces fractures filled with meltwater eroding beneath the ice sheet. Another possible explanation for their formation is they could have formed from meltwater runoff from ice masses remaining on the surrounding banks.~~

4.3 Seismostratigraphy

Two seismostratigraphic~~ic~~ units (S1 and S2) were identified in the chirp sub-bottom profiles in Store Koldewey Trough (Fig. 7).

4.3.1 Unit S1 – Glacigenic deposits and/or sedimentary bedrock

Seismic unit S1 is the lowermost seismostratigraphic unit and the base of this unit represents the acoustic basement ~~occuring in~~of the ~~entire~~ study area. ~~I~~The unit has an acoustically transparent to semi-transparent signature and an irregular top reflection with medium to high amplitude and continuity (Fig. 7B).

The unit correlates with lithological unit 5 (*Dmm*) in the sediment cores, interpreted as subglacial till, i.e. ~~that~~ it includes subglacial deposits. However, the chirp profiles (Fig. 7) reveal that the unit S1 also includes grounding-zone wedges, as well as ~~transverse and rhombohedral ridges~~recessional moraines, i.e. multiple glacigenic landforms and deposits. ~~In the majority of the study area, these glacigenic landforms define the acoustic basement. However, a relatively strong and smooth reflection can be observed beneath glacigenic deposits. This is interpreted to be caused by the top of the underlying bedrock, suggesting that S1 also includes bedrock in some areas.~~

4.3.2 Unit S2 – ~~Latest Weichselian - Holocene g~~Glacimarine sediments

Unit S2 is ~~an~~ acoustically transparent ~~unit~~ (Fig. 7). The unit is thin and only occurs locally either as an infill between the topographic highs or draping the underlying unit S1, i.e. it is~~or~~ missing from most of Store Koldewey Trough (e.g. on the outer shelf).~~, with a~~The maximum thickness of the unit is 2.5 m~~ where present~~ (Fig. 7). ~~The sediment unit~~It ~~occurs locally either as an infill between the topographic highs or draping the underlying unit S1.~~

Unit S2 is ~~sampled with all four sediment cores and is interpreted to include~~correlated with the lithological units 4 (*Fl*), 3 (*Fl (d)*), 2 (*Fm*) and 1 (*Fm (d)*), i.e. it occurs at all four core sites. The unit ~~is identified as~~contains glacimarine deposits reflecting ~~, consisting of~~ a gradual transition from glacier proximal to distal ~~glacimarine sediments from the latest Weichselian at the base to distal glacimarine Holocene sediments at the top.~~environments.

5 Discussion

5.1 Maximum ice sheet extent and influence of subglacial topography

Mega-scale glacial lineations and their terminations at grounding zone wedge *A* in the outer trough (Fig. 5 and 9: Stage 1) suggest that a grounded, fast-flowing ice stream draining the northeastern sector of the GIS extended to the shelf break in Store Koldewey Trough ~~during~~ at maximum ice extent during the last glacial, as proposed by ~~(~~Laberg et al.~~,~~ (2017)~~the LGM~~ (Fig. 8). This is ~~conform~~ consistent with reconstructions of shelf-break terminating glaciers during the LGM elsewhere on the NE Greenland Margin, i.e. ranging from our study area in the south to the Westwind Trough at 80.5° N in the north (Arndt et al., 2015, 2017; Laberg et al., 2017; Winkelmann et al., 2010) (Fig. 1A). If the ~~full-glacial conditions~~maximum glacier extent on the margin occurred synchronously, this implies that an ice sheet front covered a minimum length of 680 km along the outer shelf.

Acoustic profiles reveal an up to 2.5 m thick drape of glaciomarine sediment overlying the glacigenic deposits in certain parts of the inner and middle shelf, whereas a detectable sediment drape on the outer shelf is absent (Fig. 5). Subglacial debris/basal till) in all sediment cores provides supporting evidence that grounded ice from the GIS extended at least to the location of core HH17-1333. Laberg et al. (2017) argue that the lack of glacimarine sediments and good preservation of glacial landforms on the outer shelf indicate that the identified landforms formed during the LGM and subsequent deglaciation. Stein et al. (1996) presented a chronology of the deposition of terrigenous, coarse grained material along the continental slope off NE Greenland, suggesting that the maximum late Weichselian ice extent occurred at about 21-16 ka cal. yr BP. Radiocarbon dates from the Greenland Basin indicate that mass-wasting activity on the upper continental slope took place predominantly under full glacial and deglacial conditions, and that this had ceased after about 13 ka BP, leaving the channels largely inactive (Ó Cofaigh et al., 2004). Thus, from the data available, the outer parts of Store Koldewey Trough may have been ice covered in the period from ~21 ka BP - ~13 ka BP.

We propose that the Store Koldewey Trough was filled by grounded ice originating from the area presently covered with the Storstrømmen ice stream (Fig. 8A). Palaeo-ice sheet models have calculated that the ice covering Germania Land during LGM has been 1000-1500 m thick (Fleming and Lambeck, 2004; Heinemann et al., 2014). This implies that the northeastern sector of the GIS likely reached a thickness allowing the ice stream to flow ~~unrelated to~~across the underlying topography, including the mountain range with 500-900 m high peaks~~s~~ between present day Storstrømmen and Germania Land. Such "pure" ice streams (Bentley, 1987; Stokes and Clark, 1999), flowing unrelated to topography, are documented from the contemporary Siple Coast Ice Streams of West Antarctica. In addition, a similar flow feature has been identified in the modern ~~northeast Greenland~~North East Greenland Ice Stream (NEGIS) (Fahnestock et al., 1993; Sachau et al., 2018) (Fig. 1A), as well as for a paleo-ice stream within the Laurentide Ice Sheet (Ó Cofaigh et al., 2010). ~~Once a fast-flowing ice streams reach deep troughs, they become influenced by topography and stabilize between areas of slower moving ice (Boulton et al., 2003).~~

An alternative interpretation is that Store Koldewey Trough had a much smaller drainage-basin, limited to Germania Land, as proposed by ~~(~~Arndt et al.~~,~~ (2015). However, based on our data, including the observations of mega-scale glacial lineations, recessional moraines and grounding zone wedges, we favor the interpretation ~~of~~ that Storstrømmen filled~~ing~~ Store Koldewey Trough during full glacial conditions based on the volume of ice needed to fill a trough of this ~~magnitude~~dimension. ~~We propose that the ice sheet thinned and that the underlying topography controlled the direction of ice flow during a late phase of the last glacial, i.e. that the ice flow from the interior of the GIS was directed to Jøkelbugten in the north and Dove Bugt in the south (Fig. 8B).~~

~~Acoustic profiles reveal a thin drape of glaciomarine sediment (<2.5 m thick) overlying the glacigenic deposits in certain parts of the inner and middle trough, whereas a detectable postglacial sediment drape in the outer trough is absent (Fig. 5). Lithofacies Dmm (diamict; subglacial debris/basal till) occurring as the lowermost units in all sediment cores provides supporting evidence that grounded ice from the GIS extended at least to the location of core HH17-1333. Laberg et al. (2017) argue that the lack of postglacial sediments and good preservation of glacial landforms in the outer trough indicate that the identified landforms formed during the LGM and subsequent deglaciation. Stein et al. (1996) presented sediment data from the continental slope off NE Greenland, suggesting that the maximum late Weichselian ice extent occurred at about 21-16 ka BP. Radiocarbon dates from the Greenland Basin indicate that mass-wasting activity on the upper continental slope took place predominantly under full glacial and deglacial conditions and had ceased after about 13 ka BP, leaving the channels largely inactive (Ó Cofaigh et al., 2004). Thus, from the data available, the outer parts of Store Koldewey Trough may have been ice covered in the period from ~21 ka BP - ~13 ka BP.~~

5.2 Glacial dynamics during deglaciation

The break-up and retreat of the GIS has been attributed to atmospheric and oceanic forcing, leading to ice melting along the glacier margins, as well as ice-sheet thinning (e.g. Buizert et al., 2014). Marine-based ice streams are sensitive to sea-level rise and enhanced thinning, potentially resulting in ice stream instability and collapse (Rignot et al., 2004; Thomas, 1979) (Fig. 9: Stage 2).

The presence of four large grounding zone wedges and multiple recessional moraines indicate that ~~multiple~~ repeated halts and/or readvances interrupted the deglaciation (Fig. ~~10~~9: Stage 3 and 4). ~~(~~Dowdeswell et al.~~,~~ (2008) and ~~(~~Ó Cofaigh et al.~~,~~ (2008) defined three types of ice stream retreat; rapid, episodic and slow. Following their definition, ~~T~~the occurrence of ~~such~~ grounding zone wedges and recessional moraines overprinting mega-scale glacial lineations ~~landforms~~ demonstrates an overall relatively slow retreat. ~~of a grounded ice margin accompanied by episodes of longer stillstands (Dowdeswell et al., 2008; Ó Cofaigh et al., 2008)~~. However, the exact deglaciation rates (both regarding the overall deglaciation of Store Koldewey Trough, as well as between the deposition of the landforms) remain to be defined from other data than ours.

~~The ice margin must have remained relatively stable for a sufficient period and/or had a considerable sediment flux rate to build large sedimentary depocenters.~~

~~We interpret the break-up and retreat of the GIS to have happened in two stages; initial retreat by breaking up and calving of grounded ice due to eustatic sea level rise caused by melting of ice at lower latitudes (Lambeck et al., 2014) (Fig. 9: Stage 2) and a second phase of melting driven by ocean warming, possibly due to the onset of inflow of intermediate water masses. The latter is supported by the occurrence of meltwater channels and laminated sediments interpreted to be a result of excessive meltwater production in the middle and inner parts of the trough.~~

Whereas many paleo-ice streams on other glaciated continental shelves with reverse bed slopes have experienced a lift-off from the seafloor and an initial rapid retreat due to sea-level rise, e.g. Norske Trough (Arndt et al., 2017), Amundsen Sea in West Antarctica (Smith et al., 2011) and NW Fennoscandian ~~i~~Ice ~~s~~Sheet (Rydningen et al., 2013)), the ice stream in Store Koldewey Trough ~~stayed grounded or~~ repeatedly stabilized and readvanced. ~~as the~~

~~trough shallows towards the coast.~~ A combination of ~~There are~~ several factors~~ that~~ ~~possibly can~~ may have preconditioned this, and led to the complex geomorphology in Store Koldewey Trough: i) local highs in ~~an~~ the overall shallowing landward seafloor profile may have provided pinning points, causing ice stabilization and promoting longer stillstands during the deglaciation; ii) tr~~h~~ough narrowing towards the coast may have increased lateral stress on the retreating ice margin, thus slowing down/stabilizing ice flow~~t~~; iii)~~ repeated advances due to glacial surges during deglaciation based on the documented grounding zone wedges *A* and *B* accompanied by crevasse-fill ridges; or iv~~) the GIS in Store Koldewey Trough possibly had a more dynamic response to the changing climatic and oceanographic conditions compared to troughs of similar dimensions elsewhere on the NE Greenland Margin. The grounding zone wedges in Store Koldewey Trough occur in areas of relatively marked decreased water depths and reductions in trough width (Fig. 1), indicating that local through geometry led to a repeated re-stabilization of the grounding line. Because the formation of grounding zone wedges and recessional moraines require a grounded ice stream/glacier margin we exclude a rapid/continuous retreat by ice stream flotation.

~~Whereas many paleo-ice streams on other glaciated continental shelves with reverse bed slopes experienced a lift-off from the seafloor and an initial rapid retreat due to sea-level rise, e.g. Norske Trough (Arndt et al., 2017), Amundsen Sea in West Antarctica (Smith et al., 2011) and NW Fennoscandian ice sheet (Rydningen et al., 2013)), the ice stream in Store Koldewey Trough stayed grounded or repeatedly stabilized as the trough shallows towards the coast. Consequently, Store Koldewey Trough has a more complex landform assemblage than other ice stream settings on formerly glaciated continental shelves (Fig. 10).~~

The locations and dimensions of grounding zone wedges on the NE Greenland continental shelf ~~have up to recent years been~~are thus far poorly documented. Batchelor and Dowdeswell (2015)~~,~~ and ~~referring to~~ Dowdeswell and Fugelli (2012), mention six grounding zone wedges in Store Koldewey Trough based ~~on IBCAO~~on seismic data. ~~However, our w~~Our data set reveals ~~provides evidence for the existence of only~~ four ~~GZWs~~grounding zone wedges. ~~Large~~ Additional grounding zone wedges have been documented from other cross-shelf troughs in the region (Arndt, 2018; Arndt et al., 2015, 2017; Evans et al., 2002; Winkelmann et al., 2010). These studies reveal, however, the occurrence of only single grounding zone wedges, e.g. in Norske Trough and Westwind Trough (Arndt et al., 2015; Winkelmann et al., 2010). Arndt et al. (2017) suggest that the grounding zone wedges in Norske Trough and Westwind Trough formed as the GIS readvanced during the Younger Dryas.~~ Based on the varying numbers of GZW´s we suggest that retreat/readvances of the ice streams offshore NE Greenland occurred asynchronously.~~

The formation of grounding zone wedges typically requires a stabilization of the ice margin for decades to centuries (Dowdeswell and Fugelli, 2012) (Fig. 9: Stage 4). This period can be estimated when sediment flux across the grounding line and grounding zone wedge volume are known (Howat and Domack, 2003). Grounding zone wedges *A* to *C* in Store Koldewey have volumes of approximately 130 000 m^3, 738 000 m^3 and 150 000 m^3 per meter grounding line width. In the absence of chronology we apply sediment flux of 10^2 to 10^3 m^3 m^{-1} yr^{-1} to the grounding line, as calculated for other paleo ice streams in Greenland (Hogan et al., 2012, 2020), the West Antarctic Ice Stream (Anandakrishnan et al., 2007) and on the southern Norwegian continental margin (Nygård et al., 2007). Applying these numbers suggests that the formations of grounding zone wedges *A*, *B* and *C* took at least 130, 740 and 150 years, respectively.

The recessional moraines are generally one to three orders of magnitude smaller than the grounding zone wedges. Accumulations of retreat moraines have repeatedly been referred to as ‘annual moraines’ correlated with annual cycles including winter advances and summer retreats during the overall deglaciation (Baeten et al., 2010; Boulton, 1986; Kempf et al., 2013; Ottesen and Dowdeswell, 2006) (Fig. 9: Stage 3). Assuming that accumulations of retreat moraines reflect annual moraines, we propose the following deglaciation velocities in the study area: following the formation of grounding zone wedge *A* at the shelf edge, the grounding line retreated with an average of 80 m yr^{-1} before accelerating to 200-400 m yr^{-1} on the outer shelf (Fig. 9: Stage 6). By the time the ice margin reached mid-shelf, spacing of individual moraines indicate a reduced recession of 100-200 m yr^{-1}.

