Geohazard studies offshore the Faroe Islands: slope instability, bottom currents and sub-seabed sediment mobilisation

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Prior to the 1990s only few geological investigations of the seabed and the shallow geology around the Faroe Islands had been undertaken (Waagstein & Rasmussen 1975; Nielsen *et al.* 1981). However, in the 1990s marine geological and in particular seismic investigations were markedly intensified. Since 1993 several studies on the structure of the Faroe Islands margin and seafloor processes have been funded by the European Union, namely the ENAM (European North Atlantic Margin) project I and II (1993–1999) and the STRATAGEM (Stratigraphy of the Glaciated European Margin) project (2000–2003), and these have provided significant new information on the mechanisms shaping the Faroe Islands margin (e.g. Boldreel *et al.* 1998; Kuijpers *et al.* 1998a; Nielsen & van Weering 1998; van Weering *et al.* 1998). Due to the expertise and regional geological knowledge obtained during these projects the Geological Survey of Denmark and Greenland (GEUS) became involved in so-called 'geohazard' seabed studies of the Faroe–Shetland Channel in 1997. These investigations were financed by the petroleum industry that had begun to show significant interest in exploration of the Faroe–Shetland Channel area. The studies focused on possible natural risks that would affect

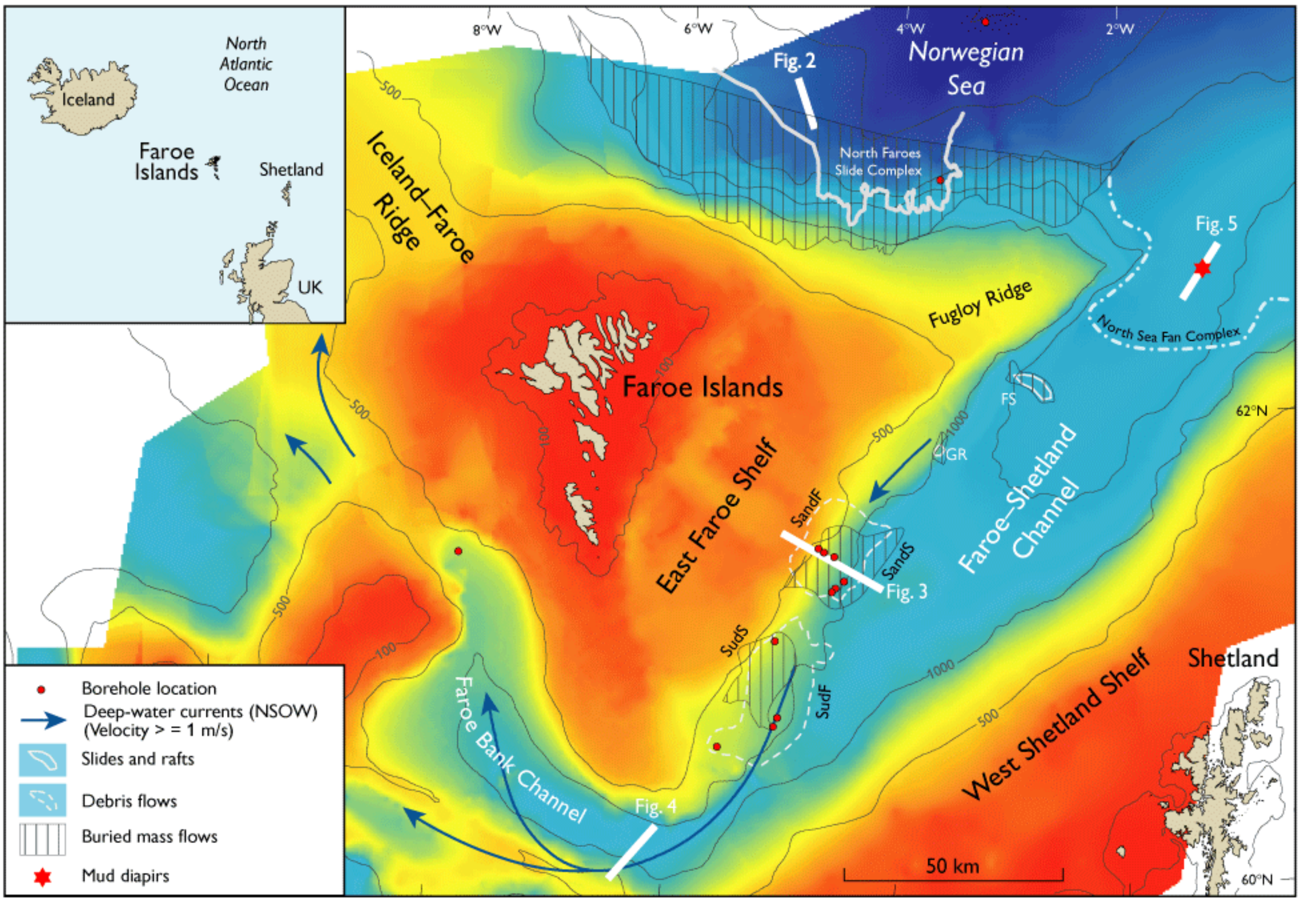

Fig. 1. Overview of the Faroe Platform area with locations of major mass flow deposits, the pathway of high-energy Norwegian Sea overflow water (**NSOW**), and location of the mud diapirs at the northern entrance of the Faroe–Shetland Channel. **FS**, FOIB slide; **GR**, GEM raft; **SandF**, Sandoy fan; **SandS**, Sandoy slump; **SudF**, Suðuroy fan; **SudS**, Suðuroy slump.

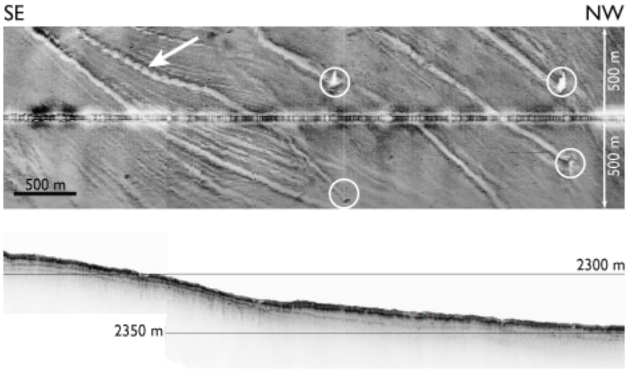

Fig. 2. Deep-tow side-scan sonar record and sub-bottom profile from the trail mark area downslope of the main slump scar in the mass flow area north-east of the Faroe Islands (see Fig. 1). The sonograph shows a large number of outrunner block tracks of varying width, with several blocks (**circles**) at the ends of their respective tracks. Crossing slide paths are also observed. **Arrow** indicates markedly irregular pattern of some tracks. From Kuijpers *et al.* (2001).

submarine structures, such as slope instability and strong bottom currents, and included both shallow seismic data acquisition and sediment core analyses. Most of the work at sea was undertaken with the Russian research vessel *Prof. Logachev*, and carried out within the framework of the international, UNESCO-supported 'Training-Through-Research' (TTR) programme co-ordinated by Moscow State University, Russia. Since 1997, more than three million DKK have been granted for various projects and this work has been documented in 14 classified reports. This paper presents some of the main results from these 'geohazard' studies, in particular with respect to the sediment instability affecting the western flank of the Faroe–Shetland Channel, the occurrence of very strong bottom currents in the channel, and the newly discovered mud diapirs at the northern entrance of the channel (Fig. 1).

