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

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

This manuscript is a considerably improved re-write/re-submission of a previously reviewed manuscript. The data are more clearly presented, the geomorphological interpretations are more logical (both with respect to morphological indicators and interpretations of glaciodynamic contexts/conditions for particular landform types), and the Discussion is better formulated. That said, I still have some concerns about the rigour of data interpretation and justification for some of the elements of the Discussion.

First of all we would like to thank the referee for a thorough and constructive review, contributing to the improvement of the manuscript. It has been very helpful and we are grateful! We have responded on all comments by the referee below, as well as adding a list of relevant changes made in the revised manuscript.

Sediment cores

The presentation of core data seems limited. The text reporting is clear and logical but I wonder if more use of valuable core material could have been developed. Was any grain size sorting analysis done? – you have quantitative data on grain size fractions. Why are clast proportions/abundance not quantitatively reported, since you've sieved clasts out as a specific size and so presumably have these data? What are the colour changes related to – organic content? Is 'high' or 'low' density just on relative terms (to the rest of the core/s) or compared to literature typical values? – does 'high' bulk density necessarily mean over-consolidation of tills? *We believe that we have provided sufficient core data for distinguishing sediment genesis and that taking the core data analysis one or several steps further would be outside the scope of this paper. We hope that this is acceptable.*
Regarding the bulk density – we have specified that "high" density means relative to the rest of the core.

Facies 3 & 4 lack any references to other literature that would guide or support your interpretations (and the interpretations of the other facies are also sparsely referenced). Yet there is a wealth of work on proximal to distal glaciomarine sedimentary characteristics and physical properties. I suggest (all of) your interpretations should be grounded in available literature. *Additional references have been included.*

Could facies 3 mark the calving front of an ice shelf (melt out of englacial debris), as often suggested for first emergence of IRD after limited sub-ice shelf sedimentation in Antarctic deglacial/glaciomarine facies succession models? Are there other indicators that IRD would be from freely floating icebergs on an at least partly open ocean? *We appreciate the suggestion and have included it to our interpretations.*

Geomorphology

The lineations are sparse, and I still question the 'mega-scale' interpretation; interpretation of an ice stream footprint shouldn't rest on one ratio, but rather a whole suite of landform and landform assemblage observations. Flutes on a valley glacier forefield can have elongation ratios of >10:1 – it doesn't make them msgls. At best, the evidence for fast flow here is limited to the outer shelf, and the discussion of this system should reflect the distribution of these limited indicators. *We see the reviewers point and have opened for the lineations on the middle shelf to be interpreted as ´glacial lineations´.*

GZW A looks no different, morphologically, to the first two larger moraines inland of wedge A (about 15 km and then a further 5 km) – based on their appearance in Figure 5. Why interpret it as a wedge? *GZW A has a more wedge-shaped form when looking at the seismic data, as well as being magnitudes larger than the moraines further inland.*

I would think there's some value in discussing overall trough morphology (orientation, depth, width, tributaries compared to other troughs along this margin), either as part of the geomorphological results or within the Discussion (part 5.1). This trough seems, from Fig 1, to have an abrupt start and a lack of obvious feeder tributaries – how does this relate to the discussion about the source of ice to the trough, or the flow velocity, sediment flux, erosional vigour? *We have rewritten parts of the discussion chapter and included what we believe is appropriate given our data, without being too speculative.*

Discussion

The Discussion is better focused and internally logical, but some passages still are rather underdeveloped. Section 5.2 (dynamics during deglaciation), in particular, comprises a set of paragraphs that clearly fit within this theme but don't really connect to or build on each other, they just appear as discrete ideas. Try to better weave a discussion together from paragraph to paragraph.

The attempt to quantify grounding line landform formation times and retreat rates is a useful addition to the work, though the authors MUST acknowledge the assumptions and caveats implicit in the approaches that they take, and give ranges for their estimates that reflect the uncertainties in the approach; it is difficult to achieve much better than order of magnitude results. The Abstract and Conclusions are too definitive and the Discussion neglects important caveats. The use of any sediment flux makes considerable assumptions about sediment supply, mode of transport, ease of transport, thermal regimes, ice flow velocity. Are the sources you take your upper and lower fluxes from describing glacial systems that would be appropriate analogues for Storstrømmen? How well do these earlier studies really know (measure? infer? with what independent assumptions?) what their sediment fluxes are? Similarly, the interpretation of some types/arrangements of recessional moraines as annually forming is a major and controversial assumption. Annual formation isn't even straightforward to conclude (debate still continues) in classical regions where there are annually-resolved varve chronologies to inform the retreat pattern and rate. It is inappropriate to simply take this assumption without at least acknowledging the debate – and, preferably, discussing the validity of the choices you make. *We appreciate the extensive comment of the reviewer! Based on that, the revised manuscript is now less definitive in its conclusions, as well as acknowledging uncertainties.*

I don't think that blindly applying conceptual interpretations of retreat rate like 'slow', 'rapid' or 'episodic' based on data that is inherently pattern-based rather than chronological, while acknowledging that you lack any chronological constraint, is especially constructive. Wishing to 'continue using the terms' put forward from previous conceptual work isn't a valid reason to do so – are they appropriate, given your data? Can you use your own evidence to evaluate whether these conceptual models are applicable, rather than just 'choosing' to apply them? I think you have more to say from your own data than just adopting a term that doesn't adequately summarise the range of retreat behaviours you see. Regardless of the interpreted retreat rate terminology, I would suggest it's more interesting that in a trough system, commonly expected to host well-formed lineations and retreat from wedge to wedge, here you have a record dominated by retreat landforms of various morphologies, marking different grounding line sedimentation processes and/or rates, different grounding line durations, and that overall the magnitude of the retreat events is rather small. The atypical landform assemblage for a trough setting is more interesting to explore than applying a conceptual model of rate that you can't say much about. *We see the reviewers point and appreciate the many good ideas. This part of the discussion chapter has been restructured and rewritten, now focusing more on our own results rather than terminology.*

Line edits

Title: ice-sheet is hyphenated here, but nowhere else in the text. *Corrected.*

Abstract

p1 line 10-12: re-consider the phrasing here in light of uncertainties/assumptions in calculations (see main comment in Discussion text). *Rephrased.*

p1 line 13-14: what evidence do you have that ice retreated directly across Store Koldewey Island and Germania Land? You can argue that at the ice sheet's maximum extent, ice was sufficiently thick to flow across this topography, but in a late stage of deglaciation? Isn't it more plausible that the high ground forced flow paths (and retreat) around the topography? The latter is in fact what you conclude. This part of the abstract should be revised. *We agree and have rephrased.*

Main text

p1 line 20: "…GIS is presently drained…" *Corrected.*

p2 line 14: explain why an absolute chronology is relevant to the previous sentence: chronology enables us to understand rates of change, while absolute ages let us tie retreat events in with external forcing (climate or ocean changes). *We have rephrased the sentence to make it clearer that in order to link retreat events with external forcing, an absolute chronology for the deglaciation is required.*

p2 line 17-19: do these cosmogenic dates record ice retreat, as in movement of the ice front landward of the island, or do they record ice sheet thinning? *We have rephrased and made it clear that the cosmogenic dates record ice front retreat at Store Koldewey Ø.*

p3 line 1: it deepens seaward but with bumps and dips along its length – it's not a smooth/steady deepening. *Rephrased.*

p3 line 5-8: while interesting, it doesn't seem relevant to the rest of the paper that this ice stream has displayed two recent surges. *We see your point and have removed this paragraph.*

p3 line 20: suggest ending this section with some sort of motivation statement for the rest of your work, or introductory statement to what you've done that builds on these previous studies that you mention. *Included.*

p3 line 33: suggest here you comment on which data have already been published in Laberg et al, and which are new (i.e. move from p5 line 36-38). There also is a bit of a methods gap between this paragraph and the next, where you explain GZW volume estimates, despite not having mentioned that you have / how you have recorded GZWs. I think a sentence or so stating that you've mapped landform outlines or crestlines is needed, and perhaps the basis for how you've interpreted the environmental origins and how/why you've re-interpreted some earlier published ideas (e.g. assessment of size, shape, arrangement, sedimentary setting…*). These are many good suggestions that we appreciate! We have now included a paragraph in the Material and Methods chapter where we inform the reader on which data is new and which has previously been reported by Laberg et al., as well as how the classification of landforms was conducted.*

p3 line 35: what do you mean by 'box volumes'? You've assumed a rectangular cross-profile? On what basis? Is this more valid than an asymmetric triangle? *We have rephrased the paragraph, now explaining that the sediment volumes of the grounding zone wedges were calculated as trapezoid prisms, using a mean thickness and length obtained from the acoustic data.*

p3 line 38: you could refer to other works that have followed a similar approach… *References are now included.*

p4 line 2: you could note that this is a common problem in cold polar waters close to ice sheet grounding lines (relatively little life at the grounding line and low carbonate preservation subsequently (dissolution)) – plenty of other Greenland and Antarctica studies suffer the same limitations. *Good idea, this is now included.*

p5 line 6: 'more dominant component AT the expense of…' *Corrected.*

p5 line 24: refer to your sand-silt-clay data, specifically, to support that facies 1 is coarser than facies 2… although, looking at these plots, the coarser nature of facies 1 is not particularly convincing. *We see a small, but an overall coarsening in grain-size going from facies 2 to facies 1 due to the introduction of IRD.*

p5 line 26: suggest you note in the facies 1 and facies 2 observations that these two facies alternate in two of the cores – there may be more than one occurrence of each/either facies in the core succession. *Corrected.*

p5 line 35: both Fig 4 and Fig 5 should be referenced here, not only Fig 5. E.g. '…data from the middle (Fig 4) and outer (Fig 5) shelf of…' *Corrected.*

p6 line 14: what data did Laberg et al interpret wedges A-D from? Presumably not all multibeam, since you present a new block here? Seismic? *Laberg et al. interpreted the two outermost wedges (A and B) on available multibeam data, whilst the two innermost (C and D) were based on IBCAO 3.0.*

p6 line 17-18: can you give more information on how you calculated these volumes? Did you choose just one cross-profile per wedge, or several, and on what basis? From the multibeam, wedge C looks considerably larger than A, more comparable to B. *We have explained our calculations in the Methods chapter. A possible explanation for GZW C appearing larger than it is may be due to differences in both the scales and water depth legends between figure 4 and 5.*

p6 line 31-32: a figure and more detailed presentation and discussion is warranted here if there are genuinely two superimposed sets of moraines. I can't see that this is evident from either the multibeam panel or the mapped interpretation of moraines in Fig 5. On what basis do you interpret superimposition? If there is, in fact, one group that sits clearly on top of another, then we must interpret that there's been a readvance: you would have one retreat assemblage buried under another. And in that case, this finding would warrant further discussion. *We have specified in Fig. 5 where the superimposing recessional moraines occur, as well as including it in the Discussion chapter.*

p7 line 10: describe or explain why you find the sawtooth-like pattern incompatible with your earlier interpretation. *Rephrased.*

p7 line 14: '…identified along the … sidewalls' sounds like channels are running parallel to the walls of the trough. These simply occur at the periphery of your data coverage, and cut obliquely through other landforms. Suggest you rephrase. *Rephrased.*

p7 line 37: either break the sentence after the list of lithological units ('… and 1 (Fm(d)). It occurs at all…') or insert 'and' before 'it'. *Corrected.*

p8 line 10-13: suggest you switch these two sentences around, it flows more logically from the previous paragraph to begin with the till, and then what rests on top of the till. *Good idea!*

p8 line 25: 1000-1500m thick, or high? (i.e. surface altitude or ice thickness?) *Rephrased to ice thickness.*

p8 line 30: since Storstrømmen is an outlet of the contemporary NEGIS, it sounds strange to talk about this as a 'similar flow feature'. Can you instead emphasise here that the disregard for topography appears (from your results) to be a characteristic of both the palaeo and contemporary NEGIS? And be specific about exactly where this independence from topographic steering occurs within the NEGIS today. *Publications indicate that the contemporary NEGIS appears to have similar characteristics as pure ice streams (Fahnestock et al., 1993; Sachau et al., 2018).*

p8 line 31: 'a palaeo-ice stream' – can you be specific, which one? *We have clarified that it is the Maskwa paleo-ice stream within the Laurentide Ice Sheet.*

p8 line 34-38: do Arndt et al propose a more restricted ice margin as well as a limited drainage basin (supply), or do they also suggest shelf-edge glaciation? If they envisage shelf-edge glaciation, then your counter-argument ('we have evidence of shelf-edge glaciation') isn't really sufficient. *Arndt et al. do not suggest any former position of the ice margin explicitly; however, they suggest that Store Koldewey Trough probably was not eroded by an ice stream during multiple glaciations. They further propose that major parts of the ice on Germania Land drained northwards into Norske Trough and to Dove Bugt in the south. If so, we believe that there would not have been sufficient amount of ice left to fill Store Koldewey Trough all the way to the shelf edge during LGM.*

