Submarine landforms and shallow acoustic stratigraphy of a 400 km-long fjord-shelf-slope transect, Kangerlussuaq margin, East Greenland

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Abstract. Kangerlussuaq Fjord is a relatively uniform, steep-walled basin, whose floor has an almost smooth surface. Debris is supplied mainly from icebergs from the fast-flowing Kangerlussuaq Glacier. Sedimentation after iceberg release from multi-year sea ice is mainly by rain-out of fine-grained englacial debris. Streamlined glacial lineations and drumlins were produced at the sedimentary bed of an ice sheet that expanded into Kangerlussuaq Trough at the Last Glacial Maximum (LGM). Bedrock channels and crescentic overdeepenings indicate warm-based ice and free water beneath parts of the former ice sheet. Cross-cutting iceberg scour marks, which characterise outer Kangerlussuaq shelf, were produced not only during deglaciation, but also occasionally through the Holocene by deep-keeled icebergs from further north in East Greenland. The outward-convex contours of the shelf edge and slope beyond Kangerlussuaq Trough, and debris flows on the slope, suggest a glacier-influenced high-latitude fan. The distribution of streamlined subglacial landforms demonstrates that the Greenland Ice Sheet extended throughout Kangerlussuaq Fjord and reached at least 200 km across the shelf in Kangerlussuaq Trough at the LGM. Streamlined-landform orientation indicates ice flow from the interior of Greenland down the axis of Kangerlussuaq Trough. There is little evidence for discrete sedimentary depocentres in the trough, implying that ice probably retreated rapidly from the outer and mid-shelf during deglaciation.

Introduction

During Quaternary glacial periods, glaciers and ice sheets expanded along fjords and across continental shelves, sometimes reaching the shelf edge, on many high-latitude margins in the Arctic and Antarctic (e.g. Mienert et al., 1992; Anderson et al., 2002; Ottesen et al., 2005; Ó Cofaigh et al., 2005a; Evans et al., 2006, 2009; Ottesen and Dowdeswell, 2009). Submarine landforms, produced by the action of these ice masses, contain a record of the past extent, flow directions and processes that took place at the ice-bed interface. The basal boundary of glaciers and ice sheets is of considerable significance to our understanding of glaciological processes, but it is a location hidden by a kilometre or more of ice in modern polar settings. Glacier and ice-sheet retreat after the last glacial period has revealed suites of submarine landforms on high-latitude margins, produced at the base of former ice masses. Marine waters have protected these landforms from much of the subsequent erosion to which subaerial landforms have been subjected, although the geomorphic imprint of past glacier activity can be obscured by subsequent deglacial and Holocene sedimentation and through reworking by iceberg ploughing at depths shallower than 400-500 m in many fjord and shelf systems (e.g. Brett and Zarudzki, 1979; Dowdeswell et al., 1992, 1993; Syvitski et al., 2001).

In this paper, we describe and discuss the submarine landforms, and their implications for modern and Quaternary ice-sheet form and flow, along a transect of about 400 km from an East Greenland fjord, across the adjacent continental shelf and onto the continental slope (Fig. 1). The area selected, the Kangerlussuaq fjord and shelf system (65°-68°N, 30°-33°W), is of particular significance for several reasons. First, this system is fed by one of the ten or so fast-flowing outlet glaciers that drain huge interior basins within the Greenland Ice Sheet. The dynamics of these large outlet glaciers are vital controls on the present and past mass balance of the Greenland Ice Sheet (e.g. Reeh, 1985; Luckman et al., 2006; Rignot and Kanagaratnam, 2006). Secondly, there is still some doubt as to which parts of the East Greenland margin experienced ice-sheet growth to the continental shelf edge at the Last Glacial Maximum (LGM) (Mienert et al., 1992; Funder and Hansen, 1996; Roberts et al., 2008) and diagnostic submarine glacial landforms should assist in resolving this question (e.g. Evans et al., 2002; Evans et al., 2009). Thirdly, Kangerlussuaq Fjord and the cross-shelf trough that extends across the shelf beyond the fjord mouth are, in part at least, deep enough to have avoided major reworking of sea floor geomorphology and shallow stratigraphy by the action of deep-keeled icebergs (Syvitski et al., 2001). The glacial geomorphic record is, therefore, preserved in many areas of the transect which we have investigated using the marine-geophysical methods of swath bathymetry and shallow sub-bottom acoustic profiling.

Study Area and Background

The study area comprises Kangerlussuaq Fjord, whose mouth is at 68°05'N 31°40'W, and the adjacent cross-shelf trough, Kangerlussuaq Trough, that reaches the East Greenland shelf edge at about 65°30'N 31°W (Fig. 1A-C). The fjord itself is about 70 km long and ranges between approximately 5 and 10 km wide. Nordfjord, Courtauld Fjord, Watkins Fjord and Amdrup Fjord form four smaller fjords, branching up to 20 km from the trunk of Kangerlussuaq Fjord. The cross-shelf trough is about 300 km long from fjord mouth to shelf break, making the distance from the terminus of Kangerlussuaq Glacier to the continental shelf edge almost 400 km.

The water depth to about 5 km beyond the margin of Kangerlussuaq Glacier is unknown, because the presence of 'sikussak', a frozen melange of multi-year sea ice with icebergs embedded within it (Syvitski et al., 1996; Reeh et al., 1999; Dowdeswell et al., 2000), prevented survey-ship access in both 1993 and 2004. Water depth immediately beyond the 1993 sikussak limit was more than 600 m, shallowing within 5 km to a sill at about 450 m (Syvitski et al., 1996; Smith and Andrews, 2000). Water deepens offshore of the sill to over 800 m at and beyond the fjord mouth in an inner-shelf basin. A further sill <500 m deep separates the inner and middle shelf basins. The latter is more than 700 m deep and the trough then shallows to about 400 m at the shelf edge (Mienert et al., 1992; Syvitski et al., 2001). Either side of the 40-60 km-wide Kangerlussuaq Trough, shallower banks reach 200-400 m deep (Syvitski et al., 2001). South of about 66°30'N, the continental shelf is made up of a thick prograding sedimentary wedge (Stein, 1996).

Regarding glacial history, the maximum ice extent in East Greenland during the LGM or Flakkerhuk (Late Weischelian) full-glacial period was from about 22 to 14,000 yr ago (Funder et al., 1998). The precise limit of full-glacial ice on the 300 km-wide Kangerlussuaq continental shelf is still not clear (Mienert et al., 1992; Andrews et al., 1996; Syvitski et al., 2001), but it is thought that retreat from the general area of the outer-shelf took place shortly after about 17,000 yr ago, reaching the inner shelf by about 15,000 yr ago and the present coast by between 13,600 and 11,500 years ago (Mienert et al., 1992; Jennings et al., 2002, 2006). Ocean temperature change, with the inflow of relatively warm Atlantic water into Kangerlussuaq Trough, was important to the relatively rapid deglaciation of the shelf and the high observed sedimentation rates (Mienert et al., 1992; Andrews et al., 1996; Jennings et al., 2006).

