Fluid flow features in fjord-fill deposits, Ullsfjorden, North Norway

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Fluid flow features are found with high-resolution acoustic data from Ullsfjorden, North Norway. The glacimarine and marine fjord-fill sediments have a total thickness of up to 150 m. The seafloor is characterised by many pockmarks and some dome structures, indicating the presence of fluids in the sediments. These features are associated with acoustic signatures attributed to gas charging of the sediments. Linear alignment of several of the pockmarks may be related to the presence of tectonic lineaments in the basement, feeding thermogenic deep earth gas. Another possibility is that groundwater seepage followed these tectonic lineaments.

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Introduction

Both pockmarks and seabed doming in the Ullsfjorden sediments have previously been described and discussed by Hovland & Judd (1988). The aim of this paper is to give further details of the morphology, distribution and origin of these fluid flow related features. Gas charged sediments and gas seepages have been reported from continental shelf areas worldwide (e.g. Field & Jennings 1987; Hovland & Judd 1988; Fader 1991; Kelley et al. 1994). However, descriptions of fluid flow features from fjord-fill sediments are scarce, and this paper provides new acoustic data (boomer, 3.5 kHz and side scan sonar), which also may be relevant for other fjord settings.

Ullsfjorden is a 70 km long, north-south oriented fjord, located in Troms County, North Norway (Figs. 1A & 1B). Its maximum depth is 285 m. The Ullsfjorden area was deglaciated between about 13 and 10 ¹⁴C ka BP. Sediment thicknesses of up to 200 m are found in the fjord, most of which are glacimarine trough fills (Vorren et al. 1989). Two prominent well-known marginal moraines delimit the investigated basin, namely the Skarpnes moraine (c. 12.2 ¹⁴C ka BP) and the Tromsø-Lyngen moraine (c. 10.5 ¹⁴C ka BP) (Andersen 1968; Vorren & Elvsborg 1979; Lønne 1993; Plassen & Vorren 2003) (Fig. 1C).

The basin is located within a bedrock province of quartz-biotite schist to the west and mica schist and phyllite, with bands of quartzite, to the south and east. The Lyngen Alps area just east of Ullsfjorden is composed of gabbroic rocks. Tectonic lineaments in NW-SE to SW-NE directions, in addition to a N-S trending regional strike-slip fault, are present in the area (Fig. 1C) (Boyd & Minsaas 1984; Elvevold & Zwaan 1989; Zwaan et al. 1998).

Results

Seismic stratigraphy

Glacimarine and marine sediments, with a total thickness of up to 150 m, occur in the basin between the Skarpnes and the Tromsø-Lyngen moraines (Fig. 1C). Plassen & Vorren (2003) have correlated four major seismostratigraphic units, A-D (Fig. 2), with a dated lithostratigraphy based on sediment cores.

The lowermost unit A, up to 55 m in thickness, appears acoustically transparent and has an onlap fill geometry. The unit was deposited during an early phase of deglaciation, in an ice proximal environment with high sediment accumulation, when the ice margin receded from the Skarpnes moraine position (c. 12.2-12.1 ¹⁴C ka BP/14.0-13.9 cal. ka BP).

Unit B has a maximum thickness of 130 m. The unit was deposited during the Allerød and the main part of the Younger Dryas (c. 12.1-10.2 ¹⁴C ka BP/13.9-11.8 cal. ka BP) in an environment characterised by the deposition of laminated clayey silt draping the seafloor. Shorter phases with high influx of ice rafted debris (IRD) as well as gravity flows also occurred. On the 3.5
kHz records, vertical columns of acoustically transparent sediments cut the distinct acoustic lamination throughout unit B. Additionally, some blurring zones are present (Fig. 2). Boomer records show these zones to be acoustically turbid, a signature that may indicate gas charging of the sediments (Hovland & Judd 1988).

