New geophysical evidence for a revised maximum position of part of the NE sector of the Greenland Ice Sheet during the last glacial maximum

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Abstract

The extent and dynamics of the north-eastern sector of the Greenland Ice Sheet (GIS) during the last glacial remain still very uncertain, and maximum ice extents to inner-shelf, mid-shelf and outer-shelf positions have been suggested. Based on recently updated regional bathymetric data we argue that the GIS reached the shelf break along part of its NE sector (from 70 – 78°N) during the last glacial maximum. Swath-bathymetry and sub-bottom profiler data from the outermost part of the Store Koldewey glacial trough reveal the first documentation of moraine ridges/grounding-zone wedges in this area, supporting ice expansion to the shelf break at ~76°N. A complex pattern of retreat moraines in the outer trough reflects a stepwise early deglaciation. It is suggested that this behavior is not in line with a deglaciation triggered by an abrupt sea level rise. According to established glacial geomorphological models this should have resulted in ice lift-off and a sea floor dominated by landforms formed during full-glacial conditions (streamlined bedforms) and ice disintegrations (iceberg plough-marks). Instead, formation of the recessional moraines must have involved other mechanisms resulting in a step-wise ice retreat. This could possibly be related to melting of the grounded ice controlled by a temperature increase of the ocean as inferred for other parts of the Greenland Ice Sheet.

Keywords: Greenland Ice Sheet, Last Glacial Maximum, subglacial landforms, recessional moraines

1. Introduction

It has been estimated that melting of the Greenland Ice Sheet (GIS) since AD1900 has contributed at least 25.0 ± 9.4 mm of global-mean sea level rise (Kjeldsen et al. 2015). This release of meltwater from the GIS may also have a potential impact on global ocean circulation and climate (Rahmstorf et al. 2015). However, as seen in the estimate of Kjeldsen et al. (2015) the precise contribution is not well constrained (15.6 – 34.4 mm) as the uncertainties are still large. Estimates for the period prior to AD1900 are even more uncertain (e.g. Alley et al. 2010). Hence there is a pressing need to investigate the natural response of the GIS to the climatic variations of the past, including the last glacial maximum and deglaciation, in order to better predict the future dynamics of the GIS (e.g. Buizert et al. 2014) including its potential contribution to the global sea-water budget.

To estimate the potential impact of the major ice sheets on the global-mean sea level during their post-last glacial maximum recession to modern positions, their maximum extent during the LGM must be known. Estimates for the extent of the northeastern sector of the GIS during the LGM differ with more than a 100 km (see Funder et al. 2011 and Arndt et al. 2015 for reviews). These discrepancies result mainly from the existence of only very sparse geological and geomorphological datasets from the continental shelf off northeast Greenland. This area is often difficult to access because of severe sea-ice conditions. During the last decade new marine-geological and –geophysical data from the east Greenland shelf have become available suggesting that the ice sheet for north and central East Greenland was extended to an inner to mid-shelf position during the LGM (Funder et al. 2011; Arndt et al. 2015). This contradicts a previous hypothesis that the eastern sector of the Greenland Ice Sheet was stable and not much larger than at present during the last glacial (e.g. Evans et al. 2008; Winkelmann et al. 2010).

However, more knowledge from the area is required to improve reconstructions of the GIS during the LGM and the subsequent deglaciation, including a better understanding of the mechanism(s) triggering the deglaciation. In this study, we first develop a hypothesis for the maximum extent of the NE sector of the GIS (from 70 – 78^{o} N) during the LGM using integrated regional bathymetric data from Jakobsson et al. (2012) and Arndt et al. (2015). We subsequently test this hypothesis using new swath-bathymetry and high-resolution seismic data from the outer parts of the Store Koldewey Trough at ~76° N. This trough is located in an area where the continental shelf is relatively wide (~200 km). Thus, it is one of the longest troughs in the area (Fig. 1). Finally, we address the potential mechanism(s) of ice recession triggering including the role of the global rise in sea level.

