Submarine glacial landforms and rates of ice-stream collapse

Article in Geology · October 2008
DOI: 10.1130/G24808A.1

Submarine glacial landforms and rates of ice-stream collapse

J.A. Dowdeswell[1], D. Ottesen[2], J. Evans[3], C. Ó Cofaigh[4], J.B. Anderson[5]
[1]Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK
[2]Geological Survey of Norway, Trondheim N-7491, Norway
[3]Department of Geography, Loughborough University, Loughborough LE11 3TU, UK
[4]Department of Geography, Durham University, Durham DH1 3LE, UK
[5]Department of Earth Sciences, Rice University, Houston, Texas 77005, USA

ABSTRACT

The rate of deglacial ice-sheet retreat across polar continental shelves, and possible ice-stream collapse and sea-level rise, has been much debated. High-resolution imagery of seafloor morphology is available for many polar shelves and fjords. The rapidity of ice retreat is inferred from diagnostic assemblages of submarine landforms, produced at ice-stream sedimentary beds. These landforms, exposed by ice retreat across high-latitude shelves, demonstrate that deglaciation occurs in three main ways: rapidly, by flotation and breakup; episodically, by still-stands and/or grounding events punctuating rapid retreat; or by slower retreat of grounded ice. Submarine landform assemblages imply, through the presence of grounding-zone wedges overprinting mega-scale glacial lineations on many polar shelves, that ice-stream retreat is more often episodic than catastrophic. These observations provide a robust test of the ability of numerical models to predict the varied response of ice-sheet basins to environmental changes.

Keywords: ice streams, ice-sheet retreat, swath bathymetry, glacial landforms, glacial lineations, grounding-zone wedges, Arctic, Antarctic.

INTRODUCTION

Ice sheets in the Antarctic and Arctic, drained mainly by fast-flowing ice streams, advanced and retreated across high-latitude continental shelves in a series of glacial-interglacial cycles over the past few million years. During ice-sheet decay, their marine margins retreated by up to several hundred kilometers from the shelf edge to their interglacial positions. Controversy has surrounded the retreat rate, and whether dramatic ice-stream collapse and rapid sea-level rise have taken place and may occur in future (e.g., Mercer, 1978). We show that the relative rapidity of ice retreat can be derived from diagnostic sets of submarine landforms, produced at ice-stream sedimentary beds and retreating ice margins. These sets of submarine landforms, exposed on high-latitude shelves, demonstrate that ice-stream margins retreat in three characteristic ways: rapidly, by flotation and breakup; episodically, with stillstands or grounding events punctuating rapid retreat; or through slower retreat of grounded ice. The retreating margins of ice-sheet basins have responded to warming deglacial climate and sea-level rise very differently. Ice streams draining into the Ross Sea from West Antarctica underwent rapid flotation and retreat, punctuated by stillstands, whereas ice streams draining from East Antarctica exhibited slower retreat of grounded ice over thousands of years. We also note that the retreat of ice across the rugged, crystalline bedrock of some Antarctic inner-shelf areas appears more variable than over the sedimentary beds we discuss (Heroy and Anderson, 2007).

Detailed observations of seafloor morphology have been acquired recently from a number of Arctic and Antarctic shelves and fjords using kilohertz-frequency high-resolution multibeam echo sounders. These data cover swaths of up to several kilometers across, enabling production of digital seabed models accurate to <1 m vertically and between a few meters and a few tens of meters horizontally.

SUBMARINE GLACIAL LANDFORMS AND RATES OF DEGLACIATION

Mega-Scale Glacial Lineations—Rapid Ice-Stream Retreat

Mega-scale glacial lineations are striking submarine landforms (Figs. 1A and 1B), formed in a deforming till layer of low shear strength (Dowdeswell et al., 2004). They are usually found in cross-shelf troughs and fjords on high-latitude margins (e.g., Ó Cofaigh et al., 2002; Ottesen et al., 2005a). They form series of streamlined curvilinear ridges with lengths of as much as tens of kilometers, amplitudes of a few meters, and wavelengths of tens of meters to a few hundred meters. Assemblages of mega-scale glacial lineations often extend for tens of kilometers to hundreds of kilometers along trough and fjord axes, and cover widths of tens of kilometers. They are interpreted as diagnostic indicators of the former presence of ice streams, which drained huge ice-sheet basins to the edges of most high-latitude shelves during the last glacial period, ~20 k.y. ago. From the distribution of mega-scale glacial lineations, the locations of fast-flowing ice streams have been reconstructed for large areas of the full-glacial Antarctic and Eurasian ice sheets (Ottesen et al., 2005a; Mosola and Anderson, 2006).

