# Submarine moraines in Southeast Greenland fjords reveal contrasting outlet-glacier behaviour since the Last Glacial Maximum

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**Key Points:**

- We use bathymetric data to identify major moraine ridges in Southeast Greenland fjords
- Inner-fjord moraines, which were probably formed during the Neoglacial, are widespread along the Southeast Greenland margin
- Mid-fjord moraines are present beyond the Julianehåb Ice Cap yet are generally absent from the Southeast Greenland Ice Sheet margin

## Abstract

Knowledge of the past behaviour of the outlet glaciers of Southeast (SE) Greenland is necessary to understand and model spatial differences in the response of the Greenland Ice Sheet (GIS) to climatic changes. Here, we use bathymetric data to map the distribution of more than 50 major moraines in SE Greenland fjords. Inner-fjord moraines are widespread along the SE Greenland margin, occurring in 65% of the surveyed fjords. We identify, for the first time, 9 mid-fjord moraines that span the *c.*150 km long eastern margin of the Julianehåb Ice Cap (JIC). In contrast, mid-fjord moraines are generally absent from the deeper and wider fjords of the SE GIS. The variable distribution of mid-fjord moraines along the SE Greenland margin reveals contrasting behaviour of the SE GIS and the eastern JIC during the last deglaciation, which probably reflects differences in fjord geometry and exposure to ocean heat.

## 1. Introduction

The Southeast (SE) Greenland margin, which includes the SE sector of the Greenland Ice Sheet (GIS) and the eastern Julianehåb Ice Cap (JIC), is drained by a number of fast-flowing, marine-terminating outlet glaciers (Fig. 1). Mountainous terrain and a lack of ice-free areas have largely prevented analysis of the deglacial and Holocene behaviour of these outlet glaciers, although several studies have investigated the past dynamics of the land-terminating outlet glaciers of Southwest (SW) Greenland (Fig. 1c) (Weidick et al., 2004; Winsor et al., 2014; Larsen et al., 2011). The SE Greenland margin is suggested to have been highly sensitive to past climatic changes as a result of its relatively high mass turnover and proximity to major ocean currents, including the Irminger Current, and sites of deep-water formation (Fig. 1a) (Weidick et al., 2004). The fjords of SE Greenland are therefore an ideal location to examine how the climatic changes of the late Quaternary (e.g. Alley et al., 1997) were translated into ice-margin responses. In particular, it is important to identify spatial variations in the past behaviour of Greenland's outlet glaciers, and to understand their controls, to predict the sensitivity or resilience of these outlet glaciers and their future behaviour.

Here, we examine bathymetric data from 36 fjords along the *c.*1200 km long SE Greenland margin to reveal the distribution of major submarine moraines (Fig. 1 and Figs. S1 to S3 in the supporting information). The geomorphology of these moraines is described alongside their implications for the behaviour of the SE GIS and the eastern JIC since the Last Glacial Maximum (LGM).

## 2. Background: Glacial history

The GIS extended to the shelf break beyond SE Greenland during the LGM (Funder et al., 2004; Roberts et al., 2008; Dowdeswell et al., 2010). Deglacial retreat was underway by around 17 ka (Jennings et al., 2006), driven, in part, by the incursion of warm (>5°C), salty, subsurface (> 300 m) water from the Irminger Current (Fig. 1a) (Knutz et al., 2011; Dyke et al., 2014). Our present understanding of the Holocene glacial history of SE Greenland is derived from deglacial ages from major fjords and from studies of threshold lakes and terrestrial moraines in the ice-free zone beyond the Qassimiut Lobe (Fig. 1). The deglacial ice margin is interpreted to have been at the outer coast of SE Greenland by around 11 to 10 ka (Bennike and Björck, 2002; Knutz et al., 2011), and to have been retracted behind its present-day extent by around 9 ka for the low-lying Qassimiut Lobe and by about 7 ka in more mountainous regions of SW Greenland (Larsen et al., 2011). In southern Greenland, the maximum Neoglacial (since *c.*4 ka; Anderson et al., 1999) ice extent was generally attained during the Little Ice Age (LIA) of between AD 1450 and 1850, which is marked by a series of terrestrial moraines (Weidick et al., 2004).

## 3. Data and methods

The bathymetric data (Fig. 1) were acquired by NASA's Earth Venture Sub-orbital Oceans Melting Greenland (OMG) mission (OMG mission, 2016). The survey was performed using a Teledyne Reson SeaBat 7160 Multibeam Echo Sounder with a system frequency of 44 kHz and 512 beams. The data were acquired in 2016 using QINSy software and processed using CARIS HIPS software by Terrasond Ltd into a 25-m spacing gridded product. Airborne gravity data are used to show the depth of the seafloor in some inner-fjord areas where bathymetric data are lacking (Fig. 2 and Figs. S1 to S3 in the supporting information), however at a degraded spatial resolution of 750 m. The gravity data were acquired in summer 2016 from an AS350-B3 helicopter using a Sanders Geophysics Airborne Inertially Referenced Gravimeter. Details of gravity data acquisition, processing and inversion modelling are described in Millan et al. (2018). The potential temperature of the water in the fjords (Fig. 2) was sampled at a rate of 16 Hz using two conductivity-temperature-depth (CTD) sensors: an AML Oceanographic Minos X CTD in thick brash/ sea ice and a Valeport Rapid CTD in ice-free conditions (OMG mission, 2016). In this study, the fjords of SE Greenland are labelled ‘A’ to ‘W’, from south to north (Figs. 1 and 2 and Figs. S1 to S3 in the supporting information).