Material and methods

Seismic data acquisition was carried out with a 100 kHz airgun and a 6-channel streamer to map subbottom structures. Seismic profiling was carried out in combination with a 10 kHz long-range (2 × 6 km) side-scan sonar for obtaining information on seabed surface sediment and topography. In selected areas a higher resolution of the seabed features was necessary, and a deep-towed side-scan sonar was deployed, operating at 30 or 100 kHz with ranges of 2 × 1000 m and 2 × 350 m, respectively. The latter device was also equipped with a 5 kHz subbottom profiler, whereas during all survey activities another, hull-mounted subbottom profiler was routinely operated. Bottom samples were retrieved with a 6-m gravity corer, a box corer, and a large video-controlled grab. In addition, underwater video was deployed. After retrieval of the sediment cores, the cores were described and magnetic susceptibility measurements were carried out on board. Selected samples were investigated using a microscope to determine mineral and microfossil content. After the cruise more extensive core studies were made, and sediments were dated using the AMS ^{14}C method.

Slope instability

Prior to of the 'geohazard' studies, mass flow deposits had not been reported from the western flank of the Faroe–Shetland Channel. In contrast, a major slide complex was known to extend over most of the north-eastern Faroe Islands margin (Fig. 1). Seismic studies carried out in the latter area during the ENAM project demonstrated that large-scale slumping and sliding had affected the middle and lower slopes below 1500 m water depth since the Miocene (Nielsen & van Weering 1998; van Weering *et al.* 1998). High-resolution side-scan sonar surveying in the area downslope of the main, *c.* 300 m high headwall, where water depth is about 2300 m, demonstrated the presence of a large number of downslope-trending tracks on a low slope gradient, locally displaying cross patterns, and occasionally a markedly irregular pattern (Fig. 2). At the termination of the tracks, outrunner blocks of sediment were observed, up to 18 m high, and with a maximum length of 70 m. Some of the blocks were found at a distance of up to 25 km from the initial mass flow terminus at the main headwall. The sub-bottom profiles in the trail-mark area indicate that most of the tracks have been filled with transparent sediment acoustically comparable to the Holocene hemipelagic surface unit, and thus may have an age older than Holocene.