Where mega-scale glacial lineations are preserved unmodified on the modern seafloor, it is inferred that deglaciation was by ice-sheet thinning, flotation, and retreat through relatively rapid iceberg calving. This mechanism allows mega-scale glacial lineations to remain unmodified, except for any subsequent iceberg-keel plowing and deposition of a thin veneer of glacial and interglacial sediments that is often insufficient to obscure them (Ó Cofaigh et al., 2002).

The essentially unmodified mega-scale glacial lineations in Marguerite Trough, Antarctic Peninsula, and in Traena Trough, north Norway, are examples of this deglacial mechanism (Figs. 1A and 1B). In Marguerite Trough, mega-scale glacial lineations can be traced almost 150 km from water depths of 500 m at the shelf edge to more than 1 km inshore (Ó Cofaigh et al., 2002) (Fig. 1A). On the shallower banks on either side of this trough, swath imagery and acoustic sub-bottom profiles show that ice-sheet grounding and stillstands took place during retreat. However, retreat of the ice stream through Marguerite Trough is inferred to have proceeded by flotation and rapid retreat, facilitated by a shoreward-deepening seafloor and rapid deglacial sea-level rise (Alley et al., 2007).

Mega-scale glacial lineations can also be traced throughout the 150-km-long Traena Trough (Ottesen et al., 2005a) (Fig. 1B), showing that they are widespread on high-latitude shelves in both hemispheres. Minimum ^{14}C ages for deglaciation, 13,640 and 13,675 yr B.P. (Laberg et al., 2002, 2007), are identical (within ^{14}C error of 70–100 yr) for sites just beyond the shelf edge at the mouth of Traena Trough and more than 200 km inshore close to the first grounding-zone wedge in Vestfjorden (Fig. 1D). Taking 100 yr for the 200 km retreat gives a rate of 2 km yr^{-1}, probably a conservative estimate. In the Norwegian Channel, where mega-scale glacial lineations are also present (Ottesen et al., 2005a), ^{14}C dated retreat of ~450 km took place at a rate between 350 and 750 m yr^{-1} (Lekens et al., 2005). This supports the interpretation that initial ice-stream ungrounding and retreat from the shelf edge were rapid.

Grounding-Zone Wedges—Episodic Retreat

On many high-latitude continental shelves, mega-scale glacial lineations are overprinted during deglaciation by the subsequent deposition of two other diagnostic submarine landforms; grounding-zone wedges, and smaller transverse ridges. The presence of either landform, generally oriented at right angles to mega-scale glacial lineations, suggests that retreat is not as simple or rapid as in troughs where mega-scale glacial lineations are found alone. Where grounding-zone wedges are present, stratigraphically above and across mega-scale glacial lineations (Figs. 1C and 1D), they record temporary stillstands in grounding-zone position during deglaciation, formed as active ice continues to deliver sediments to its margin. Grounding-zone wedge volume is linked to the rate of debris delivery and duration of stillstand (Howat and Domack, 2003). Retreat between stillstands was probably rapid, since mega-scale glacial lineations are often preserved unmodified.