## 4. Results

<u>4.1 Broad-scale bathymetry</u>

The fjords of SE Greenland are U-shaped in cross-profile and between 20 and 100 km long (Fig. 1). With typical widths of 2 to 3 km, the fjords of the eastern JIC are narrower than those of the SE GIS, which are up to 15 km wide. Fjord water depth beyond the present-day ice margin ranges from 100 to 700 m, with considerable variation between neighbouring fjords (Millan et al., 2018). Although the maximum fjord water depth is similar along the SE Greenland margin, the fjords of the eastern JIC generally have shallower mid-fjord regions (typically 200 to 300 m) compared with those of the SE GIS (typically 400 to 800 m) (Fig. 2 and Figs. S1 to S3 in the supporting information). The fjords contain over-deepened basins that are separated by shallower sills. Sills are also present where tributary fjords join the main fjord trunk, yet are generally absent from the innermost region of the fjords (Fig. 2 and Figs. S1 to S3 in the supporting information). The contrasting widths and depths of the fjords along the SE Greenland margin are related to the drainage-basin area of the outlet glaciers that drain into the fjords. The larger outlet glaciers of the SE GIS transferred greater volumes of ice and sediment during periods of ice-sheet advance compared with the smaller outlet glaciers of the JIC, resulting in higher rates of erosion within these fjords.

More than 50 large (>10 m high) ridges are identified transverse to the former ice-flow direction in the fjords of SE Greenland (Figs. 2 and 3 and S1 to S3 in the supporting information). These ridges are interpreted as major moraines that record the former positions of still-stands or readvances of the grounding zone.

4.2 Inner-fjords

Major moraine ridges are present in an inner-fjord (landwards third of the fjord length) setting for 26 (*c.*65%) of the fjords of SE Greenland (Fig. 1). The moraines occur between 1.6 and 16 km offshore of the present-day ice margin in water depths of 200 to 550 m (Figs. 2 and 3 and Figs. S1 to S3 in the supporting information). The moraines typically have a single crest and are asymmetric with a steeper ice-distal side (Fig. 3c and e). They are up to 2 km long in the former ice-flow direction, up to 150 m above the surrounding seafloor, and span the entire fjord width. Although most inner-fjords are characterised by a single moraine ridge, some contain a sequence of two or three back-stepping features (Fig. 3a;

inner-fjord recessional moraines in Fig. 2 and Figs. S1 to S3 in the supporting information). The most seaward moraine in each inner-fjord is located beyond the oldest ice-margin position that has been mapped from aerial photographs obtained in the 1930s (Figs. 2 and 3; Bjørk et al., 2012). Some of the submarine inner-fjord moraines are correlated with prominent terrestrial moraines (Fig. 3a).

The submarine ridge beyond Kangerdlussuaq Glacier, which corresponds with the LIA extent of Kjeldsen et al. (2015) as interpreted from terrestrial moraines and trimline heights, has different geometry compared to the other inner-fjord moraines. It comprises high-amplitude ridges at its lateral margins yet has a lower-amplitude wedge-like geometry in its central part (Fig. 3b). It is possible that this feature is an intermediate form between a moraine and a grounding-zone wedge (GZW; Batchelor and Dowdeswell, 2015) that formed when the glacier was grounded at its lateral margins yet had a floating ice shelf over the central, deepest part of the fjord. Short floating sections have been inferred at Kangerdlussuaq Glacier and in other glaciers around Greenland (Joughin et al., 2008).

### 4.3 Mid- and outer-fjords

Major moraine ridges are present in a mid-fjord setting (close to the fjord mid-point, beyond the inner-fjord moraines) in all of the 9 fjords of the eastern JIC yet in only 1 of the fjords of the SE GIS (Fig. 1b and c). The mid-fjord moraines are located between 8 and 37 km from the present-day ice margin in water depths of 200 to 700 m (Figs. 2 and 3). They are up to 3 km long in the former ice-flow direction, reach up to 150 m above the surrounding seafloor, and span the width of the fjord (Fig. 3d and f). Three of the moraines have a double ridge crest, with the crests spaced about 1 km apart (Fig. 3f). Although they occur in a remarkably similar, mid-fjord, position in each of the fjords of the eastern JIC (Fig. 2 and Fig.

S3 in the supporting information), the mountainous topography of this area prevents the moraines from being correlated between the fjords.

Only one moraine ridge is observed in an outer-fjord setting on the SE Greenland margin. This moraine, which is close to the present-day coastline beyond Anorituup Kangerlua Glacier (Fig. 1c), is around 2 km long and up to 100 m high.

## 5. Discussion

### 5.1 The geomorphological record of past ice dynamics on the SE Greenland margin

Our bathymetric data show that the mid- and outer-fjords of the SE GIS and the eastern JIC contain a contrasting geomorphological record of past ice dynamics. Most of the mid- and outer-fjords of the SE GIS for which we have bathymetric data lack geomorphological evidence for major still-stands or readvances of the grounding zone during the last deglaciation (Fig. 1b). This finding is in agreement with other studies that have inferred relatively rapid and continuous deglaciation of the fjords of the SE GIS, which was not punctuated by significant (at least decades to centuries) still-stands or readvances of the ice margin (Roberts et al., 2008; Dyke et al., 2014). In contrast, the presence of large (up to 3 km long and 150 m tall) mid-fjord moraines in the fjords of the eastern JIC (e.g. Fig. 3d and f) suggests that the outlet glaciers which occupied these fjords underwent at least one major still-stand or readvance in their grounding-zone position during the last deglaciation.

This contrasting style of deglaciation between the SE GIS and the eastern JIC may be a consequence of climatic differences along the SE Greenland margin, for example warmer air and ocean temperatures and/or higher snowfall in the southern part of the margin. The JIC may also have been more sensitive to climatic and oceanographic changes as a result of its proximity to the Irminger Current (Fig. 1a). However, the geometry of the fjords is also important. Whereas relatively rapid ice retreat through the fjords of SE Greenland was encouraged by the considerable depth (up to 1000 m) and width (typically >5 km) of these fjords (Roberts et al., 2008; Dyke et al., 2014), grounding-zone stabilisation would have been encouraged in the mid-fjords of the eastern JIC as a result of their generally shallower and narrower geometry (Figs. 1 and 2 and Figs. S1 to S3 in the supporting information). Narrower and shallower fjords encourage ice-margin stabilisation through increasing basal and lateral drag, which reduces mass flow across the grounding zone, and reducing the rate of iceberg calving, as well as by preventing the incursion of warm subsurface water of Atlantic origin, typically below 300 m depth, to the ice margin (Rignot et al., 2012, 2016; Porter et al., 2014). Our temperature plots show that, at present, the shallower fjords of the eastern JIC block the migration of warm subsurface water of the Irminger Current from reaching a mid- to inner-fjord position (Fig. 2). In contrast, the deep (up to 1000 m) cross-shelf troughs and mid-fjord basins of SE Greenland (Fig. 2 and Figs. S1 to S3 in the supporting information) enable changes in ocean temperature off the shelf to be transmitted more readily through the fjords to the ice margin, encouraging more rapid ice retreat (Millan et al., 2018). The distribution of mid-fjord moraines, as shown in this study (Fig. 1b and c), suggests that this pattern may have also existed along the SE Greenland margin during the last deglaciation.