Today, one of the major outlet glaciers of the Greenland Ice Sheet, Kangerlussuaq Glacier, drains into Kangerlussuaq Fjord (Reeh, 1985; Dwyer, 1995). Ice discharge from the 51,000 km^2 inland basin was about 28 km^3 yr^{-1} in 1996; almost 10% of the mass loss from the whole ice sheet (Rignot and Kanagaratnam, 2006). In August 2004 the sikussak beyond the terminus of Kangerlussuaq Glacier broke up. Since then, the glacier terminus, which was probably floating, has retreated 5 km and flow has accelerated from 7 km yr^{-1} to 13 km yr^{-1} (Luckman et al., 2006; Howat et al., 2007; Joughin et al., 2008). Sikussak breakup and terminus retreat occurred when ocean temperatures in Kangerdlugssuaq Fjord were several degrees warmer than during the previous decade, suggesting that basal melting and thinning of this floating ice contribute to rapid changes in the form and flow of Kangerlussuaq Glacier today (Christoffersen et al., Submitted).

Methods

The geophysical datasets used in this study were acquired from the RRS *James Clark Ross* (JCR) in September 2004 using hull-mounted Kongsberg Simrad multibeam swath-bathymetry and Topographic Parametric Sonar (TOPAS) sub-bottom profiler systems. The swath system was a deep-water 12 kHz EM-120 with 191 beams and a 1˚ by 1˚ beam configuration. Swath data were processed through the removal of anomalous pings and gridded at cell sizes of 30 – 60 m using Kongsberg-Simrad NEPTUNE software. Depth measurements have vertical and horizontal uncertainties of about 1 m and 5 m, respectively. The TOPAS parametric acoustic profiler has a secondary frequency of 0.5-5 kHz. Navigation data were acquired using differential GPS. The ship tracks along which geophysical data were acquired in the Kangerlussuaq fjord-shelf-slope system is shown in Figure 1.

A limited amount of high-resolution swath bathymetry was also obtained from the mouth of Kangerlussuaq Fjord using the *Autosub* autonomous underwater vehicle (AUV) deployed from the JCR (Dowdeswell et al., 2008a). A Kongsberg Simrad EM-2000 swath-bathymetry system was used, operating at a frequency of 200 kHz, with 111 individual beams, an angular coverage of over 120°, and a swath width of up to 300 m (depending on distance from target). Quantitative data on elevation were gridded at a horizontal resolution of 1 m, with RMS errors of better than 10 cm in the vertical.

Kangerlussuaq Fjord

Geophysical Observations

EM-120 swath bathymetry of about 1,500 km^2 of the floor of Kangerlussuaq Fjord shows an almost smooth surface, broken by occasional steep-sided pinnacles (Fig. 2A). The fjord forms a relatively uniform, steep-walled basin, deepening systematically down-fjord to a maximum depth of 870 m near the fjord mouth (Figs. 1D, 2B). Just beyond the fjord mouth, the fjord basin is terminated by a sill that reaches about 500 – 550 m in depth (Fig. 2B). A 1.5 km-long swath of bathymetric data, collected by the *Autosub* EM-2000 system close to the fjord mouth, provides imagery that is an order of magnitude higher in resolution than the hull-mounted EM-120. Streamlined lineations and elongate features, orientated sub-parallel to the fjord long-axis are illustrated in Figure 2C. They are found at about 840 m water depth, in an area about 30-40 m above the deepest part of the fjord.

TOPAS sub-bottom profiler data from the fjord show acoustically stratified sediments up to 30-40 m in thickness, using a sound velocity of 1.5 km s^{-1} (e.g. Elverhøi et al., 1998) (Fig. 2D). The stratified unit is often underlain by an acoustically transparent unit. Similar transparent features also appear as lenses or lobes within the stratified unit. Steep-sided pinnacles protrude through these sedimentary units in a few places, and are characterised by a strong surface return without acoustic penetration.

Interpretation

The mainly smooth floor of Kangerlussuaq Fjord (Fig. 2A), and the stratified unit that dominates the acoustic stratigraphy (Fig. 2D), are interpreted to be linked to the rain-out of debris from the many icebergs that traverse the fjord (Syvitski et al., 1996), produced from the fast-flowing Kangerlussuaq Glacier at its head (Dwyer, 1995; Rignot and Kanagaratnam, 2006). An acoustically transparent acoustic unit, set within the mainly stratified sediments (Fig. 2D), is interpreted to be produced by debris flows, some of which are derived from slope failure of the steep fjord walls in an environment of relatively rapid sedimentation. The rate of sediment delivery is estimated to average 0.7 cm yr^{-1} across the whole fjord (Syvitski et al., 1996). Pinnacles protruding through the sediments to the surface, which exhibit no penetration on acoustic records, are of bedrock, which is likely to be part of the Palaeocene basalts that form the East Greenland volcanic province (Henriksen, 2008).

Cores from Kangerlussuaq Fjord sample mainly fine-grained mud interspersed with pebbles (Smith and Andrews, 2000). It is thought that sikussak, or multi-year sea ice, traps many of the calved icebergs within a few kilometres of the glacier terminus and plays an important role in the nature of sedimentation (Syvitski et al., 1996). It has been shown from sequential satellite photographs that icebergs are trapped for at least two years in the sikussak before release (Dwyer, 1995). Basal melting removes much, or all of the few-metres thick high debris-content layer of basal ice (Azetsu-Scott and Syvitski, 1999), presumably producing heterogeneous diamictic sediment close to the ice front. Sedimentation after iceberg release is then mainly by the rain-out of fine-grained low-concentration englacial debris (Dowdeswell, 1986; Syvitski et al., 1996). Turbidity current channels have also been observed in the inner part of Kangerdlusuaq Fjord (Syvitski et al., 2006), in the area that we were unable to access in early September 2006 because of the breakup of the sikussak in August 2006. We record no sea-floor channels in our swath bathymetry of the middle and outer fjord, but turbidite sediments, sampled from cores in the fjord (Syvitski et al., 1996; Smith and Andrews, 2000), appear to contribute up to 40% of basin fill (Syvitski et al., 1996).