p8 line 37: can you be more specific about the volume of ice required, and compare to what Germania Land could sensibly supply? *We have provided information on possible ice volume on Germania Land, but not for the trough during LGM. However, we have included numbers on the area and depths of the trough.*

p8 line 42-45: I don't think these opening sentences really add anything useful. *Removed.*

p9 line 5: the phrasing here makes it sound like Store Koldewey also has a reverse slope. The fact that it doesn't is surely an important reason for any contrast in behaviour. You set up a 'problem' here that isn't really one. I would revise this paragraph as a commentary on the rather uncommon situation of having a seaward dipping trough that has led to a rather stable retreat pattern, supplemented by local trough shallow/narrow points, rather than making this more of a puzzle than it really is. *We see the reviewers point and have rewritten the paragraph.*

p9 line 13-14: what do you mean by 'had a more dynamic response to…'? Rephrase to say something direct, this is vague. *Removed.*

p9 line 16: 'local trough geometry' (typo, through) *Corrected.*

p9 line 22: where are the other 2 wedges that Batchelor & Dowdeswell find here, and why do you not include those in your reconstructions? *We find it unclear where Batchelor and Dowdeswell (2015) have identified the two remaining GZWs and have therefore not included them in our reconstructions.*

p9 line 20-27: this paragraph doesn't seem to go anywhere. What do you interpret to be the significance in the number of wedges recorded in different troughs? Are the single wedges in Norske & Westwind Troughs at the shelf break? What would be the implications for your work if these formed during the Younger Dryas? *We have removed this paragraph.*

p9 line 35: which West Antarctic ice stream? Or do you mean ice sheet? *Corrected to Whillans Ice Stream, West Antarctica.*

p9 line 37: these values use the upper sediment flux rate. Using the lower flux would give you an order of magnitude longer formation time, i.e. 1300, 7400 and 1500 years. Is there enough time available for retreat across this shelf, with those standstill durations? See also main comment about sediment flux assumptions. *We have now included the lower flux rate in our discussions.*

p9 line 40: this passage must better reflect the debate about whether recessional moraines can be interpreted as annual or not. *Included.*

p9 line 50-52: this sentence either could be removed (since you don't put it in the context of your results) or should reflect the vast literature on grounded to open marine (deglacial) sedimentological facies. Picking a random three papers that have studied this succession is rather meaningless. *Removed.*

p9 line 6: masks *Corrected.*

p9 line 7-9: Prothro et al (Marine Geology) discuss the distance for rainout of basal debris distal to the grounding line – they find it to be extremely short. *Ok.*

p9 line 25: it is intriguing that the sediment drape only occurs across the inner-middle shelf, and not the outer parts that deglaciated first. Why do you think this is? Is this a supply or a preservation/deposition question? *We have provided a possible explanation for this (current winnowing, leading to non-preservation of fine sediments).*

p9 line 30: what is the significance of facies 1 & 2 alternating in the two outer cores? How does this affect your environmental interpretations here? *Included.*

p9 line 37: would reduced sea ice not allow more icebergs to access the area? Or, conversely, expanded sea ice would limit access of icebergs and deposition of IRD? *Reconstructions of sea-ice concentrations and IRD data on the East Greenland shelf reveal that a reduced sea-ice cover during the Early Holocene was accompanied by low IRD concentrations (e.g. Müller et al. 2012).*

Figure 1: label the profile shown in panel B on the dashed white line in panel A (instead of or as well as writing in the caption). *Ok.*

Figure 5: could you make the colours for sawtooth moraines and iceberg ploughmarks more distinct from one another? *Ok.*

Changes made to the manuscript:

In the following revised version of the manuscript, we have added and re-written paragraphs, as well as corrected misspellings and rephrased sentences.

Methods:

All radiocarbon dates cited in the manuscript were calibrated using the CALIB 8.20 software, applying the Marine20 calibration curve.

We have provided information on how the mapping and classification of landforms were conducted, as well as our calculations on grounding-zone wedge sediment volumes.

Results:

In chapter *4.1 Lithostratigraphy of the uppermost trough strata*, we have added some alternative interpretations, in addition to adding additional references to our interpretations, as requested by the reviewer.

Our interpretations of mega-scale glacial lineations in the trough has been slightly modified – we have now opened for the streamlined landforms in the middle trough to be interpreted as "glacial lineations".

Discussion:

We have restructured and rewritten parts of the Discussion chapter, focusing more on our own results, as well as acknowledging the uncertainties within our interpretations and estimates of retreat rate/duration of standstills.

Finally, we added a paragraph with "Acknowledgements".

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 new swath bathymetry and high-resolution seismic data, supplemented with multi-proxy analyses of sediment gravity cores from Store Koldewey Trough~~, NE Greenland~~. Subglacial till fills the trough, with an overlying drape of maximum 2.5 m ~~thickness of~~thick 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~~ thereby previously flowing across Store Koldewey Island and Germania Land. Grounding zone wedges and recessional moraines provide evidence that multiple halts and/or readvances interrupted the deglaciation. The formation of the grounding zone wedges ~~took~~ is estimated to 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, assuming that the moraines formed annually. The complex geomorphology in Store Koldewey Trough is attributed to the trough shallowing and narrowing towards the coast. At a late stage of the deglaciation, the ice stream flowed around the topography on ~~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 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~~ is 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: 79º-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 possibly 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~~This 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 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 future evolvement of the GIS remains difficult (Nick et al., 2013). 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~~26.5-19 ka BP (Clark et al., 2009)) towards the present, is needed to validate and improve 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 (e.g. Andrews et al., 1998; Bennike et al., 2002; Dowdeswell et al., 1994, 2014; Funder et al., 2011a; 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~~ NE 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). 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, grounding zone wedges and recessional 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 ~~on the outermost shelf of the~~in the outermost part of Store Koldewey Trough (Fig. 1), suggesting a stepwise early deglaciation likely triggered by an increase in ocean temperature. However, in order to precisely link retreat events with external forcing (e.g. climate or oceanic changes), an absolute chronology for the deglaciation is ~~still pending~~required. 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 18.4 cal. ka BP (for age calibration, see Material and methods chapter)~~c. 15.3 ka BP~~, with the ice abandoning the mid-shelf before ~~13~~ 15.5 cal. ka BP and the inner shelf being ice free before ~~9~~ 10.3 cal. ka BP. Cosmogenic nuclide dating on Store Koldewey Ø, located west of Store Koldewey Trough (Fig. 1), reveals that the ice front retreated from the area c~~a~~. 12.7 ka BP (Skov et al., 2020), whereas the ice front rested east of the present coastline of Germania Land until c. 10 cal. ka BP (Landvik, 1994). By ~~7.5~~8.3 cal. ka BP the ice front had retreated close to its present position, and after further recession Germania Land became an island about ~~6~~ 5.5 cal. ka BP. Storstrømmen readvanced again c. 1 cal. ka BP, reaching its present position during the Little Ice Age (Weidick et al., 1996).

The overall objective of this paper is to provide new knowledge ~~regarding the presence of a shelf-break terminating GIS on~~about the evolution of the northeastern part of the ~~Greenland Margin by presenting evidence from~~GIS based on new acoustic data (multibeam bathymetry and Chirp seismic) and sediment cores. These new data sets expand~~s~~ and complement~~s~~ existing data in one of the largest glacial troughs offshore ~~northeast~~ NE Greenland, i.e. the Store Koldewey Trough. More specifically, the aims are to 1) reconstruct the ice drainage pathways, ice sheet extent and ice stream 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.

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 (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, 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 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 ~210 km long, 30-40 km wide and up to 400 m deep, NW-SE oriented cross-shelf trough located at ~76° N offshore ~~northeast~~ NE 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~~ trough (Fig. 1C), with 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~~ NE Greenland, because it overall 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 calving events (Hill et al., 2018).~~

Laberg et al. (2017) identified an assemblage of glacigenic landforms ~~o~~in ~~the~~ outer ~~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 ~~o~~in the outer, middle and inner ~~shelf~~ trough were interpreted as grounding-zone wedges deposited in front of the GIS ~~during~~ at 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). However, details about how these shelf-break terminating parts of the North East Greenland Ice Sheet retreated landwards remain unknown, as only very limited areas are mapped by high-resolution swath bathymetry (Arndt, 2018; Arndt et al., 2017; Evans et al., 2009; Laberg et al., 2017; Winkelmann et al., 2010).

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~~ by 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 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) 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 ~~c~~Chirp and ~~multibeam~~ swath bathymetry data were performed using Petrel 2018 and Global Mapper 19.

~~The sediment volumes of the grounding zone wedges were calculated as box volumes~~ The acoustic data sets consists of previously unpublished data from the middle trough acquired in 2017, and data from the outer trough previously presented by Laberg et al. (2017). Systematic mapping and outlining of landform elements in Store Koldewey Trough were conducted on the entire swath bathymetry data set, including some re-interpretations of the outer trough (see subchapter *4.2.4. Curvilinear ridges – Saw-tooth recessional moraines*). The landforms were mapped and classified based on shape, size, arrangement and orientation. The sediment volumes of the grounding zone wedges were calculated as trapezoid prisms, using a mean thickness and length obtained from the acoustic data. Due to the limited data coverage, we use the similar approach as Jakobsson et al. (2012a) and calculate the volume per 1-m grounding line width (m^3/m). Since the Chirp sub-bottom signal was unable to penetrate to the bases of the grounding zone wedges, a flat base beneath the proximal sides of the wedges was assumed.

The sediment gravity cores (HH17-1326, HH17-1328, HH17-1331 and HH17-1333) were retrieved from 294 m 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. A systematic description of the sediment surface was carried out and colors were determined visually using the Munsell Soil Color Chart (Munsell, 2000). The cores contained insufficient amounts of dateable material for a chronology to be established, a common problem from areas where cold polar waters lead to both relatively little calcareous organisms and dissolution of the carbonate material (e.g. Andrews et al., 1999; Zamelczyk et al., 2012).

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 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 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).

Age calibration for the radiocarbon ages cited in this study was performed using the CALIB 8.20 software (Stuiver et al., 2020), applying the Marine20 calibration curve (Heaton et al., 2020) with $\Delta R = 0 \pm 50$, as recommended by Andrews et al. (2016). All dates are presented in calibrated years before present (cal. ka BP), where zero year BP is AD 1950.

4 Results

4.1 Lithostratigraphy of the uppermost trough strata

Five lithofacies are defined based on the lithological composition, sedimentary structures and physical properties (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 (Fig. 2 and 3; Table 2). The upper boundary is sharp, and bioturbation is absent. The magnetic susceptibility varies between each core, with the highest in HH17-1326 and lowest in HH17-1328. The ~~W~~wet bulk density is generally higher than in the overlying facies, suggesting over-consolidation of the sediments.

Based on the 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).

4.1.2 Facies 4 – Interlaminated glacimarine sediments (Fl)

Facies 4 is present in the two cores ~~o~~in the inner trough~~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~~ appearance of ~~dropstone deposition~~clasts. ~~W~~The wet bulk density is medium, whilst the magnetic susceptibility varies with a decrease in HH17-1326 and an increase in HH17-1328 relative to the underlying unit.

Facies 4 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. Such laminated to massive sandy muds are typically overlying basal diamictons (i.e. facies 5) in glaciated continental margin and fjord settings (e.g. Domack et al., 1999; Prothro et al., 2018; Smith et al., 2019). ~~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.~~ 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).

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

Facies 3 occurs in all ~~sediment~~ cores.~~,~~ ~~and it~~It is 9-23 cm thick and consists of dark gray laminated mud with fine-sand~~y~~ 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 in all cores. The ~~unit has similar~~ properties are similar to~~as~~ facies 4, with medium-high wet bulk density. However, the magnetic susceptibility varies between the cores.

Facies 3 is interpreted to represent a glacier-proximal setting with glacimarine sediments containing IRD deposited in episodic calving events. The sediments are thought to have been deposited in ~~open~~ glacimarine conditions, reflecting a calving zone in a~~n~~ ~~outer ice-proximal~~more distal setting where ~~the ice front has retreated and~~ IRD becomes a more dominant component ~~on~~ at the expense of suspension settling (cf. Smith et al., 2019), compared to facies 4. Another possible explanation is that the facies reflects deposition from melt out of englacial debris at the grounding line, similar to the facies ascribed as ´stratified diamicton` by ~~(~~Smith et al.~~,~~ (2019).

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); facies 2 overlies facies 3 in all cores, except for core HH17-1331, where it overlies facies 1. In core HH17-1333, facies 2 alternates with facies 1. ~~. Both t~~The lower and upper unit boundaries are gradational. The physical properties, including wet bulk density and magnetic susceptibility vary slightly within the facies and between the cores.