A similar pattern of non-uniform ice-sheet retreat following the LGM, in which the deepest parts of fjords and the continental shelf generally experienced a rapid to episodic style of grounding-zone retreat, has been inferred for other sectors of the GIS (Porter et al., 2014; Batchelor et al., 2018) and on other high-latitude margins (Ó Cofaigh et al., 2008; Stokes et al., 2014). The extent to which warm sub-surface water was able to access the ice margin through deep fjords and cross-shelf troughs has been suggested to have been an important factor in determining the speed and style of deglaciation (Straneo et al., 2010; Dyke et al., 2014). Knowledge of the past behaviour of the SE GIS and JIC is necessary to understand and predict the future dynamics of Greenland's outlet glaciers. The depth and gradient of the seafloor, together with subglacial topography, play an important role in determining the variable ice-marginal response of individual outlet glaciers to atmospheric and oceanographic forcing (Straneo et al., 2010; Rignot et al., 2012; Millan et al., 2018).

5.2 Chronological implications

The most seaward inner-fjord moraine in each fjord is located beyond the oldest ice-margin position known from aerial photographs (Figs. 2 and 3 and Figs. S1 to S3 in the supporting information; Bjørk et al., 2012). Together with their correlation with prominent terrestrial moraines (Fig. 3b; Kjeldsen et al., 2015), this suggests that the inner-fjord moraines were formed sometime during the Neoglacial (since *c.*4 ka). The widespread distribution of the inner-fjord moraines demonstrates that much of the SE sector of the GIS, including the JIC, experienced at least one significant ice-margin still-stand or readvance during this interval, which includes the LIA (AD 1450-1850). However, the outlet glaciers of SE Greenland did not undergo uniform glacier-terminus advance during this time (Fig. 2 and Figs. S1 to S3 in the supporting information). Variations in the magnitude of glacier-terminus advance to/ retreat from the inner-fjord moraines were probably linked with the water depth close to the ice margin and the height of the sub-ice topography, with greater terminus retreat encouraged by deeper fjords with reverse-gradient seafloor slopes (Millan et al., 2018).

The broad distribution of the mid-fjord moraines, which spans the *c.*150 km long eastern margin of the JIC (Fig. 1c), together with their similar dimensions, morphology and position within neighbouring fjords (Figs. 2 and 3 and Fig. S3 in the supporting information), suggests that they were formed relatively synchronously. It is unlikely that the relatively small outlet glaciers of the JIC experienced ice-margin readvances during the Neoglacial that were considerably greater than those of the outlet glaciers of the GIS, including the much larger Kangerlussuaq Glacier (16 km; Fig. 3b), which would have experienced higher ice fluxes. It is possible that the mid-fjord moraines were formed during the Younger Dryas (11.6 to 12.8 ka), although we note that ice in SE Greenland is generally considered to have been at an inner-shelf to coastline position during this time (Fig. 1; Bennike and Björck, 2002; Jennings et al., 2006; Roberts et al., 2008). Given the distribution of published deglacial ages, which suggest that the ice margin was at the outer coast of SE Greenland by around 11 to 10 ka (Bennike and Björck, 2002; Knutz et al., 2011) and retracted behind its present-day extent by around 9 to 7 ka (Larsen et al., 2011; Fig. 1b and c), we hypothesise that the mid-fjord moraines were formed during an ice-margin still-stand or advance that occurred during the early Holocene. It is possible that this still-stand or advance had a climatic control, for example the 8.2 ka event that has been recorded from Greenland ice cores including the Dye-3 site in SE Greenland (Fig. 1b) (Alley et al., 1997). The general absence of mid-fjord moraines from the fjords of the SE GIS is probably related to the greater depth of these fjords, which discouraged ice-margin stabilisation during the early Holocene by enabling the incursion of warm Irminger Current water (Fig. 1a) to the ice margin.

## 6. Conclusions

We use bathymetric data to map, for the first time, major moraine ridges in the fjords of SE Greenland (Fig. 1). Many (*c.*65%) of the inner-fjords of the SE GIS and the eastern JIC contain moraines, which are up to 2 km wide and 150 m tall (Fig. 2 and Figs. S1 to S3 in the supporting information). Their locations beyond the oldest ice-margin position where it is known from aerial photographs and correlation with prominent terrestrial moraines suggest that the inner-fjord moraines were produced sometime during the Neoglacial (since *c.*4 ka). We also identify a series of 9 major (up to 3 km long and 150 m tall) mid-fjord moraines in the fjords of the eastern JIC (Figs. 1c, 3c to f). In contrast, mid-fjord moraines are generally absent from the deeper and wider fjords of the SE GIS to the north, in which relatively rapid and continuous ice retreat is interpreted to have occurred during the last deglaciation. We hypothesise that the mid-fjord moraines of the eastern JIC were formed during an ice-cap-wide still-stand or readvance that was superimposed upon regional deglaciation following the LGM. Contrasting behaviour between the SE GIS and the JIC since the LGM is interpreted to be a consequence of the shallower and narrower fjord geometry of the JIC, which encouraged ice-margin stabilisation by reducing the rate of iceberg calving and stronger modulation of the incursion of warm subsurface water to the glacier termini by prevailing currents and winds. Our submarine mapping work provides further incentive to understand, and provide chronological control on, the past behaviour of the marine-terminating outlet glaciers of this region of the GIS.