Kangerlussuaq Trough

Geophysical Observations

Swath bathymetry of the cross-shelf trough on the Kangerlussuaq margin shows several types of sea-floor landform on the inner and mid shelf, between about 67° and 68°N (Figs. 3, 4A). The geographical distribution and orientation of submarine landforms is mapped in Figure 5A, and each is now described. The majority of linear, streamlined forms include both simple relatively straight lineations up to a few metres high and a few kilometres to tens of kilometres long (Figs. 3C, 4), and blunt-nosed elliptical forms up to 40 m high and 3000 m long with smaller elongation ratios (between 3 – 5:1) (Fig. 3B, C). Both are positive-relief features. They are usually orientated between NNW-SSE and N-S (Fig. 5). The blunt end of the elliptical landforms always faces northward, and the streamlined 'tail' is orientated southwards (Fig. 3B, C). Crescentic overdeepenings, a few hundred metres in length and up to 35 m in depth, also occur in one area in association with the streamlined landforms (Fig. 3C). The crescentic features have a similar orientation to the linear landforms, with the crescent 'tails' facing southwards. A few channel-like features are also present on the inner shelf (Fig 3B). They are usually sinuous and up to 10 m deep and 10 km long, with long profiles that have both positive and negative slopes. Irregularly orientated grooves occur in shallower areas of the trough and approaching the banks to either side of the trough (Fig. 3A).

On the outer shelf, south of approximately 67°N, there are just a few poorly defined linear features orientated N-S (Fig. 4). This region, which is shallower than the inner shelf, is dominated by large numbers of irregular grooves that often cross-cut one another (Figs. 4B, 6D). The irregular grooves are up to about 15 m deep, 50 m wide and often hundreds of metres long; they form depressions in the general sea floor and are sometimes associated with raised berms of a metre or two in height at their margins. Acoustically, there is little prenetration beneath a very irregular and sometimes diffuse surface reflector (Fig. 5B, Reflector B3).

Several acoustic facies and reflectors are identified and mapped on the Kangerlussuaq margin (Fig. 5). An example of each acoustic unit and reflector is given in Figure 5B. The acoustically stratified unit (Facies S) is restricted to Kangerlussuaq Fjord and its mouth (Fig. 2D). Acoustically transparent to semi-transparent lobes (Facies L1 and L2) are observed in the fjord and on the slope offshore of the shelf edge, respectively (Fig. 6E). The other acoustic units, a semi-transparent to stratified drape (Facies D), a strong and impenetrable surface reflector (Reflector B1) and a transparent unit (Facies T) usually underlain by a strong basal reflector (Reflector B2), all occur on the shelf; however, only Facies T and Reflector B2, together with a highly irregular, diffuse surface reflector (Reflector B3), are present on the outer shelf (Fig. 5A).

Most of the linear, streamlined landforms on the inner shelf are associated with Facies T, the semi-transparent unit which is underlain at a depth of typically a few metres by a strong and impenetrable basal reflector (B2). The landforms appear to be formed as part of this acoustic unit (Fig. 6B, C). In one case, in a zone about 7 km wide on the inner shelf, linear features with amplitudes of up to 80 m (Fig. 3A) are linked to a strong sea-floor reflector (B1) that allows no acoustic penetration (Fig. 6A). Occasionally, these linear features are draped by a thin acoustically laminated that reaches just 1 to 2 m at most in thickness. These linear features are orientated WNW-ENE, in contrast to the more N-S orientation of the streamlined features set within the acoustically semi-transparent unit which is itself underlain by a strong basal reflector.

Interpretation

The blunt-nosed and linear streamlined landforms in Kangerlussuaq Trough (Figs. 3B-C, 4), usually underlain by acoustical semi-transparent material (Facies T) (Fig. 6B, C), are interpreted as drumlins and glacial lineations produced at the sedimentary bed of an ice sheet that was present in the trough at the LGM. The strong, continuous reflector (B2) at the base of acoustic Facies T is similar in appearance and position to that observed and cored on other high-latitude shelves, where a stiff overconsolidated till is overlain by deformation till of low shear strength whose flow facilitated past ice motion (Dowdeswell et al., 2004; Ó Cofaigh et al., 2005a, 2005b, 2007; Evans et al., 2006, 2009). These elongate and streamlined landforms are produced beneath ice sheets and have been observed forming at the bed of modern ice streams (King et al., 2009). They have been used by many previous workers to reconstruct the direction of past ice flow (e.g. Shipp et al., 1999; Canals et al., 2000; Ottesen et al., 2005; Ó Cofaigh et al., 2005a; Evans et al., 2006; Andreassen et al., 2008; Dowdeswell et al., 2009).

Some drumlins have crescentic overdeepenings on their upstream sides (Fig. 3C). These features have been interpreted to indicate water flow at the ice-bed interface around the up-ice or stoss face of drumlins (Wellner et al., 2001; Ó Cofaigh et al., 2002). There is also limited evidence of sinuous channels within a kilometre or so of some drumlins (Fig. 3B), suggesting that past subglacial water flow in this part of the trough may have formed a coherent system. The up-and-down long profile of the channels implies that water flow was within a pressurized subglacial system (Rothlisberger, 1972). South of 67°15’N, drumlins, together with crescentic overdeepenings and channels, are not observed. Instead, relatively straight but subdued linear bedforms are present (Fig. 4), again set in the surface of a sedimentary substrate (Fig. 6C). Any subglacial water flow on the outer shelf was therefore through the sedimentary substrate itself, rather than in a channel system; a situation to that found in several outer-shelf troughs in Antarctica (e.g. Wellner et al., 2001; Ó Cofaigh et al., 2002, 2005a; Evans et al., 2006).

A 7 km-wide set of linear landforms between 67°53’N and 67°48’N (Fig. 3A) has very different acoustic characteristics to the sedimentary features described above. TOPAS records show a strong and acoustically impenetrable surface reflector (B1, Figure 5B) that is draped in some places by a thin layer of sediment that is sometimes laminated acoustically (Fig. 6A). The amplitude of these linear landforms is typically between 40 and 80 m (Figs. 3A, 6A), in contrast to the few metres height of the streamlined sedimentary features described above (Fig. 6B). These features are interpreted as bedrock ridges, orientated in a WNW-ESE direction, that sometimes have a thin drape of Holocene hemipelagic sediment on their less steep faces. This interpretation is confirmed by sleeve-gun records from the area, where the presence of localised scarps and dykes is inferred (Stein, 1996). These bedrock landforms are, therefore, probably related to the regional bedrock geology of East Greenland rather than to Quaternary glacial processes in Kangerlussuaq Trough. Much of the bedrock on the inner shelf of East Greenland is made up of Palaeocene basalts of the East Greenland volcanic province, with volcanism beginning about 62 million years ago (Henriksen, 2008).

The irregular, cross-cutting grooves on much of the shelf at water depths of less than about ~450 m (Figs. 3A, 6D) are interpreted straightforwardly as sea-floor scours produced by the ploughing action of grounded iceberg keels (Woodworth-Lynas et al., 1991). They are particularly prominent on the sill separating the fjord and inner shelf (Fig. 3A), and on the outer shelf (Fig. 4), and are almost ubiquitous close to the Kangerlussuaq shelf edge (Fig. 6D). Ploughing by iceberg keels reworks shelf stratigraphy and destroys any pre-existing glacial sedimentary landforms at water depths less than about 450 m on the Kangerlussaq margin.

