Palaeo-ice streams, trough mouth fans and high-latitude continental slope sedimentation

COLM Ó COFAIGH, JUSTIN TAYLOR, JULIAN A. DOWDESWELL AND CAROL J. PUDSEY

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The classical model of trough mouth fan (TMF) formation was developed in the Polar North Atlantic to explain large submarine fans situated in front of bathymetric troughs that extend across continental shelves to the shelf break. This model emphasizes the delivery of large volumes of subglacial sediment to the termini of ice streams flowing along troughs, and subsequent re-deposition of this glacigenic sediment down the continental slope via debris-flow processes. However, there is considerable variation in terms of the morphology and large-scale sediment architecture of continental slopes in front of palaeo-ice streams. This variability reflects differences in slope gradient, the relative contributions of meltwater sedimentation compared with debris-flow deposition, and sediment supply/geology of the adjacent continental shelf. TMF development is favoured under conditions of a low (<1°) slope gradient; a passive-margin tectonic setting; abundant, readily erodible sediments on the continental shelf – and thus associated high rates of sediment delivery to the shelf edge; and a wide continental shelf. The absence of large sediment fans on continental slopes in front of cross-shelf troughs should not, however, be taken to indicate the former absence of palaeo-ice streams in the geological record.

Colm Ó Cofaigh (e-mail: co232@cam.ac.uk), Scott Polar Research Institute and Department of Geography, University of Cambridge, Cambridge CB2 1ER, UK; Justin Taylor, Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales. Aberystwyth, SY23 3DB, UK. (current address: Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK); Julian A. Dowdeswell, Scott Polar Research Institute and Department of Geography, University of Cambridge, Cambridge CB2 1ER, UK; Carol J. Pudsey, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK; *received 25th February 2002, accepted 25th September 2002.*

Ice streams are critical to the stability and dynamics of contemporary ice sheets, and palaeo-ice streams played a similar key role in the dynamics and evolution of Quaternary ice masses (e.g. Denton & Hughes 1981; Marshall *et al.* 1996; Dowdeswell & Siegert 1999; Payne & Baldwin 1999). Identification of palaeo-ice streams is therefore important and recent research, most notably that by Stokes & Clark (1999, 2001) has tried to develop criteria by which the former presence of fast-flowing ice masses may be recognized in the geological record. In many locations, Quaternary ice sheets and their associated ice streams expanded across continental shelves to the shelf break, delivering large quantities of icebergs and ice-rafted debris (IRD) into the marine environment. A record of these ice streams is frequently preserved on the continental shelf in the form of wide bathymetric troughs containing streamlined subglacial bedforms (e.g. Shipp *et al.* 1999; Canals *et al.* 2000; Ó Cofaigh *et al.* 2002; Ottesen *et al.* in press), and also, in some more ice-distal locations, by IRD layers in deep-marine sediments that can be petrographically 'fingerprinted' to specific ice streams (e.g. Scourse *et al.* 2000).

Where ice streams overlie deformable sediment and extend to the shelf break via cross-shelf bathymetric troughs, large volumes of subglacial sediment are advected to the upper continental slope (Alley *et al.* 1989). This material is subject to remobilization down the continental slope by mass-flow processes, commonly debris flow, resulting in the development of fan-shaped, diamict-dominated, sediment accumulations at the trough mouth – 'trough mouth fans' (TMFs) (e.g. Vorren *et al.* 1988, 1989; Kuvaas & Kristoffersen 1991; Aksu & Hiscott 1992; Stoker 1995). TMFs are thus potentially useful indicators of former ice streams (Dowdeswell *et al.* 1996; Vorren & Laberg 1997; Dowdeswell & Siegert 1999).

However, several key questions remain concerning the nature of continental slope sedimentation at ice-stream termini: (1) How variable is the relationship between ice streams and continental slope sedimentation; that is, do ice streams terminating at the shelf break consistently form TMFs or are other styles of large-scale sediment architecture present? (2) What are the physical controls on the sedimentary architecture of continental slopes at ice-stream termini? (3) How much variability is there with respect to the sedimentary processes and resulting deposits in TMFs; i.e. do glacigenic debris flows dominate? The aim of this article is to address these questions, drawing on examples from both the northern (Laurentide, Greenland and Fennoscandinavian ice sheets) and southern (Antarctic Ice Sheet) hemispheres. Before discussion of these specific examples, however, the classical TMF model is outlined.

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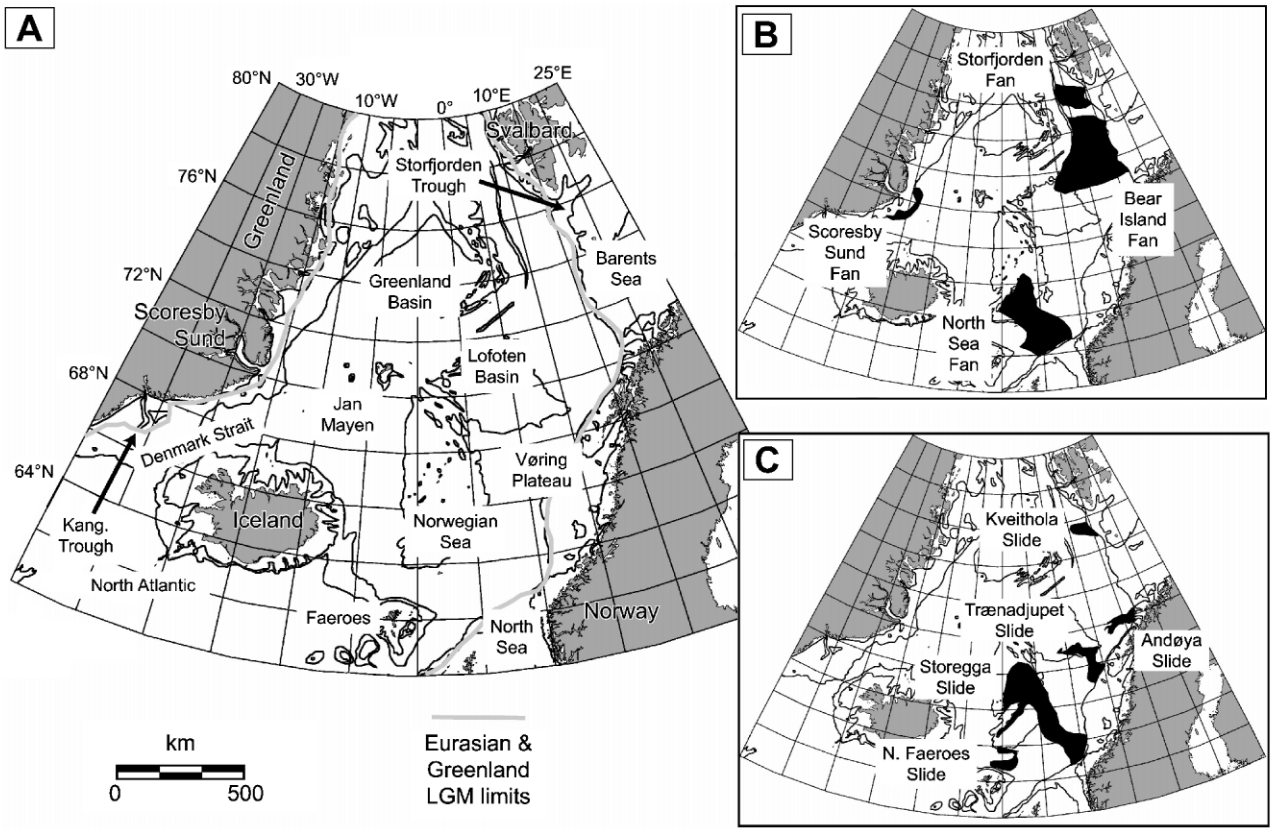


Fig. 1. A. Location map of the Polar North Atlantic with the 500 m and 3000 m bathymetric contours shown. B. Major trough mouth fans (shaded black). C. Major sediment slides (shaded black).

Continental slope sedimentation at ice-stream termini

Polar North Atlantic trough mouth fans

The classical model of continental slope sedimentation at an ice-stream terminus is based on work from the TMFs of the Polar North Atlantic. A series of major prograded submarine sediment fans is located at the mouths of cross-shelf troughs around the eastern and, more rarely, western margins of the Polar North Atlantic. These fans record the episodic delivery of poorly sorted sediment to the upper continental slope during glacial maxima when ice streams reached the shelf edge (Dowdeswell *et al.* 1996, in press; Vorren & Laberg 1997; Vorren *et al.* 1989, 1998) (Fig. 1). The largest of the Polar North Atlantic TMFs is the Bear Island Fan, with an area of approximately 125 000 km^2. Fans are also present on the Svalbard, Barents Sea and Norwegian margins (Vorren *et al.* 1998); Storfjorden Fan (35 000 km^2), Bellsund Fan (6000 km^2), Isfjorden Fan (3700 km^2), Kongsfjorden Fan (2700 km^2), as well as the much larger North Sea Fan (108 000 km^2). On the East Greenland margin, the Scoresby Sund Fan is about 10 000 km^2 in area (Dowdeswell *et al.* 1997; Taylor 1999).

According to the model of TMF formation from the Polar North Atlantic, the main process responsible for fan progradation is debris-flow deposition resulting in a fan architecture dominated by stacked debris flows. In seismic lines over several fans, a number of acoustic packages are identified, each made up of groups of seismically transparent or opaque wedges separated by thinner, often acoustically stratified, units (e.g. Vorren *et al.* 1989; Laberg & Vorren 1995; King *et al.* 1996). Each seismically transparent or opaque acoustic unit is interpreted to represent debris flows from a single glacial-interglacial, or stadial-interstadial, cycle. The debris flows are assumed to be derived from the intermittent failure of relatively clay-rich, glacier-derived diamictic sediments, deposited relatively rapidly on the upper slope at the edge of major cross-shelf troughs during full-glacial conditions when the ice-stream terminus was at the shelf break (e.g. Laberg & Vorren 1995, 2000; Dowdeswell *et al.* 1996; Elverhøi *et al.* in press).