## 7. Acknowledgments and Data

There are no conflicts of interest for any author. Profiles through all surveyed fjords are shown in Figs. S1 to S3 in the supporting information. We thank NASA's Oceans Melting Greenland (OMG) project and the crew of the M/V Neptune for collecting the bathymetric and water temperature data in SE Greenland. The data are contained at: http://dx.doi.org/10.5067/OMGEV-BTYSS, at http://omg.jpl.nasa.gov, and at https://faculty.sites.uci.edu/erignot/. During this work, C.L. Batchelor was in receipt of a Junior Research Fellowship at Newnham College, University of Cambridge, and a VISTA scholarship to the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. We wish to thank two anonymous reviewers for their helpful reviews of this paper.

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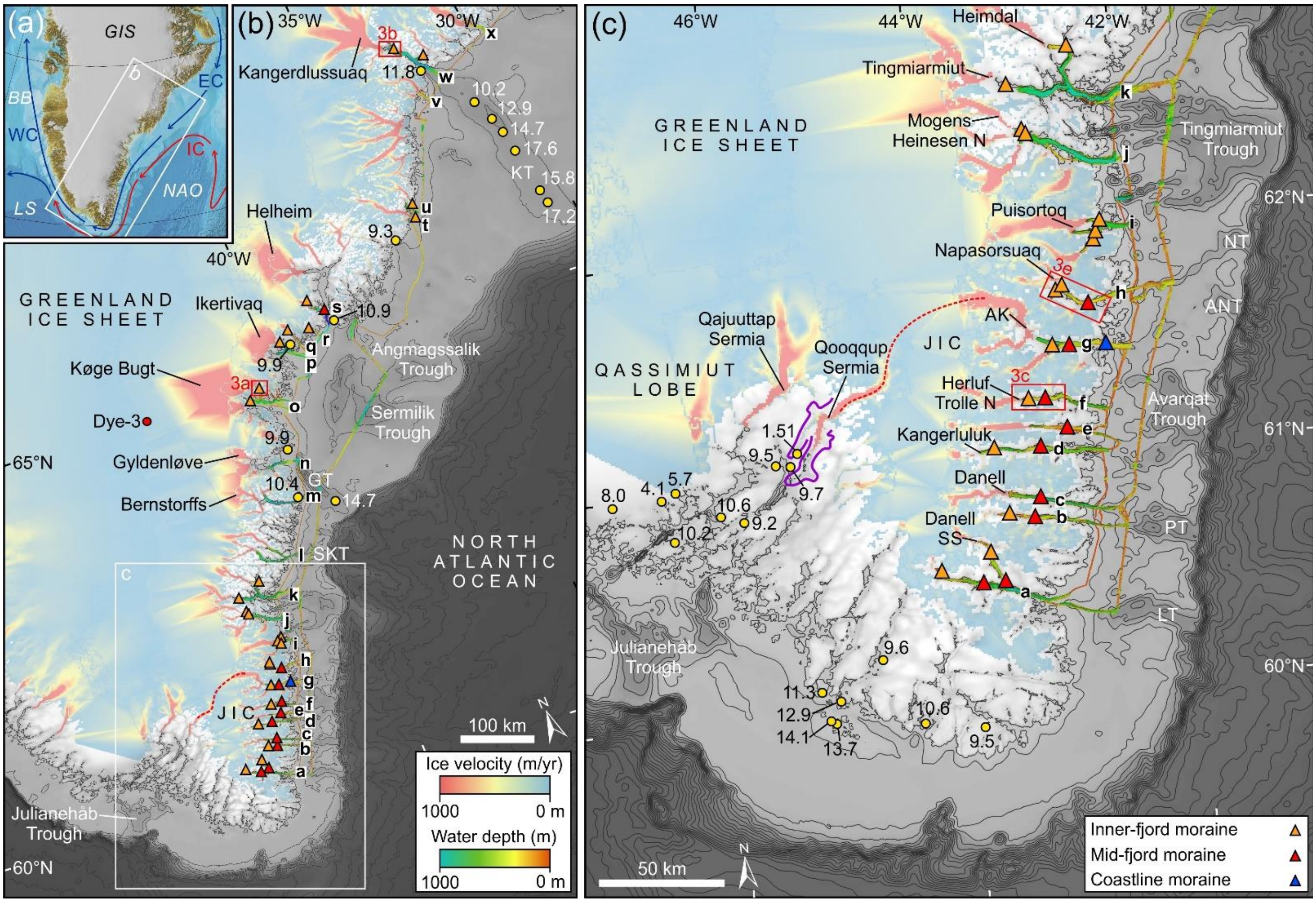
## 9. Figure Captions

**Figure 1.** The distribution of bathymetric data used in this study. (a) Map of SE Greenland and major ocean currents. BB = Baffin Bay; EC = East Greenland Current; IC = Irminger Current; LS = Labrador Sea; NAO = North Atlantic Ocean; WC = West Greenland Current. (b) Map of the SE Greenland margin, showing OMG bathymetric data and the distribution of submarine moraines. Yellow circles are published $^{10}$Be and $^{14}$C deglacial ages (Roberts et al., 2008; Dyke et al., 2014). GT = Gyldenløves Trough; KT = Kangerdlussuaq Trough; SKT = Skjoldungen Trough; Background is IBCAO bathymetry (Jakobsson et al., 2012) with 200 m contours and colour coded from black (deep) to white (shallow). The average ice velocity of the GIS (2000 to 2009) is from NASA's Making Earth System Data Records for Use in Research Environments (MEaSUREs) program (Joughin et al., 2010). Dashed red line is

boundary between GIS and JIC. (c) Map of the Julianehåb Ice Cap (JIC), showing published $^{10}Be$ and $^{14}C$ deglacial ages (Weidick et al., 2004; Bennike and Björck, 2002; Larsen et al., 2011; Winsor et al., 2014). Purple line is Tunugdliarfik moraines (Weidick et al., 2004). AK = Anorituup Kangerlua Glacier. ANT = Anoritup Trough; LT = Lindenow Trough; NT = Napassorssuaq Trough; PT = Patussoq Trough.

**Figure 2.** Selected profiles along the fjords of SE Greenland, showing the locations of major moraines and the potential water temperature of the fjords. Profiles start at 2016 glacier position. Black and dark grey areas show seafloor depth from OMG bathymetric data and free-air gravity anomaly data, respectively. Dashed red lines are former outlet-glacier positions. Potential water temperature is from conductivity-temperature-depth (CTD) casts, with CTD positions shown by grey lines.