The facies is interpreted to reflect suspension settling in an ice-distal glacimarine environment with limited iceberg or sea-ice rafting. With increased distance from the grounding line, deposition from turbid meltwater plumes typically grade into more massive, bioturbated mud (Ó Cofaigh and Dowdeswell, 2001; Prothro et al., 2018; Smith et al., 2019). The rare amount of IRD within the massive mud may be a consequence of the appearance of warm surface water during the Early Holocene causing prolonged open water conditions and ~~reduced~~ limited iceberg 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, the latter interpreted to be IRD (Fig. 2 and 3; Table 2). Facies 1 occurs twice in core HH17-1331 and HH17-1333, lying directly above facies 3 and 2. 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. Peaks in the magnetic susceptibility correspond to the depth with highest abundance of coarser material. The wet bulk density 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 ice~~berg~~ 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).

4.2 Submarine landforms: glacial – deglacial ice ~~-~~sheet dynamics

The swath bathymetry data from the middle (Fig. 4) and outer (Fig. 5) ~~shelf 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 – ~~Mega-scale glacial lineations~~Glacial lineations

Streamlined, trough-parallel grooves and ridges occur in the middle and outer ~~shelf~~ trough (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, making the determination of their maximum lengths challenging. Their minimum lengths range from 1.5 to >9 km long and their length/width ratios generally exceed 10:1, with the highest ratios occurring in the outer trough. High-resolution seismic data show that the ridges are acoustically transparent, a property that is characteristic for basal till (e.g. Ó Cofaigh et al., 2007).

Based on the spatial distribution, dimensions and orientations, we interpret the grooves and ridges as ~~mega-scale~~ glacial lineations ~~-~~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. The lineations in the outer trough have longer length/width-ratios and are more densely spaced, and are, thus, termed mega-scale glacial lineations. ~~S~~Similar streamlined 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* from multibeam data and IBCAO 3.0 (Jakobsson et al., 2012b) by Laberg et al. (2017), are present within the trough (Fig. 1B, C and 7). 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 from each other (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 extents of the grounding zone wedges exceed~~s~~ the multibeam data coverage. Smaller ridges overprint the grounding zone wedges (Fig. 4, 5 and 6). The base of the wedges is~~ not~~ impossible to identify ~~from ~~on 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, these large landforms are interpreted to be accumulations of sediments deposited at the ~~ice stream`s ~~grounding line of the ice stream, recording the ~~temporary ~~position of the grounding line during temporary stillstand, either reflecting a halt during the general retreat or the termination of a more extensive ~~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

Multiple straight to slightly curvilinear transverse/semi-transverse ridges are visible on the seafloor of Store Koldewey Trough (Fig. 4, 5, 6 and 7). 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 (Fig. 5). There are two generations of ridges ~~o~~in the outer ~~shelf ~~trough(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 ~~o~~in the middle ~~shelf ~~trough is commonly 100-200 m.

We interpret the curvilinear to straight ridges as recessional moraines formed at the grounding line during overall retreat with repeated short-term stillstand and/or small readvances (cf. Dowdeswell et al., 2008; Ó Cofaigh et al., 2008). 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 Curvilinear ridges – Saw-tooth recessional moraines

Clusters of curvilinear ridges occur both landward and seaward of grounding zone wedge *B*, and seaward of grounding zone wedge *C* (Fig. 4, 5, 6B and 7D, E). These ridges occur often closely spaced, exhibiting a saw-tooth pattern in plan view. Many of the features continue as long moraine ridges oriented sub-parallel to the ice-flow direction. Bifurcations and cross-cutting patterns occur. Individual ridges are up to 1.3 km long, 170-1100 m wide and have a relief of 5-30 m (Table 3). They are typically asymmetrical with a steeper ice distal slope and a more gentle ice proximal slope (Fig. 6E). The saw-tooth ridges partly superpose and modify the underlying transverse ridges creating locally chaotic seafloor patterns. Furthermore, grounding zone wedge *B* partly covers some saw-tooth ridges (Fig. 6B).

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) i~~o~~n the western part of the data set from the outer trough~~shelf~~.~~,~~ H~~h~~owever, we ~~found ~~find the saw-tooth-like morphology incompatible with the geometric ridge networks of rhombohedral ridges based on the ridges zig-zag pattern in plan view (cf. Bennett et al., 1996).

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 ~~on 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. The landforms are interpreted as channels formed during deglaciation and are probably related to erosion by meltwater.

4.3 Seismostratigraphy

Two seismostratigraphic units (S1 and S2) ~~were identified~~are distinguished in the ~~c~~Chirp sub-bottom profiles in Store Koldewey Trough (Fig. 7).

4.3.1 Unit S1 – Glacigenic deposits and/or sedimentary bedrock

~~Seismic u~~Unit S1 is the lower~~most~~ seismostratigraphic unit and the base of this unit represents the acoustic basement~~ of the study area~~. 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. it includes subglacial deposits. However, the internal reflection shown in Fig. 7D can either be interpreted as a bedrock surface visible on the Chirp profile due to a thin layer of till, or as an internal reflection within the till. Furthermore~~However~~, the ~~c~~Chirp profiles (Fig. 7) and sediment cores confirm ~~reveal~~ that the ~~unit S1 also includes~~ grounding-zone wedges~~, as well as~~ and recessional moraines~~, i.e. multiple glacigenic landforms and deposits.~~ consists of subglacial till.

4.3.2 Unit S2 – Glacimarine sediments

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

Unit S2 is correlated with the lithological units 4 (*Fl*), 3 (*Fl (d)*), 2 (*Fm*) and 1 (*Fm (d)*), and it occurs at all four core sites. Thus, the unit contains glacimarine deposits reflecting a gradual transition from glacier proximal to distal environments.

5 Discussion

5.1 Maximum ice sheet extent and influence of subglacial topography

Mega-scale glacial lineations ~~and their terminations at~~extending almost to grounding zone wedge *A* in the outer trough (Fig. 5 and 9: Stage 1), together with subglacial debris/basal till in sediment cores from the middle trough, suggest that a grounded, fast-flowing ice stream draining the northeastern sector of the GIS extended to the shelf break in Store Koldewey Trough at maximum ice extent during the last glacial (Fig. 8). Furthermore, acoustic profiles reveal an up to 2.5 m thick drape of glaciomarine sediment overlying the subglacial till in certain parts of the inner and middle trough, whereas a detectable sediment drape in the outer trough is absent (Fig. 5). This lack of glacimarine sediments and good preservation of glacial landforms in the outer trough indicate that the identified landforms formed during the LGM and the subsequent deglaciation, as proposed by Laberg et al. (2017). ~~, as proposed by Laberg et al. (2017) (Fig. 8).~~

The shelf break-terminating ice stream in Store Koldewey Trough~~This~~ is 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 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.~~ ~~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).~~ ~~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 24~~1~~-~~16~~ 19 cal. ka ~~cal. yr~~ BP. Radiocarbon dates from the Greenland Basin indicate that mass-wasting activity in a channel system on the upper continental slope took place predominantly under full glacial and deglacial conditions, and that this had ceased after about ~~13~~ 14.7 cal. 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 ~24~~1 ka BP~~ ~~-~~-~~~13~~ 14.7 cal. ka BP.

We propose that the Store Koldewey Trough was filled by grounded ice masses ~~originating~~ deriving from the area presently covered ~~with~~ by the Storstrømmen ice stream (Fig. 8A). Palaeo-ice sheet models have calculated that the ice covering Germania Land during LGM ~~has been~~reached 1000-1500 m ice thickness (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 across the underlying topography, including the mountain range with 500-900 m high peaks 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. Moreover, the disregard for topography appears to be a characteristic of both the palaeo and contemporary North East Greenland Ice Stream ~~In addition, a similar flow feature has been identified in the modern North East Greenland Ice Stream (NEGIS)~~ (Fahnestock et al., 1993; Sachau et al., 2018) (Fig. 1A), as well as for ~~a~~ the Maskwa paleo-ice stream within the Laurentide Ice Sheet (Ó Cofaigh et al., 2010; Ross et al., 2009).

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, as well as the estimates from Fleming and Lambeck (2004) and Heinemann et al. (2014), we favor the interpretation that the Storstrømmen ice stream ~~filled~~ sourced Store Koldewey Trough during full glacial conditions, based purely on the volume of ice needed to fill a trough of this dimension. Germania Land covers an area of ~2500 km^2, and if the ice thickness here reached 1000-1500 m during LGM (Fleming and Lambeck, 2004; Heinemann et al., 2014), the total ice volume must have been 2500-3750 km^3. Store Koldewey Trough covers an area of ~9000 km^2, and the present-day water depth at the shelf break is >400 m. Thus, the volume needed to fill the trough exceeds the ice volume estimated for Germania Land, and a local drainage basin from there is therefore unlikely.

5.2 ~~Glacial~~ Ice stream 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 repeated halts and/or readvances interrupted the deglaciation (Fig. 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, the occurrence of grounding zone wedges and recessional moraines overprinting mega-scale glacial lineations~~

~~demonstrates an overall relatively slow retreat. 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 complex glacial landform assemblage in Store Koldewey Trough, comprising transverse wedge- and ridge systems, reflects to a large degree the dynamic retreat of the ice margin during the deglaciation. The types of landforms and their spatial distributions can be attributed to the overall seafloor topography of the trough, with a seaward dipping bed slope, supplemented by local pinning points related to trough shallowing and/or narrowing. The resulting deglacial dynamics was characterized by several periods of stabilization and readvances of the grounding line in Store Koldewey Trough during overall retreat. In contrast, ~~Whereas~~ many paleo-ice streams on other glaciated continental shelves with ~~reverse~~ landward dipping beds ~~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 Ice Sheet (Rydningen et al., 2013), the ice stream in Store Koldewey Trough repeatedly stabilized and readvanced, interrupting the deglaciation.

~~. A combination of several factors may have preconditioned this, and led to the complex geomorphology in Store Koldewey Trough: i) local highs in the overall shallowing landward seafloor profile may have provided pinning points, causing ice stabilization and promoting longer stillstands during the deglaciation; ii) trough narrowing towards the coast may have increased lateral stress on the retreating ice margin, thus slowing down/stabilizing ice flow; iii)) 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.~~

The retreat landforms of various morphologies mark different retreat styles and periods of grounding line stabilization during retreat (Fig. 9: Stage 3 and 4). Whilst the spatial distribution of the moraine ridges indicates a stepwise retreat with several episodes of relatively short grounding line stabilizations, the presence of four large grounding zone wedges indicate that the glacier also grounded for a longer time during the deglaciation, allowing for larger wedges to form (Dowdeswell et al., 2008; Ó Cofaigh et al., 2008). 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.

~~The locations and dimensions of grounding zone wedges on the NE Greenland continental shelf are thus far poorly documented. Batchelor and Dowdeswell (2015) and Dowdeswell and Fugelli (2012), mention six grounding zone wedges in Store Koldewey Trough based on seismic data. Our data set reveals four grounding zone wedges. 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.~~

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 Trough 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 a 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 Whillans Ice Stream, West Antarctica ~~Ice Stream~~ (Anandakrishnan et al., 2007), and on the southern Norwegian continental margin (Nygård et al., 2007). Applying ~~these numbers suggests that~~ these upper and lower flux rates, the periods required for the formations of grounding zone wedges *A*, *B* and *C* ~~took~~ are in the range of ~~at least~~ 130-1300, 740-7400 and 150-1500 years, respectively. The lower flux rate, resulting in an order of magnitude longer formation time, seems less likely given the tight time frame available for retreat across the shelf (~14.7-12.7 ka BP (Ó Cofaigh et al., 2004; Skov et al., 2020)).

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). Whilst annual formation of moraines can be studied in situ in e.g. Svalbard (Flink et al., 2015; Ottesen and Dowdeswell, 2006), the interpretation of a series of evenly spaced recessional moraines as annually in the palaeo-record is debated (e.g. Chandler et al., 2020). However, ~~A~~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 1) ~~-~~retreated with an average of 80 m yr^{-1}, 2) readvanced and 3) retreated again, ~~before~~ accelerating to 200-400 m yr^{-1} ~~o~~in the outer ~~shelf~~ trough (Fig. 9: Stage 6). By the time the ice margin reached mid-trough~~shelf~~, spacing of individual moraines indicate a reduced recession of 100-200 m yr^{-1}. Although estimates on sediment flux and deglacial rates are presented here, we recognize that there are uncertainties in our calculations. Therefore, more precise calculations remain to be defined from other data than ours.

The lithological sequence starting with a basal till overlain by glacimarine deposits suggests the transition from sub-glacial to an ice-proximal setting and, subsequently, to a more ice-distal environment dominated by suspension settling ~~with~~ and various degrees of ice rafting. ~~Evans et al. (2002), 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, 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 t~~melt-out of debris in the area (Jennings and Weiner, 1996; Moon et al., 2015; Vorren and Plassen, 2002), ii) a high flux of sediment-laden glacial meltwater masks 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 at the grounding line (Domack and Harris, 1998; Reilly et al., 2019; Smith et al., 2017).

