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Identification and preservation of landforms diagnostic of past ice-sheet activity on continental shelves from three-dimensional seismic evidence

Julian A. Dowdeswell
Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK
Dag Ottesen
Leif Rise
Geological Survey of Norway, Trondheim N-7491, Norway
Jonathan Craig
ENI Exploration and Production Division, Via Emilia 1, 20097 San Donato Milanese, Italy

ABSTRACT

Ice ages have occurred a number of times in Earth's history, and are important in understanding changes in long-term climate. However, it is difficult to demonstrate the presence of ice sheets in the ancient record because their sedimentary products can resemble those from nonglacial processes (e.g., debris flows). Diagnostic large-scale glacial landforms, produced beneath ice sheets and preserved on continental shelves after deglaciation, can establish a glacial origin. Three-dimensional seismic evidence from the 2.7 Ma Naust Formation, Norwegian margin, illustrates several glacial landforms that are also commonly occurring features on modern high-latitude shelves: (1) streamlined mega-scale lineations produced by fast-flowing ice streams; (2) ploughmarks formed by iceberg keels; and (3) regularly spaced transverse ridges or push moraines formed during ice retreat. We have found, for example, buried ice-keel ploughmarks on a paleoshelf dating to ca. 2 Ma. Norwegian margin seismic stratigraphy data show that ice advanced and retreated many times, and some paleoshelf surfaces were preserved. Such paleosurfaces must survive ocean basin destruction for glacial landforms to be useful in identification of ancient depositional environments.

Keywords: glacial landforms, ice streams, swath bathymetry, three-dimensional seismics, ice ages, continental shelves.

INTRODUCTION

Ice ages, periods of cold or icehouse environmental conditions, have occurred a number of times during Earth's history. Their identification is an important element in understanding how the long-term climate of our planet has changed. However, it has often been difficult to demonstrate unequivocally the presence of large ice sheets in the ancient geological record because their sedimentary products can resemble those resulting from other, nonglacial processes (Hambrey and Harland, 1981). For example, poorly sorted sediment of heterogeneous grain size, diamict, may form as a result of glacial deposition as tills or by nonglacial processes such as debris flowage. In contrast, ice-rafted debris, transported by icebergs and released by melting, includes relatively large particles or dropstones within fine-grained and sometimes laminated marine sediments, and has been used to identify the onset of both the late Cenozoic glacial age and ice ages throughout geologic time (e.g., Hambrey and Harland, 1981; Jansen and Sjøholm, 1991). We show here that the presence of diagnostic large-scale glacial landforms, produced at the base of ice sheets and preserved in subaqueous continental-shelf settings after deglaciation, may provide an additional or alternative means of establishing a glacial origin for sediments in the geological record.

Both modern and ancient ice sheets have marine margins that terminate on, or at the edge of, continental shelves (e.g., Hambrey and Harland, 1981; Dowdeswell and Scourse, 1990; Dowdeswell and Ó Cofaigh, 2002). Because of the relatively rapid delivery of sediments to ice-sheet margins, high-latitude continental shelves have built up over successive glacial cycles to form major depocenters (e.g., Anderson, 1999; Dowdeswell and Siegert, 1999; Dahlgren et al., 2002; Rise et al., 2005). Recent developments in geophysics have yielded much high-resolution data on the large-scale geometry of modern and buried surfaces on glacier-influenced margins. In particular, swath bathymetry provides very detailed images of the shape of the modern seafloor, and three-dimensional (3-D) seismic data make possible the detailed reconstruction of the form of buried surfaces. These methods allow suites of characteristic glacial landforms to be identified within the geologic record for the first time.

In this paper we use geophysical evidence to describe several sets of glacial landforms that are diagnostic of ice-sheet activity and are also commonly occurring features on high-latitude continental shelves. Our examples come mainly from the mid-Norwegian shelf, where there are many 3-D seismic blocks available and the seismic stratigraphy of the 2.7 Ma Naust Formation is relatively well understood (e.g., Ottesen et al., 2005; Rise et al., 2005). We then consider the preservation potential of paleoshelf surfaces containing diagnostic glacial landforms within large-scale sedimentary depocenters on continental margins. We show examples of similar diagnostic glacial landforms preserved within the 450 Ma Late Ordovician sediments deposited at the margins of the African ice sheet.

DIAGNOSTIC SUBGLACIAL AND ICE-CONTACT LANDFORMS

We describe and interpret the origin of three types of landform that have been observed widely in modern glaciated continental-shelf settings and that we have been able to identify in 3-D seismic data sets from late Cenozoic prograding sedimentary wedges formed at the margins of former ice sheets (Fig. 1).