Iceberg scours are very common on the Greenland continental shelf (Brett and Zarudzki, 1979; Dowdeswell et al., 1993; Syvitski et al., 2001), and on high-latitude shelves in general. Deep-keeled icebergs are usually derived from the margins of fast-flowing ice streams and ice-sheet outlet glaciers (Dowdeswell and Bamber, 2007), and icebergs with keel depths in excess of 450 m are produced from both Kangerlussuaq Glacier and Daugaard-Jensen Glacier in East Greenland today (Dowdeswell et al., 1992; Syvitski et al., 1996). However, Syvitski et al. (2001) suggest that modern icebergs with keels greater than 300-400 m are prevented from entering much of the Kangerlussuaq Trough by topographic barriers and that Holocene hemipelagic sedimentation is slowly burying relict scour marks within the trough.

Kangerlussuaq Shelf Edge and Slope

Geophysical Observations

Swath bathymetry covering about ~35,000 km^2 of the outermost continental shelf and the slope offshore of Kangerlussuaq Trough is centred on 65°20’N, 30°40’W (Fig. 1A). The shelf edge is typically the shallowest part of the continental shelf along the axis of Kangerlussuaq Trough (Fig. 6D), excluding the banks to either side of the trough (Syvitski et al., 2001). The sea floor close to the shelf edge has a very rough appearance on sub-bottom profiler records (Fig. 6D; reflector B3 in Fig. 5B), and swath bathymetry on the outer shelf shows the presence of many irregular linear depressions, up to about 15 m deep, 50 m wide and often hundreds of metres long (Fig. 4).

Beyond the shelf break, there are very few features present on swath bathymetry of the 1.8 to 2° continental slope. Sub-bottom profiler records, however, reveal the presence of a number of semi-transparent lobes on the slope (Fig. 6E; acoustic facies L2 in Fig. 5B). At water depths of about 1,350 m on the continental slope, sediments with acoustically wavy sub-parallel reflectors at least 25 m thick have built up (Fig. 6F).

Interpretation

The irregular, cross-cutting linear features on the outermost Kangerlussuaq shelf (Fig. 6D) are produced by the scouring action of deep-keeled icebergs, in common with similar features covering much of the Greenland shelf above about 500 m in water depth (Brett and Zarudzki, 1979; Dowdeswell et al., 1993; Syvitski et al., 2001). These cross-cutting scour marks have been produced not only during deglaciation from the LGM, but may be produced occasionally today by deep-keeled icebergs calved, for example, from the fast-flowing outlet glaciers feeding icebergs into the East Greenland Current from further north in East Greenland (Dowdeswell et al., 1992; Rignot and Kanagaratnam, 2006).

Beyond the shelf break, the portion of the continental slope imaged by swath bathymetry shows limited morphological variability, with little evidence of upper-slope gullies or channels. However, this may be in part a function of the relatively small area of swath coverage offshore of Kangerlussuaq Trough (Fig. 1), together with the observation of hard-ground composed of gravel and sand produced by current winnowing on the upper slope (Mienert et al., 1992; Syvitski et al., 2001). Further north in East Greenland, extensive turbidite channel systems are found on the mid-slope, continuing to abyssal depths in the 250,000 km^2 Greenland Basin (Mienert et al., 1993; Dowdeswell et al., 2002; Ó Cofaigh et al., 2004; Wilken and Mienert, 2006).

Sub-bottom profiler records identify several transparent lobate features on the Kangerlussuaq slope (Fig. 6E), which are interpreted as debris flows. Similar lobate features were reported by Stein (1996) from seismic records at water depths of about 1,800 to 2,000 m on the slope. Radiocarbon dates on core material immediately above sediments interpreted as possible debris flows on the Kangerlussuaq slope suggest that mass wasting was probably active at the LGM (Stein, 1996; Andrews et al., 1998; Dunhill, 2005).

Debris flows are a characteristic part of the sedimentary architecture of trough-mouth fans around the Norwegian-Greenland Sea (Aksu and Hiscott, 1992; Dowdeswell et al., 1996; King et al., 1996; Vorren et al., 1998; Taylor et al., 2002), and are made up of diamictic material that is thought to be derived largely from the delivery of glacially eroded sediment in fast-flowing ice streams (Laberg and Vorren, 1995; Elverhøi et al., 1997). Huge fans, such as the Bear Island, Scoresby Sund and Belgica fans (Dowdeswell et al., 1997; Vorren and Laberg, 1997; Dowdeswell et al., 2008b), are built up over successive glaciations as ice advanced across high-latitude continental shelves, sometimes to the shelf edge, and the upper slope became the full-glacial focus for rapid sedimentation (Dowdeswell et al., 1996, 1998; Vorren et al., 1998; Ó Cofaigh et al., 2003). The outward-convex contours of the shelf edge and slope beyond Kangerlussuaq Trough (Fig. 1B) suggest a major sedimentary depocentre; a trough-mouth fan similar to those described above. Seismic data confirm that much of the Kangerlussuaq continental shelf, south of about 67°40'N, is a prograding sedimentary wedge (Larsen, 1984; Stein, 1996); however, part of this material may be pre-glacial marine onlap deposits and fluvio-deltaic sediments of

Eocene to Oligocene age, overlain by Quaternary glacial sediments (Larsen, 1984, 1994). Finally, in common with much of the East Greenland continental slope (Wilken and Mienert, 2006), no major slide scars or run-out areas were observed on our swath coverage of the Kangerlussuaq slope. Finally, sediments with wavy internal reflectors at the base of the Kangerlussuaq slope (Fig. 6F) are interpreted as contourites (e.g. Faugeres and Stow, 1993), produced by the strong, geostrophic East Greenland Current.

Discussion: Ice-Sheet Extent and Flow on the Kangerlussuaq Margin

A number of submarine landforms that are produced subglacially have been described and interpreted above. The distribution of streamlined sedimentary bedforms, including lineations, drumlins, and subglacial meltwater indicators in the form of crescentic overdeepenings and channels, demonstrates that the Greenland Ice Sheet extended throughout Kangerlussuaq Fjord and onto the continental shelf beyond into Kangerlussuaq Trough (Fig. 5A). The furthest across the shelf that streamlined linear features have been identified is at about 66°N, approximately 220 km from the fjord mouth (Figs. 1A, 4B, 5A). Beyond this point, the shallowing outer shelf is scoured by iceberg keels to the point that any other landforms produced during ice advance would be removed. Thus, we can state that ice reached at least 200 km across the shelf in Kangerlussuaq Trough at the LGM. Mienert et al. (1992) reported a stiff diamict in a core taken in 299 m of water to the east of Kangerlussuaq Trough at 66°28’N, 29°41’W, which also indicates the presence of grounded ice on the Kangerlussuaq shelf.