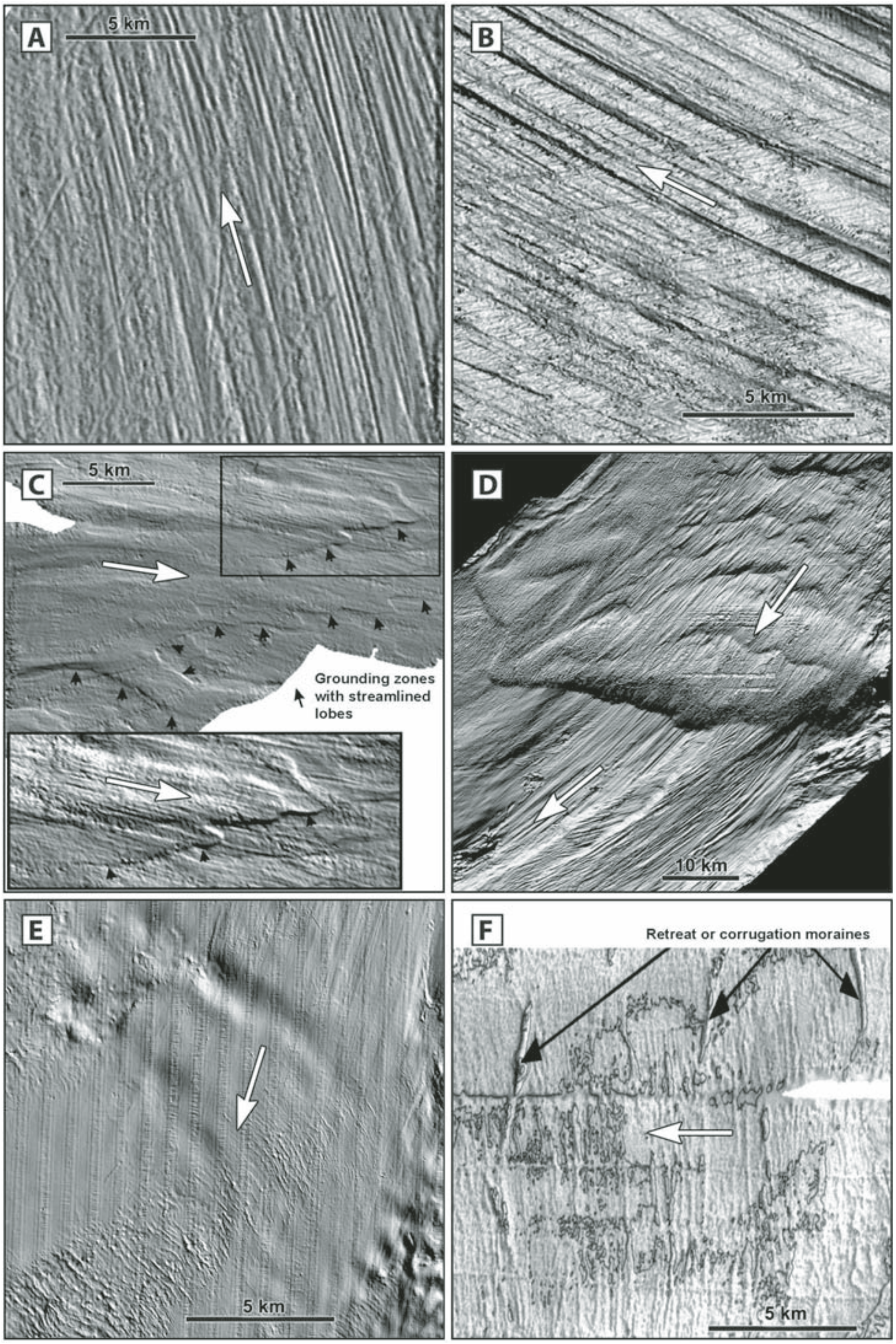

Figure 1. Glacier-produced submarine landforms on high-latitude continental shelves, indicating former presence of ice streams and nature and rate of deglacial retreat. White arrows show direction of former ice flow. A: Mega-scale glacial lineations (MSGL) from outer part of Marguerite Trough, Antarctic Peninsula (center coordinates 66°32′S, 71°02′W). B: MSGL from Traena Trough, north Norway (66°45′N, 10°30′E). C: Grounding-zone wedges (GZW) and MSGL from the area of the former Larsen A Ice Shelf, Antarctic Peninsula (64°41′S, 59°15′W) (source: Evans et al., 2005). D: GZW and MSGL in Vestfjorden, north Norway (67°20′N, 12°45′E). E: Transverse ridges from Bellsund, western Svalbard, overlying MSGL (77°15′N, 13°E). F: Transverse ridges, or corrugation moraines, in trough in western Ross Sea, Antarctica (75°27′S, 170°43′E) (source: Shipp et al., 2002).