2. Data base

Swath-bathymetry data covering an area of ~500 km^2 were collected under favorable sea-ice conditions during two cruises of the TUNU-programme (Christiansen 2012) in August 2013 and 2015 using the hull-mounted Kongsberg Simrad EM300 multi-beam echo sounder system on RV *Helmer Hanssen* of UiT - The Arctic University of Norway in Tromsø. Approx. 400 km of Chirp sub-bottom profiler data were acquired synchronously. The data were processed using the Kongsberg Simrad Neptune software. They were gridded at 50 x 50 m^2 cell size using the GMT software (Wessel and Smith 1998). Regional bathymetry was taken from the

IBCAO 3.0 bathymetry data base (Jakobsson et al. 2012). Offshore east Greenland the data base mainly includes single-beam data, most of which have been acquired south of 78°N (Jakobsson et al. 2012). Additionally, a recent update of the bathymetry published by Arndt et al. (2015) was included.

3. Results

3.1 The NE Greenland shelf landforms

The continental shelf offshore east and northeast Greenland comprises seven (1 – 7; Fig. 1) transverse cross-shelf troughs separated by shallower banks of irregular morphology north of Scoresby Sound. The southern six troughs, representing continuations of major fjord systems, have lengths between ~80 – 150 km, and are relatively uniform in width (< 50 km). However, the northernmost trough, the Store Koldewey Trough (Arndt et al. 2015), differs from the other troughs, as it does not represent a fjord continuation but terminates near Germania Land, where major inlets are absent. In this area Evans et al. (2002) has previously suggested that a moraine in the middle of the shelf, in the trough offshore Kejser Franz Joseph Fjord, represents the maximum shelfward extent of the Greenland Ice Sheet (trough nr 2; Fig. 1) during the last glacial maximum. This suggestion was later adapted by Funder et al. (2011).

North of ~77°N, the large-scale shelf morphology differs from the morphology south of 77° N by showing a large coast-parallel inner trough. This through turns into the shelf-transverse Westwind Trough towards the northeast/east and the Norske Trough towards the southeast (Fig. 1). The Northwind Shoal occurs east of the coast-parallel trough. This bank laterally extends ~250 km in N-S direction and up to ~100 km in E-W direction The bathymetry east of the Northwind Shoal is more irregular and includes smaller banks and laterally restricted E-W oriented troughs (Fig. 1). Elongated highs occur at the eastern margins of both the

Westwind and Norske troughs. Glacial landforms were identified in the northern inner shelf and upper slope by Evans et al. (2008) and Winkelmann et al. (2010). Funder et al. (2011) however, in their review favored an inner to mid shelf position for the maximum ice extent during the LGM in this area. It should be noted that water depths in parts of the continental shelf offshore northeast Greenland are shallower than 50 m, implying that part of this area may have been subaerial exposed during the LGM, thus providing conditions allowing the nucleation of local ice domes (Arndt et al. 2015).

3.2 Store Koldewey Trough landforms

The study area is located in the outermost part of the ~210 km long, 30 – 40 km wide and more than 300 m deep, NW-SE oriented Store Koldewey Trough south of the Norske Through (trough nr 7; Figs. 1, 2). The trough includes the four prominent transverse ridges A to D; the two southeastern and outermost ridges (Ridges A and B) are part of the study area. Store Koldewey Trough was chosen as study site because it is independent of any major fjord system on East Greenland, implying that the parts of the northeastern GIS must have reached a substantial thickness allowing sustained flow of grounded ice independently of the regional topography.

The outermost transverse Ridge A is located at the shelf break (Fig. 3). It is up to 50 m high, steep-sided and at least 7 km wide and is located at approx. 300 – 320 m water depth (Figs. 3, 4). Ridges with similar locations and dimensions are well known from formerly glaciated continental shelves, including the Greenland shelf, where they are interpreted as grounding-zones wedges (e.g. Dowdeswell and Fugleli 2012). Therefore, we interpret this ridge also to be a grounding-zone wedge comprising glacigenic sediments deposited in front of the GIS.