Streamlined Mega-Scale Lineations Produced by Fast-Flowing Ice Streams

Lineations in seafloor sediments have been reported from cross-shelf troughs and major fjord systems on glacier-influenced continental margins in both the Arctic and Antarctic (e.g., Shipp et al., 1999; Canals et al., 2000; Ó Cofaigh et al., 2003; Andreassen et al., 2004; Ottesen et al., 2005). The streamlined lineations are elongated in the direction of trough and fjord

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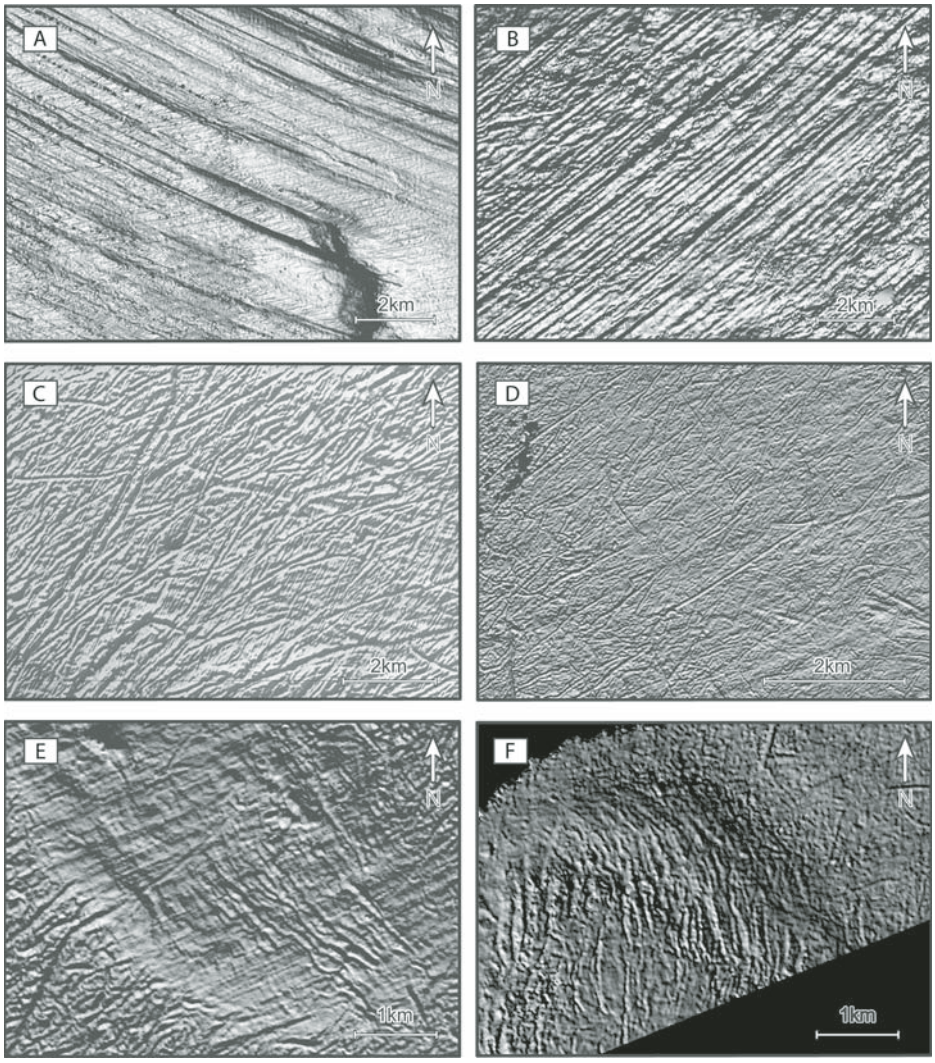

Figure 1. Seafloor and buried subglacial landforms from modern and late Cenozoic glacier-influenced continental shelves of the Norwegian margin. A: Streamlined linear bedforms on seafloor of Traenadjupet (67°N, 11°E) in 400 m water depth. Maximum ridge height is 10 m and average spacing is 400–500 m (data from three-dimensional [3-D] seismic cube ST9404). B: Streamlined linear bedforms from Traenabanken (66°30′N, 9°E), buried ~100 m below the modern seafloor. Average height of ridges is 5 m, and average spacing between ridge tops is ~300 m (data from 3-D seismic cube NLGS-95). C: Ploughmarks produced by iceberg keels in 300 m of water on seafloor of the mid-Norwegian shelf (64°25′N, 7°45′E) (data from 3-D seismic cube SH-9002). D: Buried ice-keel ploughmarks on Traenabanken (66°N, 9°E), ~100 m below modern seafloor (data from 3-D seismic cube NNE2000). E: Series of retreat moraines from seafloor of Traenabanken (66°15′N, 9°E) in 250 m water depth. Average height is 3 m and average distance between ridges is ~100 m (data from 3-D seismic cube NNE2000). F: Series of buried retreat moraines (~15 m below seafloor) from Traenabanken (66°20′N, 10°E). Average distance between ridges is 150 m with amplitude of 5 m (data from 3-D seismic cube NNE2000).

