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High-resolution 3D seismic study of pockmarks and shallow fluid flow systems at the Snøhvit hydrocarbon field in the SW Barents Sea

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ABSTRACT

The Barents Sea is an epicontinental shelf sea with a fragmented structure consisting of long fault complexes, basins and basement highs. Fluid leakage from deep-seated hydrocarbon accumulations is a widespread phenomenon and mostly related to its denudation history during the glacial/interglacial cycles. In this study, we aimed to better understand shallow fluid flow processes that have led to the formation of numerous pockmarks observed at the seabed, in this area. To achieve this goal, we acquired and interpreted high-resolution 3D seismic and multibeam swath bathymetry data from the Snøhvit area in the Hammerfest Basin, SW Barents Sea. The high-resolution 3D seismic data were obtained using the P-Cable system, which consists of 14 streamers and allows for a vertical resolution of ~1.5 m and a bin size of 6.25 × 6.25 m to be obtained. The frequency bandwidth of this type of acquisition configuration is approximately 50–300 Hz. Seismic surfaces and volume attributes, such as variance and amplitude, have been used to identify potential fluid accumulations and fluid flow pathways. Several small fluid accumulations occur at the Upper Regional Unconformity separating the glacial and pre-glacial sedimentary formations. Together, these subsurface structures and fluid accumulations control the presence of pockmarks in the Snøhvit study area. Two different types of pockmarks occur at the seabed: a few pockmarks with elliptical shape, up to a few hundred meters wide and with depths up to 12 m, and numerous circular, small, "unit pockmarks" that are only up to 20 m wide and up to 1 m deep. Both types of pockmarks are found within glacial ploughmarks, suggesting that they likely formed during deglaciation or afterwards. Some of the larger normal pockmarks show columnar leakage zones beneath them. Pressure and temperature conditions were favourable for the formation of gas hydrates. During deglaciation, gases may have been released from dissociating gas hydrates prolonging the period over which active seepage occurred. At present, there is no evidence from the 3D seismic data of active gas seepage in the Snøhvit area. Low sedimentation rates or the influence of strong deep ocean currents may explain why these pockmarks can still be identified on the contemporary seabed.

1. Introduction

Seabed fluid flow, which involves the flow of gases and liquids through the seabed, is a common phenomenon in sedimentary basins worldwide (Judd and Hovland, 2007; Mazzini et al., 2016, 2017). Fluid flow and escape is often indicated by the presence of sub-circular depressions at the seabed, commonly called pockmarks. They range in size from a few meters to a few kilometers in diameter and from a few meters to a few hundreds of meters in depth (Hovland et al., 2002; Judd and Hovland, 2007). A comprehensive study conducted above the Troll East gas field in the Norwegian North Sea revealed > 7000 pockmarks on the seafloor, present in a ~600 km^2 area as isolated structures, on average ~35 m wide and up to 100 m in size (Mazzini et al., 2016, 2017). Pockmarks are evidence of past or active gas seepage and any observation of gas flares in the water column above the pockmarks suggests that they are active today (Bünz et al., 2012; Chand et al., 2012).

Some pockmarks correspond to gas-escape features that have also

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been linked to methane hydrate destabilization (Davy et al., 2010; Hovland, 1981; King and Maclean, 1970; Mazzini et al., 2016, 2017; Pau et al., 2014a,b; Riboulot et al., 2016; Sultan et al., 2010). During the glacial maximum a large ice sheet covered the Barents Sea (Patton et al., 2016) and trapped gas within sediments beneath the ice in the form of gas hydrates. It has been suggested that the last deglaciation could have triggered gas hydrate dissociation causing methane seepage at the seabed and the formation of the extensive Troll gas field (Mazzini et al., 2016, 2017). However, not all pockmarks involve gas. They may correspond to erosive features formed by fluid escape when sediment is taken up by the escaping fluids (Judd and Hovland, 2007). Soft, fine-grained sediment that is brought into suspension can be transported by currents and thus constitute a necessary recording medium for pockmark formation, as illustrated by Rise et al. (2014).