Smaller transverse ridges occur northwest (inside) of Ridge A (Figs. 3, 4). These are maximum 40 m high, up to 2 km wide and are located less than 2 km apart from each other. In plane-view they are straight to irregular sometimes including parts convex-formed in ice-flow direction. Two generations of overlying ridges occur occasionally (Fig. 3). These small ridges are inferred to be recessional moraines (e.g. Ó Cofaigh et al. 2008; Rydningen et al. 2013; Vorren et al. 2015). The majority of these ridges were most probably formed during halts and/or minor re-advances of the grounding line.

The outermost ridges overlie km-long stream-lined landforms oriented parallel – sub-parallel to the trough axis (Fig. 3). The latter are interpreted to be mega-scale glacial lineations formed beneath fast-flowing ice during full glacial conditions (e.g. Stokes and Clark 2001; Rydningen et al. 2013) prior to the deposition of the recessional moraines. The swath-bathymetry data also display iceberg ploughmarks and areas of smaller and transverse ridges. The latter are densely spaced, straight and their relief is < 1 m (Fig. 3). They were probably also formed during smaller halts and/or readvances in an overall ice recessional phase.

Another large and transverse ridge (Ridge B) is located approx. 50 km northwest of the shelf break (Figs. 3, 4). Similar to the ridge near the shelf break this ridge has relatively steep sides, is approx. 100 m high and its crest terminates at ~300 m water depth. However, this ridge is approx. 10 km wide. We interpret this ridge to be another grounding-zone wedge that was deposited during and/or after a significant glacier re-advance and/or longer glacier halt. An assemblage of smaller, straight to curved ridges, up to ~15 m high and some 10s of m wide are located northwest of grounding-zone wedge B. In plane-view, this assemblage is more complex than the assemblage close to grounding-zone wedge A (Fig. 3). Whereas the straight ridges are interpreted as recessional moraines (see above), the curved ridges might be rhombohedral ridges as identified offshore the modern Bråsvellbreen, Svalbard, interpreted to be formed through squeeze-up of sediments into subglacial fractures immediately after a surge (Solheim 1991).

4. Discussion

4.1 Store Koldewey Trough: the assemblage of landforms and their implications

The landforms of the outer Store Koldewey Trough document that grounded ice extended to the shelf break offshore northeast Greenland at ~76° N. Mega-scale glacial lineations suggest fast ice flow during early periods of maximum ice extent. The location of grounding-zone wedge A at the shelf break indicates a longer presence of the ice front at this position (Fig. 5). Multiple halts and/or smaller re-advances leading to the formation of the assemblage of transverse ridges northwest of grounding-zone wedge A characterize the early deglaciation of the outer parts of the continental shelf off East Greenland. The occurrence of grounding-zone wedge B, about 50 km further inside the trough, is suggested to reflect a more prominent glacier re-advance and/or a surge interrupting the deglaciation (Fig. 5). These transverse ridges might be De Geer moraines. However, additional data are required to confirm this.

Thus far, systematic description of glacigenic landform assemblages from the continental shelf offshore East Greenland north of 76° N is – to our knowledge – limited to one study from a mid-shelf location in the Westwind Trough (~80° N) where multiple end moraines have been identified (Winkelmann et al. 2010). The landform assemblages identified in our study area differ in multiple ways from those identified by Winkelmann et al. (2010): 1) our landforms are located closer to the shelf break, rather than in central parts of the trough; 2) the smaller ridges in our study are wider (up to 2 km versus 50 – 250 m) and higher (maximum

40m versus 5 – 25m); 3) up to 10 km wide and ~100 m high grounding-zone wedges occur; 4) ridges in our study are generally more symmetric; 5) a detectable sediment drape is absent.