~~Absence of basal ice 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 i~~o~~n the inner ~~shelf~~trough. 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 trough~~shelf~~, resulting in a more stabilized ice front and ice-shelf formation (Fig. 9: Stage 5). Trough narrowing towards the coast could possibly have contributed to an increase in lateral drag and subsequent reduction in extensional stress as the ice front retreated to the innermost trough area, resulting in a more stabilized ice front (grounded) and ice-shelf formation from here (Fig. 9: Stage 5). Thus, facies 4 deposited in the inner trough while the glacier was grounded further to the west, in a similar setting as described by Reilly et al. (2019) for the Petermann Glacier in NW Greenland, where an IRD free depositional environment beneath the floating ice tongue was followed by an increase in IRD concentrations as the ice tongue retreated from the site.

5.3 Postglacial development

During the late phase of the deglaciation, the ~~ice stream~~ flow path of the ice stream became controlled by the topography on~~retreated across~~ Store Koldewey Island and Germania Land, i.e. it was directed into Jøkelbugten to the north and Dove Bugt in the south (Fig. 8B and 9: Stage 6). This terminated the supply of suspended sediments and icebergs from the Storstrømmen area to Store Koldewey Trough~~to Store Koldewey Trough, re-routing the material to Dove Bugt and Jøkelbugten (Fig. 8B)~~. The generally thin and patchy occurrence of seismostratigraphic unit S2 (correlating to facies 1-4; Fig. 7) could be due to a change of ice configuration in the west, with ice masses eventually being routed north- and southwards, resulting in a decrease of sediment supply to the trough. More specifically, the absence of a detectable post-glacial sediment cover in the outer trough may be a result of ocean current winnowing from the southward-flowing East Greenland Current, leading to non-preservation of fine-grained sediments here.~~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 material from sea-ice transported ~~southwards from~~across the Arctic Ocean within the Transpolar Drift, rafting by sea-ice formed along the NE Greenland coast, rainout from icebergs and meltwater plumes released from regional marine terminating outlet glaciers north of the study area (e.g. 79°-Glacier and Zachariae Isstrøm), as well as winnowing on the surrounding banks.

The low IRD content in facies 2 is probably due to multiple factors: i) ice fronts retreating on land, ii) material entrapped in icebergs calving off from marine-terminating glaciers probably melted out rapidly and icebergs only occasionally reached the continental shelf. This could correlate to the Holocene Thermal Maximum (c~~a~~. 8-5 ka BP) when temperatures in NE Greenland were higher 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 subsequent regional climatic cooling. This climate deterioration, referred to as the Neoglaciation (c~~a~~. 5 ka BP – Little Ice Age), led to glacier expansion with enhanced iceberg-rafting and increased sea-ice extent on the East Greenland shelf (Klug et al., 2009; Müller et al., 2012).

6 Conclusions

- New and previously published swath bathymetry data (Laberg et al., 2017), integrated with high-resolution seismic data and sediment gravity cores, ~~reveal the existence of mega-scale glacial lineations, grounding zone wedges and recessional moraines providing~~provide new information about the dynamics of the northeastern sector of the Greenland Ice Sheet, as well as about glacial and postglacial sedimentary environments.
- 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~~ and glacier distal deposits.
- The ice stream draining through Store Koldewey Trough probably originated from the area presently covered with the Storstrømmen ice stream. 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 various types of recessional moraines (transverse and saw-tooth recessional moraines) within the trough provide evidence that multiple halts and/or readvances interrupted the deglaciation. The formation of the grounding zone wedges probably took at least 130 years. Assuming that the recessional moraines were annually formed, the ~~D~~distances between the ~~recessiona~~l moraines indicate that the grounding line locally retreated between 80 to 400 meters/year during the deglaciation.
- The complex geomorphology in Store Koldewey Trough is attributed to the trough shallowing and narrowing towards the coast, affecting the formation of grounding zone wedges.

- 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, terminating sediment supply to Store Koldewey Trough.

Author contributions. The idea of the study developed from repeated discussions among the authors of this study and the opportunity to participate in 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 were interpreted by ILO 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.

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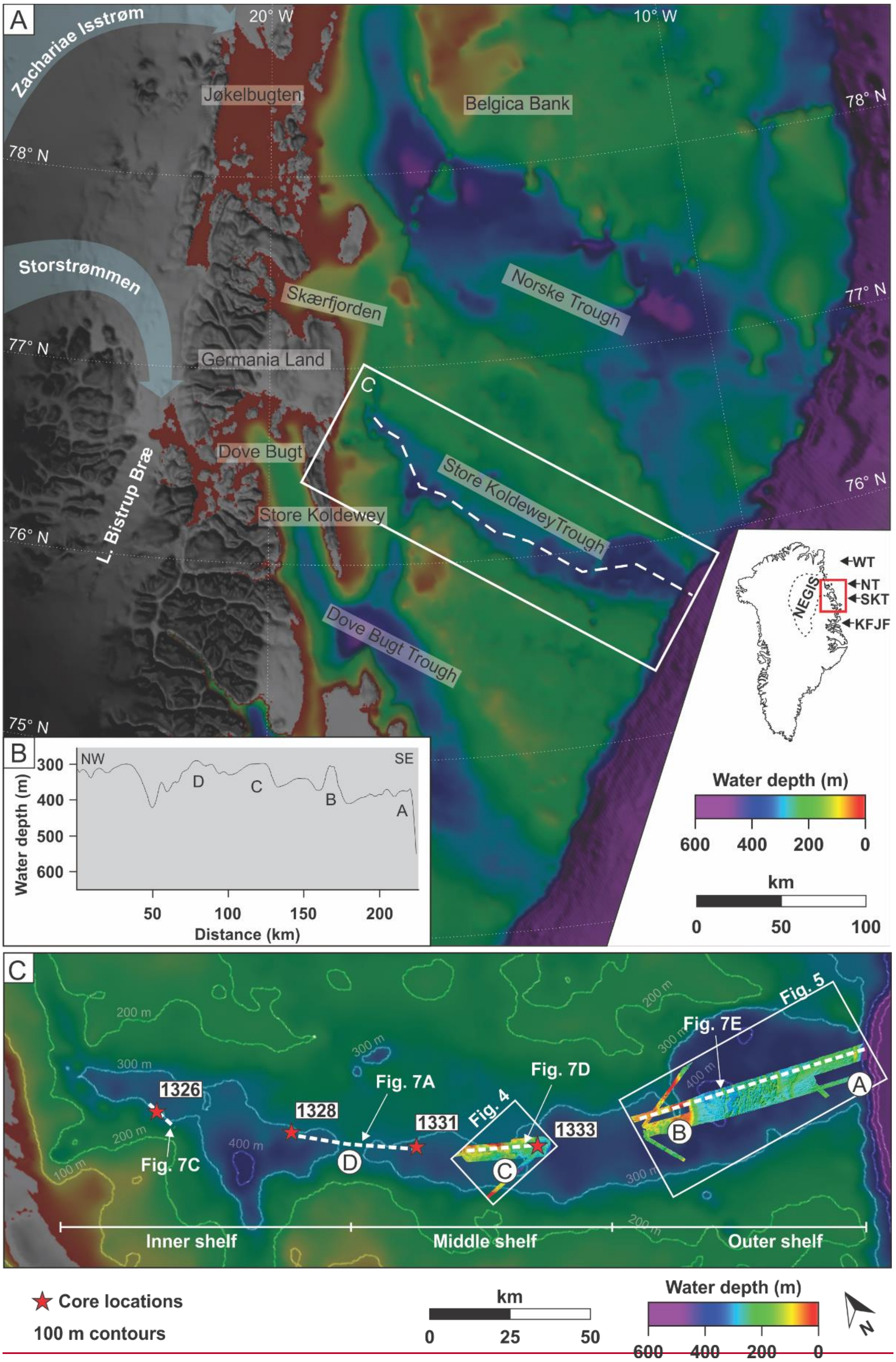
A
Zachariae Isstrøm
20° W
10° W
Jøkelbugten
Belgica Bank
78° N
78° N
Storstrømmen
Skærfjorden
Norske Trough
77° N
77° N
Germania Land
C
Dove Bugt
L. Bistrup Bræ
Store Koldewey Trough
Store Koldewey
76° N
76° N
Dove Bugt Trough
75° N
WT
NT
SKT
KFJF
NEGIS
B
Water depth (m)
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400
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600
NW
SE
D
C
B
A
50
100
150
200
Distance (km)
Water depth (m)
600
400
200
0
km
0
50
100
C
200 m
300 m
200 m
100 m
1326
Fig. 7C
400 m
1328
300 m
Fig. 7A
D
1331
Fig. 4
Fig. 7D
1333
C
200 m
300 m
400 m
Fig. 7E
Fig. 5
B
A
300 m
200 m
Inner shelf
Middle shelf
Outer shelf
Core locations
100 m contours
km
0
25
50
Water depth (m)
600
400
200
0
N

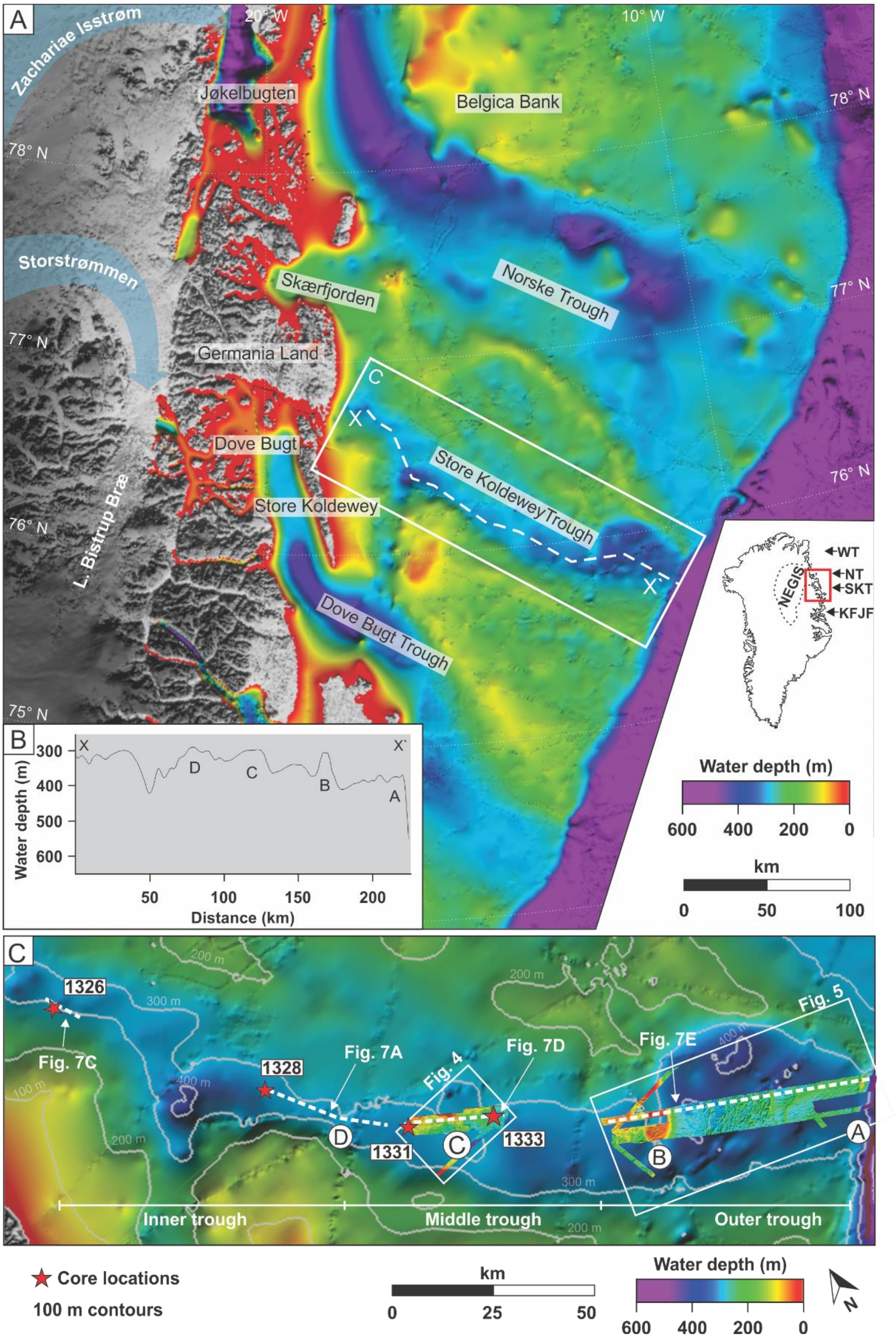
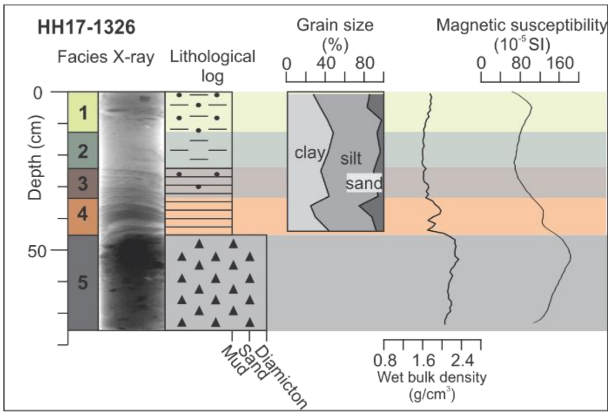
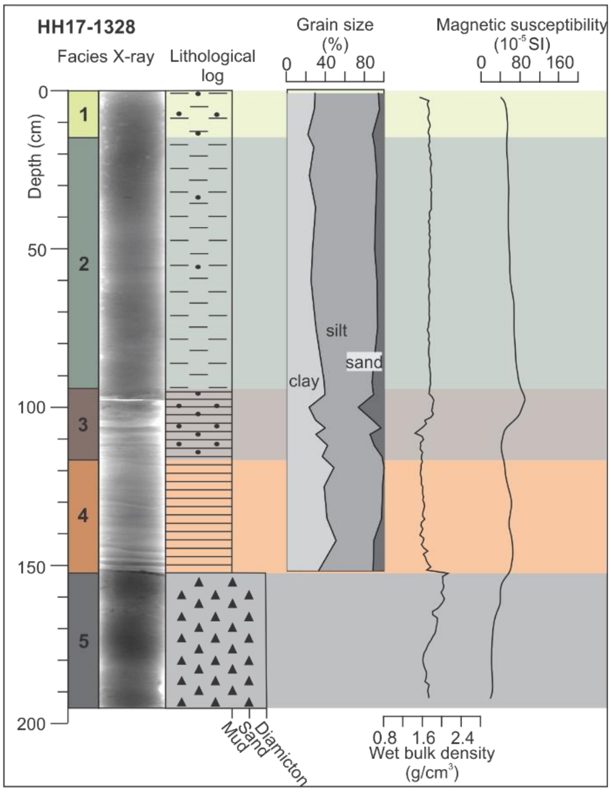