**Figure 3.** Bathymetric examples of moraines in SE Greenland fjords. Grid cell-size is 25 m. Locations are in Fig. 1. (a) Inner-fjord moraines beyond Køge Bugt North Glacier (Fjord 'O2'). Background is 1981 aerial photograph from G150 AERODEM dataset (Korsgaard et al., 2016). Red arrows show terrestrial moraines. (b) Inner-fjord ridge/wedge beyond Kangerdlussuaq Glacier (Fjord 'W1'). Background is Landsat 8 satellite imagery acquired in 2016. (c) Bathymetric data beyond Herluf Trolle North Glacier (Fjord 'F'), showing inner- and mid-fjord moraines. (d) Detail of the mid-fjord moraine in (d). (e) Bathymetric data beyond Napasorssuaq Glacier (Fjord 'H1'), showing inner- and mid-fjord moraines. (f) Detail of the mid-fjord moraine in (e).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(b)
35°W
30°W
40°W
65°N
60°N
Kangerdlussuaq
Helheim
Ikertivaq
Køge Bugt
Dye-3
Gyldenløve
Bernstorffs
GREENLAND ICE SHEET
Angmagssalik Trough
Sermilik Trough
KT
GT
SKT
NORTH ATLANTIC OCEAN
JIC
Julianehåb Trough
3a
3b
100 km
Ice velocity (m/yr)
1000
0 m
Water depth (m)
1000
0 m
(c)
46°W
44°W
42°W
62°N
61°N
60°N
Heimdal
Tingmiarmiut
Mogens Heinesen N
Puisortoq
Napasorsuaq
AK
Herluf Trolle N
Kangerluluk
Danell
Danell SS
GREENLAND ICE SHEET
QASSIMIUT LOBE
Qajuuttap Sermia
Qooqqup Sermia
JIC
Tingmiarmiut Trough
NT
ANT
Avarqat Trough
PT
LT
Julianehåb Trough
3c
3e
50 km
Inner-fjord moraine
Mid-fjord moraine
Coastline moraine

Figure 1.

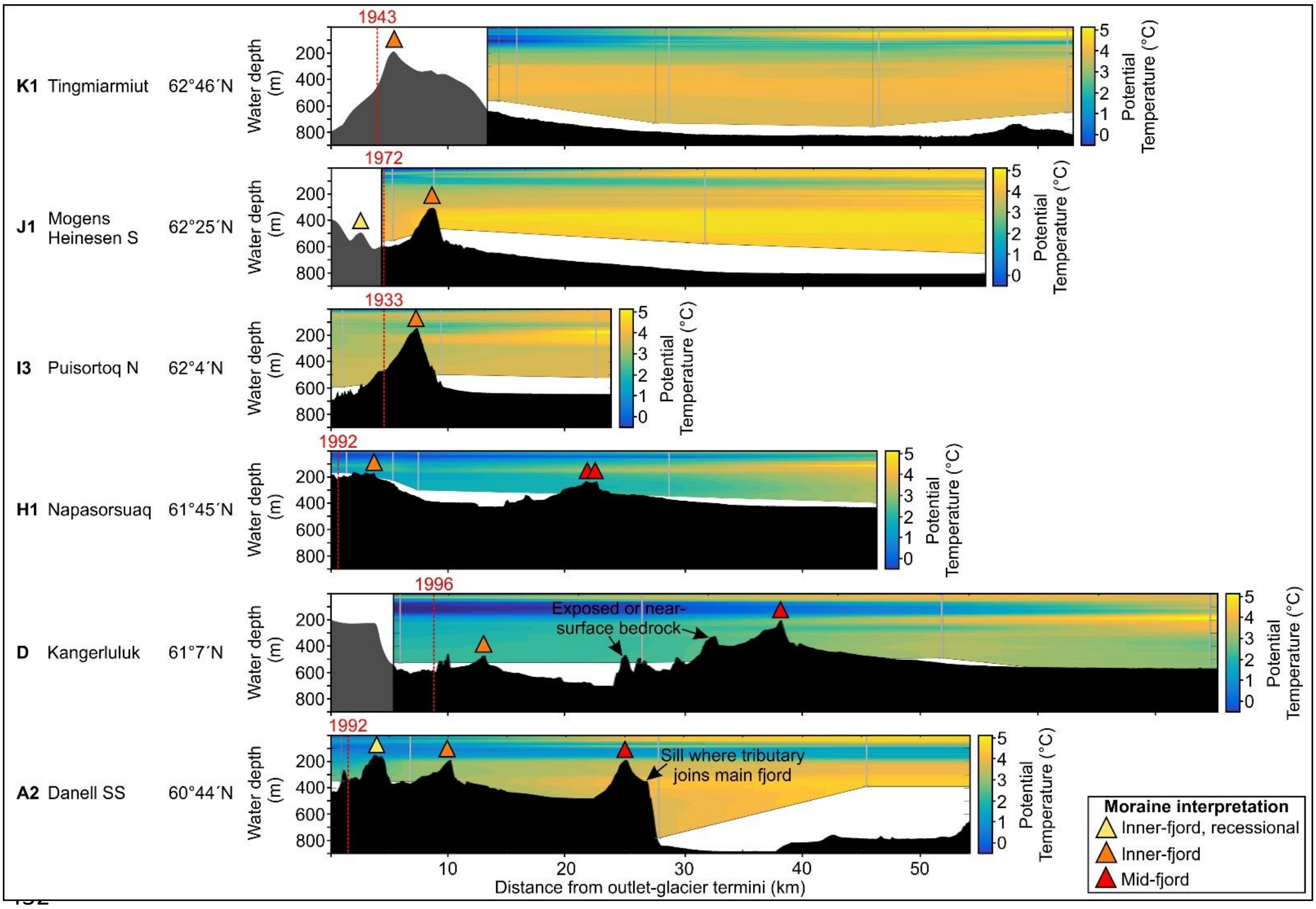
K1 Tingmiarmiut 62°46´N
J1 Mogens Heinesen S 62°25´N
I3 Puisortoq N 62°4´N
H1 Napasorsuaq 61°45´N
D Kangerluluk 61°7´N
A2 Danell SS 60°44´N
1943
1972
1933
1992
1996
1992
Water depth (m)
200
400
600
800
Potential Temperature (°C)
0
1
2
3
4
5
Exposed or near-surface bedrock
Sill where tributary joins main fjord
10
20
30
40
50
Distance from outlet-glacier termini (km)
Moraine interpretation
Inner-fjord, recessional
Inner-fjord
Mid-fjord

Figure 2.