Unit C has a maximum thickness of 20 m. The unit is thought to have been deposited between about 10.2 and 9.5 $^{14}$C ka BP (11.7-11.0 cal. ka BP), in an environment characterised by the deposition of clayey silt with IRD in addition to sandy layers, some of which are interpreted as turbidites. In the southeastern part of the basin, unit C shows bulging over an area several hundred metres across (Fig. 2). The two lowermost internal reflections terminate in the central part of the bulged zone. This may be evidence for gas charged sediments, but might also be related to mass movement activity in the area shortly after deglaciation (Dehls et al. 2000).

The uppermost unit D appears acoustically transparent and has an asymmetric lateral distribution. Its maximum thickness is 7 m. The unit reflects limited supply of sandy sediments in a bottom current affected, open marine environment after c. 9.5 $^{14}$C ka BP (11.0 cal. ka BP).

The seafloor

Pockmarks

Side scan sonar data reveal numerous high-reflective patches (about 20 m in diameter) on the seafloor (Fig. 3). Many of these are aligned N-S to NNW-SSE throughout the central basin, and are spaced at regular intervals of about 60 metres (Fig. 3B). A highly disturbed seabed, the presence of coarse sediments, or carbonate-cemented sediments may cause such dark patches (Hovland & Judd 1988). Based on ties to the seismic data, the high-reflective patches seem to coincide with

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Fig. 1. (A) Location map. (B) Map of the Ullsfjorden area, showing location of the investigated basin. (C) Map of the investigated basin, showing location of high-resolution acoustic data. The Skarpnes and Tromsø-Lyngen moraines are indicated. Tectonic lineaments and regional faults are after Boyd & Minsaas (1984), Elvevold & Zwaan (1989) and Zwaan et al. (1998). Profiles shown in Figs. 2, 4A and 4B are marked with bold lines.
depressions on the seafloor, and we have therefore interpreted them as pockmarks. The mapped pockmarks in Fig. 3 are about 1 m deep and on average 20-25 m across (Fig. 4A), but smaller pockmark-like features are also observed. The maximum diameter found for a pockmark was about 40 m. Side-wall slope gradients are 2-6 degrees, and there is no indication of infilling. The pockmarks cut into unit D, or into the upper part of unit C, where unit D wedges out towards the Skarpnes moraine and the western part of the basin (Fig. 3A). The greatest number of pockmarks is in the northern part of the basin, inside the Skarpnes moraine, where about 70 have been counted within a square kilometre. They are absent in the southwestern part of the basin, just outside the Tromsø-Lyngen ice front position.

Dome structures

Domming of the seafloor occurs in the northwestern part of the basin (Fig. 3A). Dome structures are about 2 m high and almost 100 m across, and have been described by Hovland & Judd (1988). The twin-domed structure shown in Fig. 4B is the largest observed; the northernmost dome is 4 m high and about 125 m across. Reflections below the dome structures show blurred shadowing or wipeout. On the boomer records the dome structures appear acoustically turbid. The twin-dome in Fig 4B shows doming of the uppermost sediments and a weak bulging of the unit B reflections. Further to the south (Fig. 4B), the seafloor is depressed above an area where unit B shows intra-sedimentary doming. The two southernmost dome structures found (Fig. 3) represent doming of unit B throughout the overlying units.

Discussion

Pockmarks and dome structures found on the seafloor indicate that fluids are present in the sediments, and that the fluid tends to seep upwards. Biogenic gas generated in postglacial sediments is the most commonly cited vehicle for sediment re-suspension, although thermogenic gas, fresh-water seepage and pore water release are other possibilities (Scanlon & Knebel 1989). Within the crystalline bedrock in the Ullsfjorden area, the presence of petroleum related gas is excluded. A considerable hydraulic head of pressure is considered possible since high mountains with glaciers, lakes and streams border Ullsfjorden (Fig. 1). Thus, both gas-related and groundwater-related processes may influence the seabed (Hovland & Judd 1988).