Figure 1: (A) Overview of the regional bathymetry and the hinterland topography of ~~northeast~~ NE Greenland (from IBCAO v.4~~3~~.0; ~~(~~Jakobsson et al., 2020)~~Jakobsson et al. 2012b)~~ including geographical names. The small map shows Greenland and the outline of the North East Greenland Ice Stream~~ (NEGIS)~~, with the red box showing the study area detailed in (A). The locations of Westwind Trough (WT), Norske Trough (NT), Store Koldewey Trough (SKT) and Kejser Franz Josef Fjord (KFJF) are indicated. ~~W~~The white dashed line shows the location of bathymetric profile shown in (B). (B) Bathymetric profile along the central axis 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.4~~3~~.0; ~~(~~Jakobsson et al., 2020)~~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)

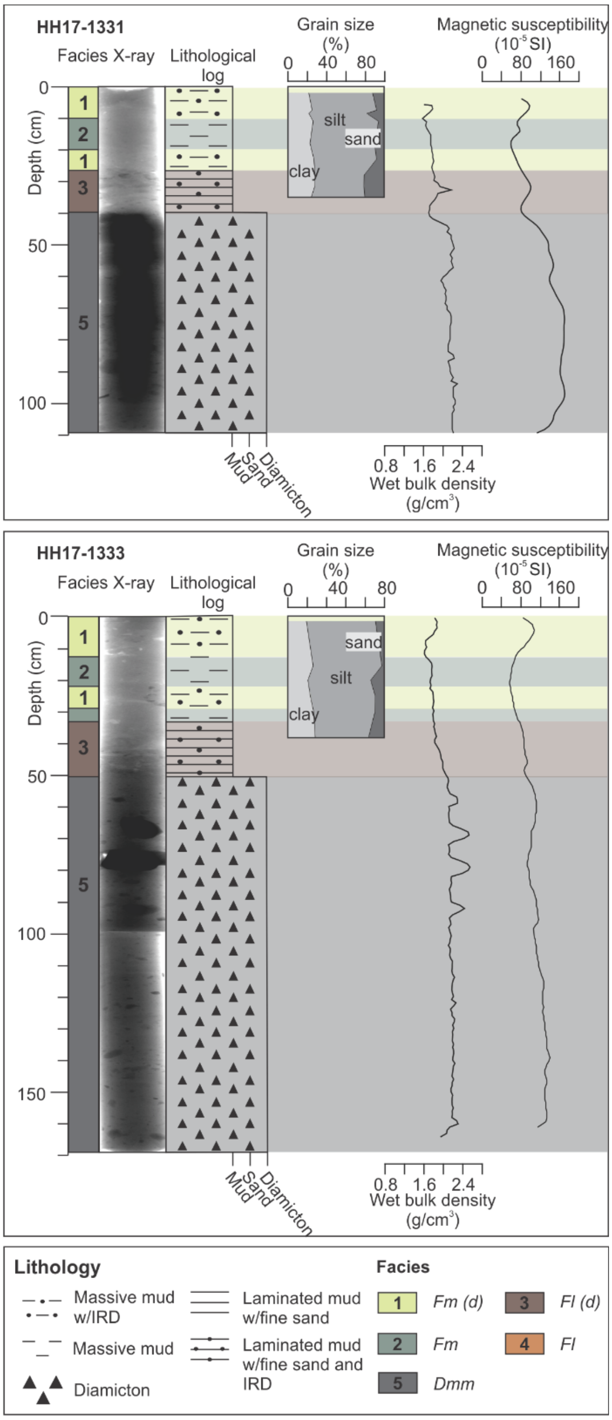


Figure 2. ~~Sedimentary l~~Lithofacies logs, X-radiographs, grain-size distribution and physical properties for the cores from inner and middle Store Koldewey Trough. The darker grey tones in the X-radiographs reflect higher density, whereas brighter grey tones reflect lower density. The locations of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

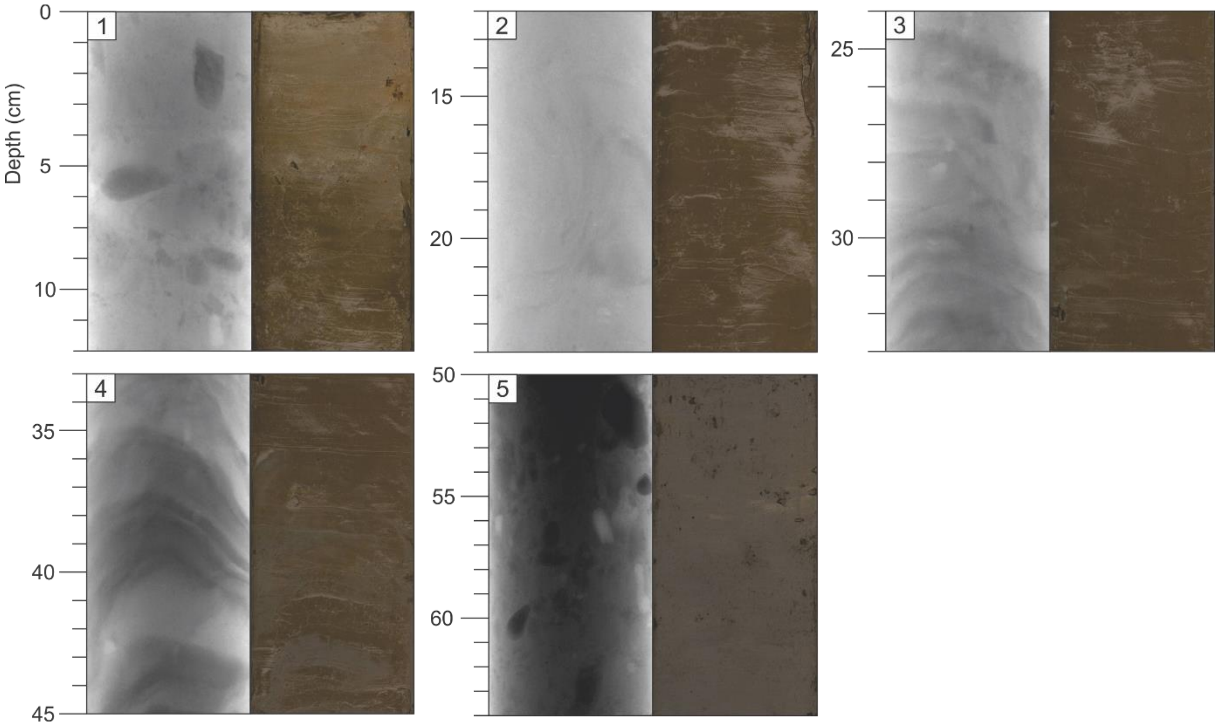
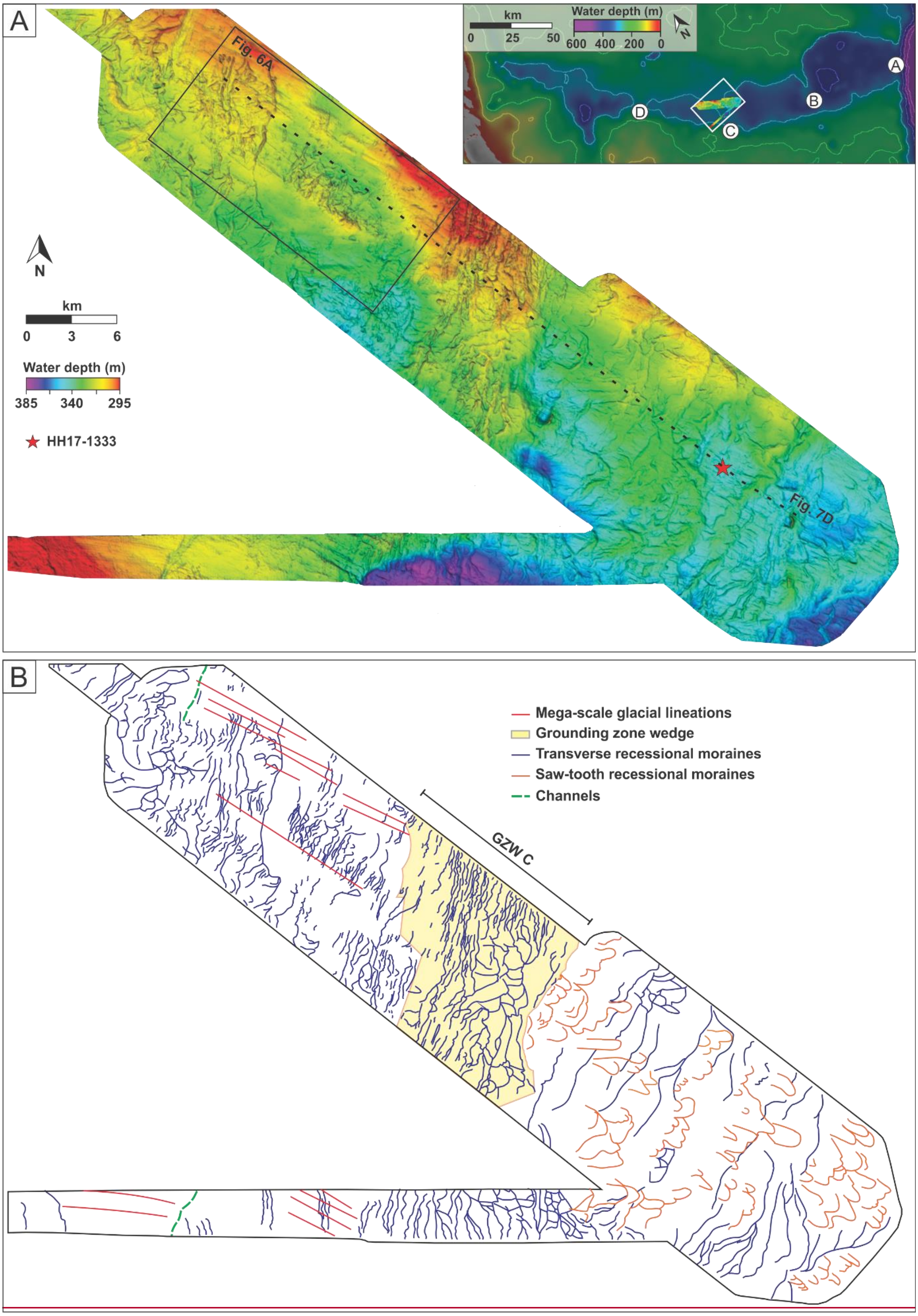


Figure 3. X-radiographs with associated photographs of representative lithofacies in this study, all from core HH17-1326. (1) Massive mud with IRD (Fm (d)). (2) Massive mud (Fm). (3) Laminated mud with occasional IRD (Fl (d)). (4) Laminated mud (Fl). (5) Diamicton (Dmm). The darker grey tones on the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