Three examples of TMFs from the Polar North Atlantic – the Bear Island TMF, North Sea TMF and

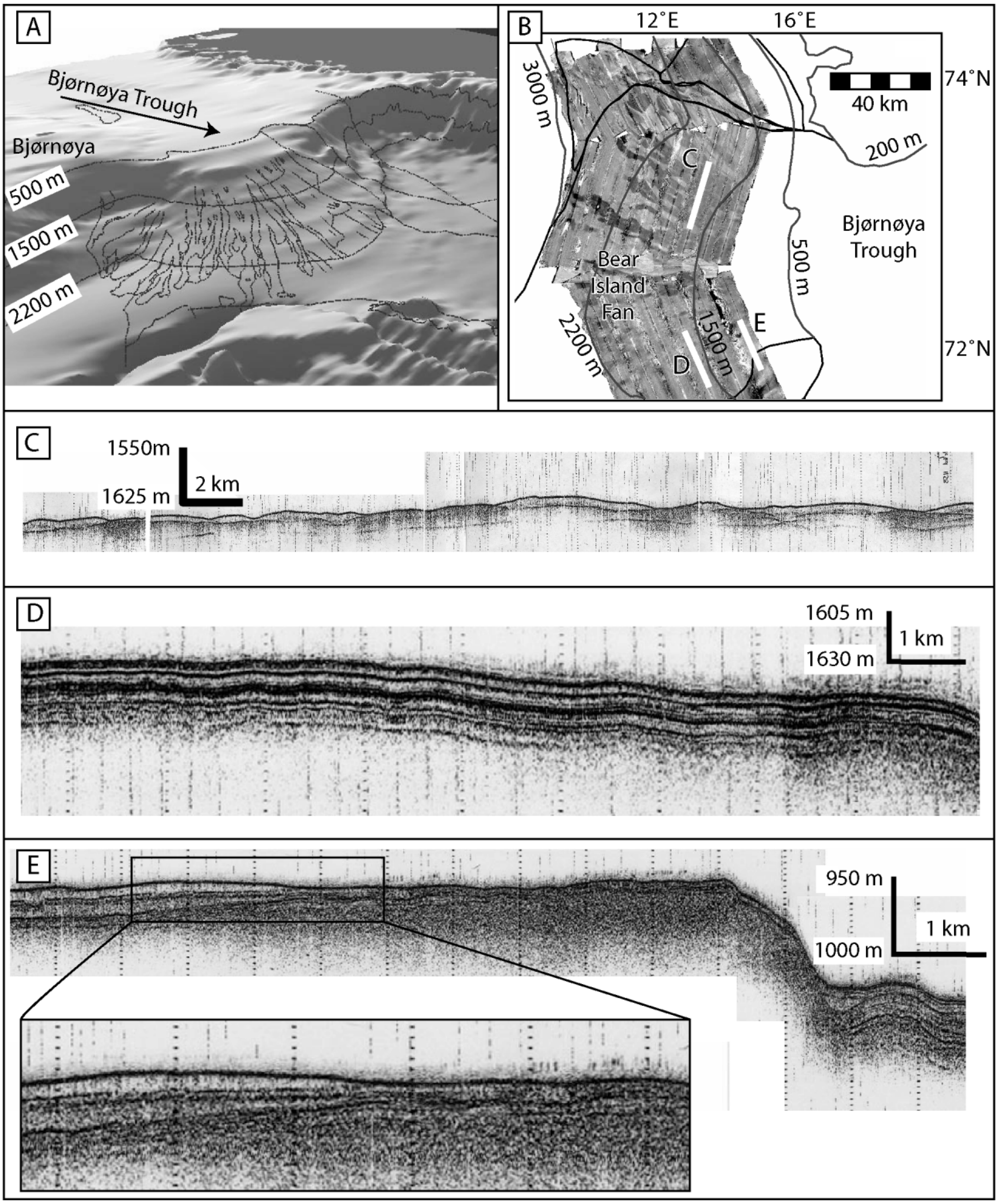


Fig. 2. A. Relationship between fan morphology and debris-flow location on the Bear Island Fan. B. GLORIA 6.5 kHz sidescan sonar image of debris-flow lobes on the Bear Island Fan. Lower backscatter is shown as darker tones. C. 3.5 kHz sub-bottom profile across debris flows on the Bear Island Fan showing the stacked nature of the flows and their convex upper surface. D. Acoustically stratified sediments from outside the area most recently affected by glacigenic debris flow activity, southern Bear Island Fan. E. The acoustic stratification can be traced laterally into the debris flow area.

Scoresby Sund TMF – are now used to illustrate the similarities and variation in morphology and sedimentary architecture between TMFs across the region.

Bear Island TMF. – The Bear Island TMF is situated in front of the Bear Island Trough in the Barents Sea (Figs 1, 2A). At its mouth, this cross-shelf trough is about 150 km wide and 500 m deep, and it served as a major drainage pathway for the Barents Sea Ice Sheet. Three-dimensional seismic data from the trough reveal several generations of subglacial streamlined bedforms on buried palaeo-surfaces (Rafaelsen *et al.* in press), recording flow of a grounded ice sheet to the shelf edge, probably as a fast-flowing ice stream (Dowdeswell *et al.* 1996; Vorren & Laberg 1997). The most recently active (late Quaternary) part of the Bear Island TMF covers an area of 125 000 km^2, with a width of about 350 km, a run-out distance of 490 km, and upper, middle and lower slope gradients of 0.8°, 0.5° and 0.2°, respectively (Taylor *et al.* in press). The fan extends from the continental shelf edge (water depth ~500 m) to over 3000 m water depth in the Lofoten Basin (Figs 1A, B, 2A). On the northern part of the fan, GLORIA long-range, sidescan sonar data reveal a series of low-backscatter, debris-flow lobes that radiate out from the top of the fan and frequently extend downslope to near its base (Fig. 2B). 3.5 kHz sub-bottom profiler records from these debris flows show that they have a stacked, lenticular geometry in cross-section (Fig. 2C). Individual lobes range from 30 to 200 km in length, 2 to 10 km in width, 10 to 50 m in thickness and have mean volumes of about 10 to 20 km^3 (Dowdeswell *et al.* 1996; Taylor *et al.* in press). Cores from these debris flows recovered massive, poorly sorted, matrix-supported diamict (Laberg & Vorren 1995, 2000a; Ó Cofaigh *et al.* in press). Based on extrapolation of the individual debris-flow lobes back to the continental shelf edge, the likely source for the flows is a relatively confined area of the Bear Island Trough, about 100 km wide.

The most recent debris flow activity appears to be confined to the northern and central parts of the Bear Island TMF. In contrast, the southern part of the fan (south of approximately 72°N) is devoid of debris flows in the uppermost part of its acoustic stratigraphy. 3.5 kHz records from this region of the fan show laterally continuous, acoustically stratified sediments at least 20 m thick (Figs. 2D, E) (Taylor *et al.* in press). Such laterally continuous acoustic stratification implies a relatively low energy depositional environment during the most recent late Quaternary period of fan development. This interpretation is supported by core sedimentology which, in conjunction with the acoustic data, indicates that the predominant depositional processes delivering sediment to this region of the fan during the late Quaternary were suspension settling from turbid meltwater plumes and contour-current activity (Taylor *et al.* in press). Buried debris-flow lenses are visible on the 3.5 kHz profiles beneath the stratified sediments, however, and indicate debris-flow delivery to this region of the Bear Island Fan in the past.

North Sea TMF. – The North Sea TMF is located in front of the Norwegian Channel and extends outwards into the Norwegian Sea (Fig. 1A, B). A variety of marine geophysical and geological data indicates that the Norwegian Channel supported a fast-flowing ice stream during the Late Weichselian (Sejrup *et al.* 2000). The fan covers an area of about 108 000 km^2, is 250 km wide and 490 km in length. The upper, middle and lower fan sections have gradients of 0.6°, 0.3° and 0.2°, respectively. Debris-flows are visible on GLORIA sidescan sonar records as elongate, high backscatter lobes (Fig. 3A). The fan stratigraphy indicates two major depositional modes (King *et al.* 1996). The earlier mode, represented by the deepest package of sediments, is the result of hemipelagic sedimentation combined with sediment failure and sliding (Faleide *et al.* 1996; King *et al.* 1996). By contrast, the upper part of the fan is made up of one or several thick ($\geq$100 m) aprons comprising stacked lensoid and/or lobate features which range from 15 to 60 m in thickness and 2 to 40 km in width (King *et al.* 1996). These are interpreted as the product of glacigenic debris flows deposited when fast-flowing ice extended to the continental shelf edge (King *et al.* 1998). Debris flows are separated by thick, generally acoustically homogeneous seismic packages that represent hemipelagic sedimentation.

