Fan-like sediments on outer Haltenbanken, mid-Norwegian shelf

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Subaqueous fans, formed in marine and lacustrine settings, have been reported from both Quaternary and more ancient glacier-influenced environments (e.g. Powell 1990; Dowdeswell *et al*. 2015). Their presence is often taken to imply a palaeo-glacial environment abundant in sediment-rich meltwater, whose load was sourced from glacial erosion and transported in subglacial channels to the ice margin. The sedimentology of these fans sometimes exhibits bedforms indicative of high-energy water-flow (e.g. Winsemann *et al*. 2009), suggesting that sudden drainage events may be important in the formation of some glacier-influenced submarine fans.

Description

A fan-like sedimentary depocentre occurs on the mid-Norwegian shelf on outer Haltenbanken, about 30 km east of the shelf edge at approximately 300 m water depth (Fig. 1a, d). It has an oval or lobe-shaped form and a relatively smooth surface where it is undisturbed by subsequent reworking. The feature's longest axis trends WSW-ENE and has a maximum length of 14 km and a maximum width of 7 km, covering an area of about 70 km^2. From bathymetric profiles across the fan, indicating its elevation above the level of the surrounding seafloor (profiles x–x' and y–y' in Fig. 1e), a maximum thickness of 30 m and a volume of 1 to 2 km^3 of sediment is inferred, indicating that the fan-like feature makes up a large local depocentre.

Beyond the fan-like deposit, a series of small ridges with a generally NNW-SSE direction is found (Fig. 1a, c); ridge orientations are approximately transverse to the inferred direction of ice flow when ice covered Haltenbanken at the Last Glacial Maximum. The average height of the ridges is about 5 m and the mean spacing is approximately 200 m. The fan-like depocentre clearly blankets and overprints the sets of ridges (Fig. 1a, d), making it the younger of these two depositional landforms.

Superimposed on both the transverse ridges and the fan-like deposit, reworking its formerly smooth surface, is a series of irregularly distributed narrow depressions, some with lateral berms (Fig. 1a). The predominant orientation of these linear depressions is NE-SW, although a sub-set on the east side of the fan-like deposit has a more southerly component (Fig. 1c). In addition, close to the fan toe, some depressions have a more chaotic appearance and cross-cut the more linear depressions (Fig. 1a, c). The depressions are the youngest morphological features in the area, with the chaotic depressions the youngest among the depressions themselves. To the north-east of the apex of the fan-like depocentre, there are four arcuate escarpments of between 10 and 30 m in height and 15 km in length, with two longer but similarly shaped features further to the north (Fig. 1d, e).

Interpretation

The oval-shaped sedimentary depocentre is interpreted as a submarine fan due to its overall geometry and clear apex, its blanketing of the small transverse ridges, its relatively smooth appearance (where undisturbed), and its relatively small thickness (estimated maximum of about 30 m). The depocentre is probably an ice-proximal fan produced by meltwater deposition. Geotechnical measurements acquired during borehole drilling near the fan apex show that up to 5 m of soft material (<50 kPa) is underlain by much stiffer debris (>150 kPa) (Forsberg & Pederstad 2009); the former is interpreted as debris forming the depocentre by water delivery from point source(s), probably overlying stiffer diamictic sediment linked to ice loading during the Late Weichelian glaciation. Thinning of the fan towards its apex may be explained by retreat of the ice front and subglacial channel mouth during deposition. The ridges blanketed by the depocentre are interpreted as small retreat moraines formed at a grounded tidewater-influenced ice margin as it retreated across the shelf towards the Norwegian coast from a full-glacial position (e.g. Todd *et al*. 2007). Morphologically, the four arcuate scarps north-east of the fan (Fig. 1d, e) appear similar to rotational slide blocks imaged on the huge Storegga Slide on the continental slope to the south (Haflidason *et al*. 2005), although their relatively high shear strength indicates they may be moraine ridges (Forsberg & Pederstad 2009).

Evidence for meltwater activity is relatively sparse on the mid-Norwegian shelf; there are few submarine landforms characteristic of channelised water flow and there is little evidence of major meltwater deposition (e.g. Ottesen *et al*. 2005). The source of the sediment-rich water inferred to have produced the fan may have been due to an outburst flood linked perhaps to the drainage of an ice-dammed lake when the ice margin was close by, or to earthquake activity (Olesen *et al*. 2004), or to failure processes that may have produced the escarpments immediately to the north-east of the fan apex (Fig. 1d). Either of the latter two mechanisms may have led to opening of new drainage pathways, leading to high-magnitude water release.

The depressions on the fan surface are interpreted as the ploughmarks of iceberg keels. The more linear sets of ploughmarks were probably produced at or close to the time of fan formation, when turbid water was released, probably rapidly, to form the depocentre and to transport icebergs directly away from the palaeo-ice margin. Once the flood was over, icebergs would have been free to drift along typically more irregular tracks, forming the more chaotic pattern of ploughmarks that represents the youngest landform on the fan surface (Fig. 1a, c). The dimensions, geometry and thickness of the fan on Haltenbanken are similar to those reported from, for example, subaqueous fans produced by flood events at the southern margin of a mid-Pleistocene Eurasian Ice Sheet (Winsemann *et al*. 2009).