Natural gas does not allow penetration by acoustic waves, and therefore seismic reflection profiles provide primary evidence that escaping gas does shape seafloor features (Maine Geological Survey Website 1997). Lack of infilling of the pockmarks suggests that fluid escape may occur frequently. Low P-wave velocity (Plassen & Vorren 2003) and acoustic transparency (Fig. 4) indicate that the lowermost parts of unit C are gas charged. Vertical columns of acoustically transparent sediments throughout unit B (Figs. 2 & 4), wipeout acoustic signatures below dome structures (Fig. 4B) and acoustic turbidity on the boomer records, indicate that gas is present throughout the stratigraphy. Seabed doming in the neighbouring fjord, Lyngen, is probably caused by expansion of sediment-trapped gas (Hovland & Judd 1988).

Pockmarks appear to be unique in former glaciated areas (Kelley et al. 1994), where thick glacigenic muddy sediments may play an important role by trapping gas that would escape more rapidly in other settings (University of Maine Website 2000). General lack of organic matter in glacimarine sediments suggests that gas does not originate from this material (Maine Geological Survey Website 1997). Thermogenic deep earth gas from the mantle may, however, migrate to the surface along tectonic lineaments from lower levels in the earth’s crusts (Söderberg & Flodén 1991). Pockmark fields may represent regions of significant sediment redistribution in areas of past seismic activity (Kelley et al. 1994). Modern earthquakes trigger enhanced gas see-
Fig. 3. (A) Map showing distribution of pockmarks and dome structures on the seafloor. Distribution of acoustic units is shaded. (B) Side scan sonar image showing high-reflective patches, interpreted as large pockmarks. Many of the pockmarks are arranged along lines oriented in a N-S to NNW-SSE direction. Smaller pockmarks are more scattered on the seafloor.
page from marine sediments on the northern California continental shelf and in the Patras Gulf (Greece) (Field & Jennings 1987; Hasiotis et al. 1996). In the northern Stockholm Archipelago, Baltic Sea, thermogenic gas accumulations are found in pockmarked glacial clay over still active tectonic lineaments in the crystalline basement (Söderberg & Flodén 1991).

In Ullsfjorden the presence of gas throughout the investigated sedimentary succession indicates that it originates from deeper sources. The basin is located within an area influenced by postglacial neotectonic activity (Dehls et al. 2000), hence it seems reasonable that the linear distribution of high-reflective patches, interpreted as pockmarks, may reflect thermogenic deep earth gas migrating to the surface along tectonic lineaments.

Fig. 4. (A) 3.5 kHz profile showing pockmarks at the eastern side of the basin. Note acoustic transparency in the lower parts of unit C. (B) 3.5 kHz profile showing a twin-dome at the western side of the basin, inside the Skarpnes moraine. Note blurred shadowing or wipeout of the underlying reflections and weak bulging of top unit B. Further to the south, the seafloor is depressed above an area where unit B shows intrasedimentary doming. For location, see Fig. 1C.
in the basement. This, possibly in addition to groundwater seepage, seem to be the most likely modes of formation of the discussed seafloor features.

Conclusions

1. Many pockmarks and some dome structures found on the Ullsfjorden seafloor indicate that fluids are present in the sediments.

2. The seafloor features have acoustic signatures attributed to gas charged sediments.

3. Migration of thermogenic, deep earth gas along tectonic lineaments in the basement may explain the linear alignment of many pockmarks. Another explanation is groundwater seepage along these lineaments.

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References


Hasiotis, T., Papaethodorou, G., Kastanos, N. & Ferentinos, G. 1996: A pockmark field in the Patras Gulf (Greece) and its activation during the 14/7/93 seismic event. Marine Geology 130, 333-344.


University of Maine Website 2000: http://www.umaine.edu/news/Archives/2000/May00/pockmarks.html

Vorren, T.O. & Elvsborg, A. 1979: Late Weichselian deglaciation and palaeoenvironment of the shelf and coastal areas of Troms, north Norway - a review. Boreas 8, 247-253.