~~The present sub-glacial topography of Storstrømmen consists of a reversed bed slope, accompanied by a floating ice tongue (Hill et al., 2018). Thus, a potential future response to increased ocean warming could result in episodes of rapid retreat as the ice front undergoes thinning and/or ice tongue collapse. Such episodes are believed to cause a dynamic response up-glacier, resulting in an accelerated ice flow, contributing directly to sea level rise (Hill et al., 2018).~~

The lithological sequence starting with a basal till overlain by glacimarine deposits suggests the transition from sub-glacial to ice-proximal and, subsequently, to a more ice-distal environment dominated by suspension settling with various degrees of ice rafting. Evans et al. (2002), ~~and~~ Smith et al. (2011) and ~~(~~Reilly et al.~~,~~ (2019) documented sedimentological facies with similar characteristics from the deglaciation of the trough offshore Kejser Franz Josef Fjord~~, and~~ the West Antarctica Ice Sheet and Petermann Glacier, respectively, implying that they recorded the transition from a grounded ice sheet to open marine environments. The deglacial lithofacies (3 and 4) reflect different depositional environments (Table 2): whereas the influence from meltwater was stronger during the deposition of facies 4, the supply of IRD was higher during the deposition of facies 3. The lack of IRD in an ice proximal setting may have several explanations;.i) the time of deposition may represent a period with an extensive sea-ice cover preventing icebergs to drift over the area (Jennings and Weiner, 1996; Moon et al., 2015; Vorren and Plassen, 2002), ii) a high flux of sediment-laden glacial meltwater mask the amount of IRD (Boulton, 1990) or iii) the sediments may be deposited in a sub-shelf environment far enough from the grounding line to be unaffected by mass flows and rain-out of basal debris (Domack and Harris, 1998; Jennings et al., 2019; Smith et al., 2017). Absence of basal debris in the ice stream seems unlikely given the underlying basal till (facies 5) and overlying facies 3 abundant of clasts and IRD. Nevertheless, Reilly et al. (2019) provided evidence of an IRD free depositional environment beneath the former ice tongue of Petermann Glacier in NW Greenland, with a following increase in IRD concentrations as the ice tongue retreated from the site. We note that facies 4, characterized by lamination and the absence of clasts, occurs exclusively in the two cores on the inner shelf. Given that the coring sites are located within depressions, it could be assumed that the ice detached from the ground leading to sub-ice shelf environments where deposition was dominated by suspension settling (compare with Reilly et al., 2019). We speculate that the trough narrowing towards the coast contributed to an increase in lateral drag and subsequent reduction in extensional stress as the ice front retreated to the inner shelf, resulting in a more stabilized ice front and ice-shelf formation (Fig. 9: Stage 5). ~~The deglacial lithofacies (3 and 4) reflect different depositional environments (Table 2): whereas the influence from meltwater was stronger during the deposition of facies 4, the supply of IRD was higher during the deposition of facies 3. The presence of facies 4 exclusively in the two westernmost cores suggest that either the style of retreat was different between the middle and inner part of the trough, or the deglacial lithofacies deposited during the initial ice retreat was removed from the middle trough area through winnowing. However, the identification of subglacial channels in the middle part of the trough indicate that meltwater was present.~~

5.3 Postglacial development

During the late phase of the deglaciation~~After the deglaciation of Store Koldewey Trough~~, the ice stream retreated across Store Koldewey Island and Germania Land (Fig. 9: Stage ~~9~~6).~~,~~ ~~terminating~~ This terminated the supply of suspended sediment and icebergs to Store Koldewey Trough, ~~and delivering icebergs and meltwater~~ re-routing the material to Dove Bugt and Jøkelbugten (Fig. 8B) ~~instead~~. ~~This resulted in the termination of sediment input from this sector of the GIS to Store Koldewey Trough, which~~The change of ice configuration and sediment supply may explain the thin sediment drape on top of the glacigenic deposits (Fig. 7).

Postglacial sedimentary processes in the trough are interpreted to comprise hemipelagic deposition of terrigenous~~estria~~l material from~~in~~ sea ice transported southwards from the Arctic Ocean with the Transpolar Drift, rainout from icebergs and meltwater plumes released from regional marine terminating outlet glaciers north of the study area (e.g. 79º-Glacier and Zachariae Isstrøm), ~~in addition to~~as well as winnowing on the surrounding banks.~~and resuspension of the finest sediment fraction within the uppermost lithological unit.~~

The low IRD content in facies 2 is probably due to ~~reflects a combination of~~ multiple factors: i) ice fronts retreating ~~from the marine realm~~on land, ii) ~~while~~ material entrapped in icebergs ~~from~~ calving off from marine-terminating glaciers probably melted out rapidly and icebergs only occasionally reached the continental shelf~~escaped the fjords~~. This could correlate to the Holocene Thermal Maximum (ca. 8-5 ka BP) when temperatures in NE Greenland were higher~~warmer~~ than at present (e.g. Dahl-Jensen et al., 1998; Klug et al., 2009), causing the Storstrømmen ice margin to retreat behind its present ice-extent (Bennike and Weidick, 2001; Weidick et al., 1996). Furthermore, sea-ice formation in the Arctic Ocean and on the NE Greenland shelf was reduced during that period (Koç et al. 1993; Funder et al. 2011b; Müller et al. 2012; Werner et al. 2016). The increasing input of IRD towards the top of the sediment cores (Fig. 2) is attributed to the ~~following~~ subsequent regional climatic cooling. This~~e~~ climate deterioration, referred to as the Neoglaciation (ca. 5 ka BP – Little Ice Age), le~~a~~d to glacier expansion with ~~increasing~~ enhanced iceberg-rafting and increased sea-ice extent on the East Greenland shelf (Klug et al., 2009; Müller et al., 2012). ~~(Fig. 9: Stage 9).~~

~~5.4 Possible surge activity during deglaciation~~

~~Crevasse-squeeze ridges are unique diagnostic landforms of glacier surges (Boulton et al., 1996; Evans and Rea, 1999; Sharp, 1985). In combination with grounding zone wedges and a seafloor characterized predominantly by iceberg ploughmarks, the landform assemblage is in coherence~~~~consistent~~ ~~with the observations from Solheim (1991) in front of Bråsvellbreen, Svalbard.~~

~~The modern surging ice stream Storstrømmen, which presumably drained through Store Koldewey Trough under full glacial conditions during the last glacial, may have undergone similar internal disequilibrium in the past, i.e. also during the deglaciation (Fig. 9: Stage 4 and 6). If correct, this is the first study to show that also paleo-ice streams draining the GIS had a surging behavior during the deglaciation. Surge activity during ice stream retreat has been proposed for other paleo-ice streams, e.g. the Bjørnøyrenna Ice Stream (Andreassen et al., 2014) and the Irish Ice Sheet (Delaney et al., 2018), in addition to modern West-Antarctic ice streams (Bindschadler, 1997; Hughes, 1973).~~

~~Triggering of an active surge phase in an ice stream is suggested to be driven by internal ice dynamics constrained by both the climate and topographic environment (Sevestre and Benn, 2015). If so, a coupling between climate as a single factor and paleo-grounding line positions in regions with surging glaciers may be problematic, possibly resulting in inaccurate climate reconstructions and modelling of the response contemporary ice sheets to future climate change (e.g. the West Antarctic Ice Sheet).~~

~~Possible surges in Store Koldewey Trough during the deglaciation could have caused an abrupt ice front collapse and reduction in the buttressing effect, leading to an increased mass flux and a larger ice volume released into the marine environment relative to other non-surging ice streams (compare with Dupont and Alley (2005) and Royston and Gudmundsson (2016)). Thus, the ice streams draining through Store Koldewey Trough might have acted as a major agent of transferring large volumes of ice from the interior of the GIS to its margin during the early deglaciation.~~

6 Conclusions

- New and previously published swath bathymetry data (Laberg et al., 2017), integrated with high-resolution seismic data reveal the existence of mega-scale glacial lineations, grounding zone wedges and recessional moraines providing new information about the dynamics of the northeastern sector of the Greenland Ice Sheet.
- ~~Mega-scale glacial lineations and a grounding zone wedge in the outer part of Store Koldewey Trough, NE Greenland, suggest that fast-flowing, grounded ice reached the continental shelf break during the LGM.~~

- The lithostratigraphy in Store Koldewey Trough, based on sediment gravity cores, includes subglacial till, covered with an up to 2.5 m thick drape of glacimarine sediments, the latter reflecting the transitions from sub-ice stream to glacier proximal to glacier distal deposits.
- The ice stream probably originated from the area presently covered with the Storstrømmen ice stream.~~,~~ ~~cutting across~~ It reached a thickness exceeding the height of the mountains on Store Koldewey Island and Germania Land, leading to ice flow independent of the subglacial topography during full glacial conditions and an early phase of the deglaciation.
- Grounding zone wedges and recessional moraines provide evidence that ~~M~~multiple halts and/or readvances interrupted the deglaciation. The formation of the grounding zone wedges took at least 130 years. Distances between the recessional moraines indicate that the grounding line locally retreated between 80 to 400 meters/year during the deglaciation.
- The ~~more~~ complex ~~assemblage of landforms~~geomorphology in Store Koldewey Trough ~~relative to other ice stream settings on high-latitude continental shelves~~ is attributed to the ~~ice retreating into shallower water during deglaciation~~trough shallowing and narrowing towards the coast, affecting the formation of grounding zone wedges.~~.~~ ~~Thus, the retreat/readvances in Store Koldewey Trough during deglaciation probably occurred asynchronously relative to other ice streams offshore NE Greenland.~~
- ~~Two sets of crevasse-squeezed ridges may indicate that the ice stream underwent at least two surges during the deglaciation.~~
- ~~At~~ Ice-sheet thinning during a late stage of the deglaciation led to topographically controlled ice flow, leading to diversion of the ice stream to Jøkelbugten and Dove Bugt, and, in consequence, ~~, the ice stream retreated across Store Koldewey Island and Germania Land,~~ terminating ~~the~~ sediment ~~input~~ supply ~~from the GIS~~ to Store Koldewey Trough.
- ~~Subglacial till fills the trough, with an overlying drape of postglacial sediments (<2.5 m).~~

Author contributions. The idea of the study developed from repeated discussions among the authors of this study and the opportunity to participate in ~~a~~ multiple scientific cruises to the study area. ILO, JS and TAR collected the new data during the *TUNU VII* cruise. The geophysical and lithological data ~~was~~ were interpreted by ILO ~~with help from~~in collaboration with MF, JSL and TAR. ILO conducted sample preparation and analyses of sediment data with help from KH. ILO wrote the manuscript with contributions from all authors.

Competing interests. The authors declare that they have no conflict of interest.

References

Aagaard, K. and Coachman, L. K.: The East Greenland Current North of Denmark Strait : Part I, Arctic, 21(3), 181–200, 1968.

Anandakrishnan, S., Catania, G. A., Alley, R. B. and Horgan, H. J.: Discovery of till deposition at the grounding line of Whillans Ice Stream, Science, 315(5820), 1835–1838, doi:10.1126/science.1138393, 2007.

Andreassen, K., Winsborrow, M. C. M., Bjarnadóttir, L. R. and Rüther, D. C.: Ice stream retreat dynamics inferred from an assemblage of landforms in the northern Barents Sea, Quaternary Sci. Rev., 92, 246–257, doi:10.1016/j.quascirev.2013.09.015, 2014.

Andrews, J. T. and Smithson, B. B.: Till fabrics of the cross-valley moraines of North-Central Baffin Island, Nortwest Territories, Canada, GSA Bull., 77(3), 271–290, 1966.

Andrews, J. T., Cooper, T. A., Jennings, A. E., Stein, A. B. and Erlenkeuser, H.: Late quaternary iceberg-rafted detritus events on the Denmark Strait-Southeast Greenland continental slope (~65°N): Related to North Atlantic Heinrich events?, Mar. Geol., 149(1–4), 211–228, doi:10.1016/S0025-3227(98)00029-2, 1998.

Arndt, J. E.: Marine geomorphological record of Ice Sheet development in East Greenland since the Last Glacial Maximum, J. Quaternary Sci., 33, 853–864, doi:10.1002/jqs.3065, 2018.

Arndt, J. E., Jokat, W., Dorschel, B., Myklebust, R., Dowdeswell, J. A. and Evans, J.: A new bathymetry of the Northeast Greenland continental shelf: Constraints on glacial and other processes, Geochem. Geophy. Geosy., doi:10.1002/2015GC005931, 2015.

Arndt, J. E., Jokat, W. and Dorschel, B.: The last glaciation and deglaciation of the Northeast Greenland continental shelf revealed by hydro-acoustic data, Quaternary Sci. Rev., 160, 45–56, doi:10.1016/j.quascirev.2017.01.018, 2017.

Baeten, N. J., Forwick, M., Vogt, C. and Vorren, T. O.: Late Weichselian and Holocene sedimentary environments and glacial activity in Billefjorden, Svalbard, Geol. Soc. Spec. Publ., 344(1), 207–223, doi:10.1144/SP344.15, 2010.

Bamber, J. L., Ekholm, S. and Krabill, W. B.: A new, high-resolution digital elevation model of Greenland fully data, J. Geophys. Res., 106(B4), 6733–6745, 2001.

Bamber, J. L., Riva, R. E. M., Vermeersen, B. L. A. and Lebrocq, A. M.: Reassessment of the Potential of the West Antarctic Ice Sheet, Science, 324(May), 901–904, doi:10.1126/science.1169335, 2009.

Batchelor, C. L. and Dowdeswell, J. A.: The physiography of High Arctic cross-shelf troughs, Quaternary Sci. Rev., 92, 68–96, doi:10.1016/j.quascirev.2013.05.025, 2014.

Batchelor, C. L. and Dowdeswell, J. A.: Ice-sheet grounding-zone wedges (GZWs) on high-latitude continental margins, Mar. Geol., 363, 65–92, doi:10.1016/j.margeo.2015.02.001, 2015.

Bendtsen, J., Mortensen, J., Lennert, K., Ehn, J. K., Boone, W., Galindo, V., Hu, Y. Bin, Dmitrenko, I. A., Kirillov, S. A., Kjeldsen, K. K., Kristoffersen, Y., Barber, D. G. and Rysgaard, S.: Sea ice breakup and marine melt of a retreating tidewater outlet glacier in northeast Greenland (81°N), Sci. Rep-UK, 7(1), 1–11, doi:10.1038/s41598-017-05089-3, 2017.

Bennett, M. R., Hambrey, M. J., Huddart, D. and Ghienne, J. F.: The formation of a geometrical ridge network by the surge-type glacier Kongsvegen, Svalbard, J. Quaternary Sci., 11(6), 437–449, doi:10.1002/(sici)1099-1417(199611/12)11:6<437::aid-jqs269>3.3.co;2-a, 1996.

Bennike, O. and Weidick, A.: Late Quaternary history around Nioghalvfjerdsfjorden and Jøkelbugten, North-East Greenland, Boreas, 30(3), 205–227, doi:DOI: 10.1111/j.1502-3885.2001.tb01223.x, 2001.

Bennike, O., Björck, S. and Lambeck, K.: Estimates of South Greenland late-glacial ice limits from a new relative sea level curve, Earth. Plane.t Sc. Lett., 197(3–4), 171–186, doi:10.1016/S0012-821X(02)00478-8, 2002.

Bentley, C. R.: Antarctic ice streams: a review, J. Geophys. Res., 92(6), 8843–8858, 1987.

Bjarnadóttir, L. R., Rüther, D. C., Winsborrow, M. C. M. and Andreassen, K.: Grounding-line dynamics during the last deglaciation of Kveithola, W Barents Sea, as revealed by seabed geomorphology and shallow seismic stratigraphy, Boreas, 42(1), 84–107, doi:10.1111/j.1502-3885.2012.00273.x, 2013.

Blott, S. J. and Pye, K.: GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments, Earth. Surf. Proc. Land., 26, 1237–1248, doi:10.1016/S0167-5648(08)70015-7, 2001.

Boulton, G. S.: Push-moraines and glacier-contact fans in marine and terrestrial environments, Sedimentology, 33(5), 677–698, doi:10.1111/j.1365-3091.1986.tb01969.x, 1986.

Boulton, G. S.: Sedimentary and sea level changes during glacial cycles and their control on glacimarine facies architecture., in Glacimarine environments: Processess and Sediments, edited by J. A. Dowdeswell and J. D. Scourse, pp. 15–52, Geological Society Special Publications., 1990.

Buizert, C., Gkinis, V., Severinghaus, J. P., He, F., Lecavalier, B. S., Kindler, P., Leuenberger, M., Carlson, A. E., Vinther, B., Masson-Delmotte, V., White, J. W. C., Liu, Z., Otto-Bliesner, B. and Brook, E. J.: Greenland temperature response to climate forcing during the last deglaciation, Science, 345(6201), 1177–1180, doi:10.1126/science.1254961, 2014.

Burki, V., Larsen, E., Fredin, O. and Margreth, A.: The formation of sawtooth moraine ridges in Bødalen, western Norway, Geomorphology, 105(3–4), 182–192, doi:10.1016/j.geomorph.2008.06.016, 2009.

Canals, M., Urgeles, R. and Calafat, A. M.: Deep sea-floor evidence of past ice streams off the Antarctic Peninsula, Geology, 28(1), 31–34, doi:10.1130/0091-7613(2000)028<0031:DSEOPI>2.0.CO;2, 2000.

Chandler, B. M. P., Evans, D. J. A. and Roberts, D. H.: Characteristics of recessional moraines at a temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat, Quaternary Sci. Rev., 135, 171–205, doi:10.1016/j.quascirev.2016.01.025, 2016.

Christiansen, J. S.: The TUNU-programme: euro-arctic marine fishes – diversity and adaption., in Adaptation and Evolution in Marine Environments, Volume 1. From Pole to Pole., edited by V. C. Di Prisco G, pp. 35–50, Springer, Berlin, Heidelberg., 2012.

Clark, C. D.: Mega-scale glacial lineations and cross-cutting ice-flow landforms, Earth. Surf. Proc. Land., 18, 1–29, 1993.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G. D., Johnsen, S. J., Hansen, A. W. and Balling, N.: Past Temperatures Directly from the Greenland Ice Sheet, Science, 282, 268–271, doi:10.1126/science.282.5387.268, 1998.