A
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50
Water depth (m)
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400
200
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N
A
B
C
D
Fig. 6A
N
km
0
3
6
Water depth (m)
385
340
295
HH17-1333
Fig. 7D
B
Mega-scale glacial lineations
Grounding zone wedge
Transverse recessional moraines
Saw-tooth recessional moraines
Channels
GZW C

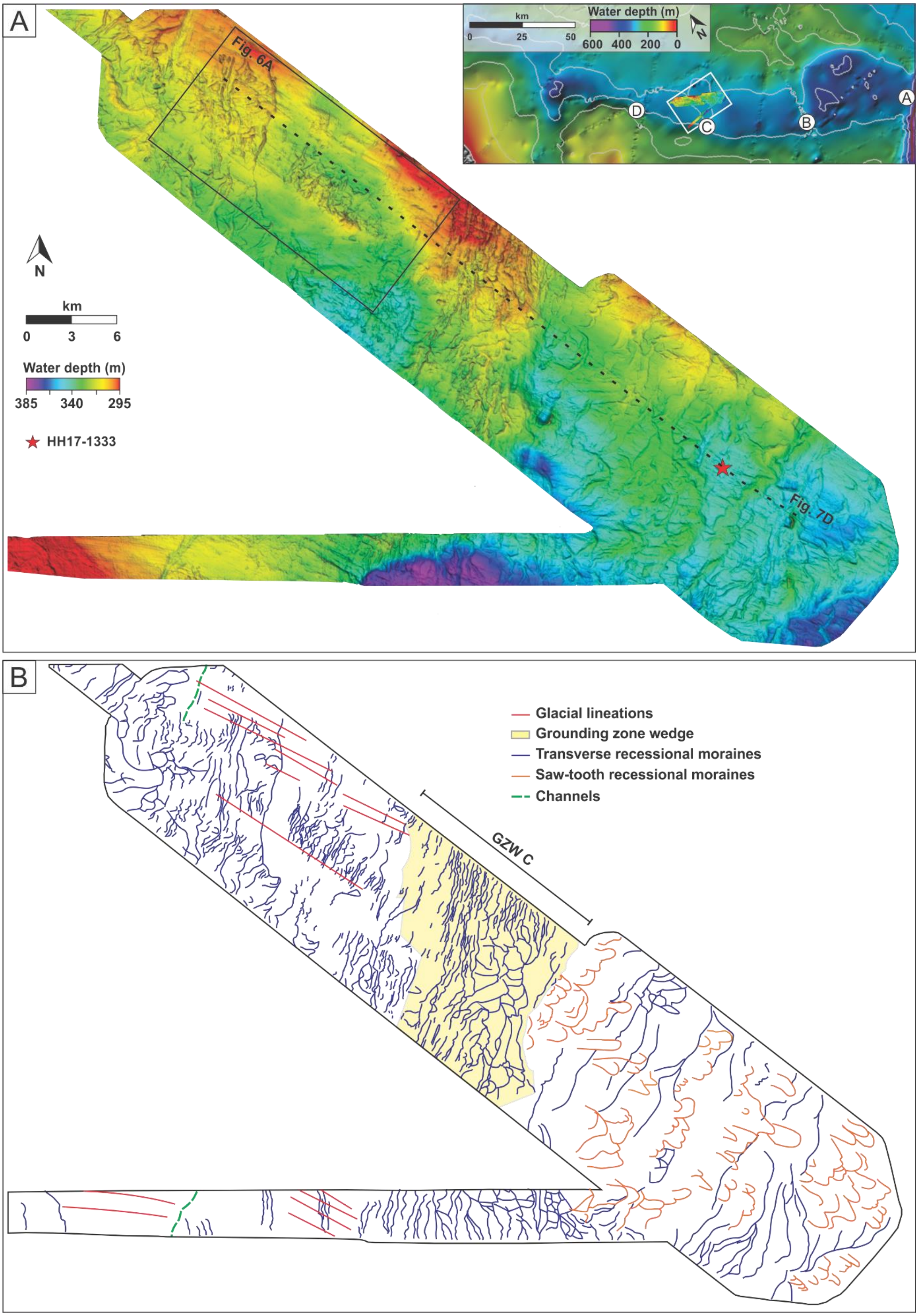
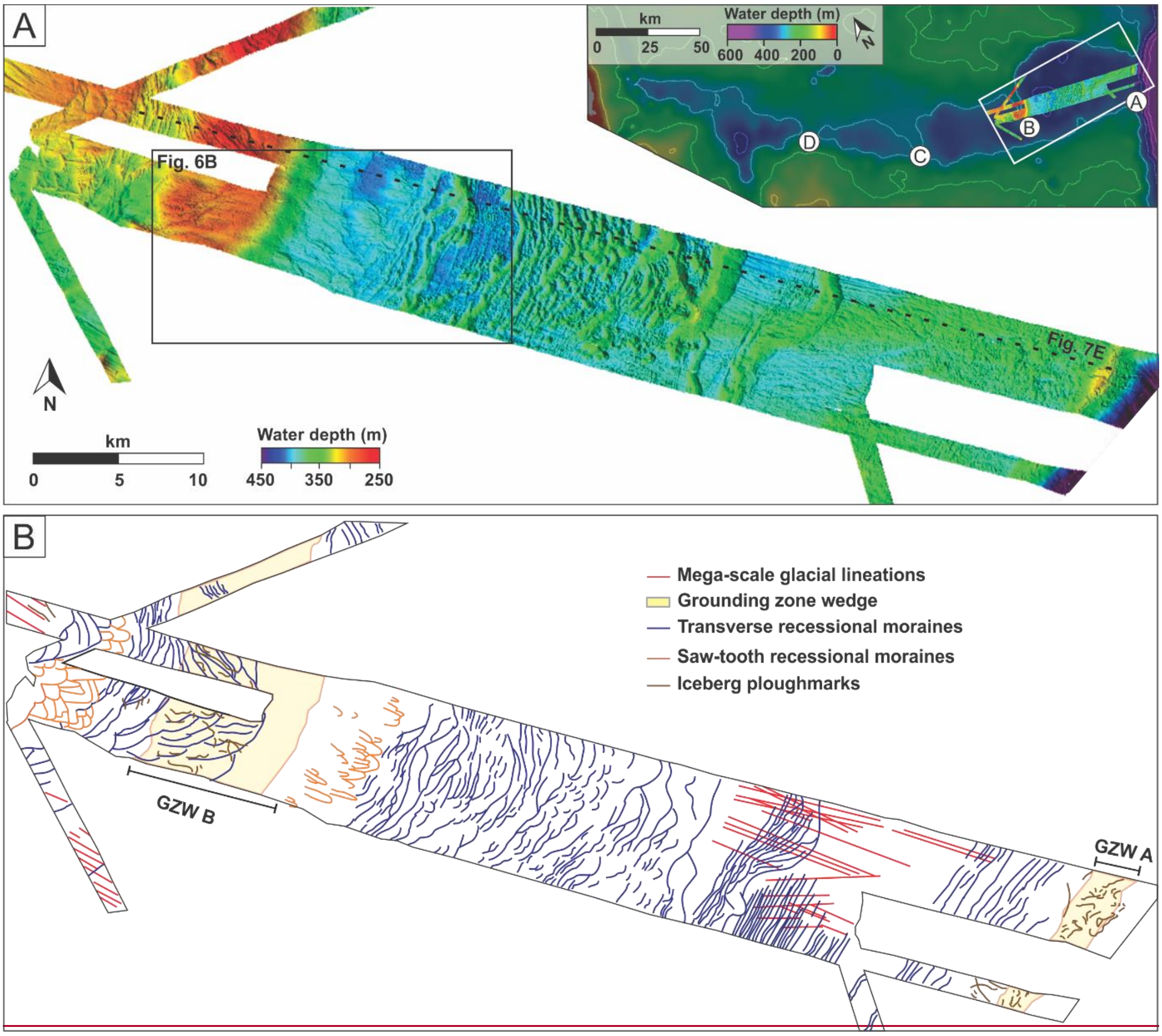


Figure 4. (A) Swath bathymetry map from the middle part of Store Koldewey Trough. The locations of grounding zone wedges *A-D* are indicated in inset map (bathymetry from IBCAO v.4~~3~~.0;~~ (~~Jakobsson et al., 2020)~~Jakobsson et al. 2012b~~). (B) Interpretation and distribution of landforms.


A
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Water depth (m)
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N
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B
C
D
Fig. 6B
Fig. 7E
N
km
0
5
10
Water depth (m)
450
350
250
B
Mega-scale glacial lineations
Grounding zone wedge
Transverse recessional moraines
Saw-tooth recessional moraines
Iceberg ploughmarks
GZW B
GZW A

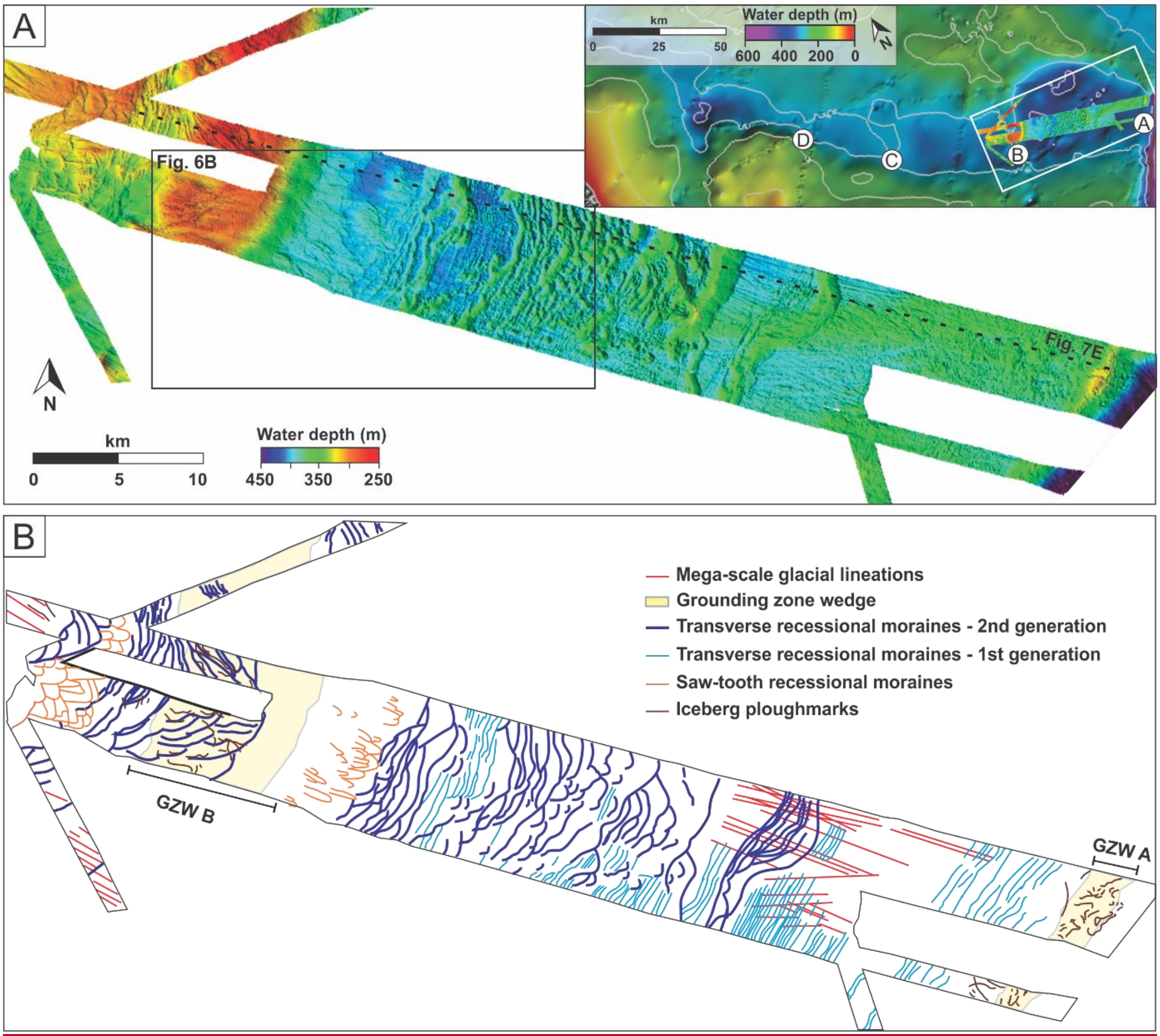
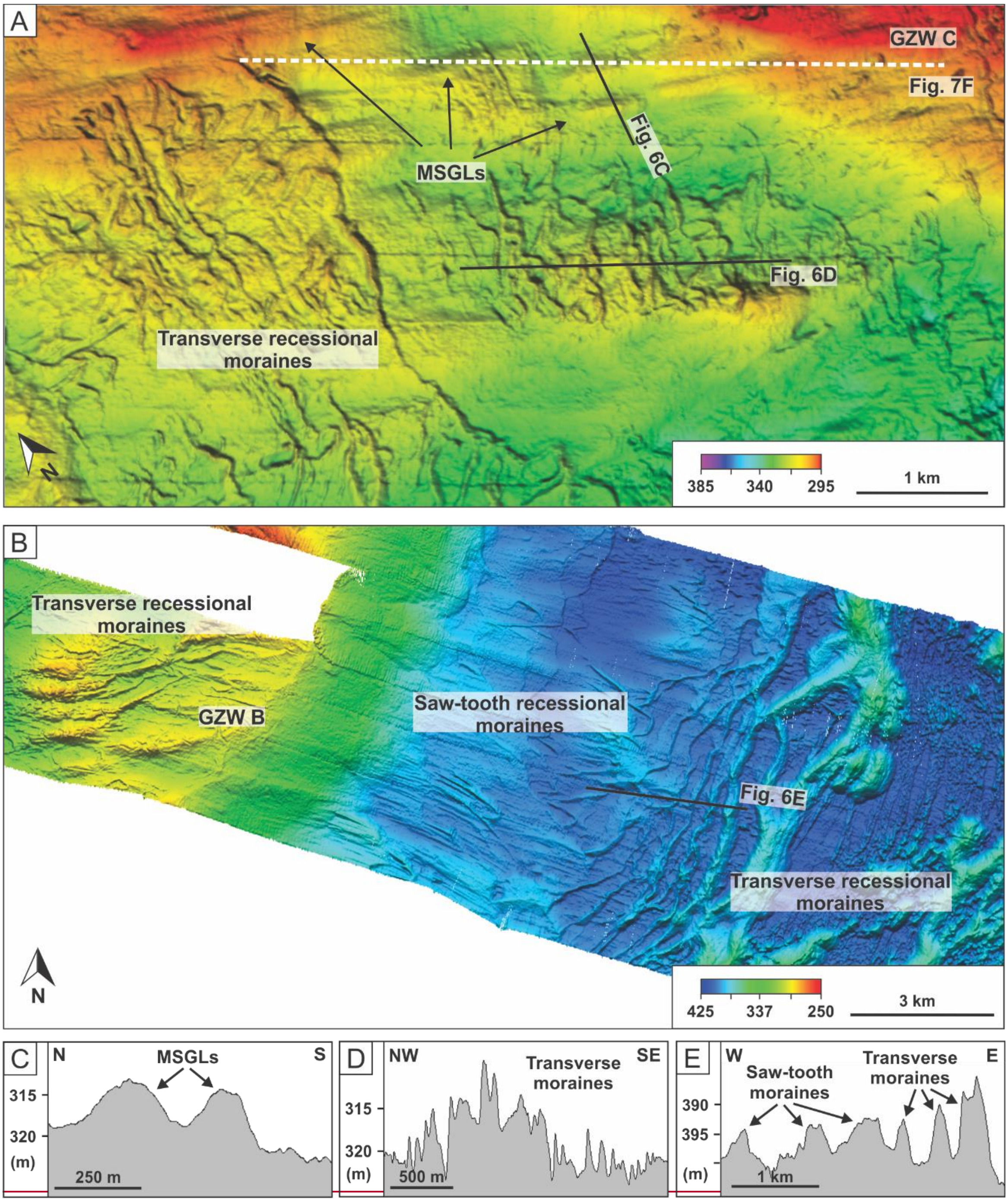


