Current-modified recessional-moraine ridges on the northwest Spitsbergen shelf

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Terminal and recessional moraine ridges are built up on high-latitude continental shelves and in fjords during glacial maxima and still-stands punctuating deglaciation. Such ridges are often found in association with relatively shallow banks and are seldom located in major cross-shelf troughs where past ice streams tend to have produced subglacial landforms streamlined in the direction of former ice flow (e.g. Dahlgren *et al*. 2002; Dowdeswell & Elverhøi 2002; Ottesen & Dowdeswell 2009). Many of these ridges are relatively large, at tens of metres in height above the general level of the seafloor, and have been modified little during the Holocene (e.g. Ottesen *et al*. 2005). The preservation of these prominent submarine glacial landforms is often linked to relatively low interglacial sedimentation rates and to the low-energy process environment that is typical of many polar shelves after deglaciation. An exception, however, is where moraine ridges are present at relatively shallow water depths, a situation sometimes enhanced by isostatic rebound during the Holocene. In these circumstances, current and wave action can result in significant modification of moraine ridges.

Description

A prominent set of large, arcuate sedimentary ridges (Fig. 1a-c) was first reported from the relatively shallow inner continental shelf of northwest Spitsbergen, beyond the mouth of Raudfjorden (Fig. 1f), by Liestøl (1972). The ridges were identified initially from single-beam echo-sounder data, and have since been imaged in more detail using swath-bathymetric methods (Ottesen & Dowdeswell 2009). Each ridge lies approximately transverse to the direction of past ice flow from the adjacent fjord to the shelf edge.

Four prominent moraines ridges, several with bifurcating crests, are present on the inner shelf (Fig. 1b). They are spaced about 1 to 2 km apart (Fig. 1b) and stand up to about 30 m above the surrounding seafloor (Fig. 1d, e). Several of the ridges have easily recognisable flat tops with wave-like bedforms superimposed upon them (Fig. 1a-c). Crest-to-crest spacing of the bedforms is on the order of tens of metres and amplitudes are just a few metres at most (Fig. 1a, c, e). Some of the moraine ridges appear to be asymmetrical in cross-section, with steeper faces on their shoreward, ice-proximal flanks (Fig. 1a); the transition from flat-top to steep flank is often abrupt (Fig. 1d, e).

Between the four large ridges, and extending further out onto the shelf beyond the most distal ridge, are several sets of smaller moraine ridges, also orientated transverse to former ice-flow (Fig. 1a, b). These smaller ridges are only a few metres in height and are usually spaced a few hundred metres apart. They are an order of magnitude less high than the four large ridges, and their crests are clearly sharper in form than the relatively flat tops of the larger moraines (Fig. 1a).

Interpretation

The four large ridges are interpreted as recessional moraines formed during still-stands or minor readvances of the ice sheet that covered Svalbard at the Last Glacial Maximum (Ottesen & Dowdeswell 2009). Their arcuate plan-form (Fig. 1a) probably reflects that of the retreating ice-sheet terminus. The smaller sets of ridges are interpreted to mark shorter halts in deglaciation which, assuming a relatively constant sediment delivery rate to the ice margin.

The detailed shape of the larger ridges is likely to be explained by their relatively shallow depth below the sea-surface (Fig. 1a-c). Their prominent flat crests are located in only about 30 to 35 m of water (Fig. 1d, e). The smaller wave-like bedforms on these flat surfaces are interpreted as sediment waves, which are usually produced by currents with a velocity often in excess of 0.5 m s^{-1} (e.g. Dyer & Huntley 1999). The asymmetry of the ridges, with a very steep face on one side, orientated sub-parallel to the sediment-wave crests (Fig. 1a, c), also implies the migration of sediment across the flat-topped ridges driven by current action. Unmodified terminal and recessional moraine ridges in both submarine and terrestrial glacier-influenced environments are typically asymmetrical, with a steeper ice distal face (Benn & Evans 2010). This is the opposite of the ridge asymmetry imaged in Figure 1a, where steeper ice-proximal faces are probably produced by current-driven sediment supply from the north and northeast, causing migration of the landform inshore and to the southwest. The steep, and in some places hooked, shoreward face of the ridges supports this inferred direction of migration (Fig. 1a).