Dahl-Jensen, D., Bamber, J. L., Bøggild, C. E., Buch, E., Christensen, J. H., Dethloff, K., Fahnestock, M., Marshall, S., Rosing, M., Steffen, K., Thomas, R., Truffer, M., van den Broeke, M. R. and van der Veen, C. J.: Summary: The Greenland Ice Sheet in a Changing Climate, SWIPA Snow, Water, Ice Permafrost in the Arctic (SWIPA), 1–22, doi:10.1007/s00018-010-0512-6, 2009.

Domack, E. W. and Harris, P. T.: A new depositional model for ice shelves, based upon sediment cores from the Ross Sea and the Mac. Robertson shelf, Antarctica, Ann. Glaciol., 27(3), 281–284, doi:10.3189/1998aog27-1-281-284, 1998.

Dowdeswell, J. A. and Fugelli, E. M. G.: 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, doi:10.1130/B30628.1, 2012.

Dowdeswell, J. A., Hamilton, G. S. and Hagen, J. O.: The duration of the active phase on surge-type glaciers: contrasts between Svalbard and other regions, J. Glaciol., 37(127), 388–400, 1991.

Dowdeswell, J. A., Uenzelmann-Neben, G., Whittington, R. J. and Marienfeld, P.: The Late Quaternary sedimentary record in Scoresby Sund, East Greenland, Boreas, 23(4), 294–310, doi:10.1111/j.1502-3885.1994.tb00602.x, 1994.

Dowdeswell, J. A., Ottesen, D., Evans, J., Cofaigh, C. Ó. and Anderson, J. B.: Submarine glacial landforms and rates of ice-stream collapse, Geology, doi:10.1130/G24808A.1, 2008.

Dowdeswell, J. A., Hogan, K. A., Ó Cofaigh, C., Fugelli, E. M. G., Evans, J. and Noormets, R.: Late Quaternary ice flow in a West Greenland fjord and cross-shelf trough system: Submarine landforms from Rink Isbrae to Uummannaq shelf and slope, Quaternary Sci. Rev., 92, 292–309, doi:10.1016/j.quascirev.2013.09.007, 2014.

Evans, D. J. A., Phillips, E. R., Hiemstra, J. F. and Auton, C. A.: Subglacial till: Formation, sedimentary characteristics and classification, Earth-Sci. Rev., 78(1–2), 115–176, doi:10.1016/j.earscirev.2006.04.001, 2006.

Evans, D. J. A., Ewertowski, M. and Orton, C.: Fláajökull (north lobe), Iceland: active temperate piedmont lobe glacial landsystem, J. Maps, 12(5), 777–789, doi:10.1080/17445647.2015.1073185, 2016.

Evans, J., Dowdeswell, J. A., Grobe, H., Niessen, F., Stein, R., Hubberten, H.-W. and Whittington, R. J.: Late Quaternary sedimentation in Kejser Franz Joseph Fjord and the continental margin of East Greenland, Geol. Soc. Spec. Publ., 203(1), 149–179, doi:10.1144/GSL.SP.2002.203.01.09, 2002.

Evans, J., Ó Cofaigh, C., Dowdeswell, J. A. and Wadhams, P.: Marine geophysical evidence for former expansion and flow of the Greenland Ice Sheet across the north-east Greenland continental shelf, J. Quaternary Sci., doi:10.1002/jqs.1231, 2009.

Fahnestock, M., Bindschadler, R., Kwok, R. and Jezek, K.: Greenland Ice Sheet surface properties and ice dynamics from ERS-1 SAR imagery, Science, 262(5139), 1530–1534, doi:10.1126/science.262.5139.1530, 1993.

Fleming, K. and Lambeck, K.: Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models, Quaternary Sci. Rev., 23(9–10), 1053–1077, doi:10.1016/j.quascirev.2003.11.001, 2004.

Funder, S., Goosse, H., Jepsen, H., Kaas, E., Kjær, K. H., Korsgaard, N. J., Larsen, N. K., Linderson, H., Lyså, A., Möller, P., Olsen, J. and Willerslev, E.: A 10,000-Year Record of Arctic Ocean Sea-Ice Variability—View from the Beach, Science, 333, 747–750, doi:10.2307/j.ctv9zcj2n.53, 2011a.

Funder, S., Kjeldsen, K. K., Kjær, K. H. and Ó Cofaigh, C.: The Greenland Ice Sheet During the Past 300,000 Years: A Review, Developments in Quaternary Sciences, 15(December), 699–713, doi:10.1016/B978-0-444-53447-7.00050-7, 2011b.

Fürst, J. J., Goelzer, H. and Huybrechts, P.: Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming, The Cryosphere, 9(3), 1039–1062, doi:10.5194/tc-9-1039-2015, 2015.

Heinemann, M., Timmermann, A., Elison Timm, O., Saito, F. and Abe-Ouchi, A.: Deglacial ice sheet meltdown: Orbital pacemaking and CO2 effects, Clim. Past, 10(4), 1567–1579, doi:10.5194/cp-10-1567-2014, 2014.

Hill, E. A., Carr, J. R., Stokes, C. R. and Gudmundsson, G. H.: Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015, The Cryosphere, 1–39, doi:10.5194/tc-2018-17, 2018.

Hogan, K. A., Dowdeswell, J. A., Noormets, R., Evans, J. and Ó Cofaigh, C.: Evidence for full-glacial flow and retreat of the Late Weichselian Ice Sheet from the waters around Kong Karls Land, eastern Svalbard, Quaternary Sci. Rev., 29(25–26), 3563–3582, doi:10.1016/j.quascirev.2010.05.026, 2010.

Hogan, K. A., Dix, J. K., Lloyd, J. M., Long, A. J. and Cotterill, C. J.: Seismic stratigraphy records the deglacial history of Jakobshavn Isbræ, West Greenland, J. Quaternary Sci., 26(7), 757–766, doi:10.1002/jqs.1500, 2011.

Hogan, K. A., Dowdeswell, J. A. and ÓCofaigh, C.: Glacimarine sedimentary processes and depositional environments in an embayment fed by West Greenland ice streams, Mar. Geol., 311–314, 1–16, doi:10.1016/j.margeo.2012.04.006, 2012.

Hogan, K. A., Colm, O., Jennings, A. E., Dowdeswell, J. A. and Hiemstra, J. F.: Deglaciation of a major palaeo-ice stream in Disko Trough , West Greenland, Quaternary Sci. Rev., 147, 5–26, doi:10.1016/j.quascirev.2016.01.018, 2016.

Hogan, K. A., Jakobsson, M., Mayer, L., Reilly, B. T., Jennings, A. E., Stoner, J. S., Nielsen, T., Andresen, K. J., Nørmark, E., Heirman, K. A., Kamla, E., Jerram, K., Stranne, C. and Mix, A.: Glacial sedimentation, fluxes and erosion rates associated with ice retreat in Petermann Fjord and Nares Strait, north-west Greenland, The Cryosphere, 14(1), 261–286, doi:10.5194/tc-14-261-2020, 2020.

Hopkins, T. S.: The GIN Sea-A synthesis of its physical oceanography and literature review 1972-1985, Earth-Sci. Rev., 30(3–4), 175–318, doi:10.1016/0012-8252(91)90001-V, 1991.

Howat, I. and Domack, E.: Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution acoustic stratigraphy, Boreas, 32(1), 56–75, doi:10.1080/03009480310001038, 2003.

Hubberten, H., Grobe, H., Jokat, W., Melles, M., Niessen, F. and Stein, R.: Glacial history of East Greenland explored, Eos Trans. AGU, 76(36), 353–356, 1995.

IPCC: IPCC special report on the impacts of global warming of 1.5 °C - Summary for policy makers, , (October 2018) [online] Available from: http://www.ipcc.ch/report/sr15/, 2018.

Jakobsson, M., Anderson, J. B., Nitsche, F. O., Gyllencreutz, R., Kirshner, A. E., Kirchner, N., O'Regan, M., Mohammad, R. and Eriksson, B.: Ice sheet retreat dynamics inferred from glacial morphology of the central Pine Island Bay Trough, West Antarctica, Quaternary Sci. Rev., 38, 1–10, doi:10.1016/j.quascirev.2011.12.017, 2012a.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G. and Weatherall, P.: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, Geophys. Res. Lett., 39(12), 1–6, doi:10.1029/2012GL052219, 2012b.

Jennings, A. E. and Weiner, N. J.: Environmental change in eastern Greenland during the last 1300 years : evidence from foraminifera and lithofacies in Nansen Fjord, 68°N, Holocene, 6(2), 179–191, 1996.

Jennings, A. E., Reilly, B., Andrews, J. T., Hogan, K. A., Walczak, M., Stoner, J., Mix, A. and Jakobsson, M.: Sedimentological and faunal evidence of ice shelves during the Early Holocene deglaciation of Nares Strait, in 49th International Arctic Workshop, Program and Abstracts 2019, p. 67, Stockholm University., 2019.

Joughin, I. R., Fahnestock, M. A. and Bamber, J. L.: Ice flow in the northeast Greenland ice stream, Ann. Glaciol., 31, 141–146, doi:10.1016/j.radphyschem.2012.12.021, 2000.

Kempf, P., Forwick, M., Laberg, J. S. and Vorren, T. O.: Late Weichselian and Holocene sedimentary palaeoenvironment and glacial activity in the high-arctic van Keulenfjorden, Spitsbergen, Holocene, 23(11), 1607–1618, doi:10.1177/0959683613499055, 2013.

Khan, S. A., Kjær, K. H., Bevis, M., Bamber, J. L., Wahr, J., Kjeldsen, K. K., Bjørk, A. A., Korsgaard, N. J., Stearns, L. A., Van Den Broeke, M. R., Liu, L., Larsen, N. K. and Muresan, I. S.: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming, Nat. Clim. Change, 4(4), 292–299, doi:10.1038/nclimate2161, 2014.

King, E. C., Hindmarsh, R. C. A. and Stokes, C. R.: Formation of mega-scale glacial lineations observed beneath a West Antarctic ice stream, Nat. Geosci., 2(8), 585–588, doi:10.1038/ngeo581, 2009.

Klages, J. P., Kuhn, G., Hillenbrand, C. D., Graham, A. G. C., Smith, J. A., Larter, R. D. and Gohl, K.: First geomorphological record and glacial history of an inter-ice stream ridge on the West Antarctic continental shelf, Quaternary Sci. Rev., 61, 47–61, doi:10.1016/j.quascirev.2012.11.007, 2013.

Klug, M., Bennike, O. and Wagner, B.: Repeated short-term bioproductivity changes in a coastal lake on Store Koldewey, northeast Greenland: An indicator of varying sea-ice coverage?, Holocene, 19(4), 653–663, doi:10.1177/0959683609104040, 2009.

Koç, N., Jansen, E. and Haflidason, H.: Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian Seas through the last 14 ka based on diatoms, Quaternary Sci. Rev., 12, 115–140, 1993.

Kurjanski, B., Rea, B. R., Spagnolo, M., Winsborrow, M., Cornwell, D. G., Andreassen, K. and Howell, J.: Morphological evidence for marine ice stream shutdown, central Barents Sea, Mar. Geol., 414(April), 64–76, doi:10.1016/j.margeo.2019.05.001, 2019.

Laberg, J. S., Forwick, M. and Husum, K.: New geophysical evidence for a revised maximum position of part of the NE sector of the Greenland ice sheet during the last glacial maximum, Arktos, 3(1), 3, doi:10.1007/s41063-017-0029-4, 2017.

Landvik, J. Y.: The last glaciation of Germania Land and adjacent areas, northeast Greenland, J. Quaternary Sci., 9(1), 81–92, doi:10.1002/jqs.3390090108, 1994.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S. and Joachim, H.: Tipping elements in the Earth's climate system, P. Nartl. Acad. Sci. USA, 105(6), 1786 –1793, doi:10.1073/pnas.0705414105, 2008.

Matthews, J. A., Cornish, R. and Shakesby, R. A.: "Saw-Tooth" Moraines in Front of Bødalsbreen, Southern Norway, J. Glaciol., 22(88), 535–546, doi:10.3189/s0022143000014519, 1979.

Mayer, C., Schaffer, J., Hattermann, T., Floricioiu, D., Krieger, L., Dodd, P. A., Kanzow, T., Licciulli, C. and

Schannwell, C.: Large ice loss variability at Nioghalvfjerdsfjorden Glacier, Northeast-Greenland, Nat. Commun., 9(1), 1–11, doi:10.1038/s41467-018-05180-x, 2018.

Moon, T., Joughin, I. and Smith, B.: Seasonal to multiyear variability of glacier surface velocity, terminus position, and sea ice/ice mélange in northwest Greenland, J. Geophys. Res-Earth, 120, 818–833, doi:10.1002/2015JF003494, 2015.

Mouginot, J., Bjørk, A. A., Millan, R., Scheuchl, B. and Rignot, E.: Insights on the surge behavior of Storstrømmen and L . Bistrup Bræ , northeast Greenland , over the last century., Geophys. Res. Lett., 45, 11,197-11,205, doi:10.1029/2018GL079052, 2018.

Müller, J., Werner, K., Stein, R., Fahl, K., Moros, M. and Jansen, E.: Holocene cooling culminates in sea ice oscillations in Fram Strait, Quaternary Sci. Rev., 47, 1–14, doi:10.1016/j.quascirev.2012.04.024, 2012.

Munsell, A. H.: Munsell soil color charts, Munsell Color Company, doi:10.1111/1911-3846.12037, 2000.

Nick, F. M., Vieli, A., Andersen, M. L., Joughin, I., Payne, A., Edwards, T. L., Pattyn, F. and Van De Wal, R. S. W.: Future sea-level rise from Greenland's main outlet glaciers in a warming climate, Nature, 497(7448), 235–238, doi:10.1038/nature12068, 2013.

Nygård, A., Sejrup, H. P., Haflidason, H., Lekens, W. A. H., Clark, C. D. and Bigg, G. R.: Extreme sediment and ice discharge from marine-based ice streams: New evidence from the North Sea, Geology, 35(5), 395–398, doi:10.1130/G23364A.1, 2007.

Ó Cofaigh, C. and Dowdeswell, J. A.: Laminated sediments in glacimarine environments: Diagnostic criteria for their interpretation, Quaternary Sci. Rev., 20(13), 1411–1436, doi:10.1016/S0277-3791(00)00177-3, 2001.

Ó Cofaigh, C., Dowdeswell, J. A., Evans, J., Kenyon, N. H., Taylor, J., Mienert, J. and Wilken, M.: Timing and significance of glacially influenced mass-wasting in the submarine channels of the Greenland Basin, Mar. Geol., 207(1–4), 39–54, doi:10.1016/j.margeo.2004.02.009, 2004.

Ó Cofaigh, C., Evans, J., Dowdeswell, J. A. and Larter, R. D.: Till characteristics, genesis and transport beneath Antarctic paleo-ice streams, J. Geophys. Res-Earth, 112(3), 1–16, doi:10.1029/2006JF000606, 2007.

Ó Cofaigh, C., Dowdeswell, J. A., Evans, J. and Larter, R. D.: Geological constraints on Antarctic palaeo-ice-stream retreat, Earth. Surf. Proc. Land., 33, 513–525, doi:10.1002/esp, 2008.

Ó Cofaigh, C., Evans, D. J. A. and Smith, I. R.: Large-scale reorganization and sedimentation of terrestrial ice streams during late Wisconsinan Laurentide Ice Sheet deglaciation, Bull. Geol. Soc. Am., 122(5–6), 743–756, doi:10.1130/B26476.1, 2010.

Ó Cofaigh, C., Dowdeswell, J. A., Jennings, A. E., Hogan, K. A., Kilfeather, A., Hiemstra, J. F., Noormets, R., Evans, J., McCarthy, D. J., Andrews, J. T., Lloyd, J. M. and Moros, M.: An extensive and dynamic ice sheet on the west greenland shelf during the last glacial cycle, Geology, 41(2), 219–222, doi:10.1130/G33759.1, 2013.

Ottesen, D. and Dowdeswell, J. A.: Assemblages of submarine landforms produced by tidewater glaciers in Svalbard, J. Geophys. Res-Earth, 111(1), 1–16, doi:10.1029/2005JF000330, 2006.

Ottesen, D. and Dowdeswell, J. A.: 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, doi:10.1130/B26467.1, 2009.

Ottesen, D., Dowdeswell, J. A. and Rise, L.: 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), Bull. Geol. Soc. Am., 117(7–8), 1033–1050, doi:10.1130/B25577.1, 2005.

Petersen, T. G., Hamann, N. E. and Stemmerik, L.: Tectono-sedimentary evolution of the Paleogene succession offshore Northeast Greenland, Mar. Petrol. Geol., 67, 481–497, doi:10.1016/j.marpetgeo.2015.05.033, 2015.