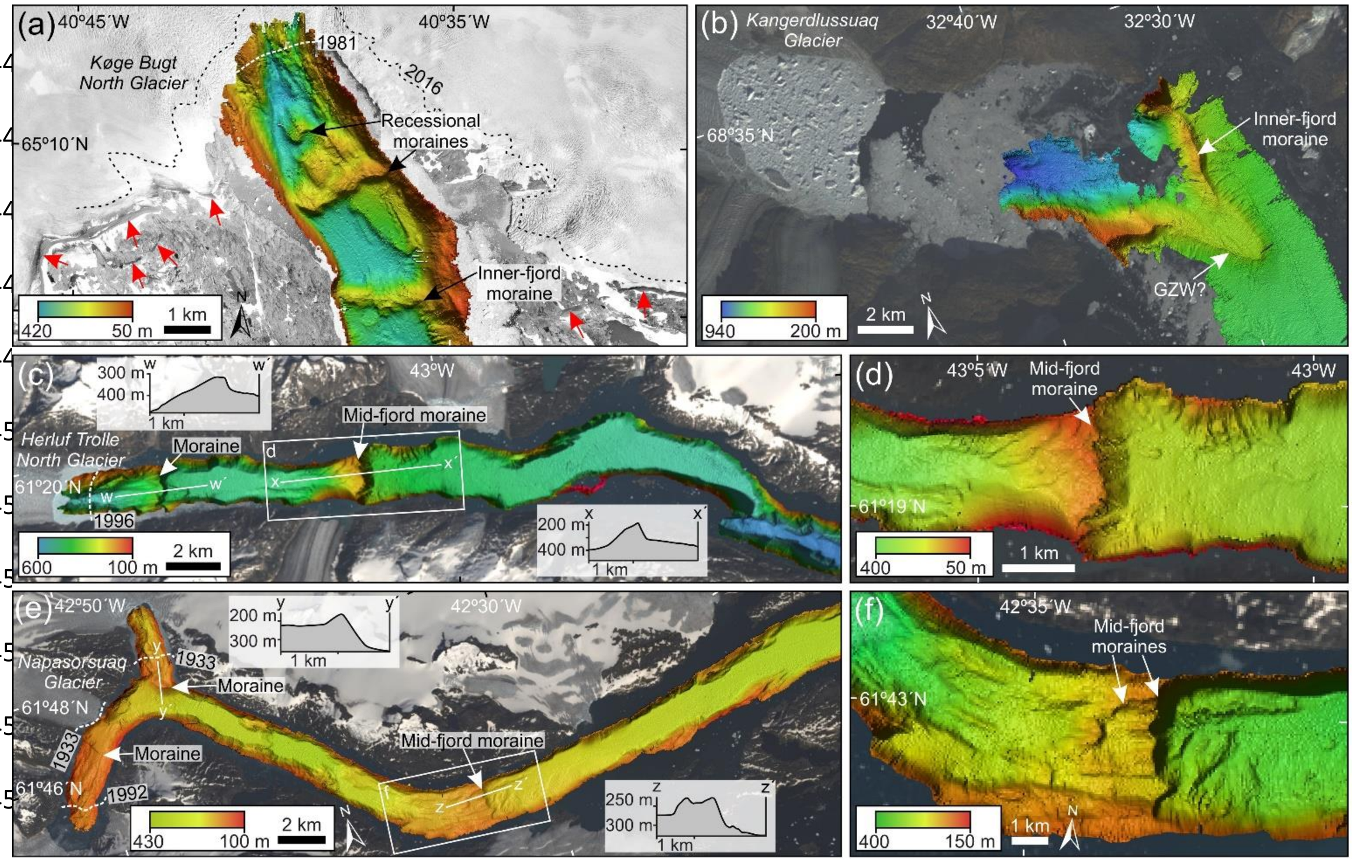
(a)
40°45´W
40°35´W
Køge Bugt North Glacier
1981
2016
65°10´N
Recessional moraines
Inner-fjord moraine
420
50 m
1 km
N
(b)
Kangerdlussuaq Glacier
32°40´W
32°30´W
68°35´N
Inner-fjord moraine
GZW?
940
200 m
2 km
N
(c)
300 m
400 m
w
w´
1 km
43°W
Mid-fjord moraine
Herluf Trolle North Glacier
Moraine
d
x
x´
w
w´
61°20´N
1996
200 m
400 m
1 km
600
100 m
2 km
(d)
43°5´W
Mid-fjord moraine
43°W
61°19´N
400
50 m
1 km
(e)
42°50´W
200 m
300 m
y
y´
1 km
42°30´W
Napasorsuaq Glacier
1933
Moraine
61°48´N
1933
Moraine
Mid-fjord moraine
f
z
z´
61°46´N
1992
250 m
300 m
1 km
430
100 m
2 km
N
(f)
42°35´W
Mid-fjord moraines
61°43´N
400
150 m
1 km
N

Figure 3.