Scoresby Sund TMF. – The Scoresby Sund TMF is situated on the East Greenland continental margin, offshore of the mouth of the Scoresby Sund fjord system, where its presence is indicated by the crescentic shape of the shelf break (Fig. 1). Based on analyses of GLORIA and 3.5 kHz sub-bottom profiler records, the fan is composed of several acoustic facies (Dowdeswell *et al.* 1997) (Fig. 4). Facies 1 consists of a series of acoustically transparent features which are elongate downslope, have a lenticular geometry (1–2 km wide) in cross-section, are about 5–15 m thick and have an irregular upper surface (Fig. 4A, B). This facies accounts for the majority of the most recent sediment delivery to the upper fan. In cores, this facies comprises a dark grey, massive, matrix-supported diamict, which is unsorted and contains frequent clasts up to pebble size in a sandy mud matrix (Ó Cofaigh in press). Occasional broken and whole marine shells are present. Contacts with bounding facies appear to be abrupt but non-erosive. Based on these acoustic and sedimentological characteristics, these sediments are interpreted as glacigenic debris flows, deposited when the ice sheet was positioned at, or close to, the shelf break (Dowdeswell *et al.* 1997). On the northern part of the Scoresby Sund TMF, an acoustically stratified facies overlies facies 1 (Fig. 4C). This area of the fan is less active and the most recent delivery of sediment has been

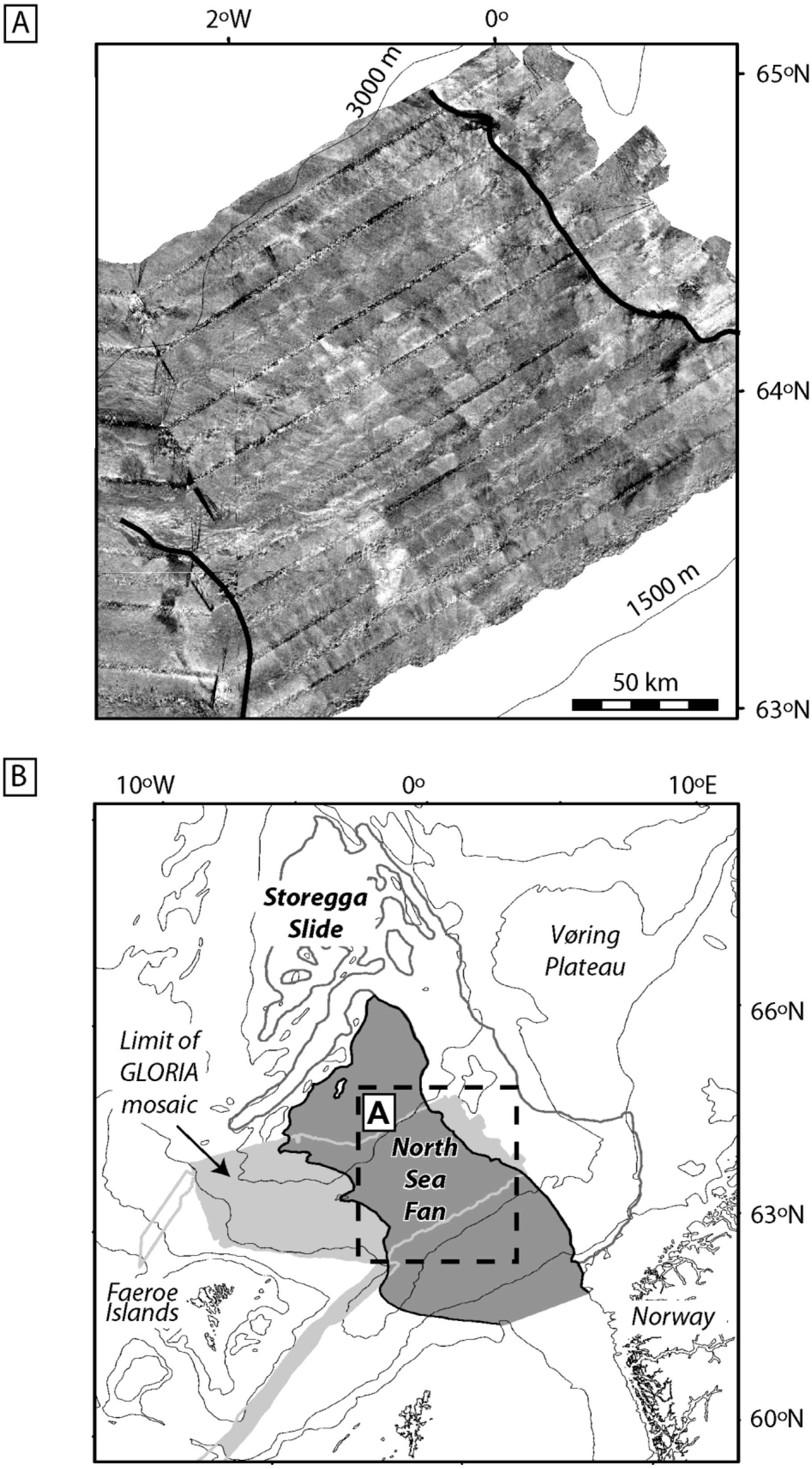


Fig. 3. North Sea Fan. A. GLORIA 6.5 kHz sidescan sonar image mosaic of the North Sea Fan (thick lines indicate fan margins). Note the elongate-downslope debris flows. High backscatter is shown as lighter tones. B. Location and extent of the North Sea Fan.

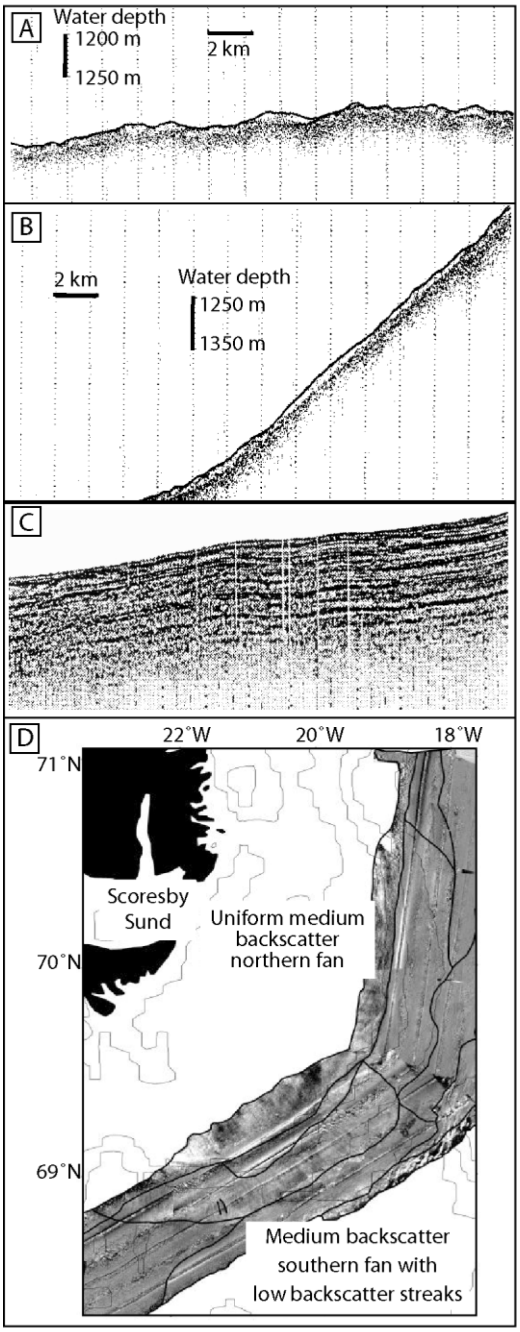


Fig. 4. Geophysical characteristics of the Scoresby Sund Fan, East Greenland continental margin. A, B. 3.5 kHz profiles of strike (A) and dip (B) lines from the southern part of the Scoresby Sund Fan illustrating the acoustic character of debris flow deposits (Facies 1) (modified from Dowdeswell *et al.* 1997). Note the hummocky surface relief of the acoustically transparent debris flow lenses in the strike section, and the elongate, lenticular nature of the debris flows in the dip section. C. 3.5 kHz record from the northern (inactive) part of the Scoresby Sund fan showing a sequence of acoustically stratified sediments (Facies 2) interpreted to record deposition by hemipelagic and turbidity current processes. D. GLORIA 6.5 kHz sidescan sonar mosaic of the Scoresby Sund Fan.

by iceberg-rafting and hemipelagic sedimentation, forming a drape over the older debris flows.

The Scoresby Sund Fan is similar to the Storfjorden Fan (Fig. 1B), which is also relatively steep (about 1.8°) and is composed of smaller-scale debris flows (5 km in width and up to 15 m thick (Laberg & Vorren 1996). However, it shows marked differences in both its morphology and sedimentation pattern from the North Sea and Bear Island TMFs (Dowdeswell *et al.* 1997). It is steeper than these two larger fans, having gradients of about 2°–4°, and the scale of the debris flows imaged on the Scoresby Sund Fan is smaller than those observed on its larger counterparts (see above). Also missing on geophysical records from the Scoresby Sund Fan are large-scale sediment slides, in contrast to the Bear Island Fan.

Antarctic trough mouth fans

While much of the Antarctic continental margin is underlain by glacially prograded sequences (Cooper *et al.* 1991), few of the areas which have been surveyed in detail have classic TMFs in the sense defined by work in the Polar North Atlantic. The geologic setting is broadly similar; passive, rifted margins with moderate to gentle slopes surround the continent except for the NW side of the Ross embayment at 160–170°E, which is a strike-slip margin, and the west coast of the Antarctic Peninsula at 55°–100°W (Fig. 5). The Antarctic Peninsula had a complex subduction history through the Mesozoic and Cenozoic (McCarron & Larter 1998) and has retained a steep continental slope (>10° in the northern part; Rebesco *et al.* 1998). There are also similarities in the glaciological setting of Antarctic depocentres. The location of present-day ice streams is known from satellite imagery (Bamber *et al.* 2000) (Fig. 5), and a number of them are thought to have also been palaeo-ice streams at the LGM. Several ice streams are associated with major troughs on the continental shelf, which are commonly floored by subglacial bedforms (e.g. Wellner *et al.* 2001). In particular, TMFs have been suggested to be present in the southern Weddell Sea (Crary TMF) and Prydz Bay.

Weddell Sea. – In the southern Weddell Sea, the 100–150 km wide Crary Trough extends from beneath the Filchner Ice Shelf (where it attains >1400 m water depth at 80°S; Vaughan *et al.* 1995) to the continental shelf edge at 30°W, where the sill depth is 630 m (Kuvaas & Kristoffersen 1991). The trough has been interpreted to be the result of glacial erosion (Haugland *et al.* 1985). The Ronne and Filchner ice shelves cover a large sedimentary basin between the Antarctic Peninsula and the East Antarctic craton, and the continental shelf extends more than 400 km north of the ice front. The Filchner Ice Shelf is a zone of convergence of several modern ice streams (Bamber *et al.* 2000) (Fig. 5).