long axes. Their lengths vary from hundreds of meters to several tens of kilometers, with wavelengths from 0.1 to 3 km and heights from a few meters to ~15 m. Examples in 3-D seismic data sets from the seafloor in Traenadjupet, north Norway, and from a surface buried beneath ~100 m of sediment on nearby Traenabanken are shown in Figures 1A and 1B. These streamlined sedimentary lineations are known as mega-scale glacial lineations, or MSGL (Clark, 1993; Stokes and Clark, 1999). They are formed from soft-sediment deformation at the base of fast-flowing ice streams draining large ice sheets (Tulaczyk et al., 2001; Dowdeswell et al., 2004; Ó Cofaigh et al., 2005). They represent the direction of past ice flow and are widely regarded as diagnostic of the presence and dimensions of fast-flowing ice streams in the geologic record (Clark, 1993).

Sets of MSGL, tens of kilometers wide and as long as several hundred kilometers, have been identified from parts of almost all modern high-latitude shelves that have been ice covered during the late Quaternary and for which observations are available (e.g., Wellner et al., 2001; Stokes and Clark, 2001; Ottesen et al., 2005). Given that ice streams and outlet glaciers flowing at 10^2 to 10^3 m yr^{-1} are found in all modern ice masses, from ice caps of 10^3 km^2 to the great ice sheets of Antarctica and Greenland (e.g., Bamber et al., 2000; Dowdeswell et al., 2002; Rignot and Kanagaratnam, 2006), these sedimentary lineations, where preserved, are expected to be a characteristic feature of ancient ice-sheet–derived sediments (e.g., Moreau et al., 2005).

Scours or Ploughmarks Formed by Iceberg Keels

Linear or curvilinear features, usually formed in an irregular pattern and crosscutting one another, are very common on ice-influenced continental shelves in both polar regions (e.g., Woodworth-Lynas et al., 1985; Barnes and Lien, 1988; Dowdeswell et al., 1993). The features are from a few meters to a few tens of kilometers long, as much as ~1 km wide, and as deep as ~15 m. They often have raised berms on either side of a central depression. Examples of ploughmarks from the modern seafloor of the mid-Norwegian shelf at 64°N and from a paleosurface buried 100 m beneath Traenabanken (66°N) are shown in Figures 1C and 1D, respectively. These submarine landforms are produced by the keels of icebergs or, in water <~20 m deep, sea ice grounding on the seafloor. The continuing forward motion of ice keels in contact with and cutting through the seabed produces the ploughmarks (Woodworth-Lynas et al., 1991). Shifts in direction within and between individual ploughing events result from changes in iceberg drift track related to currents and wind.

The production of icebergs and the presence of iceberg ploughmarks on the seafloor indicate that ice built up on land and spread out to reach the sea. Icebergs with keels as deep as ~500 m are produced in large numbers by fast-flowing ice streams and outlet glaciers of the Greenland and Antarctic ice sheets (e.g., Dowdeswell et al., 1992). For example, >90% of the ~500,000 km^2 continental shelf around Greenland is affected by scouring as a result of the drift of icebergs (Dowdeswell et al., 1993). Ploughing is therefore almost ubiquitous on high-latitude shelves. We would therefore expect similar landforms to be prevalent on ancient shelves where glaciers and ice sheets once developed and grew to reach sea level and to produce icebergs. Similar to the first occurrence of dropstones associated with iceberg rafting of debris to the deep sea being used to indicate the beginning of an ice age (e.g., Jansen and Sjøholm, 1991), the same conclusion can be drawn from the initiation of iceberg ploughing on ancient continental shelves.