Reilly, B. T., Stoner, J. S., Mix, A. C., Walczak, M. H., Jennings, A., Jakobsson, M., Dyke, L., Glueder, A., Nicholls, K., Hogan, K. A., Mayer, L. A., Hatfield, R. G., Albert, S., Marcott, S., Fallon, S. and Cheseby, M.: Holocene break-up and reestablishment of the Petermann Ice Tongue, Northwest Greenland, Quaternary Sci. Rev., 218, 322–342, doi:10.1016/j.quascirev.2019.06.023, 2019.

Rignot, E. and Kanagaratnam, P.: Changes in the velocity structure of the Greenland Ice Sheet, Science, 311(5763), 986–990, doi:10.1126/science.1121381, 2006.

Rignot, E., Casassa, G., Gogineni, P., Krabill, W., Rivera, A. and Thomas, R.: Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, Geophys. Res. Lett., 31(18), 2–5, doi:10.1029/2004GL020697, 2004.

Rydningen, T. A., Vorren, T. O., Laberg, J. S. and Kolstad, V.: The marine-based NW Fennoscandian ice sheet: Glacial and deglacial dynamics as reconstructed from submarine landforms, Quaternary Sci. Rev., 68, 126–141, doi:10.1016/j.quascirev.2013.02.013, 2013.

Sachau, T., Bons, P. and Jansen, D.: The dynamics and geometry of pure ice streams: a new numerical approach, in EGU General Assembly Conference Abstracts, p. 18623, Vienna, Austria., 2018.

Serreze, M. C. and Francis, J. A.: The arctic amplification debate, Climatic Change, 76(3–4), 241–264, doi:10.1007/s10584-005-9017-y, 2006.

Skov, D. S., Andersen, J. L., Olsen, J., Jacobsen, B. H., Knudsen, M. F., Jansen, J. D., Larsen, N. K. and Egholm, D. L.: Constraints from cosmogenic nuclides on the glaciation and erosion history of Dove Bugt , northeast Greenland, Geol. Soc. Am. Bull., 1–13, doi:10.1130/B35410.1/4966781/b35410.pdf, 2020.

Smith, J. A., Hillenbrand, C. D., Kuhn, G., Larter, R. D., Graham, A. G. C., Ehrmann, W., Moreton, S. G. and Forwick, M.: Deglacial history of the West Antarctic Ice Sheet in the western Amundsen Sea Embayment, Quaternary Sci. Rev., 30(5–6), 488–505, doi:10.1016/j.quascirev.2010.11.020, 2011.

Smith, J. A., Andersen, T. J., Shortt, M., Gaffney, A. M., Truffer, M., Stanton, T. P., Bindschadler, R., Dutrieux, P., Jenkins, A., Hillenbrand, C. D., Ehrmann, W., Corr, H. F. J., Farley, N., Crowhurst, S. and Vaughan, D. G.: Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier, Nature, 541(7635), 77–80, doi:10.1038/nature20136, 2017.

Spagnolo, M., Clark, C. D., Ely, J. C., Stokes, C. R., Anderson, J. B., Andreassen, K., Graham, A. G. C. and King, E. C.: Size , shape and spatial arrangement of mega-scale glacial lineations from a large and diverse dataset, Earth. Surf. Proc. Land., 39, 1432–1448, doi:10.1002/esp.3532, 2014.

Stein, R., Nam, S.-I., Grobe, H. and Hubberten, H.-W.: Late Quaternary glacial history and short-term ice-rafted debris fluctuations along the East Greenland continental margin, in Late Quaternary Palaeoceanography of the North Atlantic Margins, vol. 111, edited by J. T. Andrews, W. E. N. Austin, H. Bergsten, and A. E. Jennings, pp. 135–151, Geological Society Special Publications., 1996.

Stewart, F. S. and Stoker, M. S.: Problems associated with seismic facies analysis of diamicton-dominated, shelf glacigenic sequences, Geo-Mar. Lett., 10(3), 151–156, doi:10.1007/BF02085930, 1990.

Stokes, C. R. and Clark, C. D.: Geomorphological criteria for identifying Pleistocene ice streams, Ann. Glaciol., 28(4), 67–74, doi:10.3189/172756499781821625, 1999.

Straneo, F. and Heimbach, P.: North Atlantic warming and the retreat of Greenland’s outlet glaciers, Nature, 504(7478), 36–43, doi:10.1038/nature12854, 2013.

Syring, N., Stein, R., Fahl, K., Vahlenkamp, M., Zehnich, M., Spielhagen, R. F. and Niessen, F.: Holocene changes in sea-ice cover and polynya formation along the eastern North Greenland shelf: New insights from biomarker records, Quaternary Sci. Rev., 231, doi:10.1016/j.quascirev.2020.106173, 2020.

Thomas, R. H.: The dynamics of marine ice sheets, J. Glaciol., 24(90), 167–177, doi:10.3189/s0022143000014726, 1979.

Vorren, T. O. and Plassen, L.: Late weichselian and holocene sediment flux and sedimentation rates in Andfjord and Vågsfjord, North Norway, J. Quaternary Sci., doi:10.1002/jqs.662, 2002.

Vorren, T. O., Hald, M., Edvardsen, M. and Lind-Hansen, O. W.: Glacigenic sediments and sedimentary environments on continental shelves: general principles with a case study from the Norwegian shelf., Glacial Depos. north-west Eur., 61–73, 1983.

Vorren, T. O., Hald, M. and Lebesbye, E.: Late Cenozoic environments in the Barents Sea, Paleoceanography, 3(5), 601–612, 1988.

Weber, M. E., Niessen, F., Kuhn, G. and Wiedicke, M.: Calibration and application of marine sedimentary physical properties using a multi-sensor core logger, Mar. Geol., 136(3–4), 151–172, 1997.

Weidick, A., Andreasen, C., Oerter, H. and Reeh, N.: Neoglacial glacier changes around Storstrommen, north-east

Greenland, Polarforschung, 64(3), 95–108, 1996.

Werner, K., Müller, J., Husum, K., Spielhagen, R. F., Kandiano, E. S. and Polyak, L.: Holocene sea subsurface and surface water masses in the Fram Strait – Comparisons of temperature and sea-ice reconstructions, Quaternary Sci. Rev., 147, 194–209, doi:10.1016/j.quascirev.2015.09.007, 2016.

Wilson, N. J. and Straneo, F.: Water exchange between the continental shelf and the cavity beneath Nioghalvfjerdsbræ (79 North Glacier), Geophys. Res. Lett., 42(18), 7648–7654, doi:10.1002/2015GL064944, 2015.

Winkelmann, D., Jokat, W., Jensen, L. and Schenke, H. W.: Submarine end moraines on the continental shelf off NE Greenland - Implications for Lateglacial dynamics, Quaternary Sci. Rev., 29(9–10), 1069–1077, doi:10.1016/j.quascirev.2010.02.002, 2010.

Winsborrow, M. C. M., Andreassen, K., Corner, G. D. and Laberg, J. S.: Deglaciation of a marine-based ice sheet: Late Weichselian palaeo-ice dynamics and retreat in the southern Barents Sea reconstructed from onshore and offshore glacial geomorphology, Quaternary Sci. Rev., 29(3–4), 424–442, doi:10.1016/j.quascirev.2009.10.001, 2010.

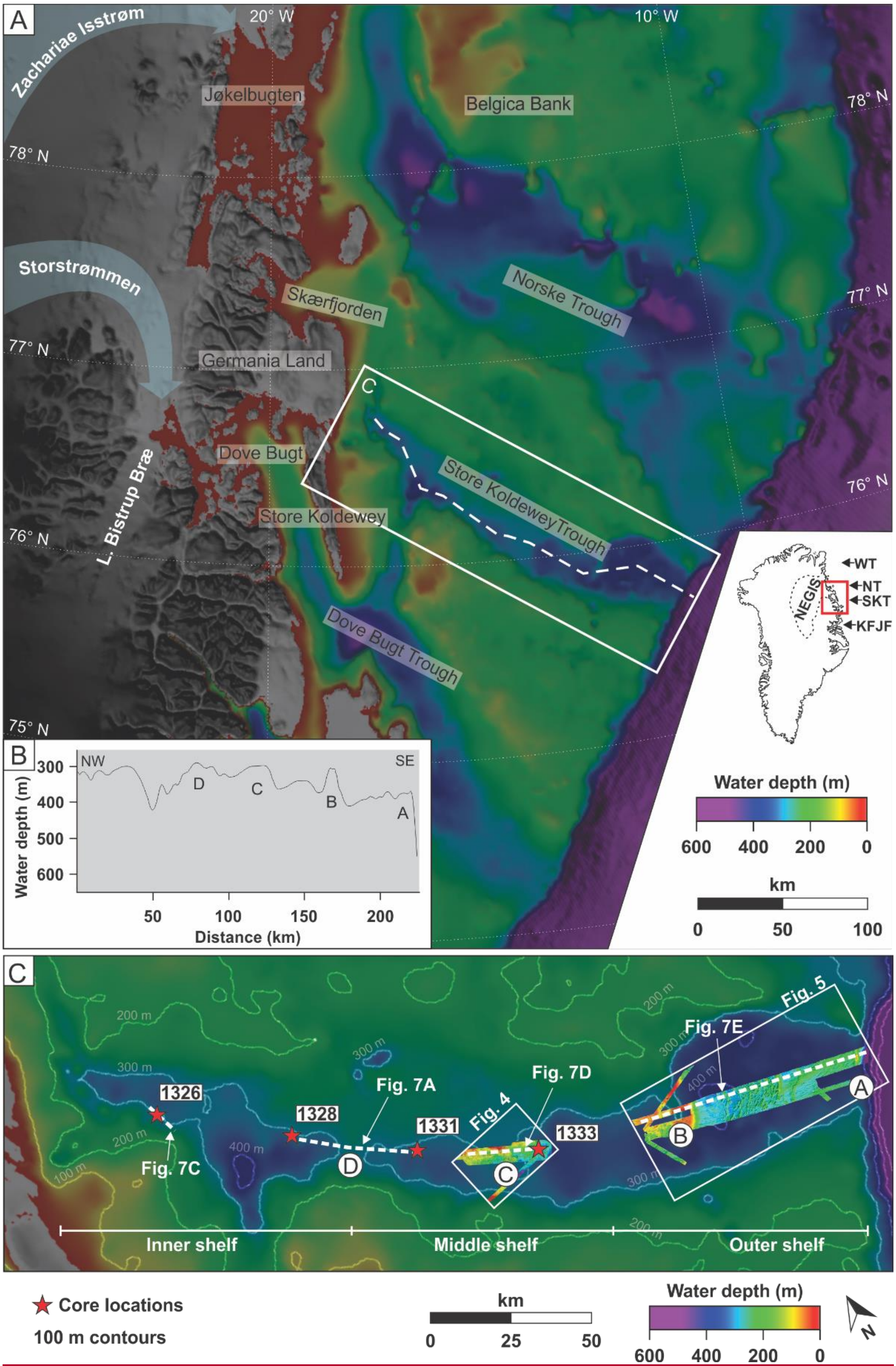
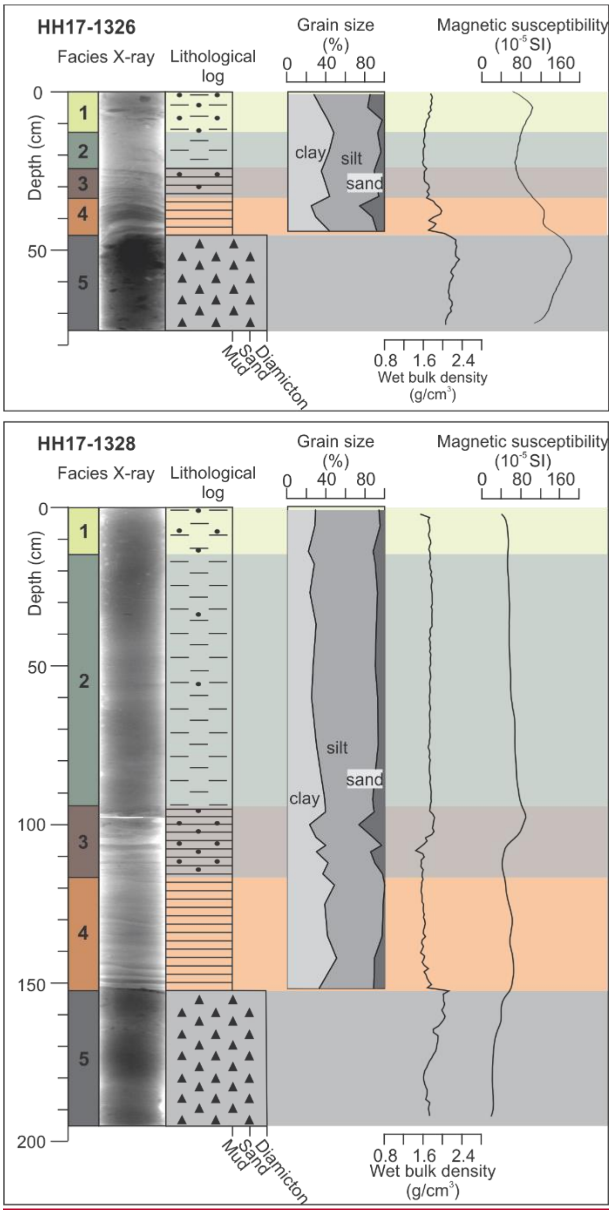


Figure 1: (A) Overview of the regional bathymetry and the hinterland topography of northeast Greenland (from IBCAO v.3.0; Jakobsson et al. 2012b) including geographical names. The small map shows Greenland and the outline of the North East Greenland Ice Stream (NEGIS). The locations of Westwind Trough (WT), Norske Trough (NT), Store Koldewey Trough (SKT) and Kejser Franz Josef Fjord (KFJF) are indicated. White dashed line shows the location of bathymetric profile shown in (B). (B) Bathymetric profile of Store Koldewey Trough. The labels A-D show the locations of interpreted grounding-zone wedges as described by Laberg et al. (2017). (C) Large-scale bathymetry of Store Koldewey Trough (from IBCAO v.3.0; Jakobsson et al. 2012b) including the swath bathymetry data analyzed in this study. The labels A-D represent grounding-zone wedges (adapted from Laberg et al. 2017), red stars show core locations.


HH17-1326
Facies
X-ray
Lithological log
Grain size (%)
0 40 80
Magnetic susceptibility (10^{-5} SI)
0 80 160
Depth (cm)
0
50
1
2
3
4
5
clay
silt
sand
Mud
Sand
Diamicton
0.8 1.6 2.4
Wet bulk density (g/cm^3)
HH17-1328
Facies
X-ray
Lithological log
Grain size (%)
0 40 80
Magnetic susceptibility (10^{-5} SI)
0 80 160
Depth (cm)
0
50
100
150
200
1
2
3
4
5
silt
sand
clay
Mud
Sand
Diamicton
0.8 1.6 2.4
Wet bulk density (g/cm^3)

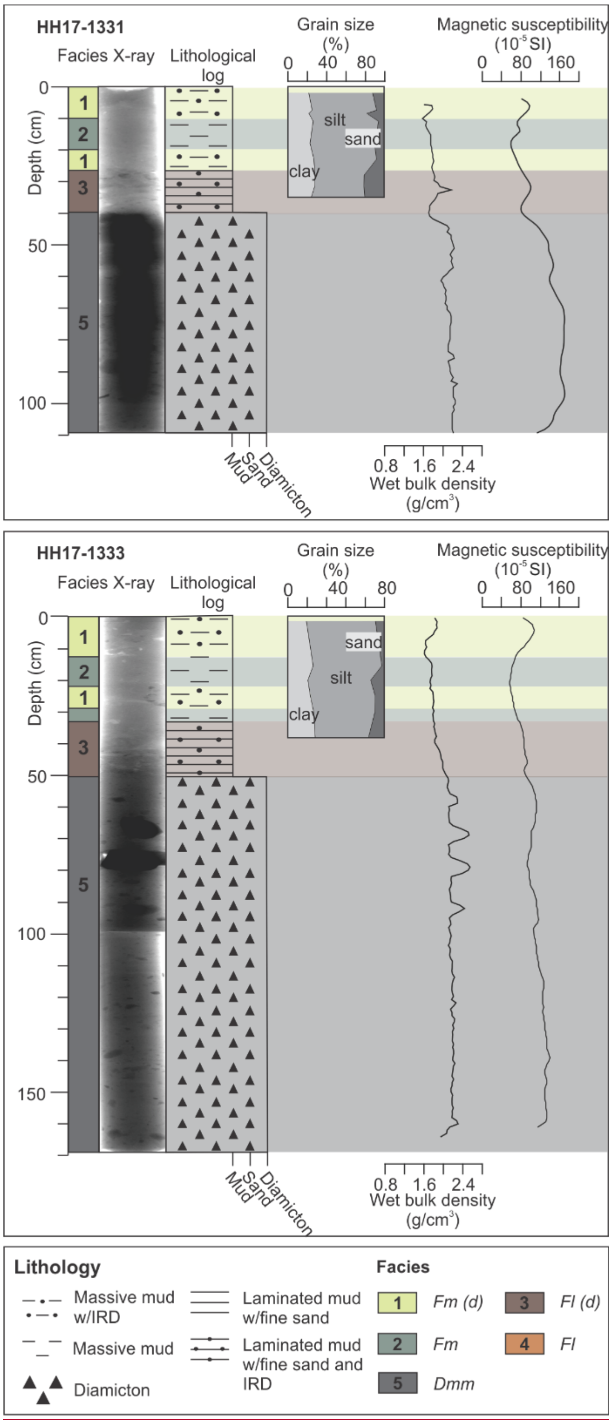


Figure 2. Sedimentary lithofacies logs, X-radiographs, grain-size distribution~~,~~ and physical properties ~~and XRF core scanning geochemistry~~ for the cores from inner and middle Store Koldewey Trough. The darker grey tones in the X-radiographs reflect higher density, whereas brighter grey tones reflect lower density. The locations of the sediment cores are shown in Fig. 1C.