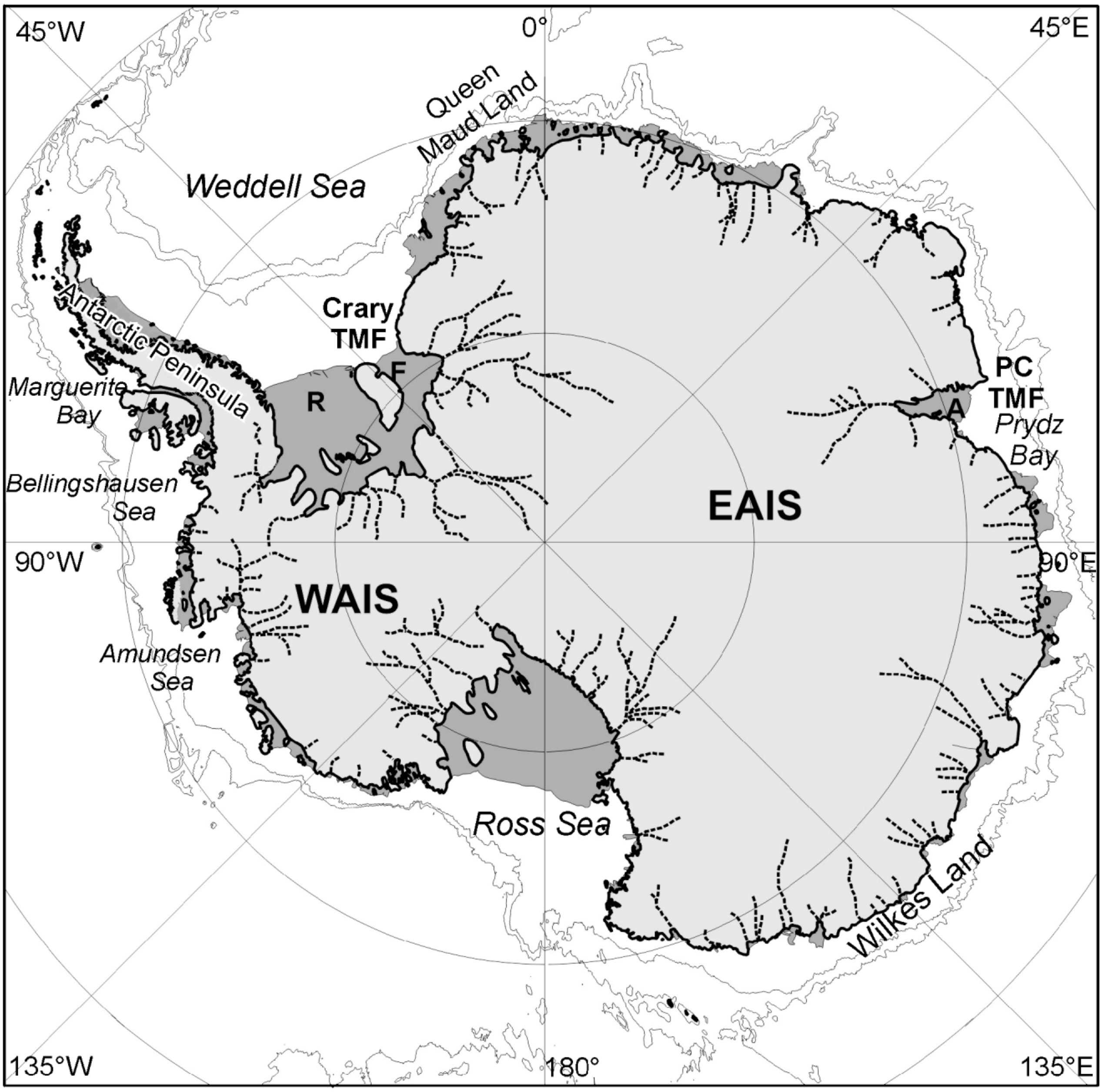


Fig. 5. Location map of Antarctica showing the locations of fast-flowing ice streams (dashed black lines) that drain the ice sheet (modified from Bamber *et al.* 2000). The positions of the 1000 m and 3000 m contours are from Smith & Sandwell (1997). A = Amery Ice Shelf, F = Filchner Ice Shelf, R = Ronne Ice Shelf, PC TMF = Prydz Channel Trough-mouth fan.

The Crary TMF is the upper (slope) part of the Crary fan–Weddell fan system, the largest high-latitude deep-sea fan in the world (De Batist *et al.* 1997). It comprises a thick, prograding slope wedge (slope angle 1°) including several large-scale lenticular seismic units. Such seismic units deeper in the fan are thought to represent migrating channel and overbank facies with extensive mass wasting. Post-early Pliocene deposition is suggested to be through glacially derived sediment remobilized from the shelf break (Kuvaas & Kristoffersen 1991). Melles & Kuhn (1993) mapped an area at least 170 km wide of 'wedging sub-bottom reflectors', i.e. lenses of acoustically transparent sediment interpreted as slumps or debris flows, in water depths of 1500–3500 m. They also drew attention to erosion and westward transport of fine sediment by ice shelf water.

Prydz Bay. – The Amery Ice Shelf–Lambert Glacier glacial system is the largest in East Antarctica, and drains about 16% of the East Antarctic Ice Sheet (some

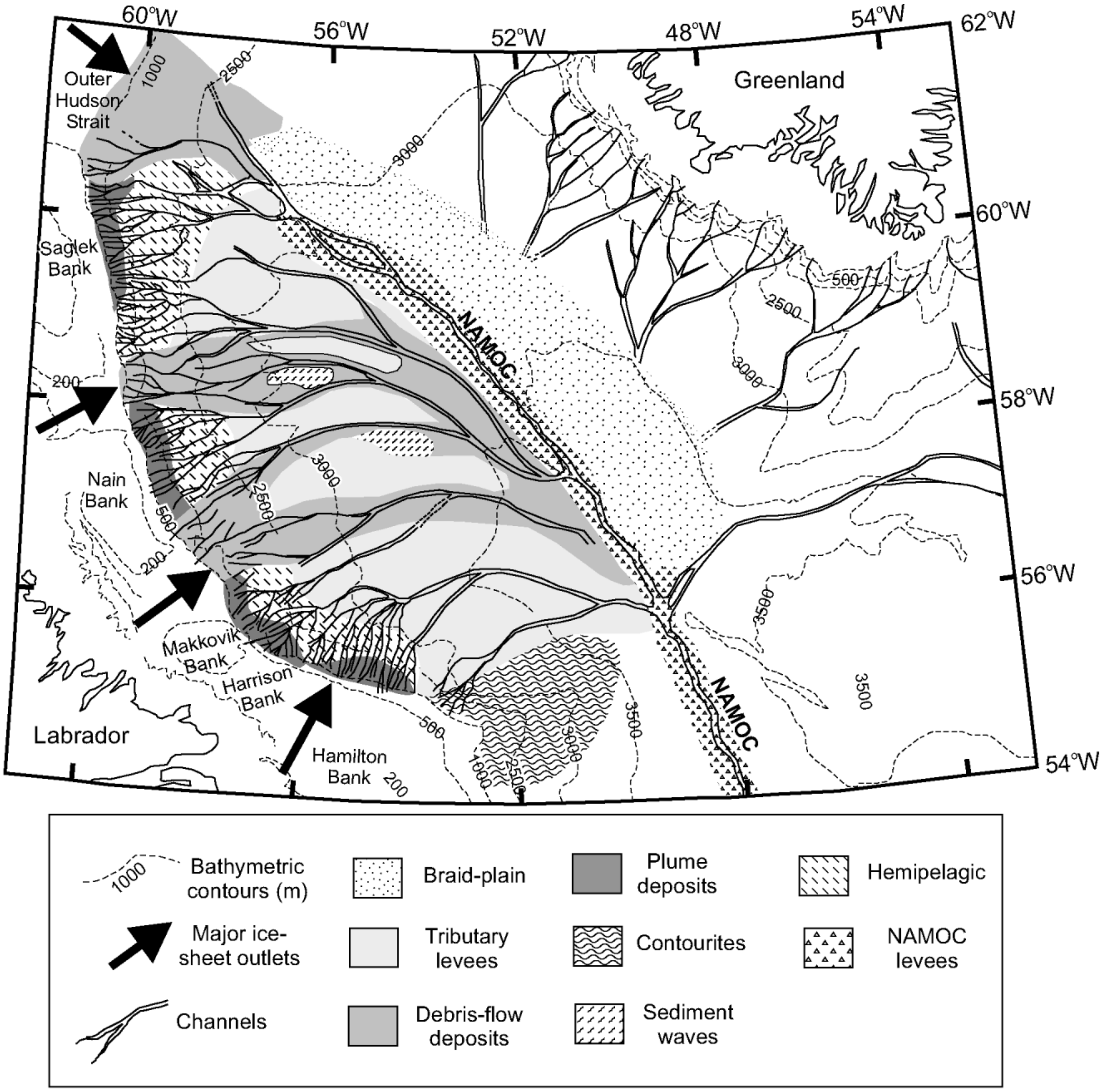


Fig. 6. Map of the Labrador Sea showing the upslope branching pattern of tributary channels on the slope and distribution of major sediment facies (redrawn from Hesse *et al.* 1997b). The inferred positions of major ice-sheet outlets (ice streams) along the Canadian margin are arrowed. 'NAMOC' = North Atlantic Mid-Ocean Channel.

11% of all Antarctic outflow). The Lambert Graben and Prydz Bay basin contains several kilometres of pre-Cenozoic non-marine sedimentary rocks as well as three sequences of Cenozoic diamictites (Hambrey *et al.* 1991). The Prydz Channel TMF on the slope offshore of Prydz Bay (Fig. 5) is 150 km wide and extends over 90 km out from the margin to a water depth of 2700 m. Construction of the fan started in the late Miocene or Pliocene (Shipboard Scientific Party 2001). Seismic reflectors in the Prydz Channel fan show a strongly sigmoidal large-scale geometry and long semi-continuous reflectors defining acoustically transparent packages at the smaller scale, consistent with the geometries seen in northern hemisphere TMFs built primarily of glacigenic debris flows (Vorren & Laberg 1997; O'Brien *et al.* 2001). The fan has gentle surface slopes and minimal signs of slumping (O'Brien & Harris 1996).