In addition, the large ridges have probably also been affected by the action of storm waves (e.g. Komar 1997). Wave base, the maximum depth to which a wave's passage causes significant water motion is typically 15–40 m for storm waves. This process, too, could therefore lead to the observed erosion of the ridge crests. This argument is supported by the sharper crests present on the smaller, deeper moraines present between the large ridges; water motion by both currents and storm-wave action would reduce in such deeper water.

High-latitude continental shelves are often low-energy settings during interglacial periods, because the locus of sediment and meltwater deliver has shifted from the shelf to inner fjords after regional ice-sheet retreat from full-glacial conditions. When, however, submarine landforms occur relatively close to the modern sea-surface, they can be affected by coastal marine processes, including both wave and current action (Komar 1997), and may undergo significant modification and reworking as a result.

References

BENN, D. I. & EVANS, D. J. A. 2010. *Glaciers and Glaciation* (2nd Edition) 802 pp, Hodder.

DAHLGREN, K. I. T., VORREN, T. O. & LABERG, J. S. 2002. The role of grounding-line sediment supply in ice-sheet advances and growth on continental shelves: an example from the mid-Norwegian sector of the Fennoscandian ice sheet during the Saalian and Weichselian. *Quaternary International*, **95–96**, 25–33.

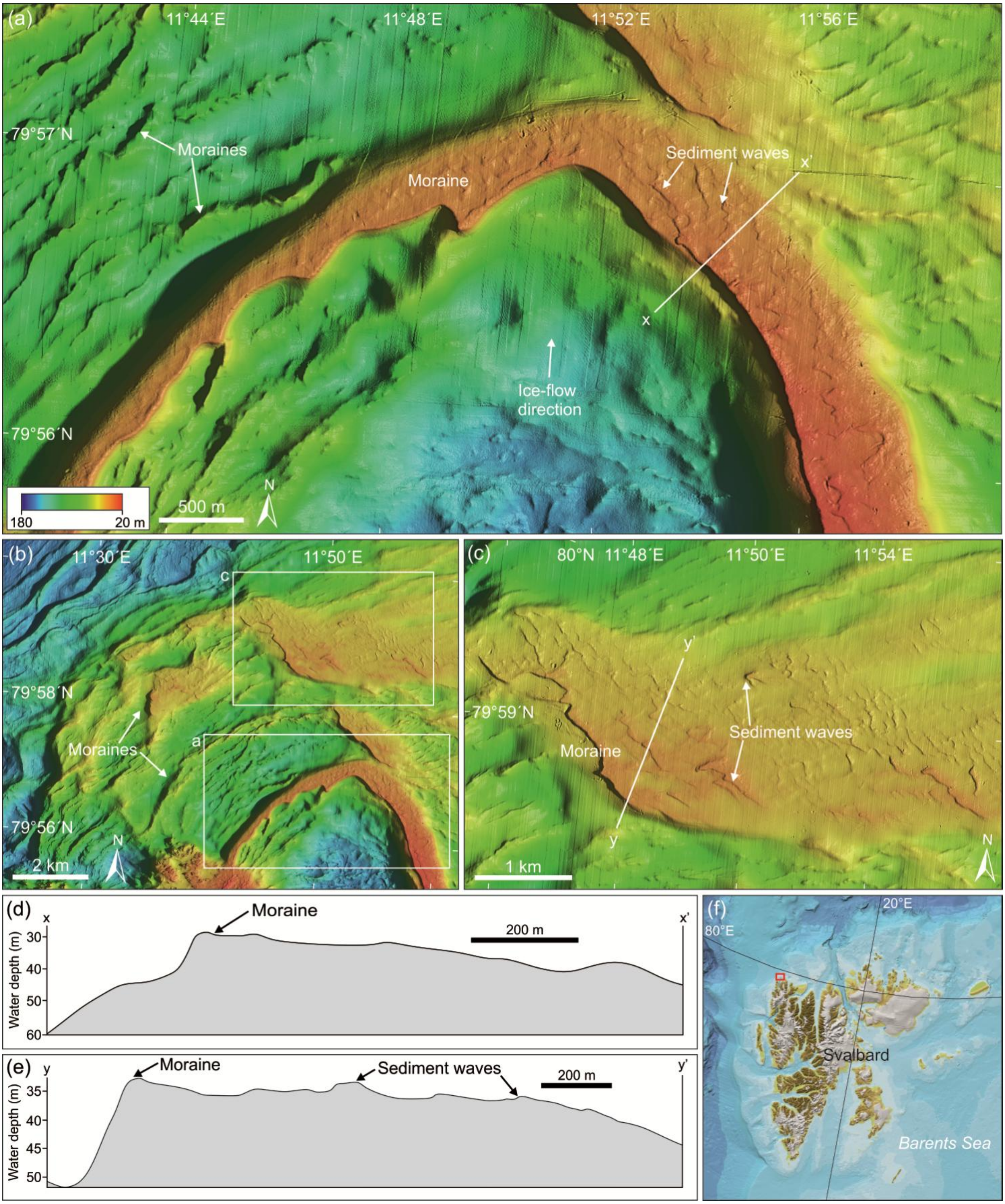
DOWDESWELL, J. A. & ELVERHØI, A. 2002. The timing of initiation of fast-flowing ice streams during a glacial cycle inferred from glacimarine sedimentation. *Marine Geology*, **188**, 3–14.