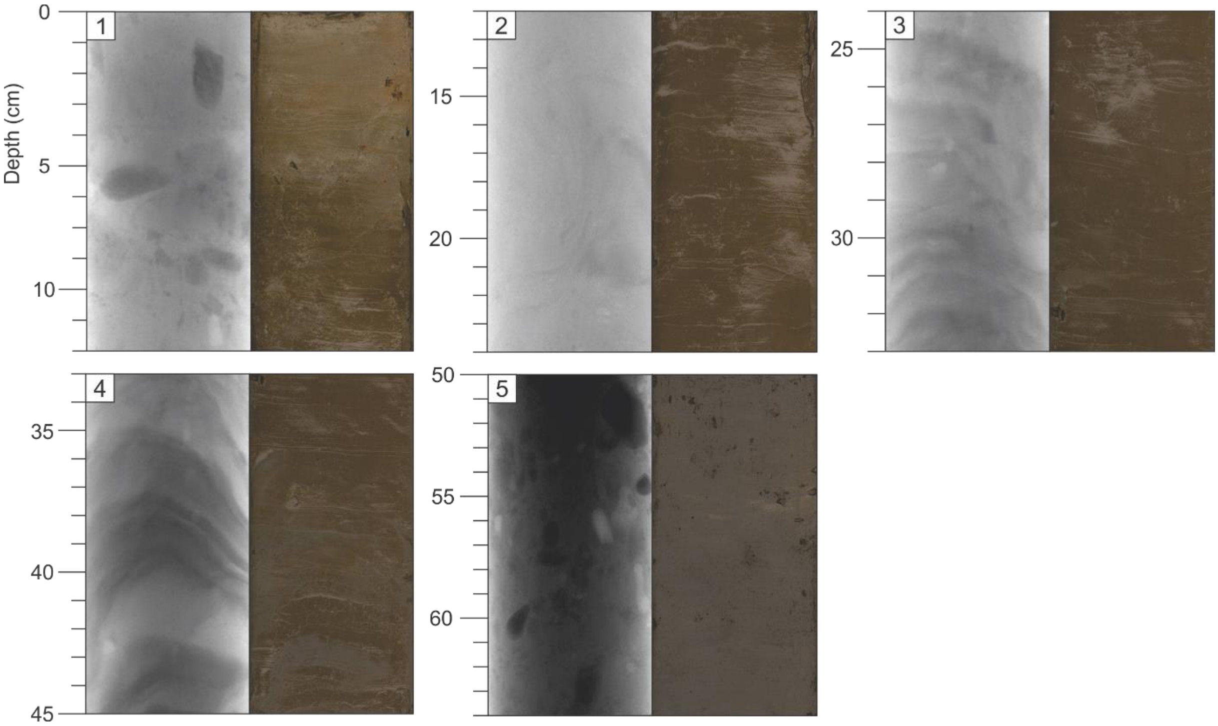


Figure 3. X-radiographs with associated photographs of representative lithofacies in this study, all from core HH17-1326. (1) Massive mud with IRD (Fm (d)). (2) Massive mud (Fm). (3) Laminated mud with occasional IRD (Fl (d)). (4) Laminated mud (Fl). (5) Diamicton (Dmm). The darker grey tones on the X-radiographs reflect higher density, whereas brighter grey tones reflect lower density.

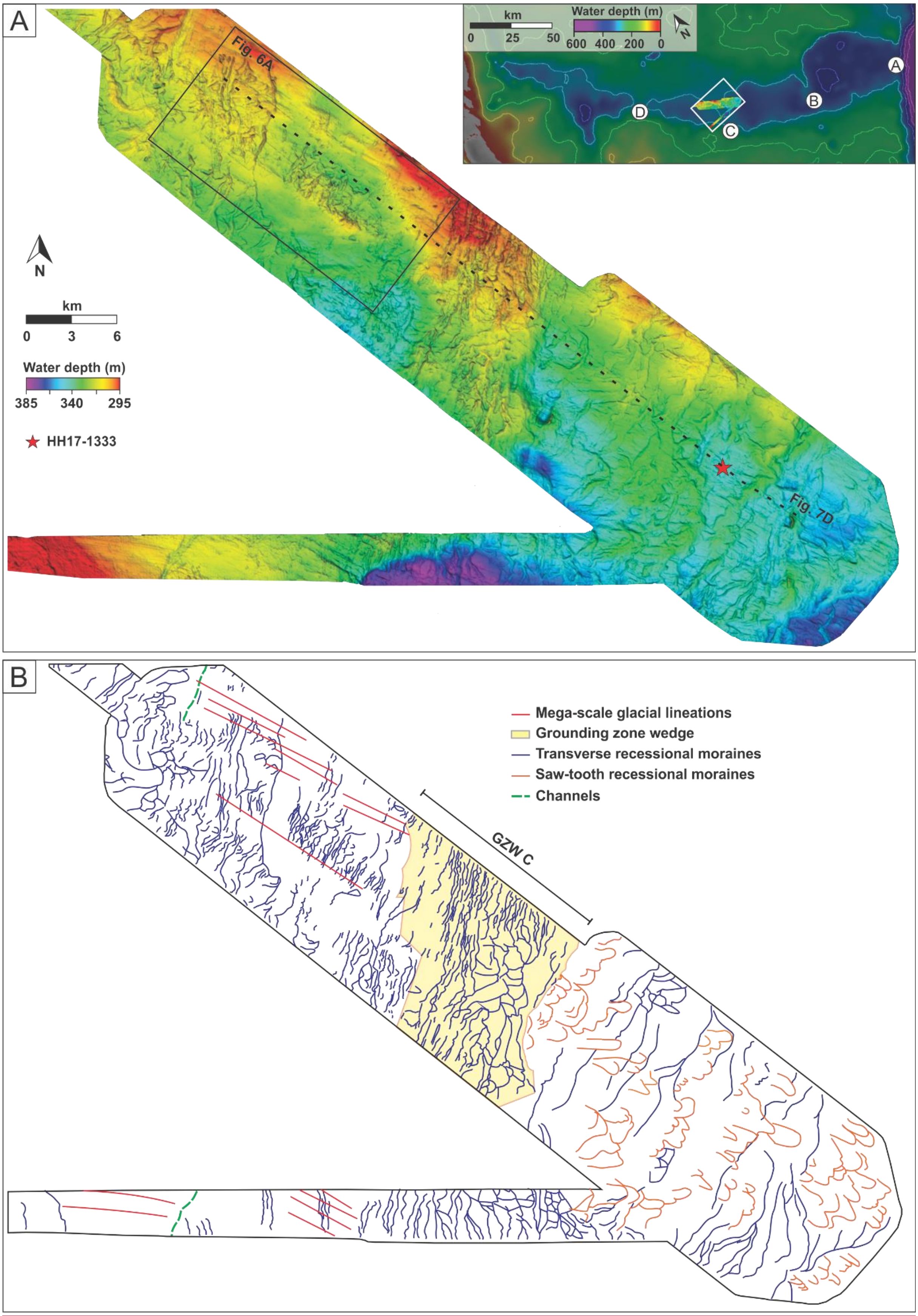


Figure 4. (A) Swath bathymetry map from the middle part of Store Koldewey Trough. The locations of grounding zone wedges *A-D* are indicated (see inset map). (B) Interpretation and ~~D~~distribution of ~~mapped~~ landforms.

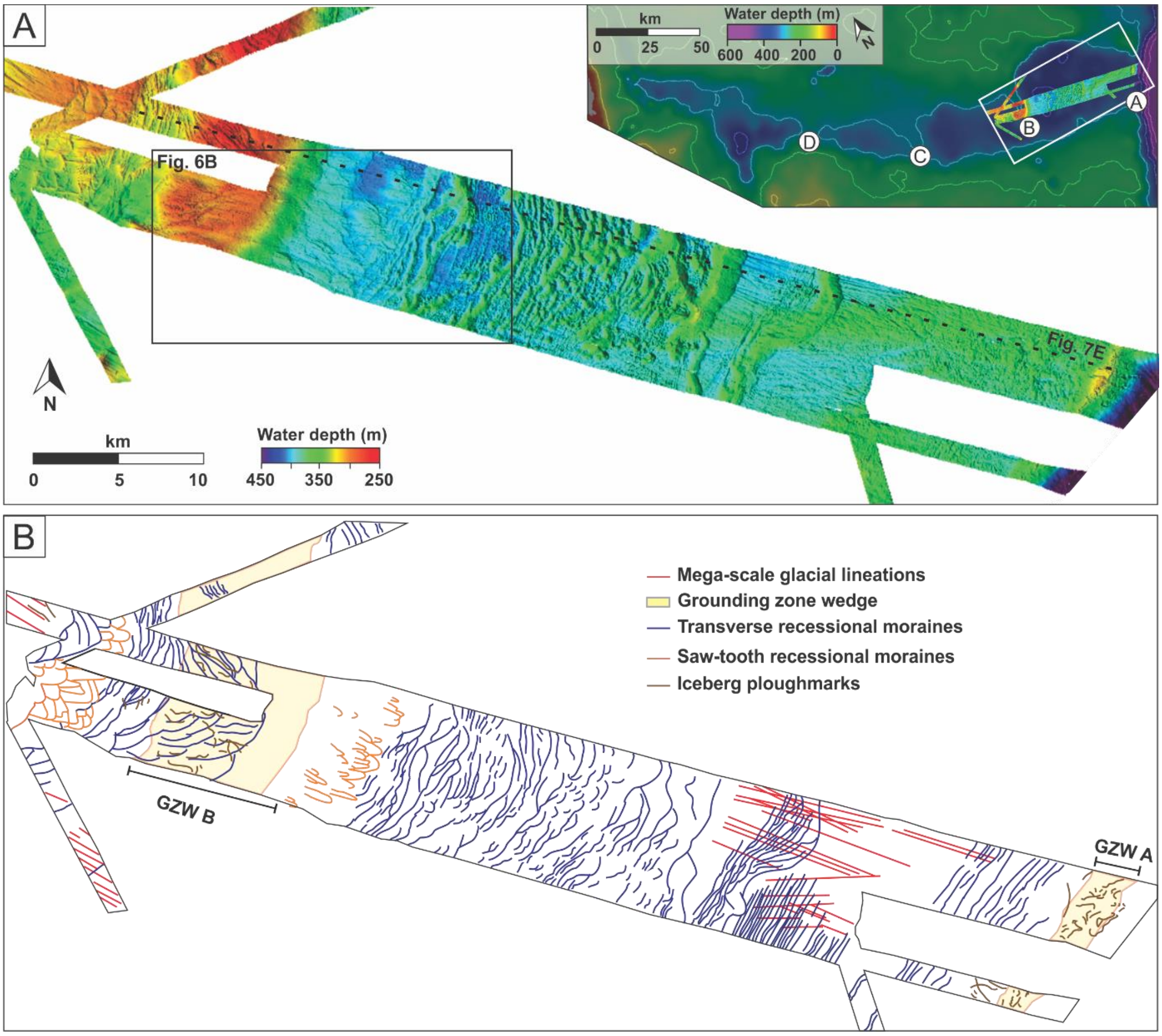


Figure 5. (A) Swath bathymetry map from the outer part of Store Koldewey Trough. The locations of grounding zone wedges *A-D* are indicated. (B) Interpretation and distribution of landforms modified after ~~(~~Laberg et al.~~,~~ (2017) and supplemented with new data.

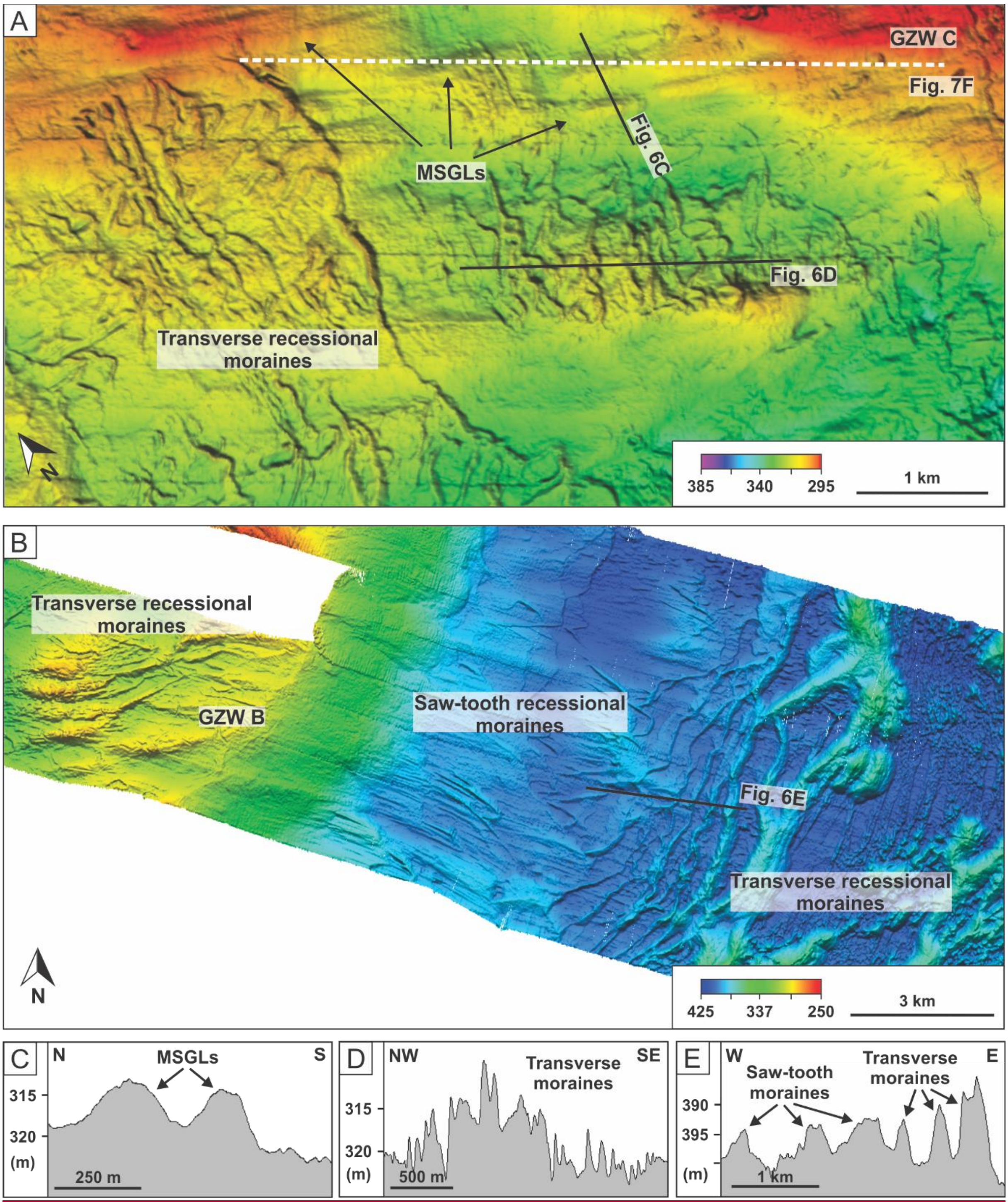


Figure 6. (A) Examples of mega-scale glacial lineations (MSGLs)~~,~~ and recessional moraines~~ and crevasse-squeeze ridges~~. (B) Examples of saw-tooth- and transverse recessional moraines~~multi-keel iceberg ploughmarks~~. (C) Bathymetric cross-profile of mega-scale glacial lineations (MSGLs). (D) Bathymetric cross-profile of transverse moraines~~crevasse-squeeze ridges~~. (E) Bathymetric profile of saw-tooth moraines and transverse moraines~~multi-keeled iceberg ploughmarks. *R*= ridges~~.