Chronological evidence from Kangerlussuaq Trough indicates that the submarine landforms were produced at the LGM (Mienert et al., 1992; Jennings et al., 2002, 2006). Radiocarbon dates on core material from previous investigations suggest that ice retreat from the outer shelf began shortly after about 17,000 yr ago, reaching the inner shelf by about 15,000 yr ago and the present coast at between 13,600 to 11,500 years ago (Mienert et al., 1992; Jennings et al., 2002, 2006). Ice extending out onto the continental shelf, and perhaps even to the shelf edge, at the LGM has been reported from several other parts of the East Greenland margin recently (Evans et al., 2002, 2009), and is also consistent with evidence of ice filling coastal valleys in South-East Greenland at that time (Roberts et al., 2008).

The orientation of streamlined landforms is consistent with ice flow sub-parallel to the axis of Kangerlussuaq Trough. Sedimentary lineations, drumlins and crescentic overdeepenings are all orientated between NNW-SSE and N-S (Figs. 3B-C, 4, 5A). In addition, both blunt-nosed drumlins, and the crescentic overdeepenings that are often associated with them, provide the full sense of ice-flow direction. The blunt faces of drumlins always face towards the direction from which ice flows, and the 'wings' of the overdeepenings orientate with ice flow (Benn and Evans, 1998). We know, therefore, that ice flowed generally from north to south down Kangerlussuaq Trough. This is clearly consistent with flow from the interior of the Greenland Ice Sheet, through the deep channel of Kangerlussuaq Fjord and then across the shelf in the trough. Although ice is also likely to have been present on the shallower banks either side of Kangerlussuaq Trough, any submarine-landform evidence of this has been removed by iceberg scouring (Syvitksi et al., 2001). Indeed, the presence of landforms indicative of subglacial meltwater, and the implication that deformation till is present in the trough as acoustic facies T, both support the notion that warm ice was present and that motion was by both internal ice deformation and basal processes (e.g. Dowdeswell et al., 2004; Ó Cofaigh et al., 2005, 2007).

Some inferences about the nature of ice-sheet retreat across the shelf at the end of the LGM can also be made from the subglacial landform record in outer Kangerlussuaq Trough. There is little evidence for sedimentary depocentres, known as grounding-zone wedges, indicative of ice-sheet still-stands during retreat (e.g. Evans et al., 2005; McMullen et al., 2006; Mosola and Anderson, 2006). Neither are there the relatively small sets of sedimentary ridges that form at the retreating margin of a grounded ice sheet (e.g. Shipp et al., 2002; Dowdeswell et al., 2008c; Ottesen and Dowdeswell, 2009). This is consistent with the observation that the East Greenland shelf deepens towards the coast, and ice would therefore have been retreating into deepening water with the exception of the inner-trough shelf (Fig. 1D). Retreat into deeper waters tends to increase the rate of iceberg calving from a retreating ice sheet, with the implication that the ice in Kangerlussuaq Trough probably retreated rapidly back at least as far as the inner shelf sill, where there is seismic evidence of a moraine (Stein, 1996), and later through the deep outer fjord, during deglaciation (Dowdeswell et al., 2008c). This is supported by chronological work on cores from the trough suggesting that retreat from the outer Kangerlussuaq shelf took place from about about 17,000 yr ago, reaching the inner shelf by about 15,000 yr ago and the outer coast of Greenland by between 13,600 and 11,500 years ago (Jennings et al., 2002, 2006).

Conclusions

- Kangerlussuaq Fjord is a relatively uniform, steep-walled basin, whose floor has an almost smooth surface, broken by occasional protruding bedrock pinnacles (Fig. 2). Debris is supplied mainly from icebergs produced from the fast-flowing Kangerlussuaq Glacier. Multi-year sea ice, sikussak, traps many calved icebergs close to the glacier terminus where basal melting removes the bulk of debris-rich basal ice. Sedimentation after iceberg release from sikussak is mainly by rain-out of fine-grained englacial debris (Syvitski et al., 1996; Smith and Andrews, 2001).
- Streamlined glacial lineations and drumlins were produced at the sedimentary bed of an ice sheet that advanced into Kangerlussuaq Trough at the LGM (Figs. 3, 4). They form the upper surface of an acoustically transparent unit, with a strong basal reflector (Fig. 6B), which is probably low shear-strength till whose deformation facilitated ice motion.
- Bedrock channels and crescentic overdeepenings indicate subglacial meltwater flow on the inner shelf (Fig. 3B, C), implying the presence of warm-based ice and free water beneath this part of the LGM ice sheet which allowed motion by both internal ice deformation and basal processes.
- Cross-cutting iceberg scour marks, formed by the ploughing of grounded iceberg keels, dominate the outermost Kangerlussuaq shelf (Figs. 4, 6D), and the surrounding banks (Syvitski et al., 2001). They were probably produced not only during deglaciation, but also occasionally through the Holocene by deep-keeled icebergs calved from fast-flowing outlet glaciers further north in East Greenland (Dowdeswell et al., 1992).
- The outward-convex contours of the shelf edge and slope beyond Kangerlussuaq Trough suggest an ice-stream influenced high-latitude fan architecture (Fig. 1). Sub-bottom profiler records show a number of semi-transparent debris flows (Fig. 6E), which are a characteristic part of many ice-sheet fed trough-mouth fans (e.g. Vorren et al., 1998).
- The distribution of streamlined subglacial landforms (Fig. 5A) demonstrates that the Greenland Ice Sheet extended throughout Kangerlussuaq Fjord and reached at

least 200 km across the shelf in Kangerlussuaq Trough at the LGM. The orientation of streamlined landforms (Fig. 5A) is consistent with flow from the interior of the Greenland Ice Sheet sub-parallel to the axis of Kangerlussuaq Trough.

- There is little evidence for sedimentary depocentres (grounding-zone wedges, transverse sedimentary ridges) in Kangerlussuaq Trough, implying that ice probably retreated rapidly at least as far as the inner shelf sill, and later through the deep outer fjord, during deglaciation (Dowdeswell et al., 2008).