Examples of grounding-zone wedges superimposed on mega-scale glacial lineations occur, for example, beneath the former Larsen A Ice Shelf, Antarctic Peninsula, in Mertz Trough, East Antarctica, and in Vestfjorden, north Norway (Evans et al., 2005; McMullen et al., 2006; Ottesen et al., 2005b) (Figs. 1C and 1D). In Vestfjorden, wedges are as high as 100 m, 50 km^3 in volume, and indicate multiple stillstands punctuating ice retreat at intervals of ~10–20 km (Ottesen et al., 2005b). ^{14}C dates on fine-grained sediments overlying grounding-zone wedge diamicts provide minimum ages for the end of stillstands. Dates of 13,700 and 12,500 yr B.P. bracket the formation of several grounding-zone wedges along a 50 km transect of Vestfjorden (Knies et al., 2007; Laberg et al., 2007). To build sedimentary wedges tens of meters thick, the grounding zone must have remained in a similar position for a significant part of this interval: stability for 50% of the ~1 k.y period would give a retreat rate of 100 m yr^{-1} and 90% would yield 500 m yr^{-1}. Given that modern tidewater glaciers are usually observed to retreat rapidly between successive stillstands (Syvitski et al., 1987), the higher rate of ice retreat appears more plausible.

In Antarctica, grounding-zone wedges in the Larsen A area are ~20 m high and 10 km wide (Evans et al., 2005). Grounding-zone wedges ~50–100 m thick and as wide as 80 km are also present in troughs across the Ross Sea (Shipp et al., 2002; Mosola and Anderson, 2006). Where grounding-zone wedge surfaces are streamlined (Figs. 1C and 1D), ice remained active during retreat. In other areas, such as the central shelf of the northwestern Weddell Sea, grounding-zone wedge tops are not overprinted by lineations, implying that streaming may have diminished during grounding-line retreat (Heroy and Anderson, 2005). Based on available sedimentation rates from high-latitude ice-sheet margins, grounding-zone wedges tens of meters in thickness suggest stillstands lasting hundreds rather than tens of years.

Transverse Ridges—Slow Retreat of Grounded Ice Margins

A further submarine landform, formed orthogonal to and overprinting mega-scale glacial lineations in Antarctic and Arctic troughs and fjords, is relatively small sedimentary ridges (Boulton, 1986; Shipp et al., 2002). These transverse ridges, similar to De Geer moraines at typical amplitudes of 2–10 m and wavelengths of a few tens to hundreds of meters, are one to two orders of magnitude smaller than grounding-zone wedges (Mosola and Anderson, 2006; Ottesen et al., 2007). However, they are usually found in assemblages that contain tens or hundreds of ridges.

Sets of transverse ridges have been observed in the fjords and shelves of Spitsbergen (Fig. 1E) (Ottesen et al., 2007), and are also present in several Antarctic troughs (Shipp et al., 2002). In the Joides-Central Basin, Ross Sea, several thousand transverse ridges (~1–2 m high, spaced 40–100 m) were deposited along the trough (Fig. 1F). In some Spitsbergen fjords, similar transverse ridges are forming today at retreating tidewater-glacier margins. Ridge locations have been compared with historical observations of ice-front position at several sites. Ridges sometimes form reentrants around deeper calving bays where local seafloor bathymetry is complex (Ottesen and Dowdeswell, 2006), a pattern similar to that of calving bays inferred from East Antarctic margin sediments (Leventer et al., 2006).

The transverse ridges are often formed annually by ice push (Boulton, 1986; Ottesen and Dowdeswell, 2006). It is thought that the presence of winter sea ice suppresses iceberg calving and minor readvance is superimposed on more general summer retreat. Assuming that the ridges are annual, we have calculated the volume and an implied sediment flux of ~100 m^3 m^{-1} yr^{-1} from the suite of transverse ridges in Bellsund (Fig. 1E). This is a similar order of magnitude to sediment-flux estimates beneath modern West Antarctic ice streams (Alley et al., 2007).