Figure 5. (A) Swath bathymetry map from the outer part of Store Koldewey Trough. The locations of grounding zone wedges A-D are indicated in inset map (bathymetry from IBCAO v.4~~3~~.0;~~ (~~(Jakobsson et al., 2020)~~Jakobsson et al. 2012b)~~. (B) Interpretation and distribution of landforms modified after Laberg et al. (2017)~~, and ~~supplemented with new data.


A
GZW C
Fig. 7F
MSGLs
Fig. 6C
Fig. 6D
Transverse recessional moraines
N
385
340
295
1 km
B
Transverse recessional moraines
GZW B
Saw-tooth recessional moraines
Fig. 6E
Transverse recessional moraines
N
425
337
250
3 km
C
N
S
MSGLs
315
320
(m)
250 m
D
NW
SE
Transverse moraines
315
320
(m)
500 m
E
W
E
Saw-tooth moraines
Transverse moraines
390
395
(m)
1 km

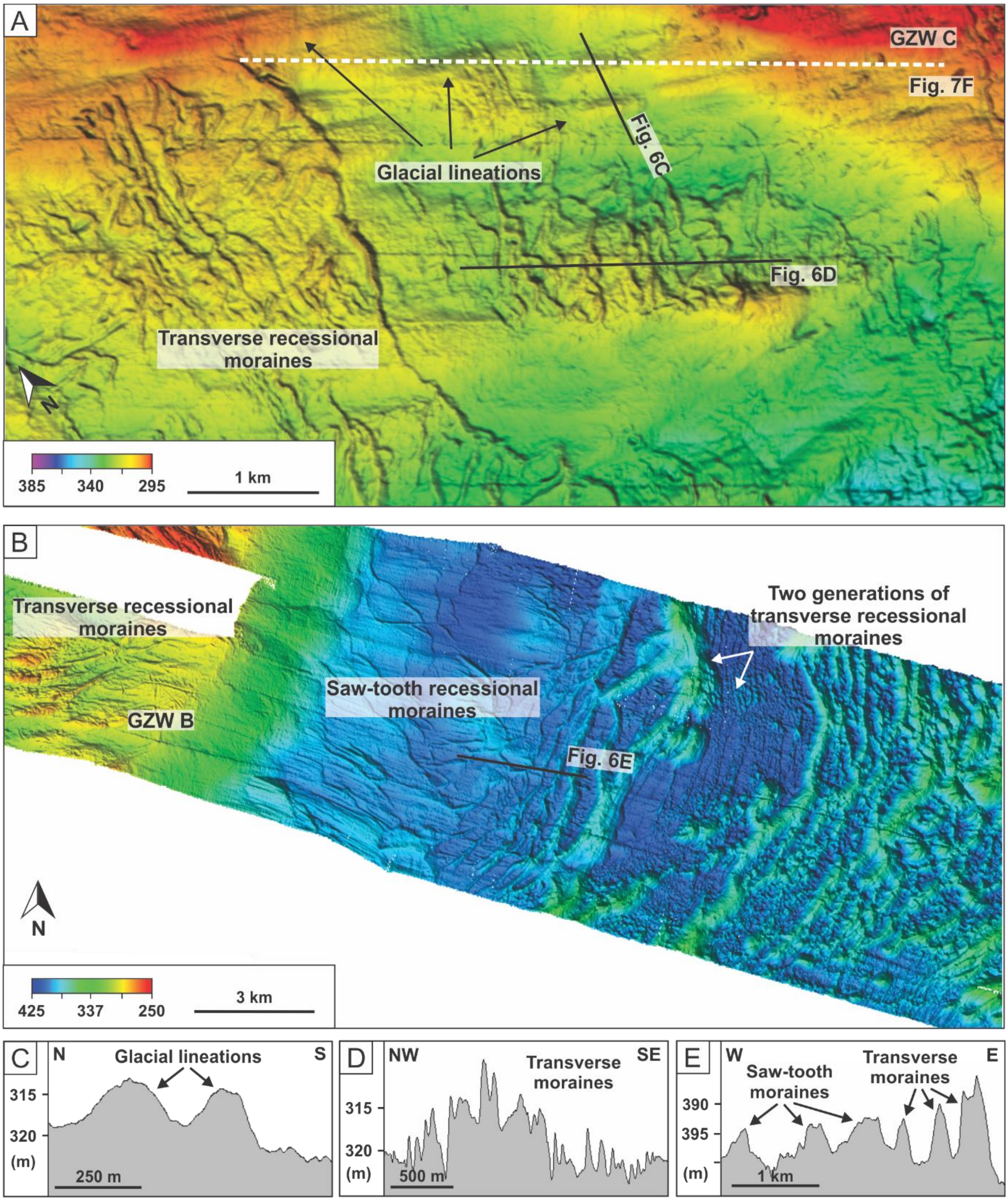
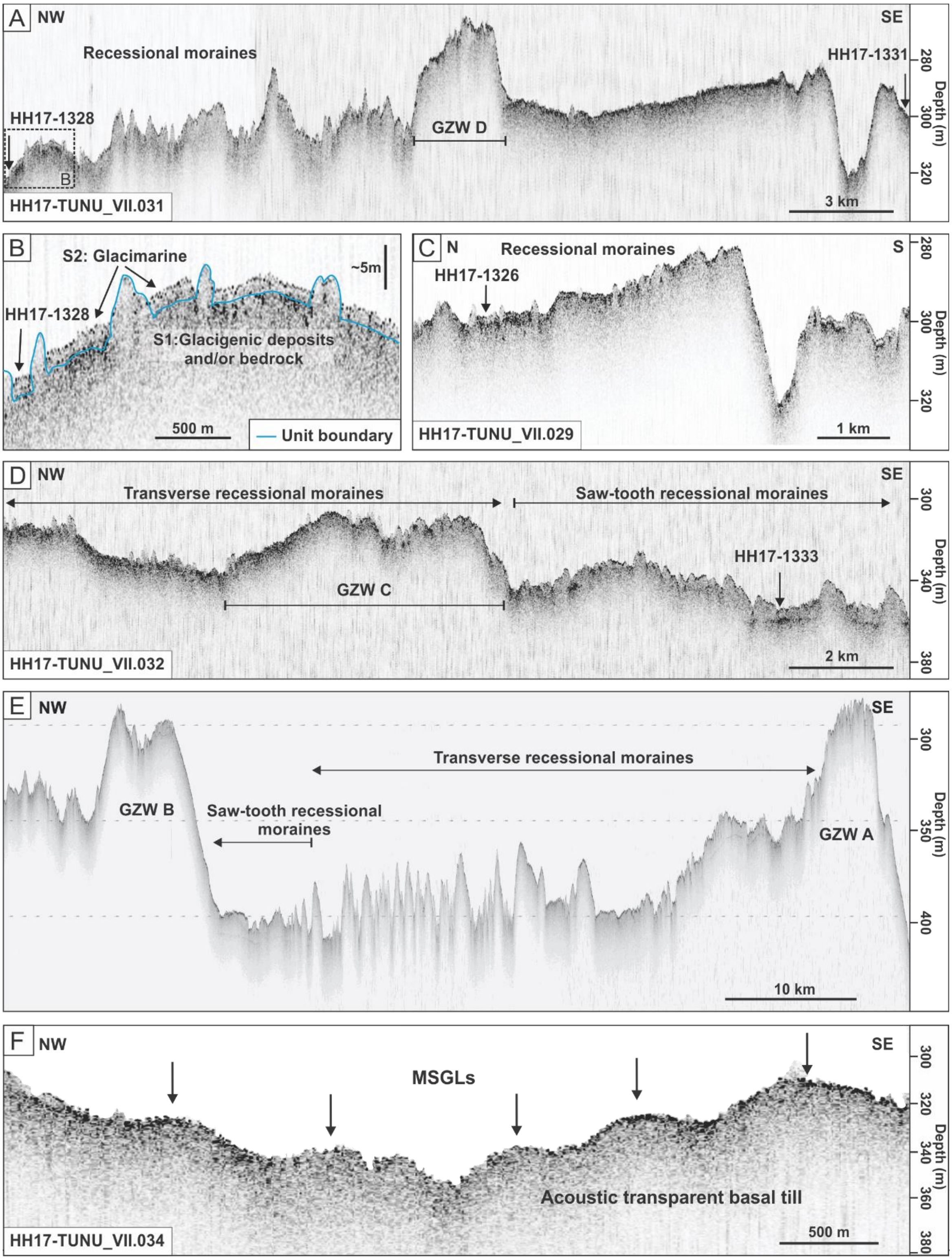


Figure 6. (A) Examples of ~~mega-scale~~ glacial lineations ~~(MSGLs)~~ and transverse recessional moraines. (B) Examples of saw-tooth- and transverse recessional moraines. (C) Bathymetric cross-profile of ~~mega-scale~~ glacial lineations ~~(MSGLs)~~. (D) Bathymetric cross-profile of transverse moraines. (E) Bathymetric profile of saw-tooth moraines and transverse moraines.