At the start of the studies of the western flank of the Faroe–Shetland Channel, it soon became evident that slope instability and associated mass flow had also occurred in this area. Seismic evidence (Fig. 3) clearly shows that these processes have taken place repeatedly since late Pliocene time. Within this context, it should be noted that no evidence has been found for any major mass-wasting activity having occurred subsequent to the early Holocene sea level rise (Kuijpers *et al.* 2001); i.e. during the past *c.* 7000 years the Faroe Islands margin appears to have been generally stable.

High-energy bottom current environments

Export of deep waters formed in the North Atlantic occurs via two major gateways: one between Greenland and Iceland and one between Iceland and Scotland (e.g. Dickson *et al.* 1990). Sediment core studies have demonstrated that these

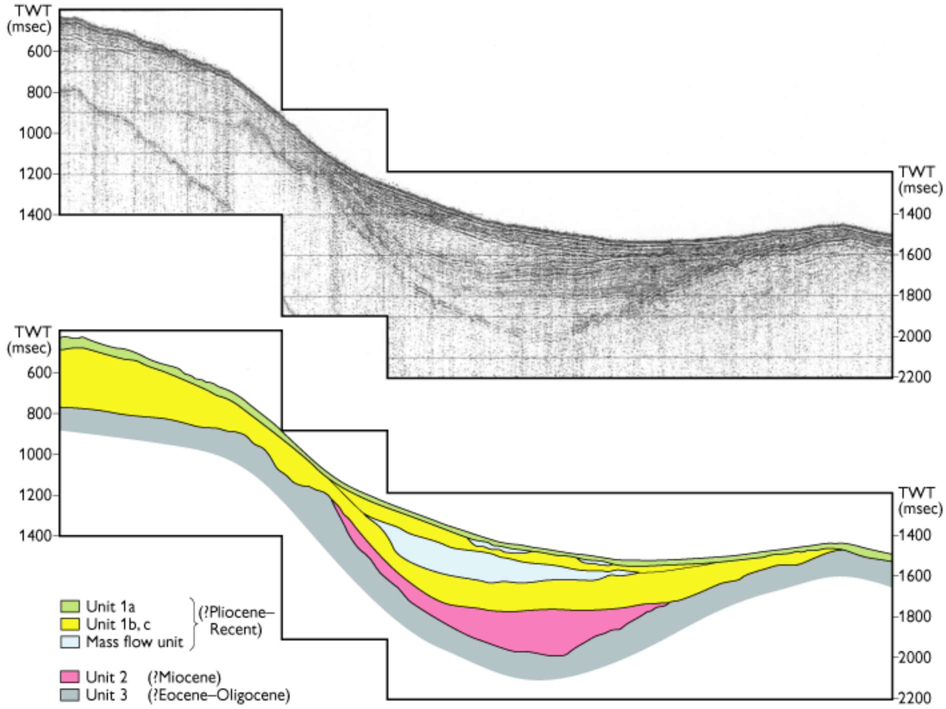

Fig. 3. Single-channel airgun profile from the western flank and basin of the Faroe–Shetland Channel and a schematic interpretation (bottom) showing the presence of a large mass flow unit of presumably late Pliocene – early Pleistocene age.

overflow currents were generally reduced or ceased during cold (stadial) climate periods, relative to interstadial and particularly interglacial conditions (e.g. Kuijpers *et al.* 1998b). Noteworthy in this context is the recent observation in the Faroe–Shetland Channel of a decreasing overflow since 1950 (Hansen *et al.* 2001). For the purpose of providing information on the high-energy overflow current environments along the Faroe–Shetland gateway, an inventory of current-induced bedforms detected by side-scan sonar was undertaken, which revealed the flow path where near-bottom current speed reaches around 1.0 m/s (Kuijpers *et al.* 2002). For comparison, supplementary information from actual current meter measurements has been added in order to determine whether the bedforms recorded (Fig. 4) could be relict features, or can be considered to be in equilibrium with the recent current regime. Our knowledge of overflow processes, which were previously based only on information from current meter stations and ship-borne hydrographic sections, has thus been extended and a regional overview of the areas most intensively influenced by the overflow currents has been obtained.