Where suites of transverse ridges are present, relatively slow retreat of grounded ice margins is inferred, the number of ridges often, although not always, approximating the years over which retreat took place. Independent evidence is needed to confirm that ridges are approximately annual at a given location. Ice-sheet retreat rates derived using this assumption are 40–100 m yr^{-1} in the western Ross Sea. The estimate is consistent with retreat of 370 km along this trough, ^{14}C dated to the interval 14,000–6400 yr B.P., giving a mean retreat rate that is presumably relatively uniform at ~50 m yr^{-1} (Shipp et al., 2002). For Bellsund, Spitsbergen, the spacing of transverse ridges suggests a retreat rate up to 100 m yr^{-1}, although ^{14}C dated mean retreat over the entire deglacial period was ~20 m yr^{-1}.

COMPLEX ICE-SHEET RESPONSE TO ENVIRONMENTAL CHANGE

As well as demonstrating the nature and rate of ice-sheet retreat in individual polar troughs and fjords, the widespread distribution of these landform assemblages also implies complexity in the response of different ice-sheet basins to the environmental changes that led to deglaciation. In the Ross Sea, for example, there are several troughs, each >250 km long (Fig. 2). However, it is only the western Joides-Central Basin trough that contains large numbers of transverse ridges that overprint mega-scale glacial lineations (Fig. 1F). The remaining troughs to the east have well-preserved mega-scale glacial lineations punctuated by several grounding-zone wedges (Fig. 2).

This suggests that the style of deglaciation in the Ross Sea was episodic in the four eastern troughs, with rapid retreat by flotation and iceberg production punctuating stillstands (Mosola and Anderson, 2006), but characterized by the slow retreat of grounded ice in the west (Shipp et al., 2002). This major difference in the nature and rate of deglaciation may be explained by the fact, supported by petrographic analysis of glacial sediments on the Ross Sea shelf (Licht et al., 2005), that the two western troughs were fed by ice from 10^6 km^2 basins draining East Antarctica through the Transantarctic Mountains, whereas the more eastern troughs were supplied from 10^5 km^2 basins draining the smaller West Antarctic Ice Sheet (Fig. 2). The two ice sheets, therefore, responded differently to the transition from full glacial to interglacial conditions, West Antarctica being the more sensitive.

DISCUSSION: STYLES OF ICE-SHEET DEGLACIATION

Submarine landform assemblages from both the Arctic and Antarctic, including the Ross Sea (Fig. 2), imply through the presence of grounding-zone wedges overprinting mega-scale glacial lineations that ice retreat was more often punctuated by stillstands than catastrophic throughout ice-stream length. These observations support modeling experiments by Alley et al. (2007), suggesting that the buildup of sedimentary wedges at ice-shelf grounding lines exerts a stabilizing effect against sea-level rises of <10 m because frictional drag is increased, slowing and thickening the overlying ice. The detailed topography and rate of buildup of grounding-zone wedges, together with the differing dimensions and variable accumulation rates within individual ice-sheet basins, make it likely that retreat is often variable in style and also asynchronous between basins even within a single ice sheet.