A
NW
SE
Recessional moraines
HH17-1328
B
GZW D
HH17-1331
280
300
320
Depth (m)
HH17-TUNU_VII.031
3 km
B
S2: Glacimarine
~5m
HH17-1328
S1:Glacigenic deposits and/or bedrock
500 m
Unit boundary
C
N
Recessional moraines
S
HH17-1326
280
300
320
Depth (m)
HH17-TUNU_VII.029
1 km
D
NW
SE
Transverse recessional moraines
Saw-tooth recessional moraines
GZW C
HH17-1333
300
340
380
Depth (m)
HH17-TUNU_VII.032
2 km
E
NW
SE
Transverse recessional moraines
GZW B
Saw-tooth recessional moraines
GZW A
300
350
400
Depth (m)
10 km
F
NW
SE
MSGLs
Acoustic transparent basal till
300
320
340
360
380
Depth (m)
HH17-TUNU_VII.034
500 m

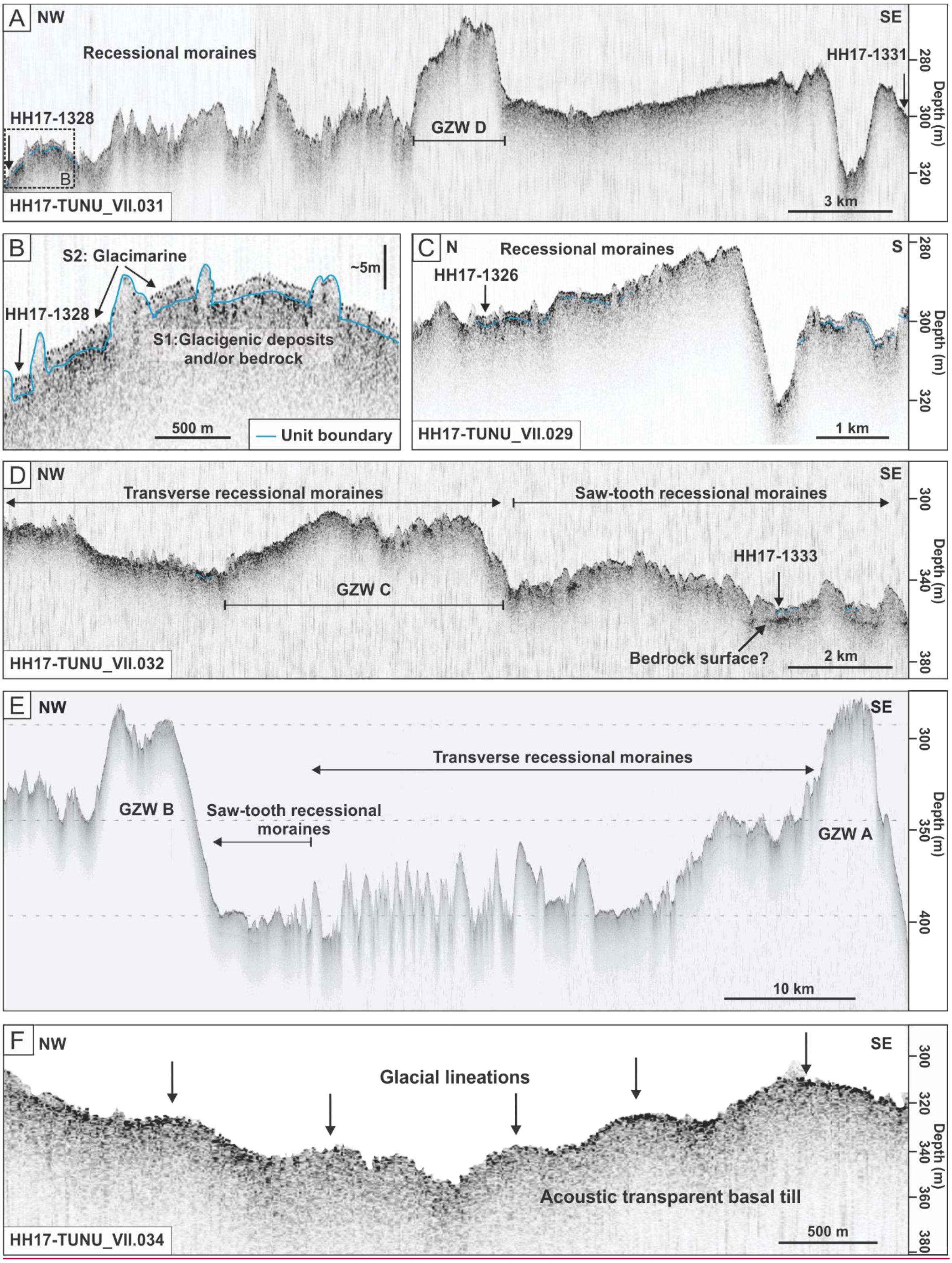
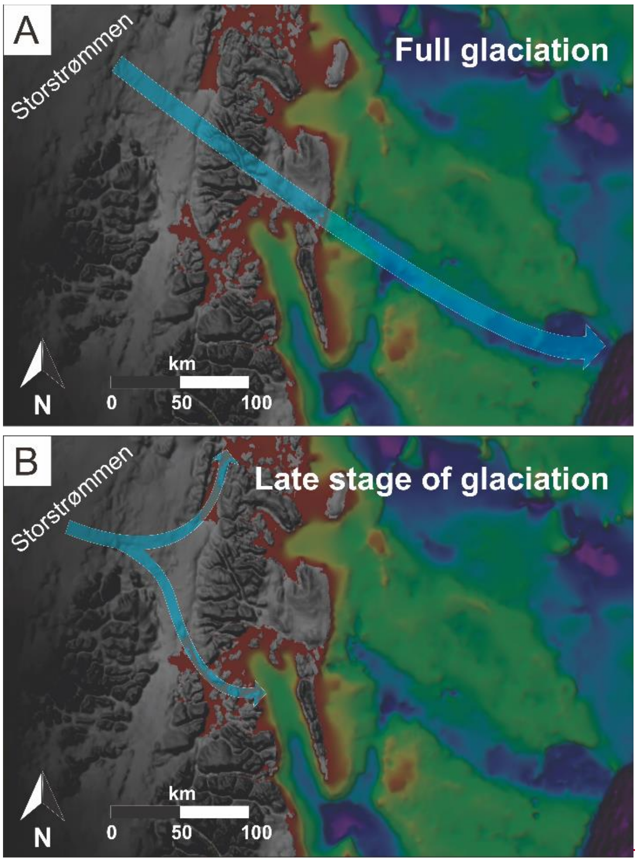


Figure 7. ~~Acoustic~~ High-resolution seismic profiles from Store Koldewey Trough. See Fig. 1C for locations. (A) Chirp line HH17-TUNU_VII.031 across grounding zone wedge D and recessional moraines from the middle trough area. Projected positions of sediment cores HH17-1328 and HH17-1331 are shown. 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. 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, 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.



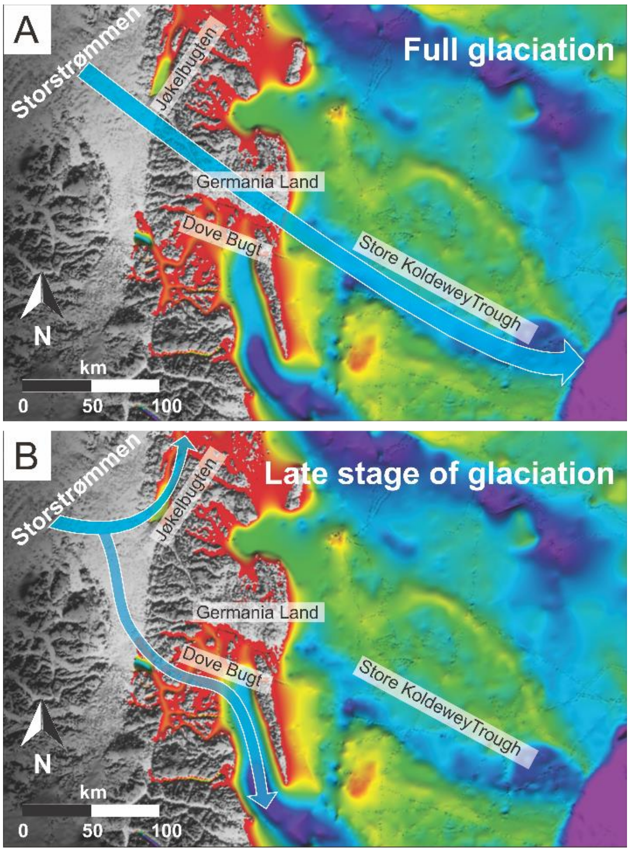


Figure 8. Reconstruction of inferred paleo ice-flow directions showing A) paleo ice-flow unrelated to the underlying topography during full glaciation and B) ice drainage paths during a late stage of glaciation. (Bathymetry and topography from IBCAO v.4~~3~~.0; ~~(~~Jakobsson et al., 2020)~~Jakobsson et al. 2012b)~~.

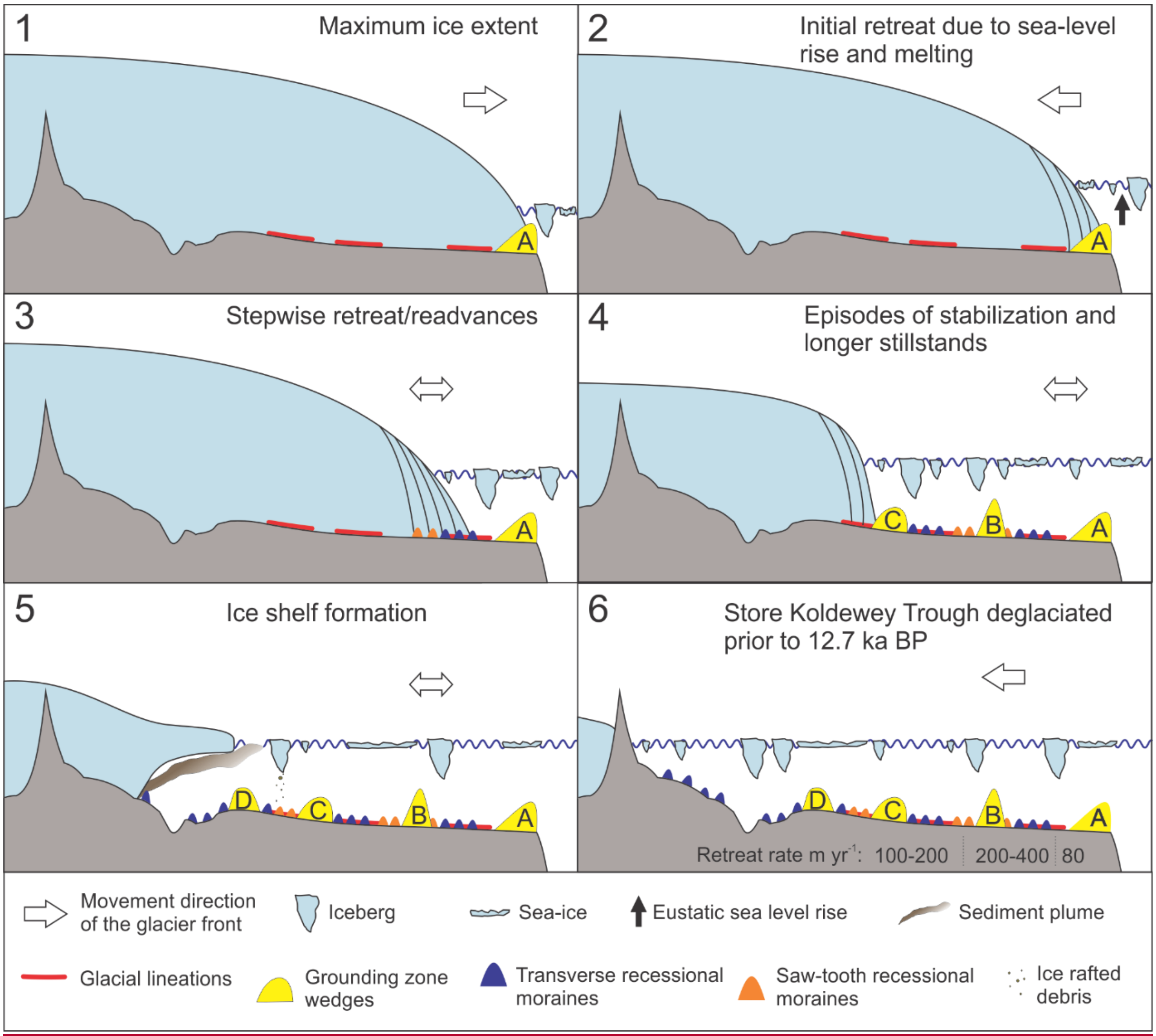


Figure 9. Reconstruction of the ice sheet dynamics in Store Koldewey Trough. Stage 1-6 show the maximum ice extent of the ice stream, as well as the ice-stream margin positions during the following deglaciation. Icebergs and sea-ice indicate iceberg calving and ice rafting. The deglaciation age in stage 6 is based on cosmogenic nucleide dating on Store Koldewey Ø (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.

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
Sedimentary environment	Subglacial till ~~(base of an ice stream)~~	Proximal glacimarine sedimentation ~~with suspension plumes and high-density underflows.~~from suspension settling. Sub-ice shelf environment	Proximal glacimarine sedimentation ~~with suspension plumes and high-density underflows.~~from suspension settling. Ice rafting in ~~open marine environment~~a glacimarine calving zone	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 g~~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
Transverse recessional moraines	N/A	<2200	<50	50-500
Saw-tooth 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.