Sub-seabed sediment mobilisation

Submarine mud volcanoes, or diapirs, can range in size between 0.5 and 800 m high. Two main mechanisms are considered to lead to the formation of mud diapirism, i.e. high sedimentation rates and/or lateral tectonic compression. Both mechanisms can result in over-pressure of a mobile sediment layer at sub-bottom depth. In the mid-1990s mound features were observed immediately east of the Fugloy Ridge (see Fig. 1) by the British Geological Survey (BGS), and were reported as possible cold-water coral mounds. Further high-

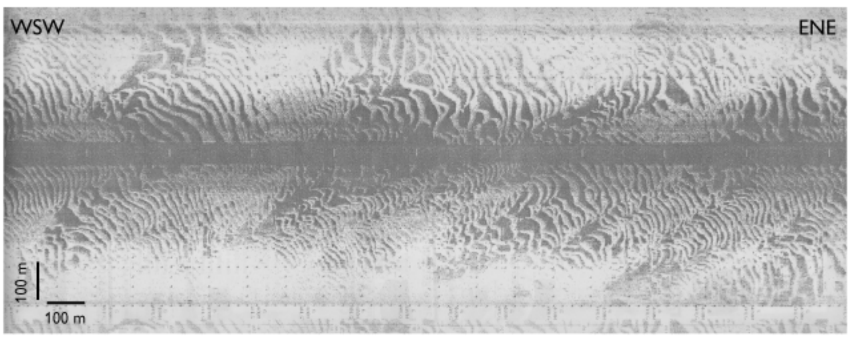

Fig. 4. Deep-tow side-scan sonar record of Norwegian Sea overflow water (NSOW)-induced sandwaves at the southern end of the Faroe–Shetland Channel. Water depth is 1100–1200 m. From Kuijpers *et al.* (2002).

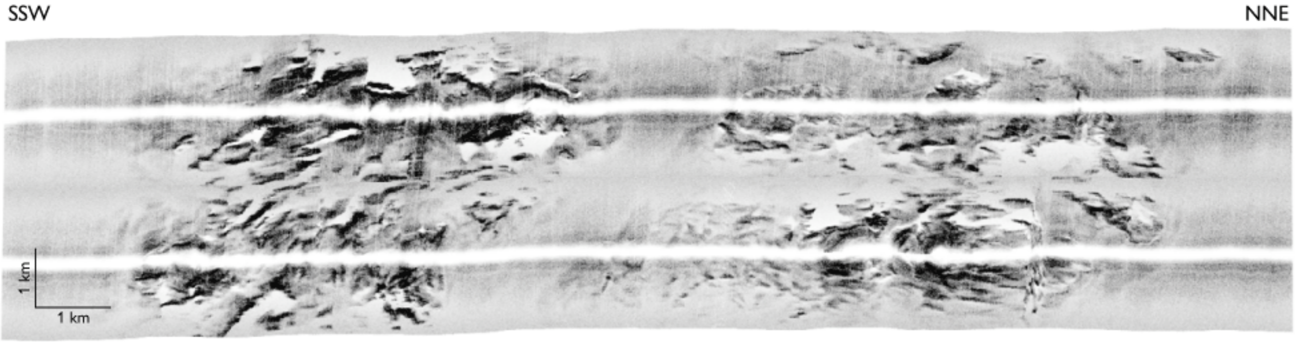

Fig. 5. Mosaic image of deep-tow side-scan sonar records of the mud diapir area at the northern entrance of the Faroe–Shetland Channel. Water depth is 1600–1700 m. From Nielsen *et al.* (2002).

resolution seismic work by BGS and the Royal Netherlands Institute for Sea Research (NIOZ) revealed, however, that the mounds were most likely mud-diapirs, an interpretation later supported by a TOBI side-scan sonar survey carried out by the Southampton Oceanography Centre (SOC). During the 2002 TTR-cruise with R/V *Prof. Logachev* GEUS made a detailed study of the mounds at the northern entrance of the Faroe–Shetland Channel (Fig. 5).

The results of this work confirm that the mound structures can be classified as mud diapirs originating from subsurface sediment mobilisation. This sediment mobilisation is probably due to the excessive load of dense, glacigenic sediments of the North Sea Fan deposited on top of low-density (Miocene) diatomaceous ooze. Several stages of maturity have been observed: (1) an initial stage where the diapirs do not pierce the seabed, (2) a young (up to 50 m high) stage displaying a marked relief, and (3) an up to 100 m high, mature stage where the diapirs have a smoother appearance. Preliminary results from AMS ^{14}C dating of sediment cores collected from the diapirs suggest an episode of major activation of the diapirs around the time of the Last Glacial Maximum (LGM).

Acknowledgements

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