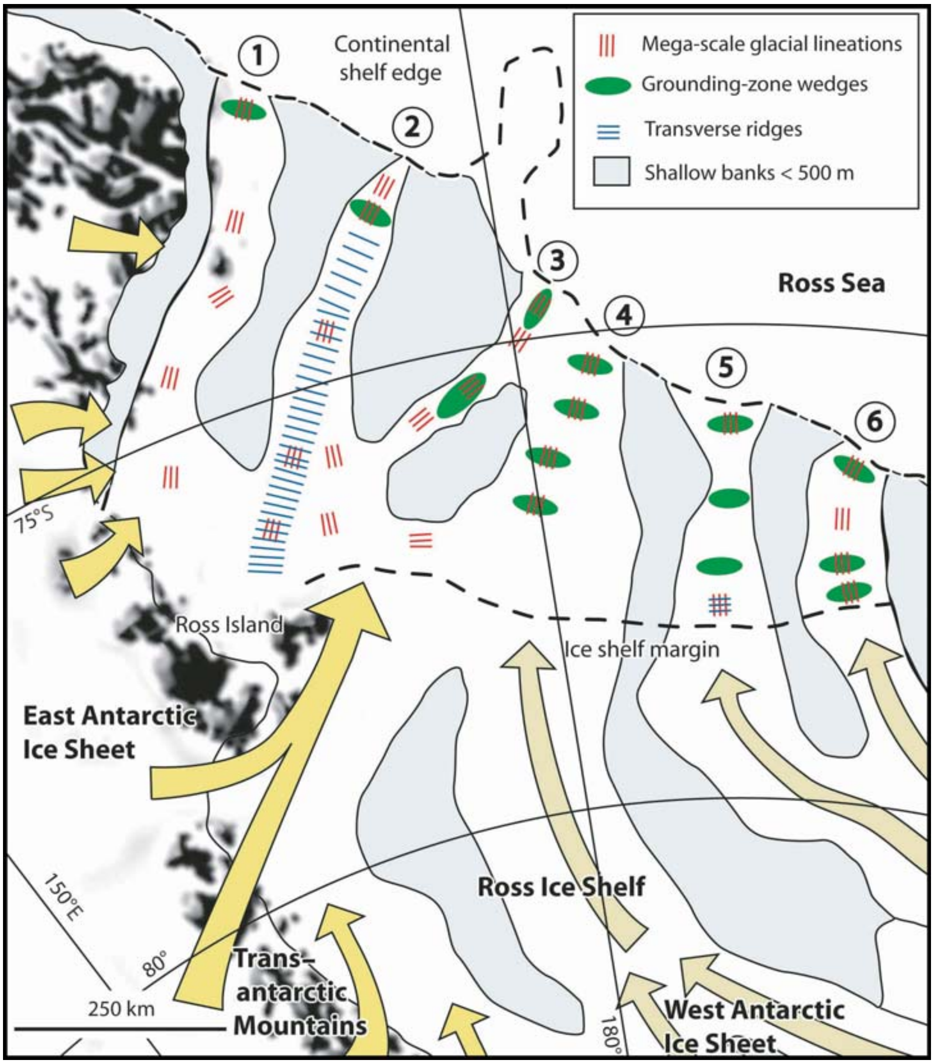

Figure 2. Schematic diagram of the six troughs on Ross Sea shelf (1–6); distribution of major submarine landforms is indicated. Sources of ice draining into Ross Ice Shelf from major basins in East and West Antarctica are also shown (yellow and light brown arrows, respectively). Shallow banks on shelf (<500 m) are light blue. Sources: Shipp et al. (2002); Licht et al. (2005); Mosola and Anderson (2006).

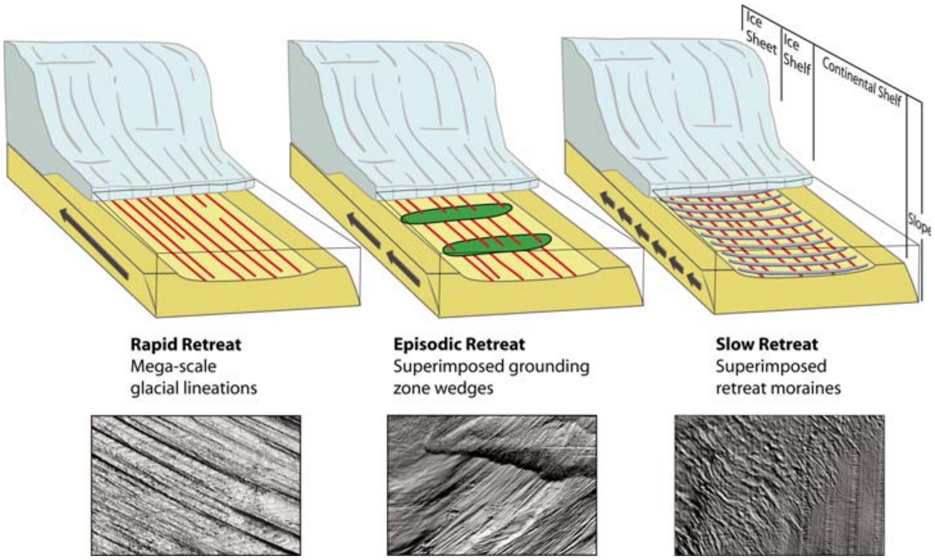

Figure 3. Schematic diagram of submarine landform sets indicating rapid, episodic, and slower retreat of ice streams across high-latitude continental shelves, with examples of swath-bathymetric data (scale across swath images: rapid retreat, 15 km; episodic retreat, 40 km; slow retreat, 10 km). We have included floating ice shelves beyond the ice-sheet grounding zone in this diagram because they are a pervasive part of the modern Antarctic ice-sheet system. However, landforms discussed here are not diagnostic indicators of their past presence or absence.