Regularly Spaced Transverse Ridges or Push Moraines Formed During Ice Retreat

Groups of regularly spaced small ridges, oriented tranverse to ice flow, are often found beyond the margins of retreating glaciers in both terrestrial and marine environments (Sharp, 1984;

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Boulton, 1986). Individual ridges are usually a few meters high, have an average width of ~50 m, and are spaced a few hundred meters apart. These ridges are fairly evenly spaced, subparallel to one another, and are almost always found in clusters rather than as isolated individual features. Examples are shown from the modern seafloor of Traenabanken and from a paleosurface buried ~15 m beneath the surface (Figs. 1E, 1F). Such sets of transverse ridges are interpreted as series of small push moraines, produced annually when a glacier terminus undergoes minor readvance each winter during more general retreat (Boulton, 1986). Winter readvance of tidewater glaciers is a result of the suppression of iceberg calving due to the presence of winter shorefast sea ice. Evidence that individual transverse ridges are produced annually comes from mapping ridge locations against the known positions of the terminus of modern glaciers (Sharp, 1984; Ottesen and Dowdeswell, 2006).

Groups of these landforms cover areas as great as a few tens of square kilometers in modern continental shelf and fjord settings. These features are smaller in size than MSGL and are more restricted in spatial extent than both the MSGL and iceberg ploughmarks described here. They are, however, characteristic landforms produced at the ice front of many retreating tidewater glaciers that are grounded but are not fast flowing.

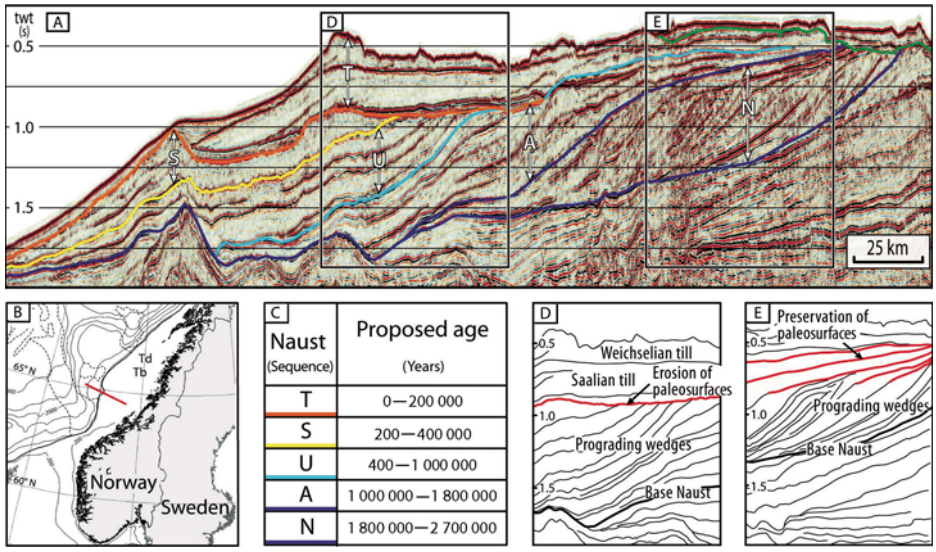

Figure 2. A: Seismic-stratigraphic section (GMNR-94–105) across shelf and slope on the mid-Norwegian margin showing sedimentary wedge making up the glacier-influenced 2.7 Ma Naust Formation (twt—two-way traveltime; 1 s is ~1000 m of sediment thickness). Letters represent five sequences within formation. B: Location of seismic line on Norwegian margin. Td—Traenadjupet; Tb—Traenabanken. C: Subdivisions and proposed ages for Naust Formation (Rise et al., 2005). Boundaries between units are color coded and shown in A. Interpreted parts of the seismic section in A show truncation of prograding wedges (marked in red) and removal of paleoshelf surfaces (D) and preservation of prograding wedges and their buried shelf surfaces (E; marked in red).

PRESERVATION OF BURIED SURFACES AND GLACIAL LANDFORMS IN ANCIENT SEDIMENTS

Landforms diagnostic of glacial activity must be preserved in the geologic record in order to be useful indicators of the presence of ice sheets in ancient sediments. Ice sheets, and especially the fast-flowing ice streams within them, deliver large quantities of sediment to continental margins (e.g., Dowdeswell and Siegert, 1999; Rise et al., 2005; Dowdeswell et al., 2006), building prograding wedges as thick as several kilometers over the successive glacial-interglacial cycles that together form an ice age. The seismic stratigraphy of the 2.7 Ma Naust Formation on the Norwegian margin provides examples of both the erosion and preservation of buried continental-shelf surfaces representing former ice-sheet activity (Fig. 2) (Rise et al., 2005).