The variable sizes of the moraines and grounding-zone wedges in the study area are most probably related to variable distances of glacier re-advances and/or various durations of glacier halts. This may imply that this sector of the GIS behaved more dynamic than the sector located in the Westwind Trough. Furthermore, the generally larger sizes of the landforms in our study compared to those presented by Winkelmann et al. (2010) may suggest the availability of larger amounts of sediments supporting the our assumption of a more dynamic ice sheet at 76° N compared to 80° N.

The transverse ridges described in our study are more than an order of magnitude wider and higher, and more irregular than sets of 1-2 m high currugation ridges identified in Pine Island Bay, West Antarctica (Jakobsson et al. 2011). It has been suggested that the latter ridges were produced daily as a consequence of tidally influenced motion of mega-icebergs from a disintegrating ice shelf and a retreating grounding line. However, based on the morphological differences, we consider such a scenario in our study area as less likely.

4.2 Age of the Store Koldewey Trough landforms and their implication for the initial ice recession: an oscillating ice front

The good preservation of the glacigenic landforms in the study area, combined with the absence of a detectable sediment drape (Figs. 3, 4) is interpreted to indicate that these landforms were formed during the LGM and the subsequent deglaciation. Little or no detectable sediment drape is also characterizing the glacigenic landforms from the LGM in the outer troughs offshore northern Norway (e.g. Laberg et al. 2007; Rydningen et al. 2013), the Barents Sea (Andreassen et al. 2008) and offshore northern Svalbard (Ottesen and Dowdeswell 2009).

The results from this study support studies from other parts of the northeast Greenland continental shelf suggesting an expansion of the eastern margin of the GIS to the shelf break during the LGM (e.g. Evans et al. 2008; Winkelmann et al. 2010). Based on this we conclude that an inner to mid-shelf position of the 70 – 78°N sector of the GIS as suggested by Funder et al. (2011) (see also Jakobsson et al. 2014) most likely can be rejected for this area. Furthermore, this also implies that the contribution from the GIS to the global-mean sea level following the LGM was most likely larger than from previous estimates based on a mid- or inner shelf position of the ice front during LGM.

Compared to other studies of glacigenic landforms in outer troughs on the Greenland shelf, as well as the Norwegian – Barents Sea – Svalbard shelves (e.g. Ottesen et al. 2005; Ottesen and Dowdeswell 2009), our data set reveals an unprecedentedly high number of transverse ridges. Also, these landforms indicate a behavior of the East Greenland Ice Sheet during the initial recession requiring a modification of present models where the glacial trough is interpreted to be dominated by streamlined bedforms formed during full-glacial conditions overlain by grounding-zone wedges in mid- or inner shelf position (e.g. Ottesen and Dowdeswell 2009; Ó Cofaigh et al. 2013).

The onset of the deglaciation occurred globally around 20 to 19 ka due to an increase in northern summer insolation (Clark et al. 2009) initiating melting of the ice sheets and providing the major source for an abrupt rise in sea level (e.g. Vaughan et al. 2013). However, an abrupt sea-level rise should have led to lift-off and/or pervasive calving of large parts of the marine-based sectors of the GIS. This should have been preserved landform assemblages generated during the glacial maximum (e.g. glacial lineations) and ice disintegration (iceberg ploughmarks; e.g Ottesen and Dowdeswell 2009) rather than a complex recession of a grounded ice sheet near the shelf break as documented here. Our data suggest the presence of an oscillating ice front during the early stage of ice recession, possibly due to the influence of surface ocean temperature fluctuations leading to enhanced melting and calving of the ice front when exposed to warmer water. Such scenarios were recently suggested for the initial break-up of the marine-terminating sectors of the SE Greenland Ice Sheet (Dyke et al. 2014) and the Norwegian Channel Ice Stream draining much of the SW Fennoscandian Ice Sheet (Svendsen et al. 2015).