The presence of three distinctive types of submarine landforms in the shelves and fjords of the Antarctic and Arctic thus provides clear evidence on the style—rapid, punctuated, or slow (Fig. 3)—and in some cases the absolute rate of the last major deglaciation of high-latitude margins. These landform assemblages are present on most polar shelves that have been swath surveyed. They provide a spatially extensive observational record against which the predictions of ice-sheet numerical models can be tested; for the presence of paleo-ice streams, for the nature and rate of deglaciation, and to stimulate investigations as to why the response of individual ice-sheet basins to a given environmental change may be complex. It is not until ice-sheet numerical models can reproduce this variability that they will be able to predict the likelihood or otherwise of rapid collapse of major basins in modern Antarctica and Greenland.

ACKNOWLEDGMENTS

This work was supported by grants from the UK Natural Environment Research Council (Dowdeswell), the Geological Survey of Norway (Dowdeswell, Ottesen) and the U.S. National Science Foundation Office of Polar Programs (Anderson).

REFERENCES CITED

Alley, R.B., Anandakrishnan, S., Dupont, T.K., Parizek, B.R., and Pollard, D., 2007, Effect of sedimentation on ice-sheet grounding-line stability: Science, v. 315, p. 1838–1841, doi: 10.1126/science.1138396.

Boulton, G.S., 1986, Push-moraines and glacier-contact fans in marine and terrestrial environments: Sedimentology, v. 33, p. 677–698, doi: 10.1111/j.1365–3091.1986.tb01969.x.

Dowdeswell, J.A., Ó Cofaigh, C., and Pudsey, C.J., 2004, Thickness and extent of the subglacial till layer beneath an Antarctic paleo-ice stream: Geology, v. 32, p. 13–16, doi: 10.1130/G19864.1.

Evans, J., Pudsey, C.J., Ó Cofaigh, C., Morris, P.W., and Domack, E.W., 2005, Late Quaternary glacial history, dynamics and sedimentation of the eastern margin of the Antarctic Peninsula Ice Sheet: Quaternary Science Reviews, v. 24, p. 741–774, doi: 10.1016/j.quascirev.2004.10.007.

Heroy, D.C., and Anderson, J.B., 2005, Ice-sheet extent of the Antarctic Peninsula region during the last glacial maximum (LGM)—Insights from glacial geomorphology: Geological Society of America Bulletin, v. 117, p. 1497–1512, doi: 10.1130/B25694.1.

Heroy, D.C., and Anderson, J.B., 2007, Radiocarbon constraints on Antarctic Peninsula Ice Sheet retreat following the Last Glacial Maximum (LGM): Quaternary Science Reviews, v. 26, p. 3286–3297.

Howat, I.M., and Domack, E.W., 2003, Reconstructions of western Ross Sea palaeo-ice-stream grounding zones from high-resolution acoustic stratigraphy: Boreas, v. 32, p. 56–75, doi: 10.1080/03009480310001038.

Knies, J., Vogt, C., Matthiessen, J., Nam, S.-I., Ottesen, D., Rise, L., Bargel, T., and Eilertsen, R.S., 2007, Re-advance of the Fennoscandian Ice Sheet during Heinrich Event 1: Marine Geology, v. 240, p. 1–18.

Laberg, J.S., Vorren, T.O., Mienert, J., Evans, D., Lindberg, B., Ottesen, D., Kenyon, N.H., and Henriksen, S., 2002, Late Quaternary palaeoenvironment and chronology in the Traenadjupet Slide area offshore Norway: Marine Geology, v. 188, p. 35–60, doi: 10.1016/S0025–3227(02)00274–8.