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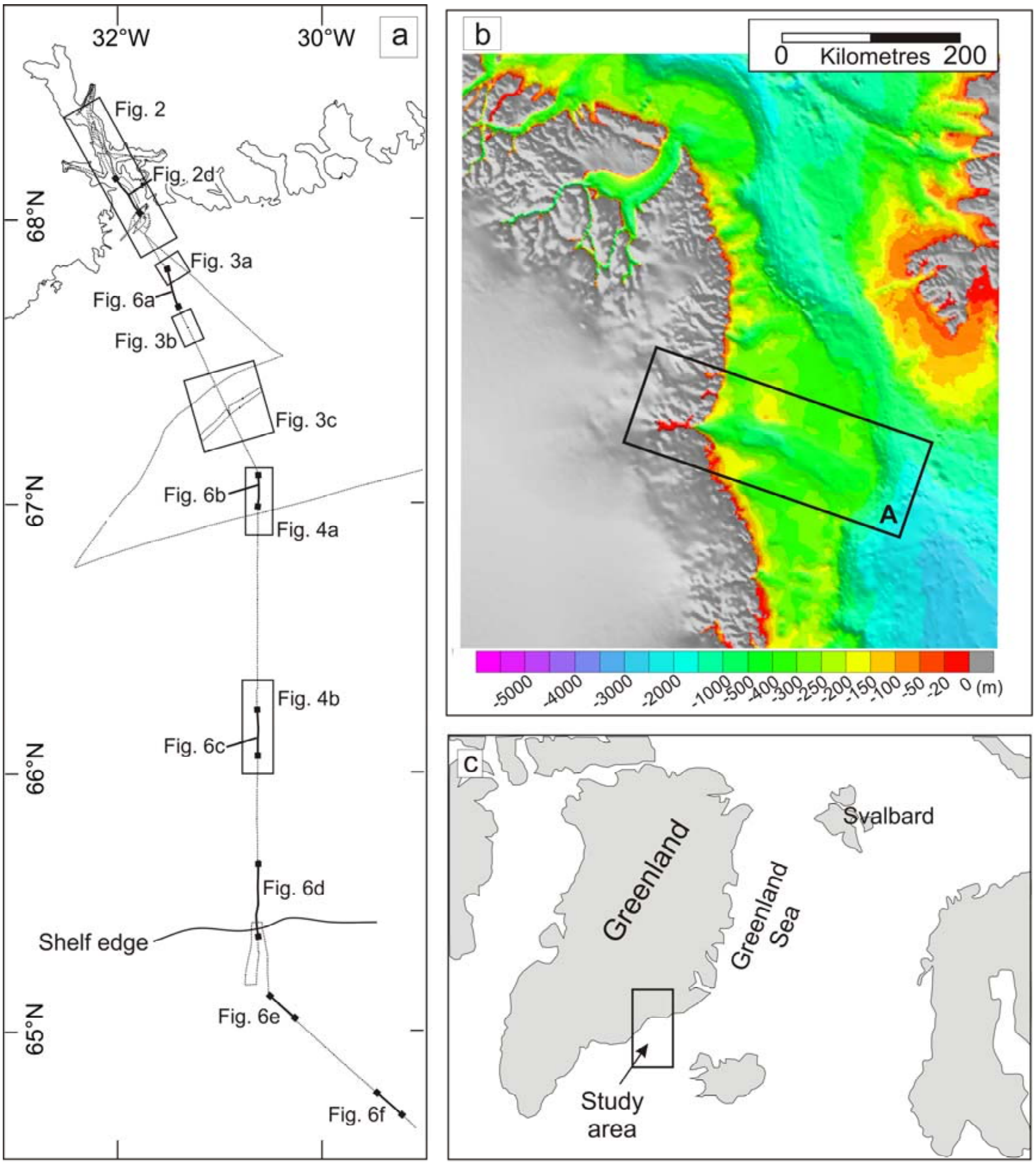

Figure 1. (A) Map of the Kangerlussuaq fjord-shelf slope system, East Greenland margin, showing track-lines of our geophysical data coverage. Subsequent swath-bathymetric images and sub-bottom profiles are located. (B) Bathymetric map of the East Greenland shelf. (C) Location of study area on Greenland.

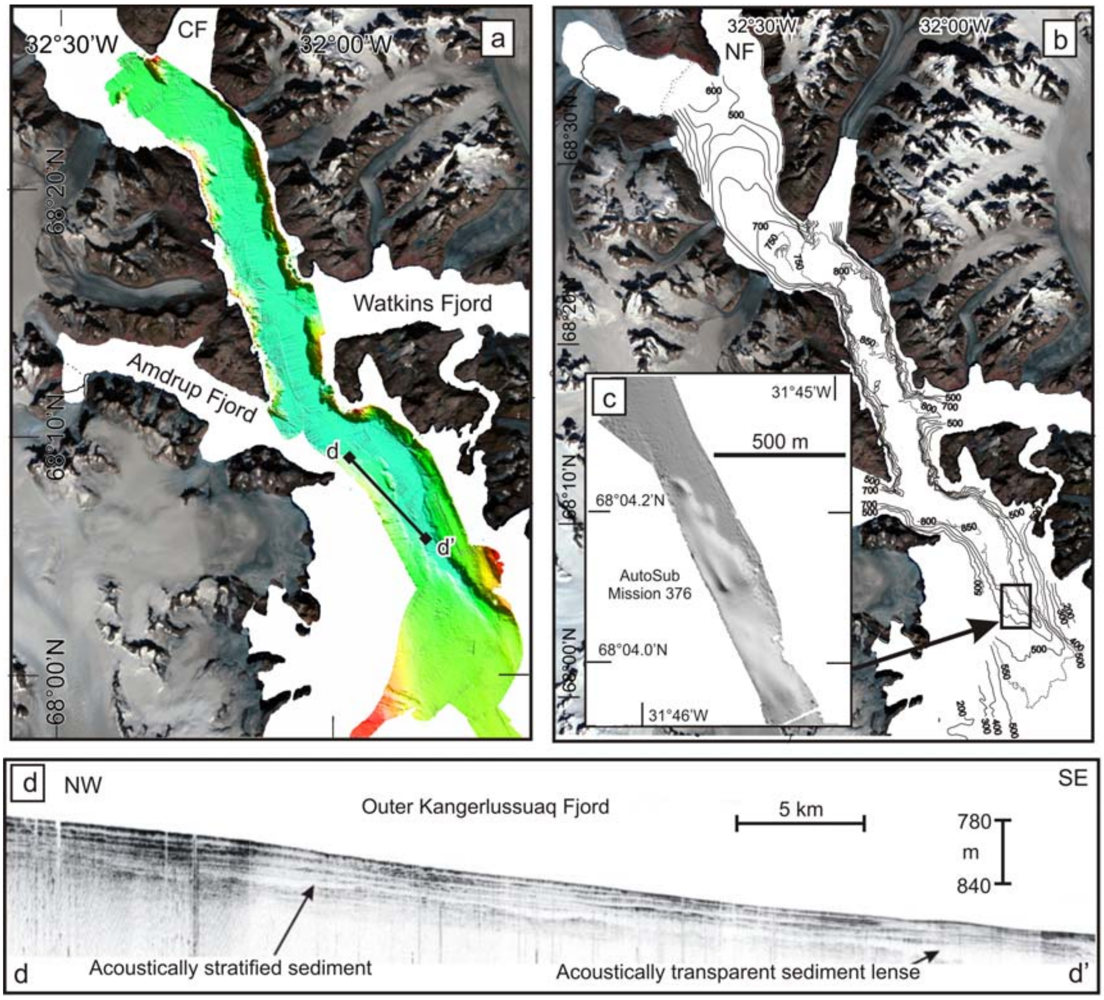

Figure 2. Swath bathymetrice imagery and TOPAS records from Kangerlussuaq Fjord. (A) Swath bathymetry from the EM-120 system on the RRS *James Clark Ross* superimposed on a Landsat satellite image of the surrounding glaciers and mountains. CF is Courtauld Fjord (B) Bathymetric contour map of Kangerlussuaq Fjord produced using data from part A and from Syvitski et al. (1996). The location of the sikusssak, or multi-year shorefast sea ice that broke up in August 2004 is to the left of the dotted line at the fjord head where bathymetric contours cease. (C) High-resolution EM-2000 data acquired from the *Autosub* autonomous underwater vehicle (located in part A). (D) TOPAS sub-bottom profile along the central axis of Kangerdlusssuaq Fjord.