Both in eastern Prydz Channel and in the Lambert Deep farther west, megascale flutes and lineations on sidescan records are interpreted as subglacial bedforms moulded in till (O'Brien *et al.* 1999). The flutes terminate near the crests of grounding zone wedges on the mid-shelf, suggesting that the Lambert Glacier may not have advanced to the shelf edge during every Quaternary glacial episode. When ice did reach the shelf edge, however, glacial debris was deposited as debris flows, turbidites and meltwater plume deposits on the fan. Seismic data (Kuvaas & Leitchenkov 1992; O'Brien & Harris 1996) show little evidence of large-scale sediment gravity flows, and 3.5 kHz profiles show only small-scale slump-scars near the shelf edge. ODP Site 1167 recovered debris flows and interbedded hemipelagic muds (Shipboard Scientific Party 2001). Some of the fine sediment transported to the shelf edge by glacier ice bypasses the slope and is swept into large bodies of hemipelagic sediments and turbidites on the continental rise off Prydz Bay. Kuvaas & Leitchenkov (1992) identified the influence of both turbidity currents and west-flowing bottom currents in these accumulations.

Elsewhere around Antarctica, the Wilkes Land margin (130–145°E) (Fig. 5) has submarine canyons on the slope and a series of submarine fans on the continental rise (Escutia *et al.* 2000). Compared with most river-sourced fans, steeper middle and lower fan gradients and larger and deeper fan channels are attributed to a glacial rather than fluvial source, but the fans are dominated by turbidites rather than debris flows. The Queen Maud Land margin (12–18°W) (Fig. 5) is typical of much of the East Antarctic margin in not containing significant TMF depocentres. Kristoffersen *et al.* (2000) suggest this results from the small ice streams and outlet glaciers of the East Antarctic Ice Sheet taking different courses across the continental shelf during successive glaciations; the timing of shelf progradation can be different in different areas. In the Amundsen and Bellingshausen seas (85–110°W) (Fig. 5) shelf bathymetry is almost unknown, but the continental slope is gentler than the northern part of the Antarctic Peninsula. Nitsche *et al.* (2000) found evidence for slumps and debris flows on the slope and widespread mounds, channels and sediment wave fields on the continental rise.

Variations from the 'classic' trough mouth fan/ice stream model

Labrador slope, Canada. – The Hudson Strait drainage basin was the largest drainage basin of the Laurentide Ice Sheet (1–2 $\times$ 10^6 km^2) and fed the Hudson Strait ice stream during the Quaternary. This ice stream was the principal source of the ice-rafted Heinrich layers in the North Atlantic (Bond *et al.* 1992; Andrews & Tedesco 1992; Dowdeswell *et al.* 1995; Andrews 1998). Ice streams also occupied deep transverse troughs on the Labrador Sea continental shelf south of Hudson Strait (Hesse *et al.* 1997a, 1999).

The upper continental slope directly offshore from the mouth of Hudson Strait (Fig. 6) is a relatively low-gradient area of the Labrador Slope and is dominated by debris-flow deposits and turbidites, indicating sediment progradation of the margin. Canyons do occur in this region of the slope, although they are generally shallow (<150 m deep) and have broad floors that are flanked either by steep ridges or by broad levees that are in turn gullied (Hesse *et al.* 1999). The levees or ridges consist of large pockets of weakly stratified to acoustically transparent sediment with occasional distinct reflectors. This relatively smooth and prograded area of the slope is succeeded immediately to the south by a 200-km-long region consisting of deeply incised, narrow canyons between 200 and 500 m in depth (Fig. 6). Topographic relief in this area of the slope decreases progressively southwards. The canyons range from those which are V-shaped and lack sediment to broad, flat-bottomed canyons that are sediment filled. Inter-canyon ridges are steep and sub-bottom reflectors within the ridges generally conform to the external ridge morphology.

This pattern of alternating high to moderate- and low-relief sectors is repeated southwards along the Labrador margin and reflects differences in the processes by which sediment was transferred through outlets of the Laurentide Ice Sheet and down the continental slope (Hesse *et al.* 1999). Low relief sectors are dominated by debris flow and turbidity current sedimentation, and are located in front of ice-sheet outlets on the slope (Fig. 6). Deposition is predominantly by downslope resedimentation of glacigenic debris from the upper continental slope. By contrast, high- to moderate-relief sectors showing a dendritic pattern of upslope canyon branching are the result of suspension sedimentation from turbid meltwater plumes and occur predominantly south of the major ice-sheet outlets along the margin. The distribution of meltwater deposits reflects the influence of the southward-flowing Labrador Current, which entrained meltwater plumes exiting from the glacier front and transported them southwards along the margin. The high-relief topography results from headward canyon erosion by mass-wasting processes of an originally smooth mud surface during both glacial and interglacial periods.

Thus, deposition in front of these ice streams was by a combination of mass-flow and suspension settling from turbid meltwater plumes, resulting in alternating areas of high- to moderate-relief and low-relief topography. The topographic variation reflects contrasts in the processes by which sediment was delivered to, and reworked on, the upper continental slope during glacial maxima.

Trænadjupet, Norwegian Continental Shelf. – On the continental shelf off central Norway, swath-bathymetric

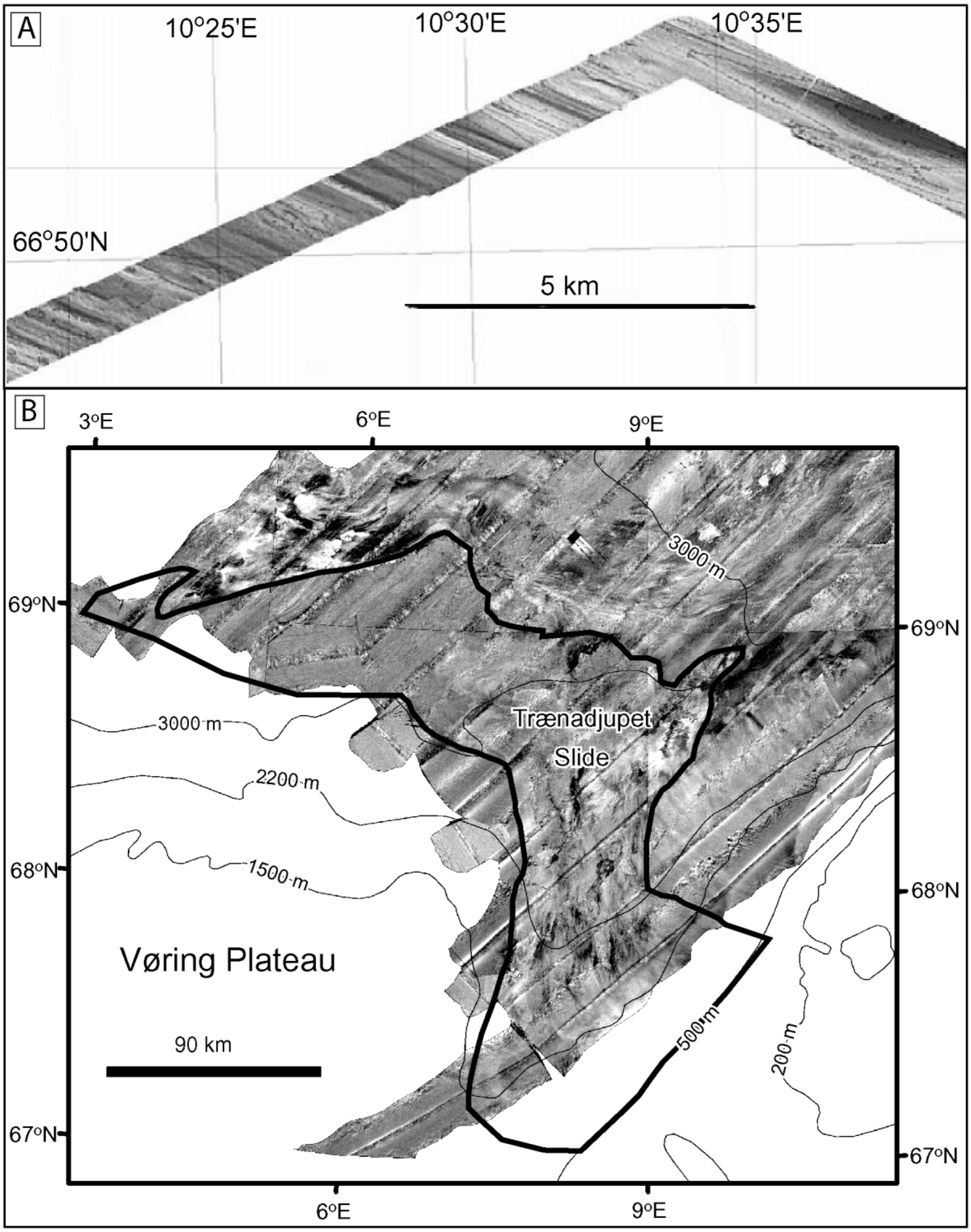


Fig. 7. A. Streamlined subglacial bedforms, Trænadjupet, mid-Norwegian continental shelf. The bedforms occur on the floor of a cross-shelf trough that extends to the shelf break at about 500 m water depth, where the large-scale sediment failure, the Trænadjupet Slide starts (Fig. 7B). B. GLORIA 6.5 kHz sidescan sonar mosaic of the Trænadjupet Slide (outlined in black). Lower backscatter is shown as darker tones.

