Deeply buried glacigenic-debris flows imaged in 3D-seismic data from the early Quaternary sediments of the northern North Sea

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Debris flows composed of diamictic glacial sediment are found on the continental slope offshore of many former ice streams in the Arctic and Antarctic (Vorren *et al*. 1998). The debris flows are often stacked, making up important building-blocks of the major trough-mouth fans that form huge depocentres on high-latitude margins (e.g. Laberg & Vorren 1995; King *et al*. 1996; Taylor *et al*. 2002). Such debris flows have been investigated previously using 2D-seismic methods and have also been mapped in plan using side-scan sonar and multibeam systems (Vogt *et al*. 1993; Dowdeswell *et al*. 1996; Nygård *et al*. 2002; Pedrosa *et al*. 2011). 3D-seismic data can be used to image and map these and other glacigenic landforms buried within Quaternary sediments (e.g. Dowdeswell & Ottesen 2013).

Description

During the early Quaternary, the northern North Sea (Fig. 1e) was part of an open 100-150 km-wide N-S-trending basin between Norway and the Shetland Islands (Ottesen *et al*. 2014). This basin was infilled from the east, with shelf-progradation towards the west and northwest represented by a series of sedimentary clinoforms between 59 and 62°N (Fig. 1c, d). Individual clinoforms dip at between 0.5 and 1.5° and are buried beneath hundreds of metres of overlying sediment. They downlap onto the relatively flat base-Naust surface and its equivalent in the North Sea (Fig. 1c, d). This surface represents the base of the Quaternary, and the beginning of glacier-influenced sedimentation in the Norwegian and North seas (Ottesen *et al*. 2009, 2014). When clinoform surfaces are mapped out in plan-form from data in 3D seismic cubes, lobe-like features are observed that trend downslope in a generally NW or W direction (Fig. 1a, b).

Many of the clinoforms are cut in their upper parts by an Upper Regional Unconformity (URU) surface (Fig. 1c, d) which here represents the base of the Norwegian Channel. The Norwegian Channel itself was eroded by ice streams since about 0.5 M yr ago (Ottesen *et al*. 2014). The composition of the clinoform sediments from drill cores is generally fine-grained diamict with outsized clasts, interpreted as Ice-Rafted Debris (IRD), together with occasional thin sandy layers (Eidvin *et al*. 2013).

Interpretation

In plan-form, the lobe-like features observed in 3D seismic cubes (Fig. 1a, b) clearly resemble the geometry and dimensions of late Weichselian glacigenic-debris flows on the North Sea Fan immediately north of our study area (King *et al*. 1996; Taylor *et al*. 2002). Glacigenic-debris flows close to the surface of the North Sea and Bear Island fans have typical widths of about 2-10 km, thicknesses of 10-50 m, and lengths of 30-200 km down the faces of these large Late Weichselian trough-mouth fans (e.g. Taylor *et al*. 2002). The clinoforms are therefore inferred to be glacigenic-debris flows with an internal architecture similar to those reported from many late Weichselian trough-mouth fans on Arctic and Antarctic margins (e.g. Laberg & Vorren 1995; Dowdeswell et al. 1996; Vorren *et al*. 1998; Nygård *et al*. 2002; Ottesen *et al*. 2009).

The glacigenic-debris flows are interpreted to have been sourced from an ice sheet covering most of southern Norway during parts of the early Quaternary (Ottesen *et al*. 2014). In the Norwegian Sea, the frequency of IRD increased markedly from 2.75 Myr ago (Jansen & Sjøholm 1991), reflecting the growth and expansion of the ice cover of northern Europe and demonstrating that ice-sheet termini reached the sea west of Scandinavia to deliver basal sediments and debris-laden icebergs into the northern North Sea and the Norwegian Sea during the early Quaternary (Fig. 1e). The palaeo-ice sheet reached the shelf break, which was located a few kilometres outside the coast of Norway at that time, delivering deformable sedimentary debris from its base. This glacigenic debris failed on the upper slope, infilling the basin as demonstrated by the observed debris flows (in plan) and clinoforms (in cross-section) (Fig. 1a-d). The vertical extent of the clinoforms, which represent the surface of palaeo-debris flows, provide an indication of the depth of the basin during deposition, which was at least 600 m.

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From: DOWDESWELL, J. A., CANALS, M., JAKOBSSON, M., TODD, B. J., DOWDESWELL, E. K. & HOGAN, K. A. (eds) *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. Geological Society, London, Memoirs, **xx**, 1-2. DOI: xx.xxxx/xxx.x.