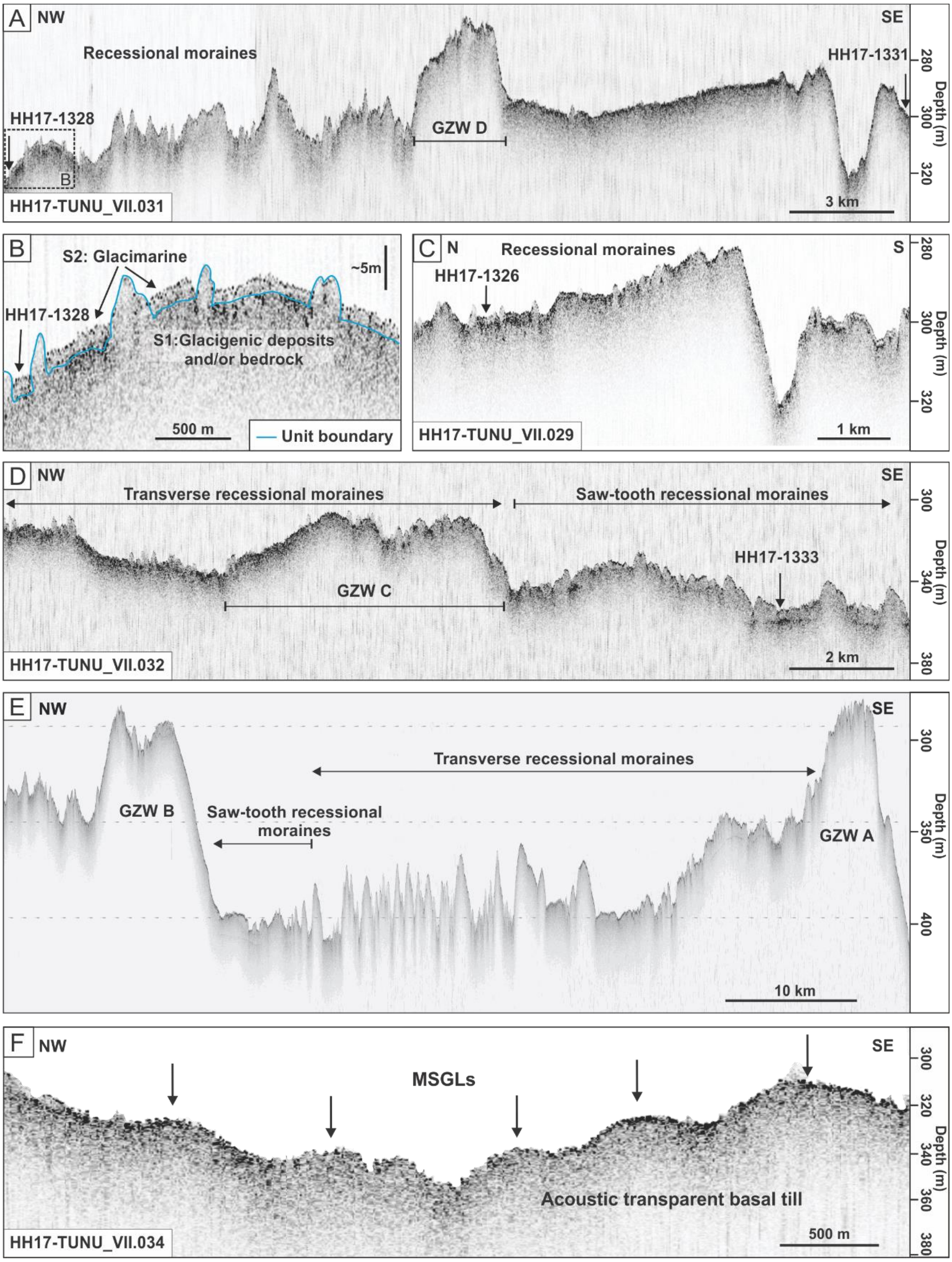


Figure 7. Acoustic profiles from Store Koldewey Trough. See Fig. 1C for locations. (A) Chirp line HH17-TUNU_VII.031 across grounding zone wedge D and recessional moraines from the middle trough area. ~~The approximate~~ Projected positions of sediment cores HH17-1328 and HH17-1331 are shown. Black dotted rectangle shows extent of the profile in (B). (B) Part of chirp line HH17-TUNU_VII.031 showing a zoom-in example of the configuration of units S1 and S2. (C) Chirp line HH17-TUNU_VII.029 from the inner part of the trough, with recessional moraines. ~~The approximate~~Projected position of sediment core HH17-1326 is indicated. (D) Chirp line HH17-TUNU_VII.032 across grounding zone wedge C. The locations for transverse recessional moraines, ~~and crevasse-squeeze ridges, multi-keel iceberg ploughmarks~~saw-tooth recessional moraines and sediment core HH17-1333 are indicated. (E) Chirp line across grounding zone wedge A and B, separated by saw-tooth- and transverse recessional moraines. Modified from Laberg et al. (2017). (F) Part of chirp sub-bottom profile HH17-TUNU_VII.034 showing the acoustically transparent deposits interpreted as basal till/mega-scale glacial lineations. The ridges of the latter are indicated with arrows.

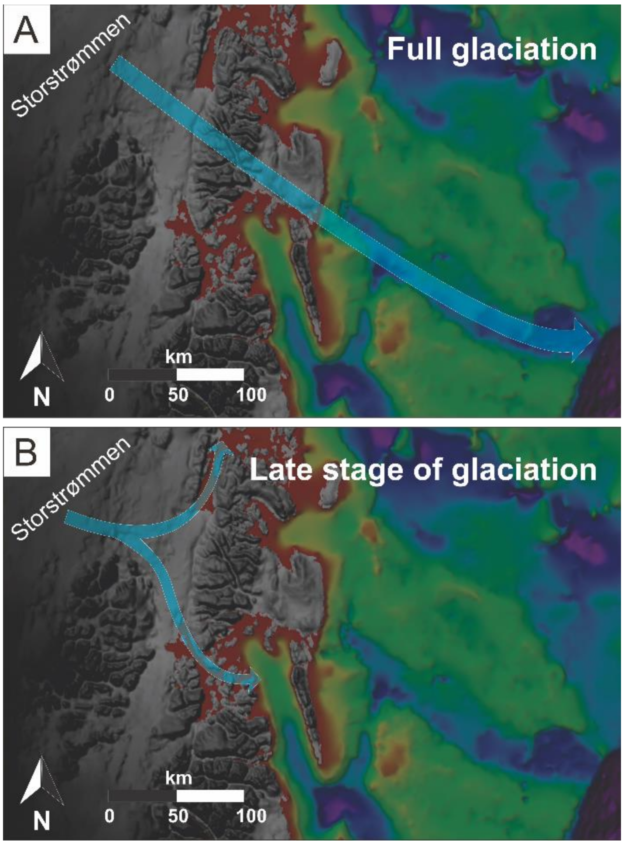


Figure 8. Reconstruction of inferred paleo ice-flow directions showing A) paleo ice-flow unrelated to the underlying topography during full glaciation and B) ice drainage paths during a late stage of glaciation.

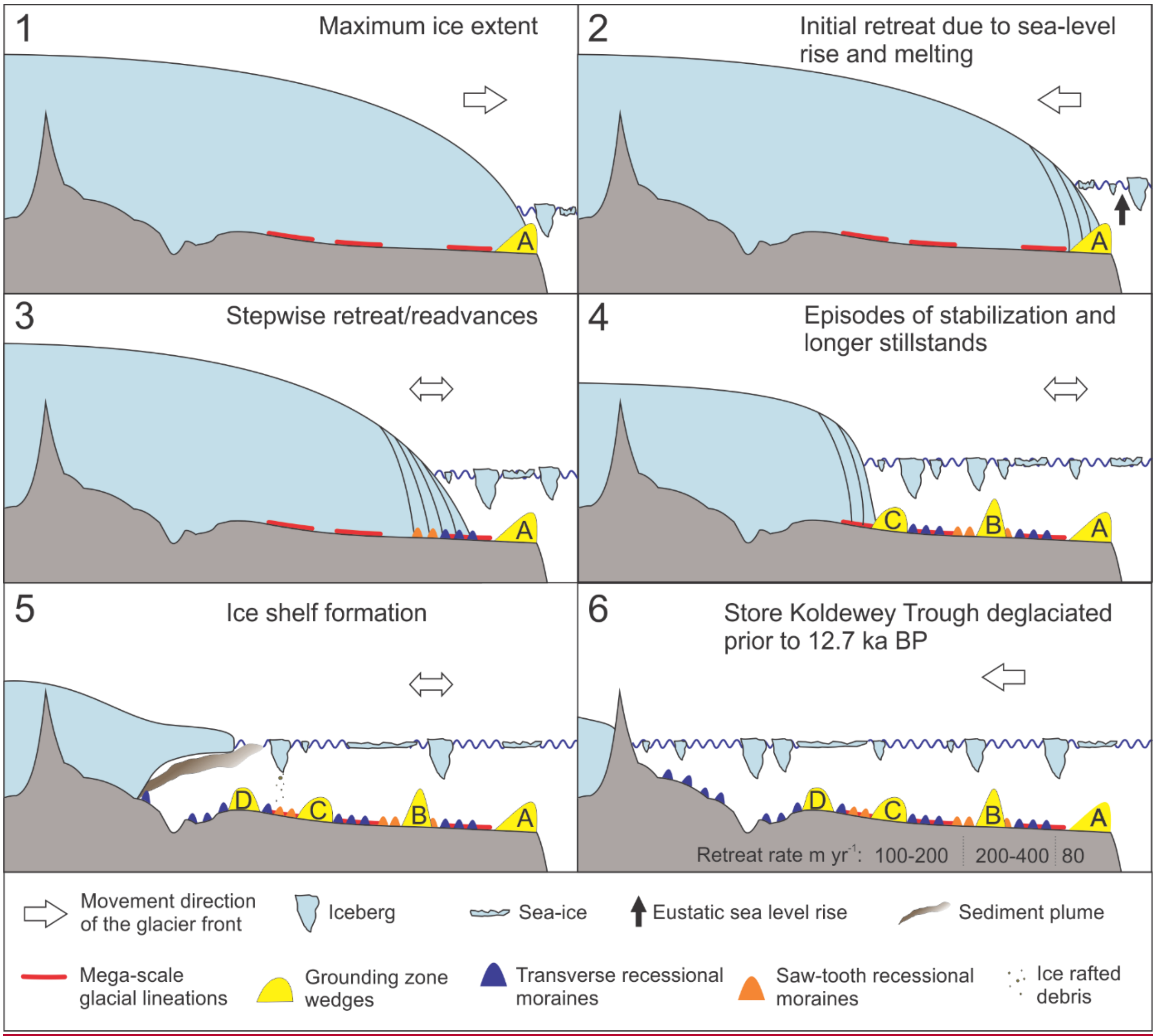
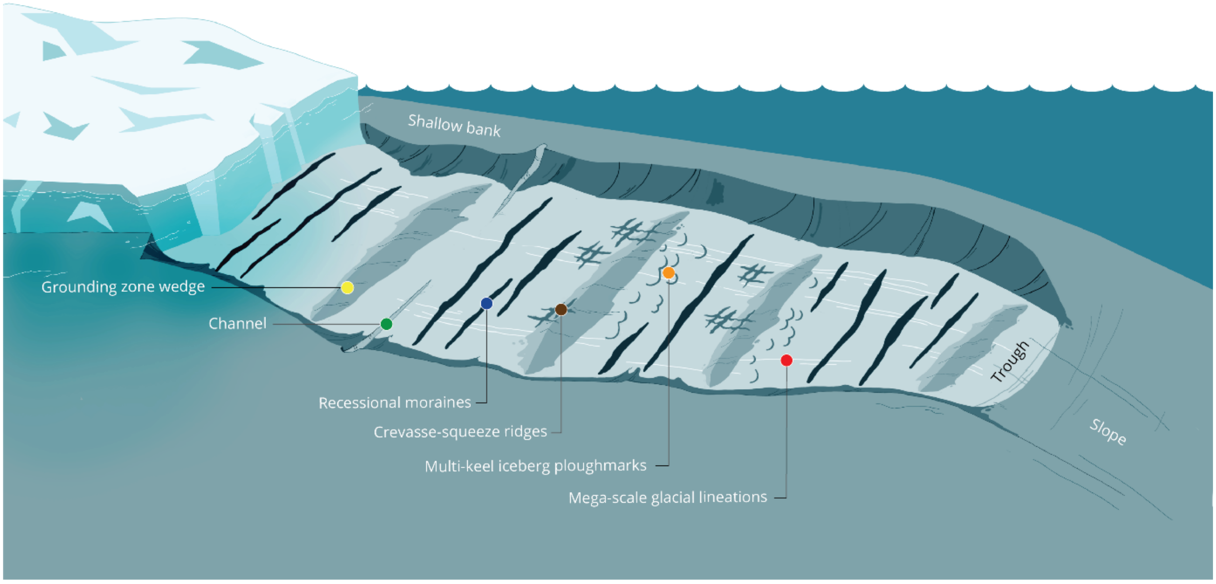


Figure 9. Reconstruction of the ice sheet dynamics in Store Koldewey Trough. Stage 1-6~~9~~ show the maximum ~~LGM~~ ice extent of the ice stream, as well as the ice-stream margin positions during the following deglaciation. Icebergs and sea-ice indicate calving and ice rafting. The deglaciation age in stage 6~~9~~ is based on cosmogenic nucleid dating~~lake sediment cores~~ on Store Koldewey Ø ~~(Klug et al., 2009)~~(Skov et al., 2020).



Core ID	Latitude (ºN)	Longitude (ºW)	Water depth (m)	Recovery (cm)
HH17-1326-GC-TUNU	76º21.55´	17º05.54´	294	75
HH17-1328-GC-TUNU	76º14.07´	16º05.42´	316	195
HH17-1331-GC-TUNU	76º06.50´	15º07.25´	306	110
HH17-1333-GC-TUNU	76º00.41´	14º09.36´	345	169

Table 1. Core locations, water depths and recoveries.

5

Lithofacies	5 - *Dmm*	4 - *Fl*	3 - *Fl (d)*	2 - *Fm*	1 - *Fm (d)*
HH17-1326-GC-TUNU (75 cm)	45 cm - end of core	33-45 cm	24-33 cm	12-24 cm	Top of core - 12 cm
HH17-1328-GC-TUNU (195 cm)	152 cm - end of core	117-152 cm	94-117 cm	14-94 cm	Top of core - 14 cm
HH17-1331-GC-TUNU (110 cm)	40 cm - end of core	Absent	26-40 cm	10-20 cm	Top of core - 10 cm 20-26 cm
HH17-1333-GC-TUNU (169 cm)	51 cm - end of core	Absent	33 cm - 51 cm	12-22 cm 28-33 cm	Top of core - 12 cm 22-28 cm
Lithology	Diamicton, massive and matrix-supported with a sandy mud matrix. Randomly oriented clasts	Laminated mud with fine sandy layers	Laminated mud with fine sandy layers and dropstones	Massive mud with rare dropstones	Massive mud with occasional dropstone
Color (Munsell Soil Color Chart)	Very dark gray (2.5Y 3/0)	Dark gray (10YR 4/1)	Dark gray (10YR 4/1)	Olive gray (5Y (/2) Dark gray (10YR 4/1)	Dark grayish brown (2.5Y 4/2) Dark olive gray (5Y 3/2) Olive gray (5Y (4/2) Brown (7.5YR 4/2)
Clast amount	High amounts	Absent	Scattered in layers	Rare	Sections containing clasts
Bioturbation	Absent	Absent	Absent	Little to moderate	Little
Lower unit boundary	Not recovered	Sharp	Gradational or sharp	Gradational	Gradational
Upper unit boundary	Sharp	Gradational	Gradational	Gradational	Top of cores
Bulk density (g/cm^3)	1.61-2.55	1.54-2.03	1.60-2.15	1.60-1.84	1.55-1.78
Magnetic susceptibility (10^{-5} SI)	20-182	46-148	66-100	53-114	41-106
~~Shear strength (kPa)~~	~~3-52~~	~~2-24~~	~~2-30~~	~~2-14~~	~~4-14~~
~~Ca/Sum~~	~~0.03-0.12~~	~~0.04-0.10~~	~~0.03-0.07~~	~~0.04-0.10~~	~~0.03-0.11~~
~~Ti/Sum~~	~~0.05-0.07~~	~~0.05-0.06~~	~~0.05-0.07~~	~~0.05-0.07~~	~~0.03-0.06~~
~~Fe/Sum~~	~~0.50-0.62~~	~~0.55-0.72~~	~~0.55-0.70~~	~~0.52-0.84~~	~~0.52-0.72~~
Sedimentary environment	Subglacial till (base of an ice stream)	Proximal glacimarine sedimentation with suspension plumes and high-density underflows. ~~Ice rafting is absent~~Sub-ice shelf environment.	Proximal glacimarine sedimentation with suspension plumes and high-density underflows. ~~Enhanced ice rafting~~Ice rafting in open marine environment.	Distal glacimarine sedimentation dominated by suspension settling. Ice rafting is limited	Distal glacimarine sedimentation dominated by suspension settling. Enhanced ice rafting

Table 2. Overview of the main properties and compositional characteristics of the lithofacies, including depositional environment.