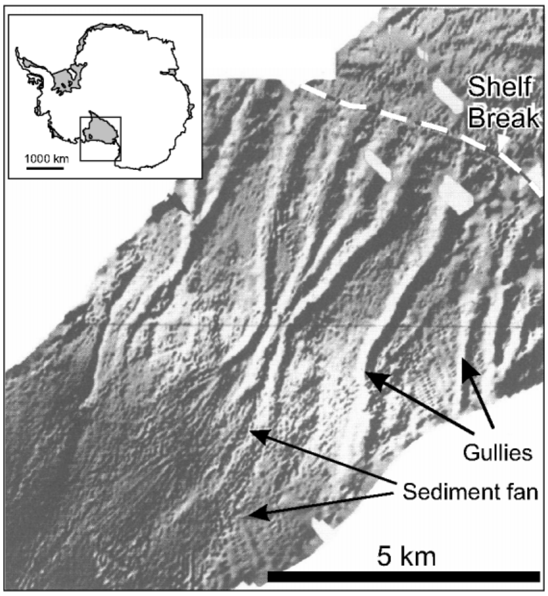


Fig. 8. Swath bathymetric record of gullies in water depths >600 m at the continental shelf edge and on the upper slope in the central Ross Sea. Gullies are inferred to indicate locations of ice streams at the shelf edge and were eroded by turbidity currents sourced from sediment-rich meltwater exiting from the ice-stream terminus. Modified from Shipp *et al.* (1999). Inset map shows location of Ross Sea (boxed).

mapping reveals a series of deep troughs separated by shallower banks that extend from the inner continental shelf to the shelf break. One such trough is Trænadjupet. Geophysical data from the floor of the trough show a series of streamlined sediment ridges aligned along the trough long axis (Fig. 7A) (Ottesen *et al.* in press). Ridge spacing varies from 400 to 500 m, maximum ridge height is about 10 m (typically less than 5 m) and the width of individual ridges averages about 250 m. On the inner continental shelf, where Trænadjupet splits in two, mega-scale glacial lineations (Clark 1993) are present on the floors of both troughs and exhibit convergence shelf-wards where the two troughs join. However, streamlined bedforms are absent from the adjacent shallow banks that border the trough. Lateral moraines are present on both the northern and southern margins of Trænadjupet. These features have been interpreted by Ottesen *et al.* (in press) as recording the former presence of an ice stream that flowed through Trænadjupet to the shelf break.

The continental slope beyond the mouth of Trænadjupet is characterized by a large sediment failure – the Trænadjupet Slide (Fig. 7B) (Kenyon 1987; Dowdeswell *et al.* 1996; Vorren *et al.* 1998; Laberg & Vorren 2000b). The headwall of the slide is located at about 500 m water depth and is about 80 km wide. The total area of the slide is about 24 900 km^2, the run-out distance of sediments transported downslope is 330 km and the total length of the continental shelf edge affected by sliding is about 130 km (Taylor 1999). Thus, even though Trænadjupet supported a fast-flowing ice stream during the Late Weichselian, the continental slope offshore of the trough mouth is not characterized by a TMF.

The main phase of large-scale failure on the Trænadjupet Slide appears to have occurred during the Holocene (Laberg & Vorren 2000b). Estimates from seismic data suggest that this region of the mid-Norwegian continental shelf has undergone about 100 km of progradation during the Late Pliocene to Early Pleistocene (Henriksen & Vorren 1996). It is thus likely that any pre-existing TMF deposited during glacial maxima was simply removed by the large-scale slide event.

Ross Sea, Antarctica. – Recent work from the Ross Sea, Antarctica, reveals the former presence of ice streams that drained to the shelf edge during the LGM (Shipp *et al.* 1999, in press; Wellner *et al.* 2001). Ice streaming is inferred on the basis of: (1) the configuration of bathymetry, with glacially eroded troughs extending across the continental shelf; (2) presence of deformation tills within the middle to outer reaches of the troughs; and (3) mega-scale glacial lineations developed in this till. However, the mouths of the cross-shelf troughs do not correspond to TMF morphology on the slope; indeed, upper slope contours are straight or curve slightly inwards in front of the JOIDES and Drygalski basins.

Rather swath-bathymetric data from the upper continental slope in this region reveal an extensive network of gullies that commence abruptly at the shelf edge immediately downslope of a prominent grounding-zone wedge, and develop into deep channels over distances of less than 1 km (Fig. 8) (Anderson 1999; Shipp *et al.* 1999). The gullies reach maximum widths of 700 m and depths of 45 m and may extend for distances of 6–7 km. With increasing distance downslope, gullies coalesce into larger channels before bifurcating into distributary channels that feed small sediment fans on the upper slope (Fig. 8). The gullies have been interpreted as the products of turbidity currents, sourced from subglacial meltwater released at the grounding-line of the expanded ice sheet when it was located at the shelf break. These turbidity currents flowed downslope and eroded channels that coalesced and diverged, depending on slope gradient, and deposited sediments in a series of small fans on the upper slope (Fig. 8). The lower slope of the Ross Sea region is characterized by more gentle gradients; swath bathymetric records from this region show an irregular sea floor with complex networks of channels extending seawards (Anderson 1999).

Marguerite Bay, Antarctic Peninsula. – Recent swath bathymetric data from Marguerite Bay on the west Antarctic Peninsula continental shelf (Fig. 9) provide strong support for drainage of a major palaeo-ice stream to the shelf edge during the LGM. In this region, a

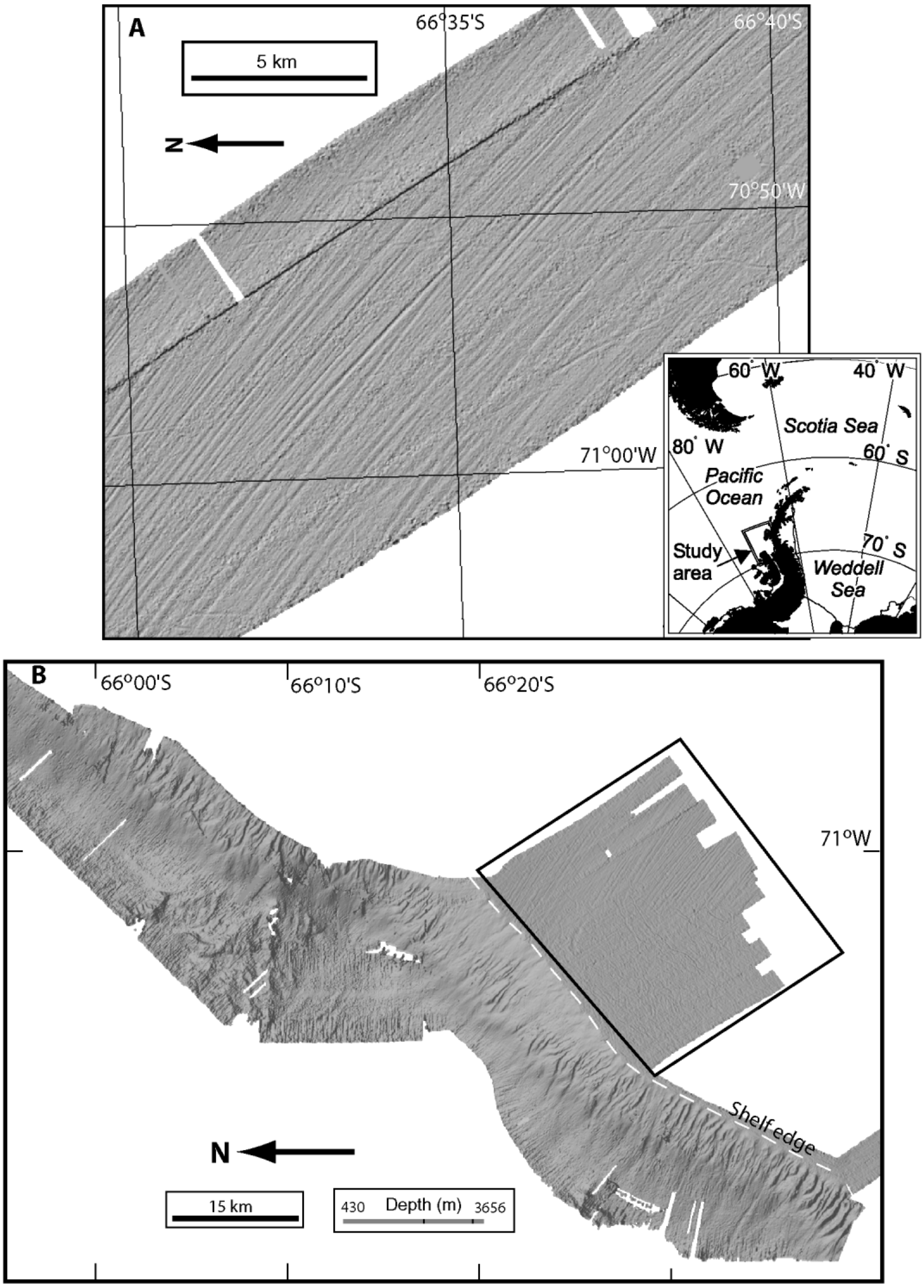


Fig. 9. A. EM120 (12 kHz) multibeam swath bathymetry shaded relief image of mega-scale glacial lineations in outer Marguerite Trough, west Antarctic Peninsula continental shelf. Maximum height of the lineations is 15 m, and widths range from 130 to 300 m. Grid cell size = 25 m × 25 m. The lineations shown in the image occur in water depths of about 520–550 m. B. EM120 shaded relief image of continental slope offshore of Marguerite Trough. Grid cell size = 50 m × 50 m. The location of the continental shelf break is marked by the dashed line. Water depths range from 430 m to 3656 m. The Marguerite trough palaeo-ice stream extended to the shelf edge, infilling the area defined by the box on the continental shelf.

prominent cross-shelf trough extends about 370 km from inner Marguerite Bay to the continental shelf break. Multibeam swath bathymetric data from the trough reveal well-developed, streamlined subglacial bedforms which show progressive elongation with distance along the trough (Ó Cofaigh *et al.* 2002). Bedforms evolve from ice-moulded bedrock and crudely streamlined forms on the inner shelf to well-developed elongate drumlins and lineations on the mid-shelf to mega-scale glacial lineations formed in sediment on the outer shelf (Fig. 9A).