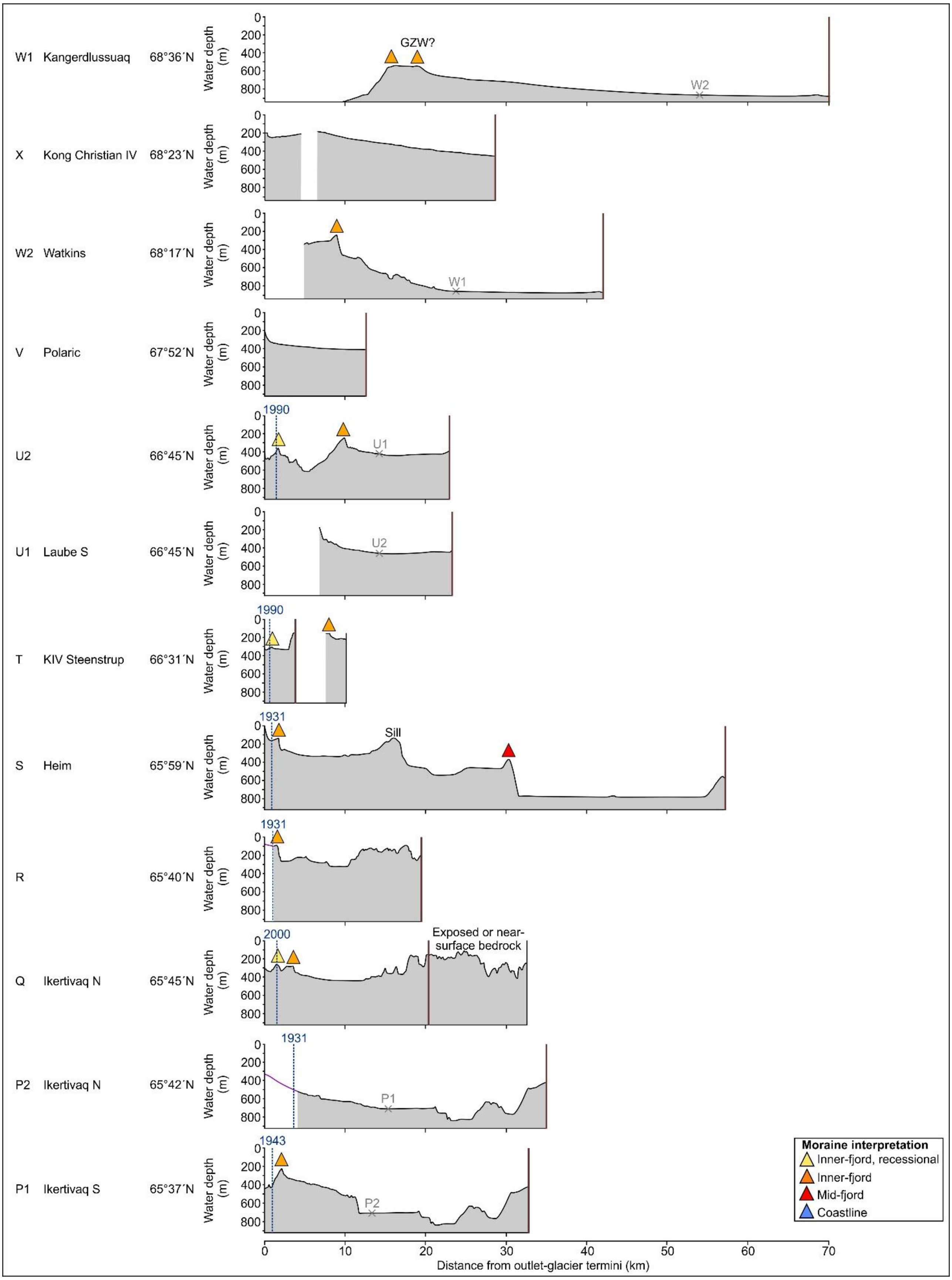


**Figure S1.** Profiles along the surveyed fjords of SE Greenland, showing the locations of major (>10 m high) moraines in fjords 'P' to 'W'. With the exception of in Fjords U2 and T, which are short fjords of less than 25 km in length, moraines are classified as 'inner-fjord' when they are present within the landward third of the total fjord length. ‘Mid-fjord’ moraines are defined as those that are close to the mid-point of the length of each fjord. ‘Inner-fjord recessional’ moraines are those that are landwards of another inner-fjord moraine. Profiles start at 2016 glacier position. Grey areas are seafloor depth from OMG bathymetric data. Purple lines are seafloor depth derived from free-air gravity anomaly data (Millan et al., 2018). Dashed blue lines show the oldest ice-margin position that has been mapped from aerial photographs (Bjørk et al., 2010). Vertical brown lines show the approximate position of the present-day coastline. Fjords are labelled ‘A’ to ‘W’ from south to north, as in Fig. 1, with numbers denoting tributaries of the main fjords. Grey crosses show the position at which tributary fjords converge. GZW = Grounding-zone wedge.