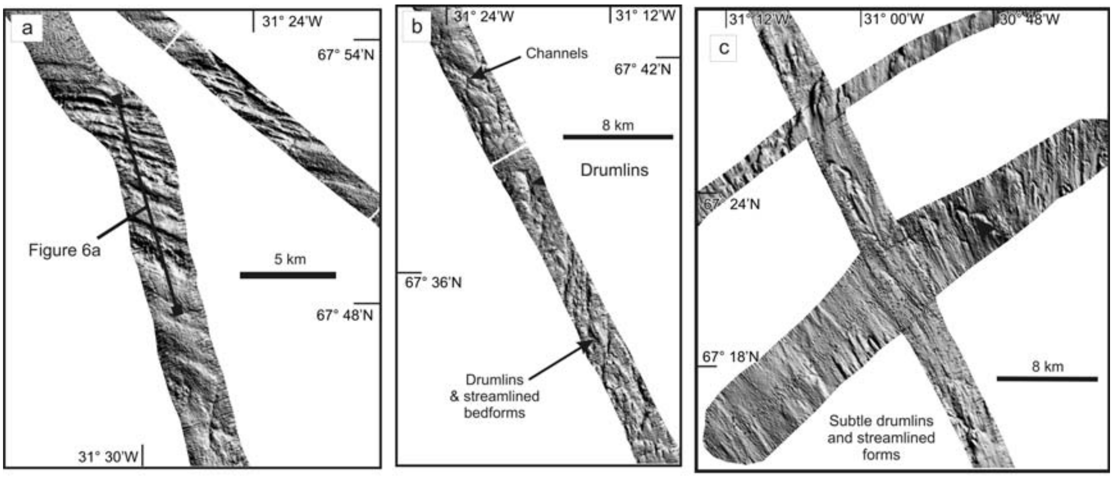

Figure 3. (A) Swath bathymetry of draped bedrock. Iceberg scours are also present at the top left of the image. (B) Swath bathymetry of channels and drumlins. (C) Swath bathymetry of drumlins, sedimentary lineations and crescentic features. The swath images are located in Figure 1A.

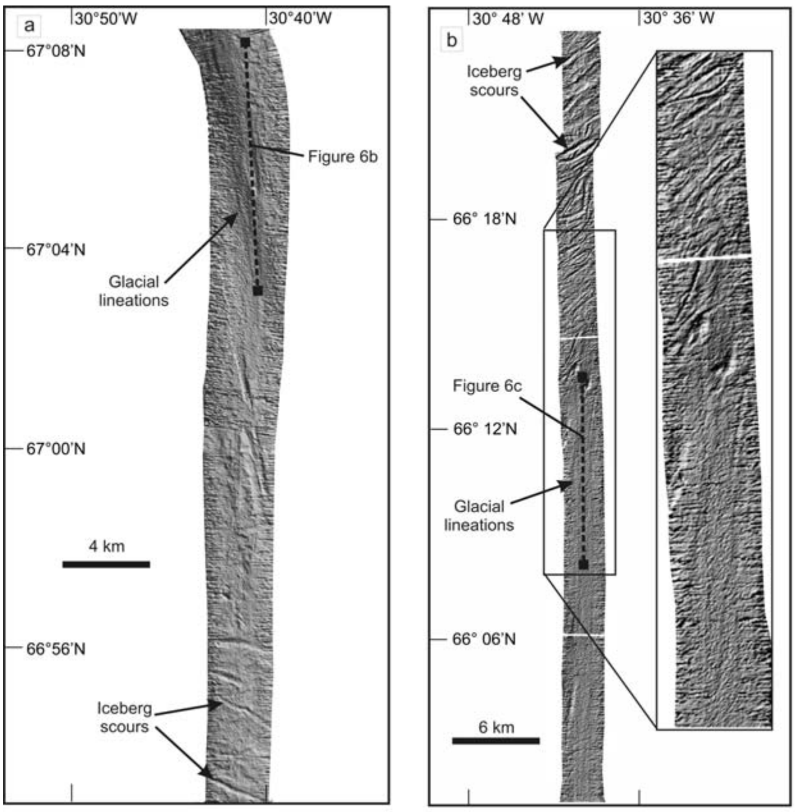

Figure 4. Swath bathymetry of two parts of the outer shelf showing subdued sedimentary lineations and occasional iceberg scours. The swath images are located in Figure 1A.