Swath bathymetric data from the continental slope offshore of the mouth of Marguerite Trough show that the upper slope in this region is incised by a series of gullies. Gullies are most clearly developed in areas to either side of the former ice-stream terminus, where slope angles are 10–12° (Fig. 9B). In contrast, the slope directly in front of the trough mouth is both gentler (9°) and smoother in appearance, and gullies, although present, are shallower and less frequent (Fig. 9B). These morphological contrasts along the upper slope in this region reflect former ice-sheet dynamics, such that where the ice stream terminated at the shelf break during the LGM, slope progradation occurred in front of the ice-stream margin. However, sediment delivery to adjacent areas of the slope was lower and this is reflected in the well-developed gullies and a steeper slope. Indeed, much of the sediment delivered to the ice margin by normal ice flow may have been transported through these channels and onto the adjacent continental rise and abyssal plain, thereby essentially by-passing the slope. The record of sedimentation preserved in cores from sediment drifts along the continental rise offshore of Marguerite Trough shows elevated sedimentation rates during glacial periods back to oxygen isotope stage 6 (Pudsey 2000; Ó Cofaigh *et al.* 2001). This provides indirect support for the presence of an ice stream in Marguerite Trough on more than one occasion. It should be noted, however, that although sediment progradation appears to have occurred in this region beyond the trough mouth, a TMF is absent and upper slope bathymetric contours exhibit a slightly concave pattern downslope.

Discussion

Sedimentation on continental slopes by palaeo-ice streams: variability and controls

The above case studies from both the Arctic and Antarctic show that considerable variation exists in the morphology and sedimentary architecture of continental slopes in front of palaeo-ice streams. The classic TMF model was developed to explain the large sediment depocentres found in front of many cross-shelf troughs around the Polar North Atlantic (e.g. Dowdeswell *et al.* 1996, 1997; King *et al.* 1996, 1998; Vorren & Laberg 1997). This work highlighted the role of debris-flow processes in the downslope remobilization of glacigenic sediment delivered to the continental shelf edge and upper slope by subglacial sediment advection beneath palaeo-ice streams. Although debris flows are undoubtedly a key component of TMFs around the Polar North Atlantic, it is increasingly recognized that other processes, such as suspension settling from turbid meltwater plumes, may also contribute to fan formation in this region. These processes operate either concomitantly with debris-flow activity during intervals of maximum ice-sheet extent (Taylor *et al.* in press), or during periods when debris-flow activity has ceased or switched in location (Davison & Stoker in press).

In most cases, continental slope sedimentation in front of palaeo-ice streams is associated with margin progradation. However, a key point is that the resulting slope morphology and sedimentary architecture may vary significantly from the classical TMF model. Thus, along the steep Antarctic continental margins, channels and gullies frequently characterize the upper slope and testify to erosion by turbidity currents generated by sediment-laden, subglacial meltwater emanating from the ice stream. This contrasts with the large TMFs of the Polar North Atlantic. Similarly, along the upper Labrador slope, alternating sectors of high and low relief reflect differences in the processes by which sediment was delivered to the slope, most notably in the respective roles of suspension sedimentation, debris flows and turbidity currents. This depositional system shows considerable variation from the Polar North Atlantic TMFs in that, although the slope directly in front of the mouth of Hudson Strait has prograded and contains debris-flow deposits, it feeds directly downslope into a major submarine channel system, the Northwest Atlantic Mid-Ocean Channel (NAMOC) (Chough & Hesse 1976; Hesse *et al.* 1997a, 1999). The giant submarine braid plain that is associated with the NAMOC (Fig. 6) is composed of predominantly sandy and gravelly sediment and records deposition from bedload-rich meltwater discharges from the Hudson Strait ice stream (Hesse *et al.* 1997b).

Given the variability in the morphology and sediment architecture of continental slopes adjacent to palaeo-ice streams, what are the underlying factors that control this variation? We propose that much of this variation reflects the influence of three principal factors: (1) slope gradient and associated tectonic history of the margin; (2) the geology of the adjoining continental shelf; and (3) the contribution of meltwater.

Slope gradient. – The gradient of the continental slope exerts a fundamental control on the processes of sediment delivery and, hence, on the resulting slope morphology and sediment architecture. The large-scale TMFs around the passive margins of the Polar North Atlantic are characterized by extremely low gradients (Vorren *et al.* 1998; Taylor 1999). For example, the

Bear Island and North Sea TMFs, the largest of the Polar North Atlantic fans, have gradients of less than 1° across their upper, middle and lower slopes. These low gradients facilitate incremental development of a TMF by debris-flow deposition and suspension settling from meltwater plumes during glacial maxima, and would militate against the rapid reworking of debris into turbidity currents. By contrast, in areas where the continental slope is relatively steep, for example, along the Antarctic Peninsula margin where slope gradients of >10° are present, subglacial debris deposited at an ice-stream terminus is more likely to be reworked into turbidity currents. This would facilitate erosion of channels on the upper slope (cf. Ross Sea and Marguerite Bay) and sediment transport into the deep ocean, thereby effectively by-passing the upper slope (cf. Pudsey & Camerlenghi 1998).

In this regard, it may be difficult for fan development to occur in areas characterized by steep slopes. Rapid initiation of turbidity currents and sediment by-pass may result in the slope being a relatively sediment-starved environment and in the maintenance of a steep slope angle, thereby precluding development of a large TMF. In the Polar North Atlantic, the existence of pre-Quaternary depocentres composed of prograded low-stand, fluvial sediments (Vorren *et al.* 1991; Fiedler & Faleide 1996; King *et al.* 1996) may thus have facilitated subsequent TMF development by decreasing the gradient of the continental slope prior to glaciation.

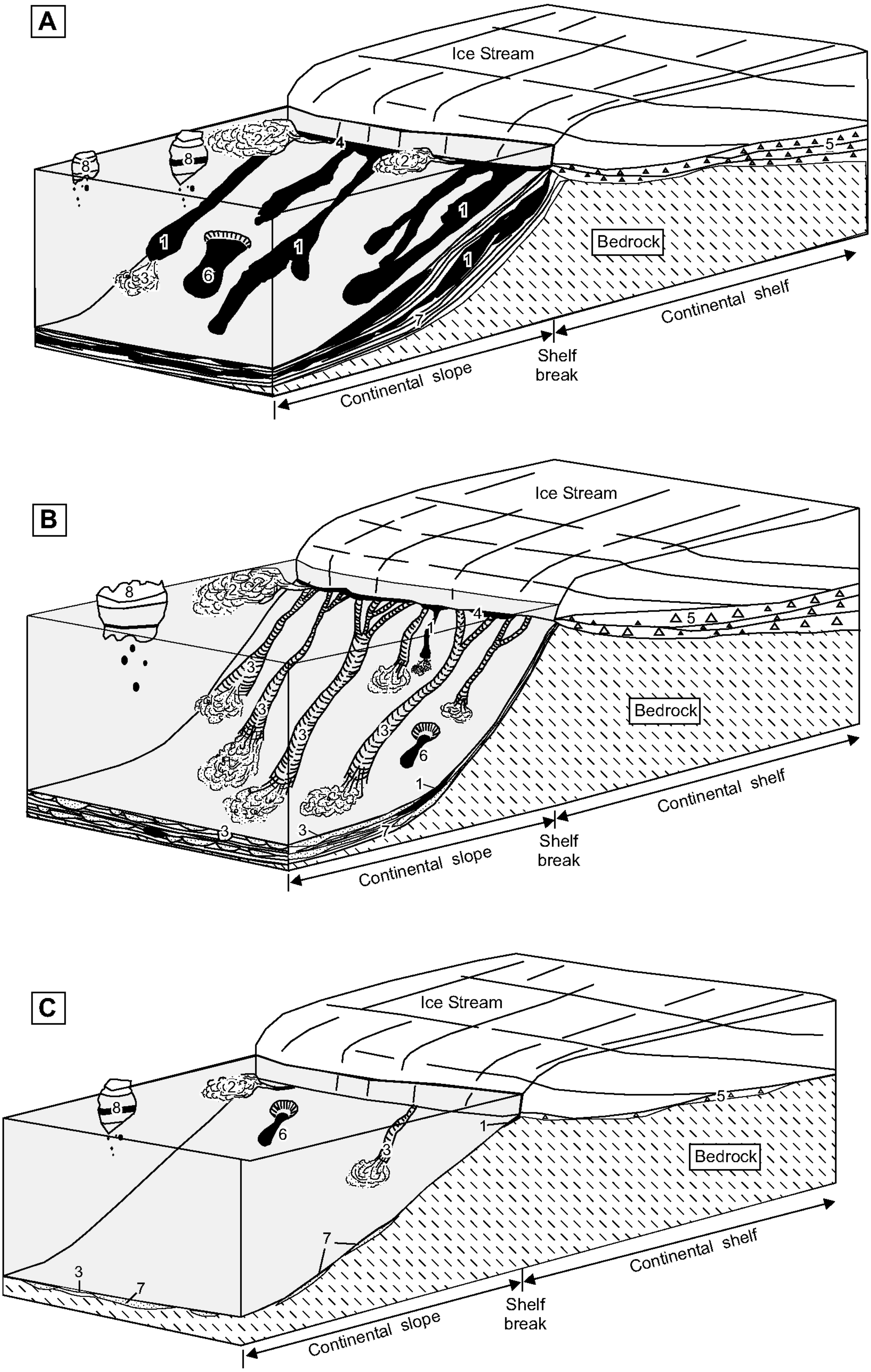
The tectonic history of the margin is also relevant. In the case of an active margin, the slope will be steep and sediment accommodation space will be continually created at the foot of the slope, with the result that sediment delivered to the slope is rapidly transported into the deep sea, precluding large-scale TMF development (e.g. Gulf of Alaska; Dobson *et al.* 1996, 1998). In contrast, passive margins will provide a more stable setting, with limited sediment accommodation space, and this will facilitate subsequent fan development, as in the case of the large TMFs of the Polar North Atlantic.

Continental shelf geology. – It is increasingly recognized that subglacial geology is an important control on the basal mechanics and depositional processes of ice streams in both modern and Pleistocene environments. In West Antarctica today, ice streams are generally underlain by soft, readily deformable sediment (e.g. Alley *et al.* 1986; Anandakrishnan *et al.* 1998; Studinger *et al.* 2001, Tulaczyk *et al.* 2001), and research on Pleistocene ice streams demonstrates a similar relationship (e.g. Marshall *et al.* 1996; Ó Cofaigh & Evans 2001; Clark & Stokes 2001; Wellner *et al.* 2001; Ó Cofaigh *et al.* 2002). Subglacial transport of this sediment can deliver large volumes of debris to the ice-stream terminus, producing thick sequences of subglacial till close to, and at, the ice-stream margin (cf. Alley *et al.* 1989; Boulton 1996; Evans & Rea 2001; Shipp *et al.* in press). Where the ice stream reaches the continental shelf edge, this material is delivered directly to the continental slope, where it may undergo subsequent downslope remobilization as debris flows.