	Length (km)	Width (m)	Relief (m)	Spacing (m)
Mega-scale glacial lineations	~~>~~1.5->9	150-500	4-8	200-700
Grounding zone wedges	N/A	3500-10,000	35-100	45,000-60,000
~~Small t~~Transverse ~~ridges~~recessional moraines	N/A	<2200	<50	50-500
~~Multi-keel iceberg ploughmarks~~Saw-tooth ~~ridges~~recessional moraines	<1.3	170-1100	5-30	N/A
Channels	N/A	150-300	3-10	N/A

Table 3. Dimensions of submarine landforms.

The authors' replies on the comments are written in red, bold and italics

Review: Olsen *et al.*

Last Glacial ice-sheet dynamics offshore NE Greenland – a case study from Store Koldewey Trough.

This manuscript presents a mix of new and previously published (by the co-authors) geophysical, geomorphological and sediment core data from the continental shelf off NE Greenland – a region for which we have limited knowledge of ice extent, behaviour or retreat dynamics at and following the last glacial maximum. This sector merits investigation since it is presently drained by the largest ice stream in Greenland whose geometry is unusual and driving mechanism not well understood; it has a broad continental shelf (space to accommodate significant expansion) dissected by troughs (past ice streaming, potentially with a rather different regime to today); and ice-ocean feedbacks through deglaciation are potentially important/variable given the location near the zone of exchange between Atlantic and Arctic waters.

A large part of the geophysical data has been previously published (Laberg et al. 2017), and it should be made more explicit in this manuscript that mapping and interpretations from these data is not new (or should highlight explicitly if earlier interpretations are revised here). The mid-shelf dataset is, as far as I'm aware, new, as are the core data and interpretations.

I would contest some of the landform interpretations (detailed below) and think the sedimentological interpretations could be more specifically discussed with reference to both the authors' analyses and the literature. The Discussion is rather weak and the structure hops around from paragraph to paragraph, without building a sound argument that draws on the evidence presented or rigorously examines the literature. Potentially interesting themes (for example, drivers of retreat; role of melting vs calving; effect of bed slope) therefore aren't fully developed.

There are a handful of grammatical errors in the manuscript (largely subject – verb agreements). Figures are all well put together, but I am not sure that all of figs 8, 9 and 10 (interpretative figures) are required.

We included the data set from Laberg et al. (2017) into this manuscript with the purpose of improving the regional understanding of the bathymetry of Store Koldewey Trough. We have clarified what part of the data that is previously published by Laberg et al. (2017). As part of the inclusion, we have re-interpreted the published data from the outer shelf in greater detail.

We have restructured and rewritten the discussion chapter, by adding new paragraphs as well as reorganizing existing paragraphs. New paragraphs focus on possible drivers of retreat, the role local trough topography may have had on the retreating ice front, as well as calculations on GZW volumes and the relative length of time of grounding line stabilization.

We removed figure 10, a schematic landform-assemblage model for Store Koldewey Trough.

Interpretations

Sediment cores:

- You refer to grain size and sorting characteristics but present neither for the diamict units (or even diamict matrix) and no sorting data for any unit. Similar for clast count/abundance. ***When mentioning clast amount we refer to the relative abundance, based on visual observations in the X-ray images. We refrained from presenting clast counts as we regarded this irrelevant in the context of the current paper, as it lacks absolute chronologies.***

- How consistent is your interpretation of meltwater plumes & underflows with the characteristics of meltwater sediment facies reported elsewhere (eg Witus et al 2014, Smith et al 2017, Prothro et al 2018)? ***We think that our interpretation is consistent with the mentioned publications, given the data available.***

- The explanations offered for a lack of IRD in an ice-proximal setting (facies 4 vs 3) all assume an ice shelf wouldn't have any basal debris. Examine whether that is valid here. ***We have not excluded the presence of IRD in an ice shelf. However, we have provided possible explanations for an absence of IRD in such a setting and moved the previous suggestions in chapter 4.1.2 (Facies 4) to the discussion chapter (chapter 5.2 Glacial dynamics during deglaciation).***

Landforms:

- This section should make clear that the outer block of multibeam has already been reported on and interpreted by Laberg et al 2017 and isn't new here. I suggest this is acknowledged explicitly, or state that the earlier reported assemblages are re-interpreted here if that is the case (and in which case, why?). ***In the revised version of the manuscript we mention that the data set from the outer shelf has been published by Laberg et al. (2017), however, we have re-interpreted the data set in greater detail.***

- I question the 'megascale' interpretation of lineations in the mid-trough data. They are rather few, sparse, short and individually distinct compared to a more typically dense ridge-groove arrangement (such as those on the outer shelf shown in the Laberg paper). ***We understand the reviewer`s point. However, we keep our suggestion that the landforms are fragments of/partly buried MSGLs, because the lengths/width ratios exceed 10:1 (cf. Clark, 1993).***

- I am not convinced by the examples given of distinct differences between the interpreted recessional moraines, crevasse-squeeze ridges and multi-keel ploughmarks (and the consequent interpretation that they are formed by different mechanisms/in different environments).
  - In Fig 6, I see little difference between the recessional moraines that are slightly irregular (i.e. branch/merge, where part of the grounding line has retreated while pinned elsewhere) and the labelled CSRs. Similarly, the sinuous and (?) composite form of the curvilinear, transverse to ice flow ridges in 6B (interpreted as due to ploughing by icebergs) have the same kind of size and form as curvilinear ridges due to push at the grounding line (i.e. moraines). Most of the supposed ploughmarks in 6B seem to lack an 'inbound' scour that leads to the transverse ridge.
  - All three of these types are distributed throughout the assemblage. Is it not a simpler explanation that moraines are formed by push at the grounding line, and that spatially differential push (small differences in sediment mobility) will create a sinuous and potentially complex product? Three different landform types require fundamentally different ice flow dynamics or environments – how can these be reconciled in this setting?
  - E.g. Ploughing by icebergs requires a fundamentally different environment and time period to grounded, coherent ice approaching the grounding line. What strong evidence is there that these ridges were ploughed in front of (an) iceberg keel(s) rather than pushed up at the grounding line?
  - E.g. Moraines are interpreted here as a product of slow, steady retreat with repeated pauses. Crevasse squeeze ridges, on the other hand, are interpreted as infill of crevasses at the end of a fast flow episode, and the ridges are implicitly synchronously formed rather than in sequence. Yet these two landforms and dynamic interpretations intermingle. At least a discussion of this problem is warranted.
  - If moraines and CSRs are argued to be present here, then mapping them in the same class (same colour) is misleading.
  - Wedge C (? – mid Fig 4 – suggest label wedges A-D where appropriate on Figs 4&5) is superimposed by both (?) moraines and CSRs. Given that wedges are typically associated with prograding debris flows at the grounding line, moraines by local push, and CSRs by basal crevasse infill, how do you reconcile (dynamically) the three being formed on

top/immediately adjacent to one another?
We appreciate the extensive comment of the referee! Based on that, we revisited the data set and changed our interpretations from crevasse-squeeze ridges and multi-keel ploughmarks to saw-tooth moraines. Therefore, we rewrote the part of the result chapter regarding these specific landforms as well as the following discussion chapter.

Discussion:

- The non-topographically controlled (rather, exceeding topography) aspect of ice stream onset/source is under-developed. What amplitude topography does the ice stream have to override – what ice thickness would ignore a tendency to funnel either side of the higher ground (and is this a reasonable thickness)? Does SKT contrast with other troughs along the coast that are fjord-fed? Could this explain why it might exhibit a different style of retreat to 'typical' troughs? (I note that Laberg et al have already made this interpretation.) ***We have elaborated on this topic by providing information on the altitude that the Storstrømmen Ice Stream had to overcome to drain into Store Koldewey Trough (single peaks of 500-900 m), complimented with modelling results of paleo-ice sheet thickness on Germania Land during LGM (1000-1500 m; Fleming and Lambeck (2004) and Heinemann et al. (2014)).***

- Regular/many grounding line landforms are interpreted as a product of slow retreat. Why *slow*? Retreat proceeds in steps, yes, but is there independent evidence that these steps occurred slowly? The start of section 5.2 rather treats wedges and moraines (of quite different sizes) as providing the same sort of information: that the ice margin was stable "for a sufficient period" or "had a considerable flux" to build the landforms. I think this passage should explore the basis for "slow" retreat or prolonged standstills, and explain how this model of retreat fits with the later interpretation of surging. ***The terms "slow" and "episodic" retreat have been introduced by both Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008) discussing styles of ice retreat accompanied with the formation of recessional moraines and grounding zone wedges, respectively. We wish to continue using these terms and have, therefore, rephrased the paragraph, hopefully making our use of terms more clear to the reader.***

- Arguments for drivers of retreat are muddled.
  - Laberg et al reject the hypothesis of retreat driven by sea level rise, yet here, based on the same data, you favour it. Why? I'm not convinced by the arguments for either (I don't think you have enough data), but they should be more rigorously discussed. If grounded ice is thick (which you argue for based on it passing over Germania Land) and its lateral extent is curtailed by the continental shelf break rather than because it is supply-limited, then it may be more resilient to sea level rise – the argument here is that a rise should cause ice to go afloat and the grounding line to make a large back-step, but this is contingent on ice thickness being close to the buoyancy threshold, and the bed topography allowing for such a back-step (difficult if landward-shallowing). On page 9, in fact, you point out contrasts between this system with others driven by sea level rise – so why do you call on this mechanism?
  - I wouldn't call on evidence for subglacial meltwater flow as the most immediate support of ocean warming-driven retreat (p8 final paragraph) – explain the logic for this.
  - A potentially interesting discussion of the roles of meltwater and/or calving doesn't really develop (p9 penultimate paragraph). Are these mutually exclusive modes of retreat? Facies 3 bears similar characteristics to facies 4, except with IRD: do we have continual meltwater with suppressed calving (absence of facies 4)? Or an increase in meltwater-related sediments? The Results report IRD in layers – are you detecting episodic calving events, or continuous delivery? If meltwater sediments and landforms are more abundant towards the inner shelf,

is this a temporal effect (i.e. more melt production later in deglaciation), or a spatial effect (e.g. preferential channelisation of water with a certain topography/substrate/ice surface profile)? You ought to be able to develop these ideas more than "retreat style was different" – in what way, and with what significance? ***We have rewritten this part of the manuscript, providing a more in-depth discussion of the relationship between local trough geometry and locations of the GZWs, as well as the sedimentary environments regarding the different lithofacies.***

- Comparisons of the numbers/positions of GZWs between troughs with very sparse multibeam/seismic data coverage (e.g. page 9) can at best lead to a speculative conclusion. Contrasting stabilisation points, if that is how a GZW is interpreted, also doesn't necessarily mean asynchronous retreat: retreat may be triggered by a synchronous forcing, but may be locally anchored in different ways. Contrasting pattern doesn't necessarily translate to contrasting timing (or forcing). ***We agree that there might be undiscovered GZWs in Norske Trough and Westwind Trough. We rephrased this paragraph, focusing on the presentations of facts, rather than speculating on differences in deglaciation dynamics between different troughs.***

- The discussion of surging is under-developed with respect to models for landform formation, drivers and with respect to both literature and the actual data. The basis for the surge interpretation here is the occurrence of crevasse-squeeze ridges. While I'm unconvinced by the figure examples shown, if these are present here then I think the discussion needs to:
  - Justify why these must indicate a surge. Is there a difference between a surge (in the sense used here) and a period of ice stream acceleration (externally driven?) which would cause extension and feasibly open up basal crevasses?
  - Address the spatial distribution, intermingled with moraines, wedges and iceberg scours – your actual data. Are there multiple patches of CSRs? Do these each, therefore, belong to a different surge? Why? How is this reconciled with "slow and steady" retreat indicated by the moraines? Why should a surge lead to ice front collapse *followed by* increased ice flux? And do you see any evidence for such ice front collapse? This seems at odds with the interpretation of slow, grounded retreat. ***We have re-interpreted the landforms initially suggested to be related to surging, to be saw-tooth moraines. Thus, the discussion of surges is irrelevant for the manuscript, so we have removed this section.***

Line-by-line

P1-line19: "exposed to" increasing ice loss? Rather, 'experienced', or simply 'has increasingly lost mass'… ***Corrected.***

1-20: 16% of the GIS is… ***Corrected.***

1-26: instability (also 2-45) – what do you actually mean by this? ***Here we use the term ´instability´ to refer to a possible disequilibrium within the GIS caused by external forces.***

1-27: identified as a tipping element ***Corrected.***

1-30: this sentence is awkward. '…precise predictions of the future potential decay of the GIS…' ***Changed.***

P2-first paragraph: you give almost as many references for 'sparse' as 'multiple studies'. ***We have added more examples of references.***

2-15: stepwise – this term isn't especially meaningful, since every pattern showing any kind of paused grounding line could be said to show 'stepwise' retreat. ***We use the term ´stepwise retreat´ to explain interruptions in the retreat. This term has been used in other articles and we therefore wish to keep it.***

2-19: *west* of Store Koldewey Trough, *reveals* that… ***Corrected.***

2-26: I have a bit of a problem with an objective being 'to confirm' something. And in this case, the data you have available with which to 'confirm' (or test) the interpretation of shelf-break glaciation is exactly the same data as has been used to propose it. ***Changed.***

3-10: episodic calving ***Corrected.***
3-12/13: this sentence isn't necessary, unless you make it relevant to your work ***We agree and have removed this sentence.***
3-30: were acquired ***Corrected.***
4-5: were estimated ***Corrected.***
4-9: chemical treatment…was conducted ***Corrected.***
4-35: it could help throughout the presentation of results to use inner/outer shelf or proximal/distal either instead of or as well as compass directions. i.e. here westernmost = innermost, or for example SE of wedge X = distal to or seaward of ***We have rephrased from compass directions where practical to make it easier for the reader to follow.***
5-15: Facies 3 interpretation – laminated mud with sandy layers sounds like Facies 4, interpreted as proximal, so if the 'background' sediments that are interrupted with IRD event layers are the same, does this not imply that the position is sufficiently proximal to still be receiving meltwater sediments? ***We have rephrased our interpretation, making it more clear that both suspension settling and iceberg rating is present.***
6-16: grounding zone wedges A-D ***Corrected.***
6-18: exceeds the… ***Corrected.***
6-21: wedge A (outermost) has more the shape of a moraine ridge – symmetric form, comparable to the more pronounced of the moraine ridges between here and wedge B. 'A' does not have the asymmetric shape typical of a prograding wedge. ***Noted. We base our interpretation on the fact that other ridges with similar dimensions and locations on the continental shelf of Greenland are interpreted as GZWs.***
7-13: what do you mean by meltwater runoff from the banks? Proglacial (ie bottom-hugging submarine flows)? Or subglacial from a semi-independent ice sheet sector? ***We believe the channels are not important for reconstruction the ice dynamics and have therefore made a simple interpretation of their origin, suggesting that they are formed during deglaciation and are related to meltwater. In order to further study their genesis, additional data is needed.***
7-29: can you distinguish between a buried bedrock surface and buried till surface (from previous glaciation)? ***We have included Petersen et al. (2015), showing that there is a thick Paleogene sedimentary succession offshore NE Greenland, ruling out bedrock sills.***
7-45: This conforms with… (or This is consistent with…) ***Corrected.***
8-3: covered a minimum length… ***Corrected.***
8-11: but this is the NE Greenland ice stream (or a distributary of) that you're talking about, so this 'comparison' is a little odd. ***We find it interesting that a similar flow feature is identified in modern day NEGIS.***
8-12: Once fast-flowing ice streams reach… ***Corrected.***
8-30: what sediment data? ***We have clarified that Stein et al. (1996) presented terrigenous, coarse grained material along the continental slope off NE Greenland.***
8-39: The occurrence … demonstrates ***Corrected.***
9-3: ii) trough narrowing ***Corrected.***
9-second paragraph: this repeats point (i) above ***Corrected.***
9-19: your high-res data reveal four wedges, but your data coverage is incomplete, so how can you reject the interpretation of six along the whole trough with full (albeit poorer resolution) coverage? You have also consulted IBCAO: do you agree with their interpretations of six wedges, and how does the expression of these in IBCAO compare to their expression in your high res data, where available? ***The paragraph has been altered and include now the possibility for GZWs outside our data coverage.***
9-fourth paragraph: how does this relate to the rest of your Discussion? ***We see your point and have removed this paragraph.***
10-5: what sedimentological evidence do you have for winnowing and resuspension? ***We have rephrased this statement.***
10-21: grounding zone wedges are not surge-indicative landforms ***Corrected.***
10-22: is consistent with ***Corrected.***

Figures

1. Present-day flow directions for Zachariae Isstrøm and Storstrømmen would be useful, and/or outline of NEGIS. ***Included.***

   Caption line 2: 'The small map shows…' ***Corrected.***

4&5. Suggest label wedges A-D on the illustrated mapping in each figure. I also don't think it's helpful or appropriate to show recessional moraines and crevasse-squeeze ridges as part of the same group, since you interpret their formational environment and palaeo-glacial significant differently. ***GZW A-D have been labeled, whilst the mapping of landforms have been updated.***

9&10. Both of these figures are not necessary – one or the other should suffice. I'm also not sure all panels of Fig 9 are really necessary – are these really all discrete, distinct 'stages' of retreat that can be clearly defined? ***We agree and have therefore simplified figure 9. Figure 10 has been removed from the manuscript.***

The authors' replies on the comments are written in red, bold and italics

Interactive comment on "Last Glacial ice-sheet dynamics offshore NE Greenland – a case study from Store Koldewey Trough" by Ingrid Leirvik Olsen et al.