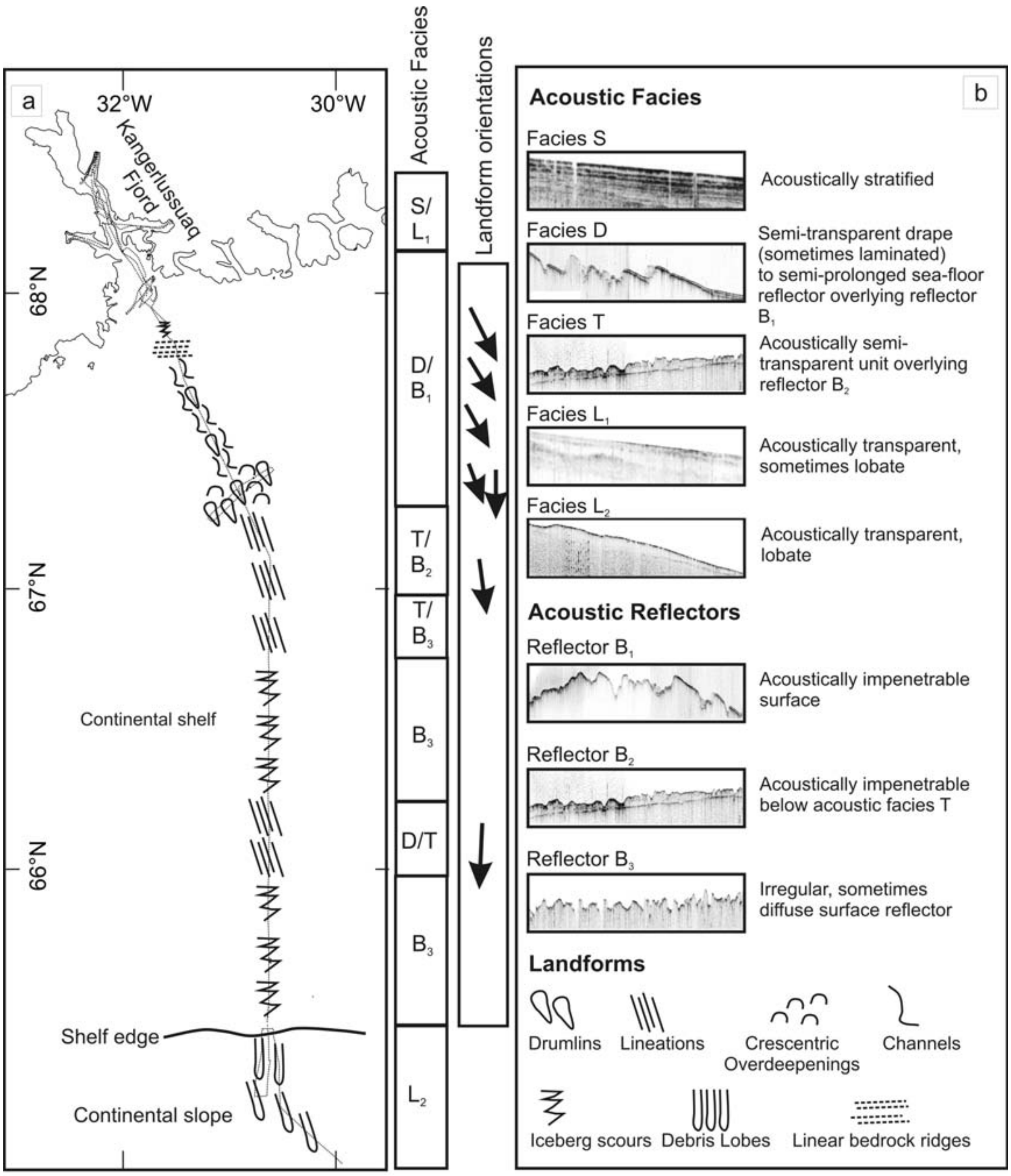

Figure 5. Character and distribution of shallow-acoustic units and submarine landforms in the Kangerlussuaq fjord-shelf-slope system. (A) Location map with the distribution of submarine landforms shown. The distribution of acoustic facies and landform orientations along the fjord-shelf-slope transect are also shown. (B) Examples, descriptions and interpretations of acoustic units and reflectors in the Kangerlussuaq system.

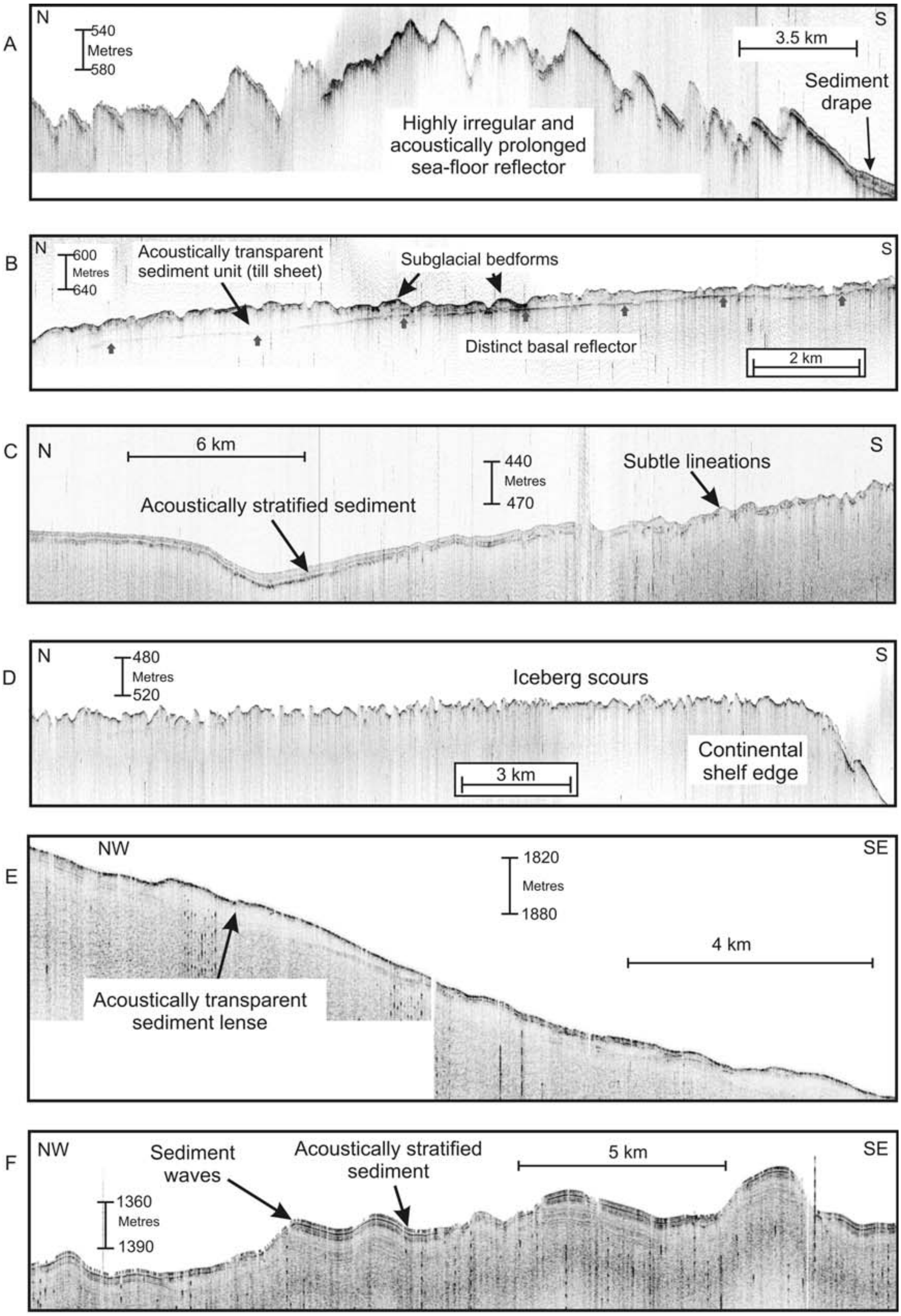

Figure 6. TOPAS sub-bottom profiler records from the Kangerlussuaq Trough and adjacent slope along a N-S transect from the fjord mouth across the shelf edge (located in Figure 1A). (A) Inner-mid shelf. (B) Mid shelf. (C) Outer shelf. (D) Shelf edge. (E) Base of the continental slope. (F) Upper slope.