An ice front position at the shelf break instead of at the inner or mid shelf implies a larger ice volume for this sector of the GIS during the LGM. It also implies a larger contribution of meltwater from GIS during the deglaciation.

3.3 The influence of continental shelf bathymetry on the response to climate forcing

The influence of continental shelf bathymetry on the response to climate forcing was discussed by Bart et al. (2016) from their modelling of the Antarctic Ice Sheet. As compared to much of the continental shelf surrounding Antarctica the continental shelf of NE Greenland is shallow, i.e. banks of 50 - 200 m and troughs of 200 – 400 m water depth, without a pronounced landward deepening (Fig. 1). This may have permitted the NE sector of the Greenland Ice Sheet to respond dynamically to climate forcing allowing for grounding-line advance onto the continental shelf due to lower flux of calving. As a result, landforms formed from a dynamic ice sheet should be expected on shallow shelves as exemplified in our study.

In addition to a relatively shallow water depth, the continental shelf offshore northeast Greenland is dominated by troughs representing continuations of the major fjord systems, except of the Store Koldewey Trough. This is interpreted to imply a relatively thin marine-based ice for this sector of the NE Greenland Ice Sheet as thicker ice would imply drainage more independent of the topography and larger (wider and deeper) shelf troughs.

4. Conclusions

- The presence of cross-shelf troughs and banks on regional bathymetric data suggest that the GIS reached the shelf break between 70 – 78°N during the LGM.
- New swath-bathymetry and high-resolution seismic data from the outermost part of the Store Koldewey Trough reveal megascale glacial lineations, grounding-zone wedges and moraine ridges, supporting the expansion of grounded ice to the shelf break at ~76°N.
- A complex pattern of retreat moraines in the outer trough reflects a stepwise early deglaciation, rather than a deglaciation triggered by an abrupt sea level rise. The formation of the recessional moraines was possibly related to melting of the grounded ice controlled by a temperature increase of the ocean, i.e. ocean warming preceded ice recession of this sector of the NE Greenland Ice Sheet.
- An ice front position at the shelf break instead of at the inner or mid shelf implies a larger ice volume for this sector of the GIS during the LGM. It also implies a larger contribution of meltwater from GIS during the deglaciation.

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6. References

Alley RB, Andrews JT, Brigham-Grette J, Clarke GKC, Cuffey KM, Fitzpatrick JJ, Funder S, Marshall SJ, Miller GH, Mitrovica JX, Muhs DR, Otto-Bliesner BL, Polyak L, White JWC (2010) History of the Greenland Ice Sheet: paleoclimatic insights. Quat Sci Rev 29: 1728-1756.

Andreassen K, Laberg JS, Vorren TO (2008) Sea floor geomorphology of the SW Barents Sea and its glaci-dynamic implications. Geomorphology 97: 157-177.

Arndt JE, Jokat W, Dorschel B, Myklebust R, Dowdeswell JA, Evans J (2015) A new bathymetry of the Northeast Greenland continental shelf: Constraints on glacial and other processes. Geochem Geophys Geosyst 16: 3733–3753, doi:10.1002/ 2015GC005931.

Bart PJ, Mullally D, Golledge NR (2016) The influence of continental shelf bathymetry on Antarctic Ice Sheet response to climate forcing. Glob Plan Ch 142: 87–95.

Buizert C, Gkinis V, Severinghaus JP, He F, Lecavalier BS, Kindler P, Leuenberger M, Carlson AE, Vinther B, Masson-Delmotte V, White JWC, Liu Z, Otto-Bliesner B, Brook EJ (2014) Greenland temperature response to climate forcing during the last deglaciation. Science 345: 1177 – 1180.

Christiansen JS (2012) The TUNU-Programme: Euro-Arctic Marine Fishes – Diversity and Adaption. In: Di Prisco G & Verde C (eds) Adaption and Evolution in Marine Environments 1, From Pole to Pole; DOI: 10.1007/978-3-642-27352-0_3. Springer-Verlag Berlin-Heidelberg, pp 35-49.