Anonymous Referee #2

Received and published: 8 April 2020

The manuscript provides a multi-method dataset comprising geophysical, sedimentcore and geomorphological data from the little studied area of the NE Greenland continental shelf. Therefore, our understanding of ice sheet history and associated icedynamics and sediment processes in this region is poorly constrained. Therefore, a study on this understudied region is welcome and should garner widespread interest. The disappointing aspect of the study was the lack of chronological constraints on the geomorphological dataset and interpretations even though sediment cores were part of the study. Apart from the middle shelf coverage, the swath bathymetry dataset and the interpretation of it seems to be identical to that published in Laberg et al. 2017, but the sediment-core data, middle shelf geophysics and interpretations are new. The identification of the landforms in swath bathymetric imagery does not appear to be correct. The authors do not make enough use of the sediment core analyses or data, and interpretations need to draw on this data more as well as the literature. The sedimentcore aspect of the study could be expanded as core information in NE Greenland is extremely limited in published work to date. The discussion needs to be developed further and there needs to be a natural flow and emergence of a central argument between paragraphs that uses the geomorphological and sedimentological evidence. At times, there does not appear to be a natural link between paragraphs and some paragraphs appear to be dropped in without reference to previous paragraphs. ***We acknowledge the feedback from the referee and tried to address the issues mentioned in our revision. Please see below for details.***

Section 1-3 Is this paper 'contributing to validation and improvement of numerical models' i.e. will this be examined in this paper based on the data and interpretations presented? If not, then this is a misleading statement and should be altered or removed. I do not see any point in making the observation that "It has been suggested that the northeastern part of the GIS reached the inner or middle parts of the continental shelf during its maximum extent during the last glacial (see Funder et al. 2011 for a review)" as more recent studies of Evans et al. 2009, O Cofaigh et al. 2004, Arndt 2018, Arndt et al. 2015, 2017, Arndt and Evans 2016, and Laberg et al. 2017 show quite clearly that ice went beyond the inner and middle shelf. The authors make this same point so there is no need to repeat an outdated debate. Include Evans et al. 2009, O Cofaigh et al. 2004, Arndt et al. 2015, and Arndt and Evans 2016 in the studies that have indicated ice was much more extensive on the NE Greenland shelf than the original summaries of Funder et al. 1998 and Funder et al. 2011 implied.
We have altered the sentence regarding `validation and improvement of numerical models', emphasizing the need for paleo-reconstructions. Furthermore, we removed the "previously suggested maximum extent of the GIS in NE Greenland" by Funder et al. (2011), replacing it with more updated studies as suggested by the referee.

The authors need to highlight how the swath bathymetric data presented in this paper differs to that presented in Laberg et al. 2017, and then detail how this study is different to that of Laberg et al. 2017. The same data for the outer shelf is presented again and there needs to be a clear statement or discussion differentiating what is published and what is new. I suggest that the authors add a section detailing what is known about the swath bathymetry and sub-bottom profiler data and implications for ice sheet history and sedimentary processes of the Laberg et al. 2017 study.

We rewrote the introduction to chapter "4.2 Submarine landforms", providing information about what part of the data is new, and what has been previously published in Laberg et al. (2017). In the re-submitted version of the manuscript we clarify which part of the data set from Laberg et al. (2017) we have re-interpreted and why.

Section 4.1 The range of analyses performed from geochemistry, sediment grain size, shear strength, etc. are outlined in the paper, but there is no reference to the actual data within the description of the lithofacies o, even in the interpretation of the lithofacies or the discussion. For instance, the 'magnetic susceptibility and Ca/Sum ratio vary between each core, with the highest in HH17-1326 and lowest in HH17-1328. Wet bulk density and shear strength are generally high: : :'. This is vague and does not serve the paper well. There is no subsequent use of much of this detailed data when it comes to the discussion of the glacial history later in the paper. I am still uncertain as to the point of including the magnetic susceptibility, XRF and wet bulk density data in this paper beyond including them for the sake of it. ***We agree and have, therefore, taken out the XRF core scanner and shear strength data in the re-submitted manuscript.***

The interpretation of Facies 3 should explain what is meant by 'open conditions' and explain how the 'outer ice-proximal setting' inferred to be the location of the depositional environment differs from that envisaged for Facies 4. The paper notes the similarity of Facies 2 and 1 apart from the presence of IRD. Does this merely reflect the stochastic behaviour of icebergs rather than anything to do with permanent sea-ice or 'increased influence of drifting ice' in the sense of increased iceberg calving. The differences between the facies is essentially down to the vagaries of iceberg processes. ***We rephrased these paragraphs and hope it is more clearly now (see page 5, lines 4-7, 15-19 and 28-32).***

Section 4.2 I am not convinced that there are MSGL in Figure 4 and 6. The features shown in Figure 5 appear to be lineations rather than MSGL and the description of them only refers to their length as >1.5 km. ***We understand the reviewer`s point. However, we keep our suggestion that the landforms are fragments of/partly buried MSGLs, because the lengths/width ratios exceed 10:1 (cf. Clark, 1993).***

Do sub-bottom profiler records across the GZWs exist in order to rule out that they are bedrock sills? ***We have included the publication by Petersen et al. (2015) showing that there is a thick Neogene sedimentary succession offshore NE Greenland, ruling out bedrock sills.***

Figures 4 and 5 are misleading as the recessional moraines and crevasse squeeze ridges are merged and have the same colour scheme, and it is difficult to distinguish where the crevasse-squeeze ridges are located. ***Corrected.***

I am not convinced that some of the ridges represent a rhombohedral network indicative of crevasse-squeeze ridges. There appears to be little difference between the recession moraines and the crevasse-squeeze ridges apart from slight differences in morphology that might be linked to variations in grounding line processes and behaviour. The CSR appear to have a limited distribution and are not pervasive or widespread implying that the interpretation of 'surging' is unlikely and that they are more likely to be a localised feature maybe related to complex pattern of recessional moraines linked to ice-margin processes during standstill and retreat. Therefore, the idea of surging behaviour may not be correct and that the landform assemblages only record variable rates of grounding ice margin retreat and stabilisation. ***We appreciate the extensive comment of the referee! Based on that, we revisited the data set and changed our interpretations from crevasse-squeeze ridges and multi-keel ploughmarks to saw-tooth moraines. Therefore, we rewrote the part of the result chapter regarding these specific landforms as well as the following discussion chapter.***

If indeed these features are CSR, why do they have to be associated with a surge rather than an advance/acceleration of an ice stream (linked to mass balance) and formation of basal crevasses due to tensile stress and ice break-up as it steps back to a stillstand position? Also, if it's a surge or even a simple readvance/acceleration of an ice stream, why aren't these features more widespread across the trough floor as presumably, a wider area would stagnate? The limited distribution implies a more complex recessional moraine pattern linked to complex ice retreat in some areas. ***See reply to comment regarding rhombohedral network and crevasse-squeeze ridges, above.***

I'm not convinced that the features identified as multi-keel iceberg ploughmarks is correct as they appear identical to the recessional moraines in Figure 4, 5 or 6. How would you even differentiate between a multi-keeled iceberg ploughmarks and the intervening ridges they create from those that are recessional moraines? ***See reply to comment regarding rhombohedral network and crevasse-squeeze ridges, above.***

Section 5 The authors state that "We propose that the Store Koldewey Trough was filled by grounded ice originating from the area presently covered with the Storstrømmen ice stream (Fig. 8A). This implies that the northeastern sector of the GIS reached a thickness allowing the ice stream to flow unrelated to the underlying topography, including the mountain ranges between present day Storstrømmen and Germania Land." This is speculative statement on its own. On what basis or geomorphological evidence are you making this assertion? Why wouldn't Storstrommen have preferentially flowed along and filled Dove Bugt Trough? The authors then go on to note that "An alternative interpretation is that Store Koldewey Trough had a much smaller drainage-basin, limited to Germania Land (Arndt et al., 2015). However, based on our data, including the observations of mega-scale glacial lineations, recessional moraines and grounding zone wedges, we favor the interpretation of Storstrømmen filling Store Koldewey Trough during full glacial conditions based on the volume of ice needed to fill a trough of this magnitude. We propose that the ice sheet thinned and that the underlying topography controlled the direction of ice flow during a late phase of the last glacial, i.e. that the ice flow from the interior of the GIS was directed to Jøkelbugten in the north and Dove Bugt in the south (Fig. 8B)." What is being proposed is speculative. Therefore, the discussion on the topographic and non-topographic controls on ice stream flow pathways, source and development from one to the other needs to be developed further. ***We have elaborated on this topic by providing information on the altitude that the Storstrømmen Ice Stream had to overcome to drain into Store Koldewey Trough (single peaks of 500-900 m), complimented with modelling results of paleo-ice sheet thickness on Germania Land during LGM (1000-1500 m; Fleming and Lambeck (2004) and Heinemann et al. (2014)).***

Why does the retreat of the grounded ice margin have to be 'slow' between stillstands? What evidence is used to support this assertion? There are no radiocarbon dates from the study cores that constrain ice stream retreat, so it is not possible to conclude the relative rate of retreat. Evidence from Antarctica shows that ice streams can abandon their groundling zone very quickly and then retreat at variable rates to the next stabilization point. It is worth exploring the issue of terrain factors (e.g. trough dimensions, trough depth distribution, underlying bed slope, etc.) modulating externally driven ice sheet retreat. The authors should consider the literature on GZW morphology and volume as an indicator of the relative length of time that the grounding line remains stable in one place (e.g. Dowdeswell et al. and Batchelor et al.). The authors need to develop the discussion in terms of what the smaller recessional moraines versus the larger GZWs mean for ice stream retreat rates, length of time of stabilisation and ice margin behaviour during temporary stillstands. For instance, the smaller moraines may be winter advances during stillstand.
These are many good suggestions that we appreciate! The terms "slow" and "episodic" retreat have been introduced by both Ó Cofaigh et al. (2008) and Dowdeswell et al. (2008) discussing styles of ice retreat accompanied with the formation of recessional moraines and grounding zone wedges, respectively. We wish to continue using these terms and have, therefore, rephrased the paragraph, hopefully making our use of terms more clear to the reader. Furthermore, we provide a more in-

depth discussion of the relationship between local trough geometry and locations of the GZWs, as well as the sedimentary environments regarding the different lithofacies.

The authors note that "We interpret the break-up and retreat of the GIS to have happened in two stages; initial retreat by breaking up and calving of grounded ice due to eustatic sea level rise caused by melting of ice at lower latitudes (Lambeck et al., 2014) (Fig. 9: Stage 2) and a second phase of melting driven by ocean warming, possibly due to the onset of inflow of intermediate water masses. The latter is supported by the occurrence of meltwater-channels and laminated sediments interpreted to be a result of excessive meltwater production in the middle and inner parts of the trough". On what basis, evidence or studies are you making this assertion for this region of Greenland, particularly the impact of sea level rise or inflow of intermediate water masses? What intermediate water masses are you referring to? There is no sediment evidence such as iceberg rafted lithofacies recorded in the cores to support iceberg calving and margin retreat due to sea level rise. Meltwater derived sediment facies cannot be used the defining piece of evidence indicating ocean warming retreat as the ice sheet will always produce and discharge meltwater due to the simple fact the ice at the subglacial bed is at pressure melt point. In fact, meltwater sediments will be deposited even when sea levels are rising and causing the ice margin to retreat.
The impact of these external factors will depend on the relative balance between atmospheric warming, precipitation, ocean warming and sea level rise, but stating that sea level rise causes a first stage of retreat is too simplified. For instance, studies in Antarctica show that maximum grounded ice extent in some sectors of the Ross Sea occurred during deglaciation even though there was atmospheric and oceanic warming and sea level rise because precipitation had a more dominate impact on mass balance, but eventually ocean factors dominated to cause retreat. How do you know there are two phases to the retreat of the ice sheet in this region without age constraints? In fact, the geomorphology implies more than two stages to ice sheet retreat. It is also worth noting that ice sheet retreat history is not merely a simple function of sea level rise, ocean warming and atmospheric warming but also due to terrain factors that can modulate ice sheet response and the rate of response to these external factors. The authors note the importance of the terrain for ice sheet retreat but do not really consider the literature that have looked at the impact of terrain factors on ice stream retreat. For example, Stewart et al. 2012 and Livingstone et al. 2012. These studies show the importance of trough width and depth on the rate of ice sheet retreat and try to quantify rates of retreat. ***Following the comments of the referee, we revisited the paragraphs mentioned above, and concluded that additional proxy information is needed to identify the driving forces causing the retreat of the GIS. In consequence, we have removed the paragraph.***

The authors note that "Based on the varying numbers of GZW0s we suggest that retreat/ readvances of the ice streams offshore NE Greenland occurred asynchronously." Whilst I agree that it is possible that ice streams over such a large region as NE Greenland will experience asynchronous behaviour, I am not convinced of the evidence that is presented for this assertion. The data from Norske Trough, Westwind Trough and elsewhere do not provide a complete coverage of the respective areas and it is possible that there may be GZWs that exist, but have yet to be discovered undermining the suggestion that the number of GZWs indicates asynchronous ice stream behaviour. Secondly, without chronological constraints on regional ice stream behaviour during deglaciation or the ages of GZWs then the assertion of asynchronous behaviour is speculative. ***We agree that there might be undiscovered GZWs in Norske Trough and Westwind Trough. We rephrased this paragraph, focusing on the presentations of facts, rather than speculating on differences in deglaciation dynamics between different troughs.***

The authors note that "The present sub-glacial topography of Storstrømmen consists of a reversed bed slope, accompanied by a floating ice tongue (Hill et al., 2018). Thus, a potential future response to increased ocean warming could result in episodes of rapid retreat as the ice front undergoes thinning and/or ice tongue collapse. Such episodes are believed to cause a dynamic response up-glacier, resulting in an accelerated ice flow, contributing directly to sea level rise (Hill et al., 2018)". It is not entirely clear how this statement links, and is relevant, to the previous paragraphs discussing ice sheet behaviour during deglaciation. ***We see the referee`s point and have removed this paragraph.***

The authors equate 'surge' behaviour with an ice stream. Why does the ice stream have to surge rather than simply readvance/accelerate? I am not convinced that the features they describe are crevasse-squeeze ridges but if they are then the section needs to be developed further to explain and justify why the ice stream surges as opposed to accelerate and readvance. The authors also need to explain why the CSR are limited in their spatial extent and distribution within the swath bathymetry dataset and why they have a close association with the GZW and recessional moraines. ***The landforms interpreted as surge-related landforms in the first version of the manuscript have been re-interpreted in the resubmitted version (see above), making the concept of surging irrelevant for the manuscript.***