Laberg, J.S., Eilertsen, R.S., Salomonsen, G.R., and Vorren, T.O., 2007, Submarine push moraine formation during the early Fennoscandian Ice Sheet deglaciation: Quaternary Research, v. 67, p. 453–462, doi: 10.1016/j.yqres.2007.01.014.

Lekens, W.A.H., Sejrup, H.P., Haflidason, H., Petersen, G.Ø., Hjelstuen, B., and Knorr, G., 2005, Laminated sediments preceding Heinrich event 1 in the Northern North Sea and Southern Norwegian Sea: Origin, processes and regional linkage: Marine Geology, v. 216, p. 27–50, doi: 10.1016/j.margeo.2004.12.007.

Leventer, A., Domack, E., Dunbar, R., Pike, J., Stickley, C., Maddison, E., Brachfeld, S., Manley, P., and McClennen, C., 2006, Marine sediment record from the East Antarctic margin reveals dynamics of ice sheet recession: GSA Today, v. 16, p. 4–11, doi: 10.1130/GSAT01612A.1.

Licht, K.J., Lederer, J.R., and Swope, J.R., 2005, Provenance of LGM glacial till (sand fraction) across the Ross Embayment, Antarctica: Quaternary Science Reviews, v. 24, p. 1499–1520, doi: 10.1016/j.quascirev.2004.10.017.

McMullen, K., Domack, E., Leventer, A., Olson, C., Dunbar, R., and Brachfeld, S., 2006, Glacial morphology and sediment formation in the Mertz Trough, East Antarctica: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 231, p. 169–180, doi: 10.1016/j.palaeo.2005.08.004.

Mercer, J.H., 1978, West Antarctic ice sheet and CO_2 greenhouse effect: A threat of disaster: Nature, v. 271, p. 321–325, doi: 10.1038/271321a0.

Mosola, A.B., and Anderson, J.B., 2006, Expansion and rapid retreat of the West Antarctic Ice Sheet in eastern Ross Sea: Possible consequence of over-extended ice streams?: Quaternary Science Reviews, v. 25, p. 2177–2196, doi: 10.1016/j.quascirev.2005.12.013.

Ó Cofaigh, C., Pudsey, C.J., Dowdeswell, J.A., and Morris, P., 2002, Evolution of subglacial bedforms along a paleo-ice stream, Antarctic Peninsula continental shelf: Geophysical Research Letters, v. 29, no. 8, 1199, doi: 10.1029/2001GL014488.

Ottesen, D., and Dowdeswell, J.A., 2006, Assemblages of submarine landforms produced by tidewater glaciers in Svalbard: Journal of Geophysical Research, v. 111, F01016, doi: 10.1029/2005JF000330.

Ottesen, D., Dowdeswell, J.A., and Rise, L., 2005a, Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2,500 km-long Norwegian-Svalbard margin (57º–80ºN): Geological Society of America Bulletin, v. 117, p. 1033–1050, doi: 10.1130/B25577.1.

Ottesen, D., Rise, L., Knies, J., Olsen, L., and Henriksen, S., 2005b, The Vestfjorden-Trænadjupet palaeo-ice stream drainage system, mid-Norwegian continental shelf: Marine Geology, v. 218, p. 175–189, doi: 10.1016/j.margeo.2005.03.001.

Ottesen, D., Dowdeswell, J.A., Landvik, J.Y., and Mienert, J., 2007, Dynamics of the Late Weichselian ice sheet on Svalbard inferred from high-resolution sea-floor morphology: Boreas, v. 36, p. 286–306, doi: 10.1080/03009480701210378.

Shipp, S.S., Wellner, J.A., and Anderson, J.B., 2002, Retreat signature of a polar ice stream: Subglacial geomorphic features and sediments from the Ross Sea, Antarctica, *in* Dowdeswell, J.A., and Ó Cofaigh, C., eds., Glacier-influenced sedimentation on high-latitude continental margins: Geological Society of London Special Publication 203, p. 277–304.

Syvitski, J.P.M., Burrell, D.C., and Skei, J.M., 1987, Fjords: Processes and products: New York, Springer, 379 p.

Manuscript received 24 January 2008
Revised manuscript received 1 July 2008
Manuscript accepted 8 July 2008

Printed in USA