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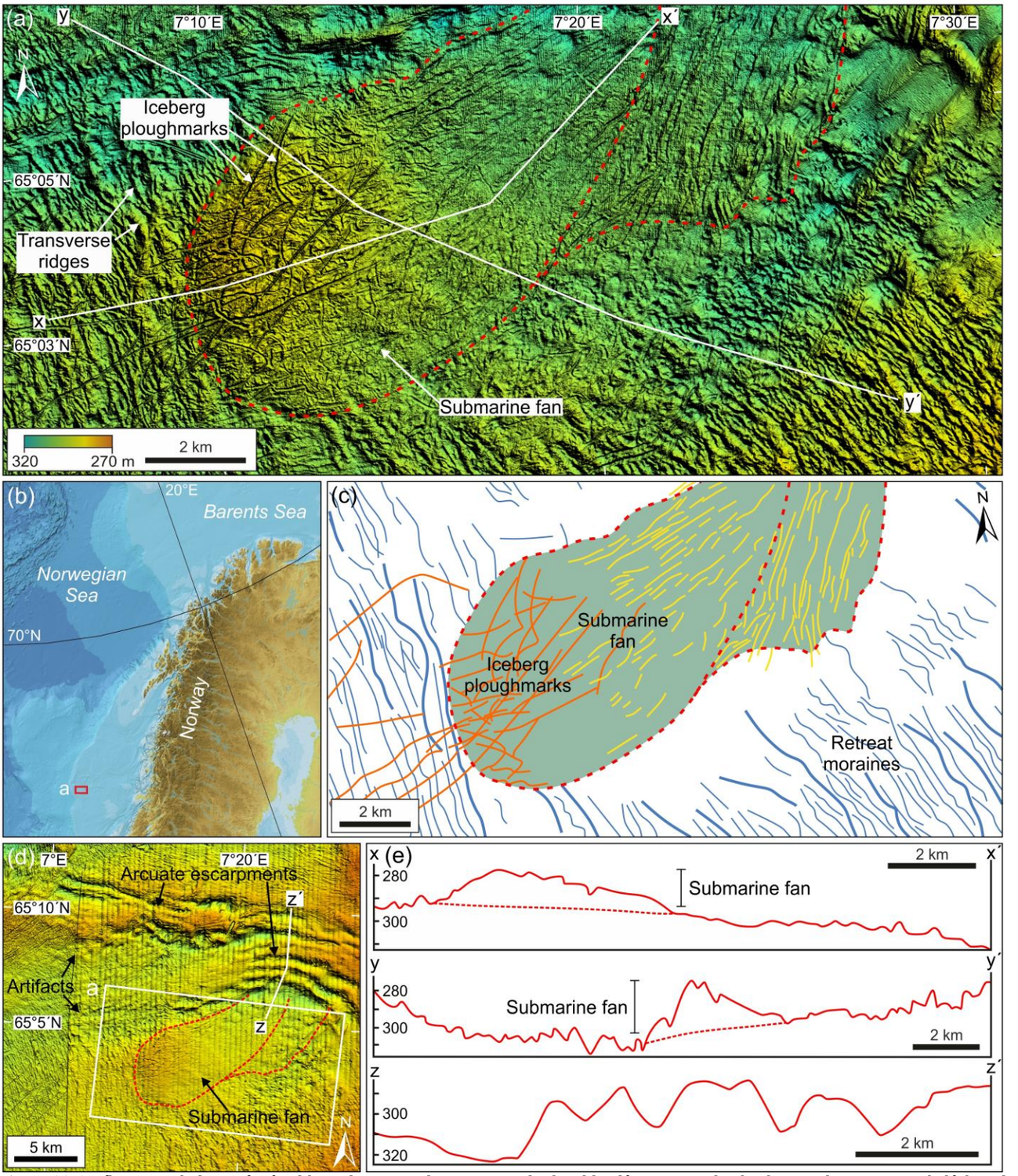

Fig. 1. (a) Seafloor morphology of a fan-like sedimentary depocentre and related landforms on Haltenbanken, mid-Norwegian shelf, based on high-resolution multibeam bathymetry. Acquisition system Kongsberg EM1000. Frequency 95 kHz. Grid-cell size 5 m. (b) Location of study area (red box; map from IBCAO v. 3.0). (c) Interpretation of morphological features in (a). Linear iceberg ploughmarks are coloured yellow and more chaotic ploughmarks in orange. Light and dark blue lines are smaller and relatively larger retreat moraines. (d) Regional seafloor morphology from the surface pick of 3D seismic data. Grid cell size 25 m. (e) Bathymetric cross-profiles of the sedimentary depocentre and adjacent escarpments, located in (a) and (d). Dashed lines represent inferred base of depocentre. VE is x 50 for x–x', x 55 for y–y, and x 33 for z–z'. The multibeam and 3D seismic imagery, and the geotechnical data, are courtesy of Statoil ASA.