Clark PU, Dyke AS, Shakun JD, Carlson AE, Clark J, Wohlfarth B, Mitrovica JX, Hostetler SW, McCabe AM (2009) The Last Glacial Maximum. Science 325: 710 – 714.

Dowdeswell JA, Fugelli EMG (2012) The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets. Geol Soc Am Bull 124, 1750-1761.

Dyke LM, Hughes ALC, Murray T, Hiemstra JF, Andresen CS, Rodés Á (2014) Evidence for the asynchronous retreat of large outlet glaciers in southeast Greenland at the end of the last glaciation. Quat Sci Rev 99: 244-259.

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

Evans J, Ó Cofaigh C, Dowdeswell JA, Wadhams P (2008) Marine geophysical evidence for former expansion and flow of the Greenland Ice Sheet across the north-east Greenland continental shelf. J Quatern Sci 24, 279–293.

Funder S, Kjeldsen KK, Kjær KH, Ó Cofaigh C (2011) The Greenland Ice Sheet During the Past 300,000 Years: A Review. In: Ehlers J, Gibbard PL, Hughes PD (eds) Developments in Quaternary Science 15, Amsterdam, The Netherlands, pp 699-713. ISBN: 978-0-444-53447-7. Elsevier B.V.

IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)].

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 29 pp.

Jakobsson M, Anderson JB, Nitsche FO, Dowdeswell JA, Gyllencreutz R, Kirchner, N, Mohammad R, O'Regan M, Alley RB, Anandakrishnan S, Eriksson B, Kirshner A, Fernandez R, Stolldorf T, Minzoni R, Majewski W (2011) Geological record of ice shelf break-up and grounding line retreat, Pine Island Bay, West Antarctica. Geology 39: 691-694, doi: 10.1130/G32153.1.

Jakobsson M., and 29 others, 2012, The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0: Geophysical Research Letters, v. 39, L12609, doi:10.1029/2012GL052219.

Jakobsson, M and 21 others (2014) Arctic Ocean glacial history. Quat Sci Rev 92: 40-67.

Kjeldsen KK, Korsgaard NJ, Bjork AA, Khan SA, Box JE, Funder S, Larsen NK, Bamber JL, Colgan W, van den Broeke M, Siggaard-Andersen ML, Nuth C, Schomacker A, Andresen CS, Willerslev E, Kjaer KH (2015) Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. Nature 528: 396-400.

Laberg JS, Eilertsen RS, Salomonsen GR, Vorren TO (2007) Submarine push moraine formation during the early Fennoscandian Ice Sheet deglaciation. Quat Res 67: 453-462.

Nielsen T, Kuijpers A (2013) Only 5 southern Greenland shelf edge glaciations since the early Pliocene. Sci Rep 3: 1875; DOI:10.1038/srep01875.

Ó Cofaigh C, Dowdeswell JA, Evans J, Larter RD (2008) Geological constraints on Antarctic palaeo-ice-stream retreat. Earth Surf Proc Landf 33: 513-525.

Ó Cofaigh C, Dowdeswell JA, Jennings AE, Hogan KA, Kilfeather A, Hiemstra JF, Noormets R, Evans J, McCarthy DJ, Andrews JT, Lloyd JM, Moros M (2013) An extensive and dynamic ice sheet on the West Greenland shelf during the last glacial cycle. Geology 41: 219 – 222.

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

Ottesen D, Dowdeswell JA, Rise L (2005) Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57°–80°N). Geol Soc Am Bull 117: 1033-1050.

Rahmstorf S, Box JE, Feulner G, Mann ME, Robinson A, Rutherford S, Schaffernicht EJ (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Clim. Change 5: 475-480.

Rydningen TA, Vorren TO, Laberg JS, Kolstad V (2013) The marine-based NW Fennoscandian ice sheet: glacial and deglacial dynamics as reconstructed from submarine landforms. Quat Sci Rev 68: 126-141.