As ice sheets advanced and retreated across the Norwegian margin during the late Cenozoic, a series of prograding wedges was formed by the delivery of glacial sediments during successive ice advances (Dahlgren et al., 2002; Rise et al., 2005). The sediments are 1.5 km thick and shelf-edge progradation is as much as 150 km (Fig. 2A). However, not all of the former glacier beds or paleosurfaces have been preserved in this series of large-scale depocenters. Ice advanced many times across the former shelf, and a number of the paleosurfaces were eroded by the ice. The sloping faces of several individual wedges are illustrated in Figure 2D, but the paleoshelf has been removed in each case. The situation is different in Figure 2E, where both the sloping faces and the subhorizontal paleoshelves survived subsequent ice readvance to be preserved within the Naust Formation. Where loading of the shelf with glacier-derived sediments results in subsidence, the probability of preservation of paleosurfaces is increased through the continuing provision of accommodation space. We have observed ice-

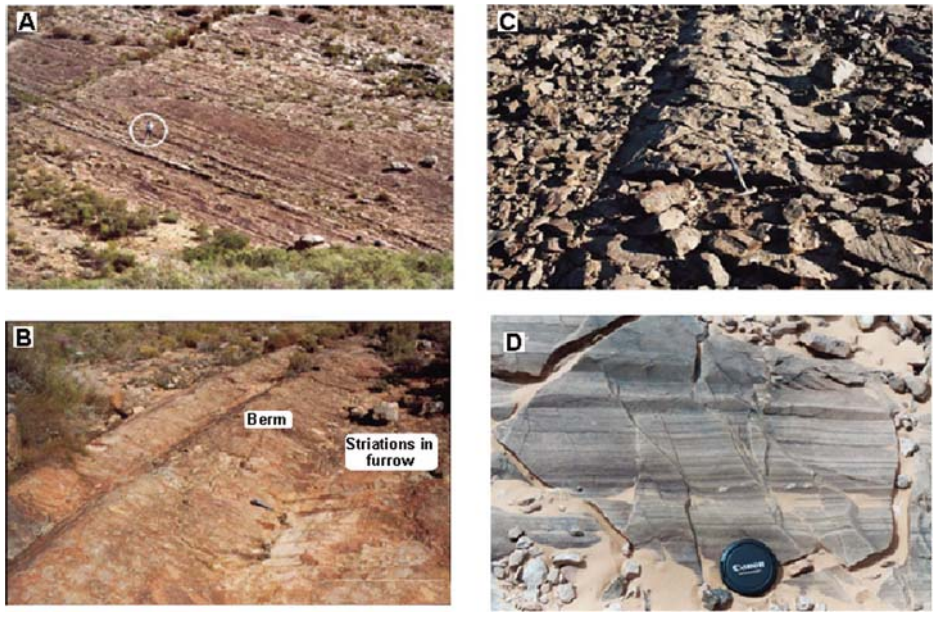

Figure 3. Examples of landforms diagnostic of past glacial activity in Late Ordovician sediments of North and South Africa. A: Fluted soft-sediment striated surface at the top of the Late Ordovician Peninsula Formation, Pakhuis Pass, South Africa. Note circled person for scale. B: Detail of berms and furrows with parallel striations on fluted soft-sediment surface at the top of the Late Ordovician Peninsula Formation, Pakhuis Pass, South Africa. C: Detail of ridge with associated cross-fractures on fluted soft-sediment striated surface in the Late Ordovician Tamadjert Formation, Dider, Algeria, North Africa. Photograph is ~2 m across. D: Detail of soft-sediment striated surface within the Late Ordovician Mamuniyat Formation, Gargaf Arch, Libya, North Africa.

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keel ploughmarks on paleoshelves in the upper part of the Naust N sequence, dating to ca. 2 Ma (Fig. 2C), in 3-D seismic cube NLGS-95.

A seismic stratigraphy that includes undisturbed sedimentary wedges, containing both the sloping face and paleosurface of a former continental shelf, is required for the long-term preservation of the diagnostic glacial landforms described above. The presence or absence of such surfaces can be identified with relative ease on conventional seismic records (Fig. 2A), although 3-D data sets are required in order to image the detailed morphology of these paleoshelves (Fig. 1).

Continental-margin depocenters must survive ocean-basin closure and destruction at plate margins in order for glacial landforms to be a useful tool in the identification of ancient depositional environments. Intracratonic, passive margin, and ocean basins have particularly long lives (Woodcock, 2004). Evidence from the 450 Ma Late Ordovician rocks of North and South Africa shows clearly that suites of glacial landforms are preserved and exposed at the surface (Fig. 3), allowing the identification of ice streams within a former ice sheet (e.g., Le Heron et al., 2005; Moreau et al., 2005). The 3-D seismic records from these Late Ordovician rocks are now being examined for the presence of buried landforms diagnostic of past glacial activity.

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