A key question in relation to the development of TMFs is whether there is a sufficient sediment supply to enable fan formation (slope gradient and tectonic setting being favourable). TMFs are associated with those areas of the shelf where ice streams traverse predominantly sedimentary terrain, either in the form of sedimentary bedrock or unconsolidated Quaternary sediments. These sediments are readily susceptible to erosion and incorporation in a subglacial deforming layer. The large volumes of glacigenically derived sediment deposited in TMFs requires an abundant supply of sediment, a requirement that is more likely to be met where an ice stream traverses a soft bed rather than crystalline bedrock. The subglacial geology of the adjoining continental shelf is therefore an important limiting control on TMF development.

The width of the continental shelf may also be significant (O'Grady & Syvitski in press). On narrow continental shelves, there may be insufficient distance for streaming flow to develop (cf. Wellner *et al.* 2001). Hence, large-scale subglacial sediment advection does not occur and there will be insufficient sediment to build

Fig. 10. Conceptual model of continental slope sedimentation in front of an ice stream reaching the shelf edge. Slope morphology and sedimentary architecture will vary depending on slope gradient, relative dominance of meltwater versus debris-flow deposition and sediment supply. A. Classic trough mouth fan (e.g. Polar North Atlantic). Abundant sediment supply, wide continental shelf, low slope gradient (<1°). Debris-flow activity and suspension settling from turbid meltwater plumes dominate sedimentation. This differs from previous depositional models of trough mouth fans (e.g. Vorren & Laberg 1997) due to the increased contribution of meltwater sedimentation to fan formation during glacial maxima: (1) debris flows sourced from glacigenic sediment at the shelf edge; (2) buoyant turbid meltwater plume; (3) turbidity current formed by downslope evolution from a debris flow; (4) subglacial till extruded along the ice-stream front/grounding line; (5) subglacial (deformation) till; (6) slump generated debris flow; (7) stratified sediments deposited by suspension settling from meltwater plumes, contour-current and minor turbidity-current activity; (8) iceberg rafting. B. Steep slope (>10°), abundant sediment supply, wide continental shelf (e.g. west Antarctic Peninsula continental margin). Large volumes of subglacial sediment are advected to the ice-stream terminus and upper continental slope and turbidity currents quickly develop due to the steep slope. Channels and gullies are eroded by the turbidity currents on the slope and debris is transferred rapidly downslope. Numbers as in (A). C. Hypothetical case of low sediment supply and wide continental shelf. Sediment-starved setting. The ice stream traverses a hard bed (e.g. crystalline bedrock) on the continental shelf, with fast-flow occurring by enhanced basal sliding. Limited advection of subglacial sediment to the ice-stream terminus due to the hard bedrock substrate. Numbers as in (A).


A
Ice Stream
Bedrock
Continental shelf
Shelf break
Continental slope
B
Ice Stream
Bedrock
Continental shelf
Shelf break
Continental slope
C
Ice Stream
Bedrock
Continental shelf
Shelf break
Continental slope

a TMF. This effect will also be accentuated in areas where the shelf is underlain by a crystalline rather than sedimentary substrate.

Role of meltwater. – The classical TMF model (e.g. Dowdeswell *et al.* 1996; Vorren & Laberg 1997; Laberg & Vorren 1995, 2000a) emphasizes the role of debris-flow processes in the downslope remobilization of large volumes of glacigenic debris delivered to the upper continental slope. Resulting debris-flow deposits are considered to form the building blocks of TMFs. More recently, it has been recognized that these debris flow packages may be separated by, and pass laterally into, acoustically stratified sediments (Taylor *et al.* in press). Cores from these acoustically stratified units recovered massive to weakly laminated muds that record suspension settling from turbid meltwater plumes and contour current activity. Taylor *et al.* (in press) estimate that about 40% of the area of the Bear Island TMF has not experienced debris flow activity for at least the past 50 000 years, but rather that sediment delivery to these areas during glacial maxima was dominated by suspension settling and contour current activity. Thus, even in the Polar North Atlantic, depositional processes and sediments within TMFs are considerably more diverse than the classical TMF model suggests.

The importance of meltwater processes to the sedimentary architecture and morphology of continental slopes in front of palaeo-ice streams is also illustrated by the examples from Antarctica and the Labrador Sea discussed above. In the Ross Sea, sediment-laden meltwater released from the ice-stream front formed turbidity currents which eroded channels on the upper slope (Shipp *et al.* 1999; Anderson 1999). These channels start at the continental shelf break and indicate rapid initiation of turbidity currents at the shelf edge rather than progressive downslope evolution from debris flows. Similarly, along the Labrador Sea margin, meltwater processes appear to have played a key role in sedimentation with deposition of fine-grained muds, which were subsequently channelled by turbidity currents (Hesse *et al.* 1997a, 1999). Further downslope, the transition into the NAMOC channel system and its associated giant sandy braid-plain records discharge of bedload-rich meltwater directly onto the slope from the Hudson Strait ice stream (Hesse *et al.* 1997b). Meltwater-related processes therefore impart considerable variety to the morphology and sedimentary architecture of continental slopes in front of palaeo-ice streams.

A conceptual model of continental slope sedimentation in front of palaeo-ice streams

Based on the case studies that we document above and the preceding discussion, we suggest that the ideal criteria for the formation of a well-developed TMF are: (1) a favourable depositional setting along a passive continental margin, in front of a cross-shelf trough containing a large, fast-flowing ice stream; (2) abundant and readily erodible sediments on a wide continental shelf, which the ice stream can cannibalize into a subglacial deforming layer; and (3) a low-gradient (<1°) continental slope, on which mass-movement is dominated by debris flows. This will probably be facilitated by a pre-existing low-gradient sedimentary depocentre prior to ice-sheet expansion. Sediment supply on the continental shelf is thus a key factor. TMF formation will cease once sediment supply becomes exhausted, which, in turn, will impact directly on the fast flow of the ice stream. Depending on the relative importance of meltwater sedimentation, debris-flow activity, sediment supply and slope gradient, the resulting morphology and sediment architecture of the continental slope in front of an individual ice stream can vary considerably.

Figure 10 provides a summary conceptual model illustrating this variability. The first two cases shown are based on geophysical and geological data from the Polar North Atlantic and Antarctic Peninsula margins, respectively. The last case (Fig. 10C) is hypothetical. Figure 10A illustrates the classic TMF model but also highlights the role of meltwater sedimentation based on recent work from the Bear Island Fan (Taylor *et al.* in press). In this case, a wide continental shelf floored by an unconsolidated or weakly consolidated substrate, low gradient slope (<1°) and presence of abundant subglacial meltwater results in a high sedimentation rate, with depositional processes dominated by debris flows and suspension settling from meltwater plumes. Figure 10B differs due to the much steeper continental slope (>10°). In this setting, large volumes of subglacial debris are delivered to the shelf edge, but the steep slope results in the rapid development of turbidity currents and associated rapid transfer of this debris to the deep sea.

The last case shown (Fig. 10C) depicts the likely sedimentary processes operating on the continental slope where an ice stream overlies a predominantly hard bed on the continental shelf. Although this scenario is hypothetical, several recent investigations from the Antarctic Peninsula and northern Canada have presented evidence in the form of streamlined subglacial bedforms that support an interpretation of streaming flow across areas of crystalline bedrock (Ó Cofaigh *et al.* 2002; Stokes & Clark 2002). Furthermore, ice-sheet modelling results also indicate that zones of streaming flow can develop independently of topography and soft sediments over areas of hard bed such as the Baltic Shield (Payne & Baldwin 1999). A hard substrate would depress subglacial till production and, thus, sedimentation rates at the ice-stream terminus would be lower than in the former two cases. Resulting sedimentary processes would be limited to occasional debris flows, turbidity currents and suspension settling from meltwater plumes, as well as iceberg rafting.

In conclusion, the sedimentary architecture and morphology of continental slopes in front of ice streams is highly variable and reflects the relative dominance of the processes by which sediment is transferred from the ice-stream terminus/shelf edge to the upper slope. These processes are, in turn, controlled by factors such as slope gradient and sediment supply. The absence of a TMF cannot, therefore, be used as direct evidence that a palaeo-ice stream was not present on the continental shelf.

Conclusions

Where ice streams expand across continental shelves underlain by a sedimentary substrate, they deliver large volumes of subglacial sediment to the shelf edge, which is then redeposited down the continental slope. The classical model of TMF formation was developed in the Polar North Atlantic to explain large sediment fans situated in front of cross-shelf troughs. This model emphasizes advection of large volumes of subglacial sediment to the ice-stream terminus and upper continental slope and subsequent remobilization of this sediment by debris-flow processes. Subsequent work, however, has emphasized the significance of meltwater sedimentation in Polar North Atlantic TMF development (Taylor *et al.* in press). The acoustically stratified sediment packages that result from such meltwater deposition can contribute significantly to the overall sediment pile.

- The morphology and large-scale sediment architecture of high-latitude continental slopes in front of ice streams may vary considerably from that associated with classical TMFs. This variability reflects differences in slope gradient, the relative contributions of meltwater sedimentation versus debris flow deposition, sediment supply/geology of the adjacent continental shelf and shelf width.
- TMF development is favoured under conditions of a low (<1°) slope gradient; a tectonically passive marginal setting; abundant, readily erodible and deformable sediments on the adjacent continental shelf, and thus high rates of sediment delivery to the shelf edge; and a wide continental shelf.
- Given the variability in the morphology and sedimentary architecture of continental slope environments in front of palaeo-ice streams, the absence of a TMF should not necessarily be taken to indicate an absence of palaeo-ice streams on the adjoining shelf.

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