Solheim A (1991) The depositional environment of surging sub-polar tidewater glaeiers: a case study of the morphology, sedimentation and sediment properties in a surge affected marine basin outside Nordaustlandet, the Northern Barents Sea. Norsk Polarinstitutt Skrifter 194: 97pp.

Stokes CR, Clark CD (2001) Palaeo-ice streams. Quat Sci Rev 20: 1437-1457.

Svendsen JI, Briner JP, Mangerud J, Young NE (2015) Early break-up of the Norwegian channel ice stream during the last glacial maximum. Quat Sci Rev 107: 231-242.

Vaughan DG, Comiso JC, Allison I, Carrasco J, Kaser G, Kwok R, Mote P, Murray T, Paul F, Ren J, Rignot E, Solomina O, Steffen K, Zhang T (2013) Observations: Cryosphere. In: Climate Change 2013: The Physical Science Basis. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. ed. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp 317-382.

Vorren TO (2003) Subaquatic landsystems: continental margins. In: Glacial Landsystems, London, Arnold Publishers, 289-312.

Vorren TO, Rydningen TA, Baeten N J, Laberg JS (2015) Chronology and extent of the Lofoten–Vesterålen sector of the Scandinavian Ice Sheet from 26 to 16 cal. ka BP. Boreas 44: 445–458.

Weidick A, Kelly M, Bennike O (2004) Late Quaternary development of the southern sector of the Greenland Ice Sheet, with particular reference to the Qassimiut lobe. Boreas 33: 284–299.

Wessel P, Smith WHF (1998) Improved version of the Generic Mapping Tools released: EOS [Transactions, American Geophysical Union] 79: p 579, doi:10.1029/98EO00426.

Winkelmann D, Jokat W, Jensen L, Schenke .-W (2010) Submarine end moraines on the continental shelf off NE Greenland—implications for Lateglacial dynamics. Quat Sci Rev 29: 1069–1077.

Xu Y, Rignot E, Fenty I, Menemenlis D, Mar Flexas M (2013) Subaqueous melting of Store Glacier, west Greenland from three-dimensional, high-resolution numerical modeling and ocean observations, Geophys Res Lett 40: 4648–4653, doi:10.1002/grl.50825.

Zwally HJ, Abdalati W, Herring T, Larson K, Saba J, Steffen K (2002) Surface melt-induced acceleration of Greenland ice-sheet flow. Science 297: 218–221.

Figures

Figure 1: Bathymetric map of the NE Greenland continental shelf. The seven transverse troughs (1 – 7) located from 70 – 77^{o}N are indicated (DBT = Dove Bugt Trough, HT = Hochstetterbugten Trough). Troughs further north includes the Store Koldewey Trough (SKT), the Norske Trough (NT) and the Westwind Trough (WT). BB = Belgica Bank, NS = Northwind Shoal, CPT = coast-parallel trough, H = high. Inferred GIS ice front position in this area during LGM is indicated by white stippled line.

Figure 2: Bathymetric map showing the study area in the outer Store Koldewey Trough (red box) offshore NE Greenland. A, B, C and D indicate the locations of transverse ridges, interpreted to be grounding-zone wedges. The bathymetry is from Jakobsson et al. (2012).

Figure 3: Swath bathymetry showing Grounding-Zone Wedges (GZW) A and B separated by multiple, relatively small, transverse ridges (area a), the smallest are densely spaced and less than 1 m high. Note that some ridges are buried by younger ridges (two generations of small ridges, indicated by black arrow). S = streamlined bedforms (mega-scale glacial lineations), RR = rhombohedral ridges. For location, see Figure 1.

Figure 4: Part of chirp sub-bottom profile showing Grounding-Zone Wedges A and B separated by an area of small transverse ridges (area a; for location see Fig. 3).

Figure 5: Conceptual model proposing the origin of the landforms of the outer Store Koldewey Trough.