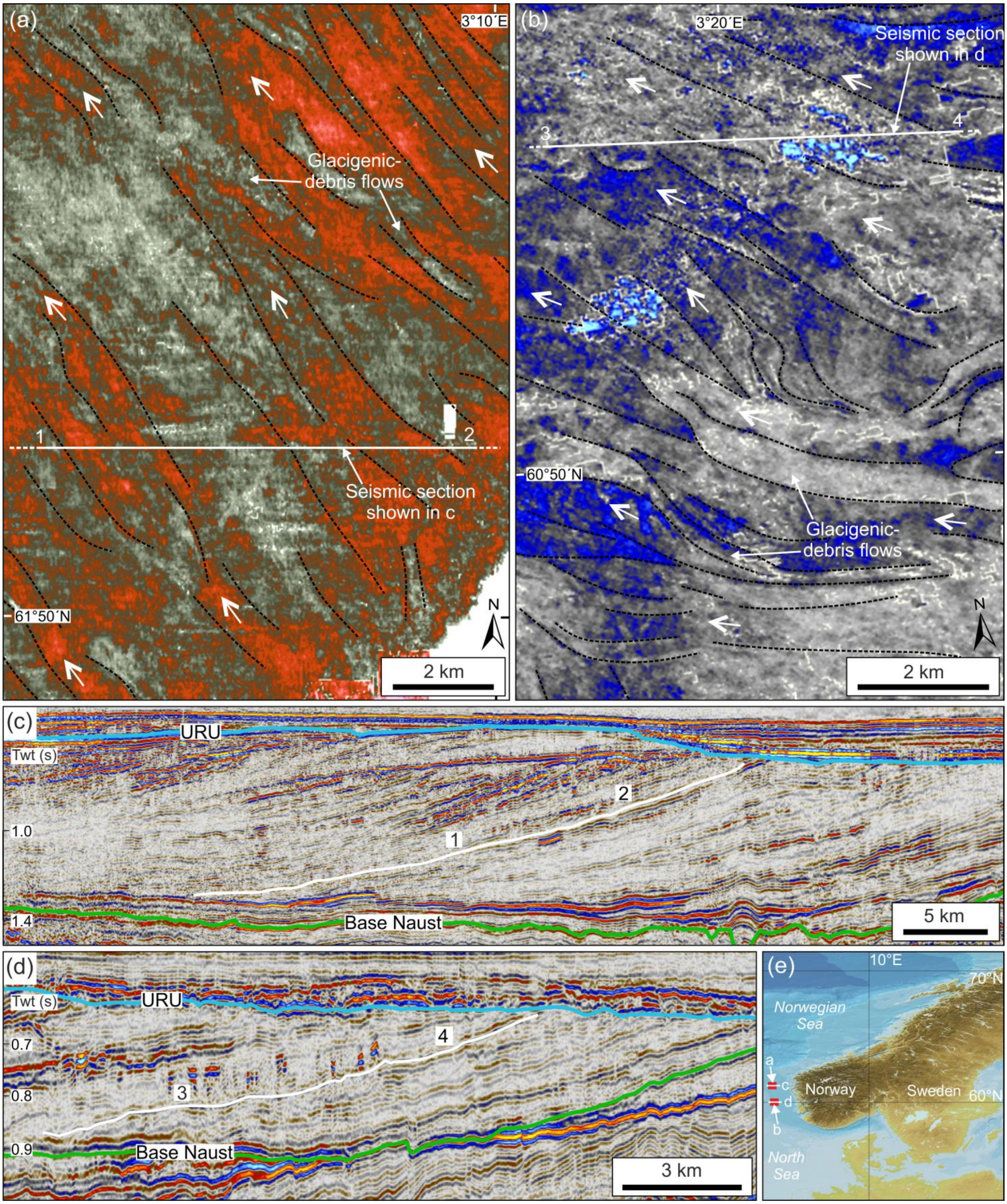

Fig. 1. (a) and (b) Seismic amplitude maps showing amplitude variations on the interpreted surfaces shown as white lines in (c) and (d). These amplitude variations show sets of glacigenic-debris flows on buried clinoforms in the northern North Sea (located in e). White arrows represent the direction of glacigenic-debris flows on buried clinoforms in the North Sea (located in e). Modified from Ottesen *et al*. (2014). (c) and (d) Seismic profiles with a series of buried clinoforms and debris flows in the northern North Sea. VE x 9. White lines x-x' and y-y' mark the interpreted horizons shown in (a) and (b). The locations of numbers 1 to 4 on the interpreted horizons correspond with the locations of numbers 1 to 4 on the seismic amplitude maps in (a) and (b). URU is the Upper Regional Unconformity (light blue), which is the erosive base of the Norwegian Channel in this area (Fig. 1e). (e) Location of study area, with amplitude maps (a, b) and seismic profiles (c, d) shown (red boxes; map from GEBCO_08).