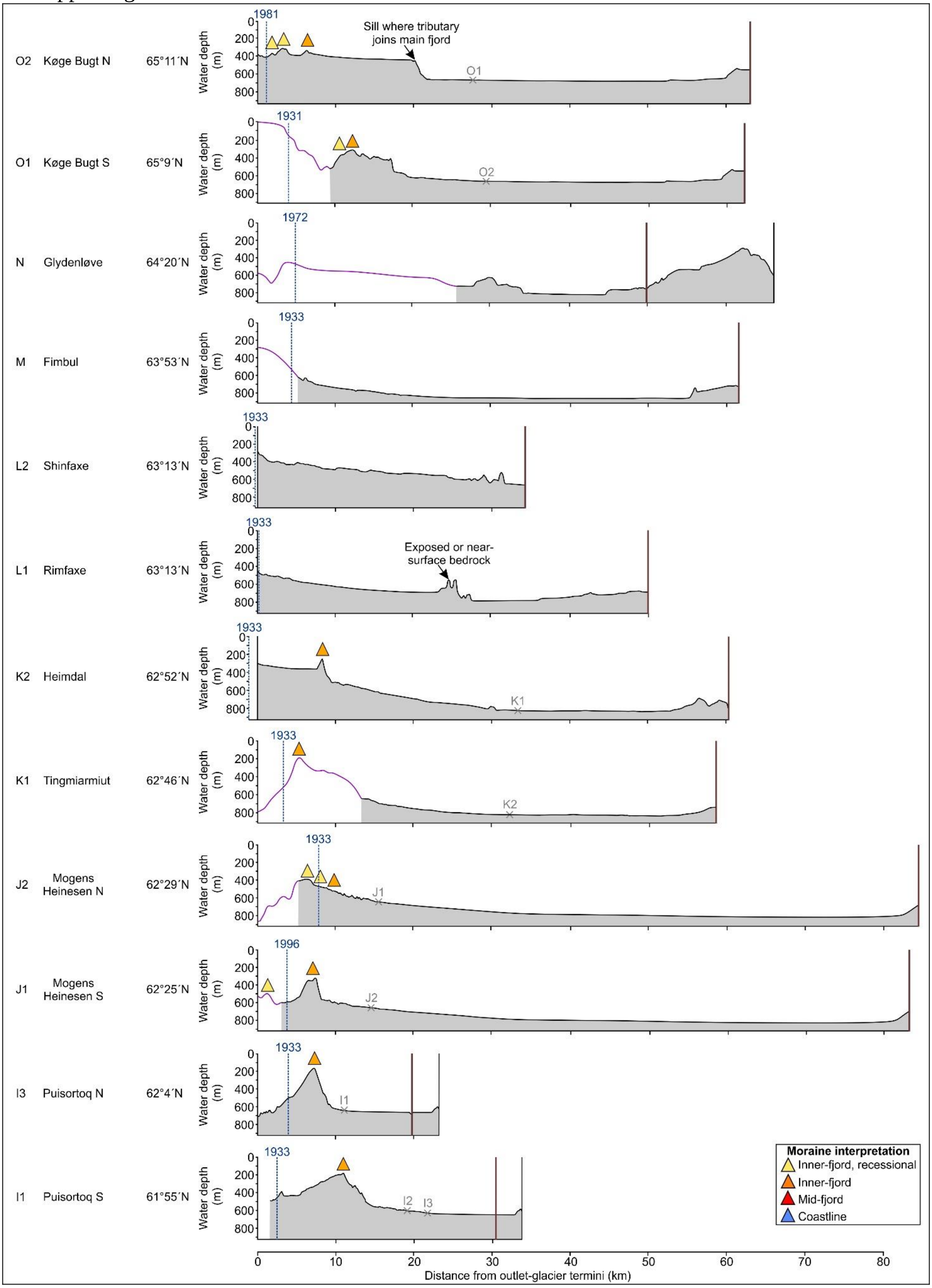


**Figure S2.** Profiles along the surveyed fjords of SE Greenland, showing the locations of major (>10 m high) moraines in fjords 'O' to 'I'. Key is the same as in Fig. S1.

Supporting Information

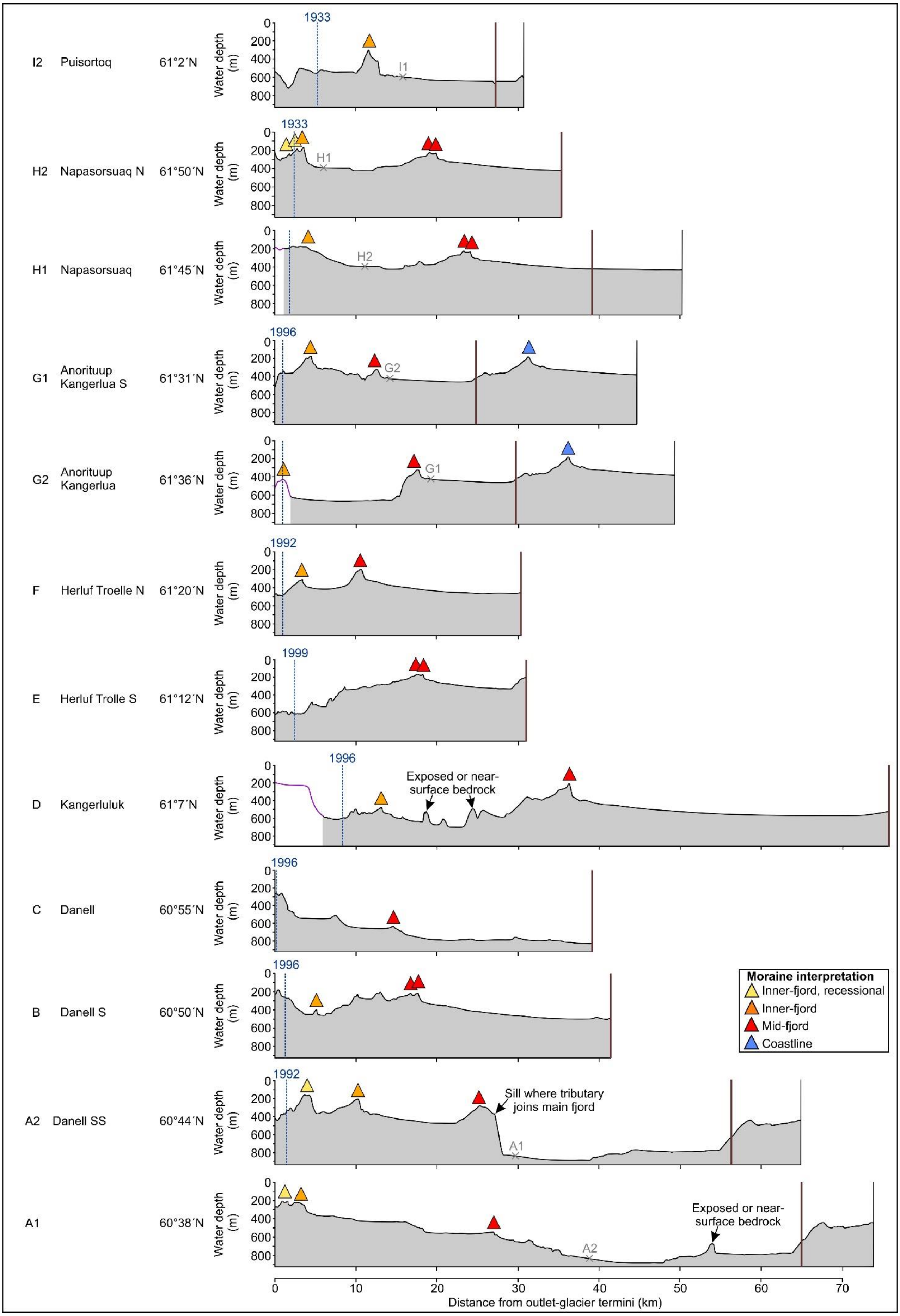

**Figure S3.** Profiles along the surveyed fjords of SE Greenland, showing the locations of major (>10 m high) moraines in fjords 'I' to 'A'. Key is the same as in Fig. S1.