DYER, K. R. & HUNTLEY, D. A. 1999. The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, **19**, 1285–1330.

KOMAR, P. D. 1997. *Beach Processes and Sedimentation* (2nd Edition). Prentice-Hall.

LIESTØL, O., 1972. Submarine moraines off the west coast of Spitsbergen. *Norsk Polarinstitutt Årbok 1970*, 165–168.
OTTESEN, D. & DOWDESWELL, J. A. 2009. An inter-ice stream glaciated margin: submarine landforms and a geomorphic model based on marine-geophysical data from Svalbard. *Geological Society of America Bulletin* **121**, 1647–1665.
OTTESEN, D., DOWDESWELL, J. A. & RISE, L. 2005. Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: the 2500-km-long Norwegian-Svalbard margin (57°–80°N). *Geological Society of America Bulletin* **117**, 1033–1050.

Fig. 1. Current-modified moraine ridges at the mouth of Raudfjorden, NW Spitsbergen. (a) Swath-bathymetric image of a large arcuate recessional moraine ridge and smaller transverse moraine ridges on the continental shelf about 10 km from the mouth of Raudfjorden. For a, b, c the acquisition system is Kongsberg EM1002. Frequency 97 kHz. Grid-cell size 2 m. (b) Swath-bathymetric imagery of the set of arcuate recessional moraines on the NW Spitsbergn shelf beyond Raudfjorden (panels a and c are located). (c) Sediment waves imaged on the surface of a moraine being reworked by current activity (located in Fig. 1b). (d) and (e) Bathymetric profiles through the current-modified moraines shown in a and c. VE x 6 and 15, respectively. (f) Location of study area (red box; map from IBCAO v. 3.0). Swath-bathymetric images courtesy of the Norwegian Hydrographic Service (Permission no. 14/G754).



(a)
11°44´E
11°48´E
11°52´E
11°56´E
79°57´N
79°56´N
Moraines
Moraine
Sediment waves
x'
x
Ice-flow direction
180
20 m
500 m
N
(b)
11°30´E
11°50´E
c
a
79°58´N
79°56´N
Moraines
2 km
N
(c)
80°N
11°48´E
11°50´E
11°54´E
79°59´N
y'
y
Moraine
Sediment waves
1 km
N
(d)
x
x'
Moraine
200 m
Water depth (m)
30
40
50
60
(e)
y
y'
Moraine
Sediment waves
200 m
Water depth (m)
35
40
45
50
(f)
20°E
80°E
Svalbard
Barents Sea