Seepage phenomena have been found in many parts of the world's oceans and in various geological settings (Hovland, 1981; Paull et al., 1984; Suess et al., 1999; Zühlsdorff and Spieß, 2004). They can occur in association with various seabed features such as mud volcanoes, pockmarks or diatremes (Judd and Hovland, 2007). Understanding pockmarks and gas seepage phenomena is important for estimating the impact of the latter on global climate change (Judd et al., 2002), deep sea ecosystems (Sibuet and Olu, 1998) and seafloor stability (Evans et al., 1996).

Pockmarks in the Barents Sea are widespread with most pockmarks in the greater Snøhvit area measuring about 20–30 m in width and < 3 m in depth (Rise et al., 2014). Their shapes and forms range from oval to elongated to even more complex ones. The elongated pockmarks have their long axis orientation parallel to the prevailing bottom current direction (Bøe et al., 1998; Farin, 1980).

The mode of activity in pockmark formation can be either continuous or periodic, during special external events such as storm surges (Hovland et al., 2002) and earthquakes (Reusch et al., 2016). Pockmarks also occur in a post-glacial setting in the presence of very hard sediments, where the mechanisms of pockmark formation may be less well understood compared to other settings. Some large pockmark-like depressions, however, may have been formed by icebergs impinging the seafloor (Bass and Woodworth-Lynas, 1988; Eden and Eyles, 2001). Such icebergs scoured the seabed during ice retreat in late Weichselian times (Judd and Hovland, 2007).The overall objective of this paper is to unveil the fluid flow pathways and better understand the driving mechanisms and fluid flow dynamics in the shallow subsurface leading to pockmark formation at the seabed in the vicinity of the Snøhvit gas field. Moreover, we will assess the age and duration of pockmark development. The paper thus aims to provide a better understanding of the shallow fluid flow processes that have led to the formation of pockmarks at the seabed. It will achieve this by collecting and analyzing high-resolution 3D seismic data from the Snøhvit area in the Hammerfest Basin, SW Barents Sea (Fig. 1). The P-Cable data have proven more useful than conventional 3D seismic for mapping fluid leakage systems, including seabed depressions interpreted as pockmarks (Figs. 1b and 2a) and shallow gas and thus for better understanding fluid flow processes (Petersen et al., 2010; Rajan et al., 2013). With the high-resolution P-Cable system, the temporal resolution is improved by 3–5 times and the spatial resolution can be at least one order of magnitude higher than for conventional 3D seismic (Bellwald et al., 2018; Planke et al., 2009). For making the reproducibility of scientific findings possible and for reinforcing the validity of data gleaned from research, the precise location of any figures produced is indicated by Fig. 1b.

2. Geological setting

The Barents Sea is a ~300 m shallow shelf sea on the Norwegian continental margin (Breivik et al., 1998; Faleide et al., 1993). Typical water depths are in the range of approximately 315 m to 355 m (Fig. 1). The Barents Sea is composed of a mosaic of platforms and basins, formed by two major continental collisions. The first event corresponds to the Caledonian orogeny, taking place ~400 Ma ago, and the second one to the collision between Laurasia and Western Siberia which led to the creation of the eastern margin of the Barents Sea ~240 Ma ago (Dore, 1995). The study area is located in the Hammerfest Basin (southwestern Barents Sea) (Fig. 1), which is characterized by an uplifted reservoir and faults running in an E-W direction (Section 4.3 and related figures). The tectonic features of the Hammerfest Basin were created mainly by Upper Jurassic-Lower Cretaceous faulting (Berglund et al., 1986; Dore, 1995; Faleide et al., 1993; Gabrielsen, 1990).

The seabed in the Snøhvit area is characterized by generally straight or curved grooves (Bellec et al., 2008; Chand et al., 2009). Exceptionally, they can reach a depth of up to 15 m. These grooves were formed after the last glacial maximum and have been interpreted as iceberg ploughmarks (Andreassen et al., 2008; Winsborrow et al., 2010). Calving and drifting icebergs related to the collapse of the Bjørnøyrenna Ice Stream carved the seabed in multiple directions.

A major Upper Regional Unconformity (URU) separates the glacial sediments from the underlying westward-dipping inclined layers (clinoforms) of the Torsk Formation of Paleocene-Eocene age (Sections 4.2 and 4.3 and related figures) (Linjordet and Olsen, 1992; Nagy et al., 1997).

Upper Jurassic and thick Cretaceous shales act as a cap rock for most of the structures in the Barents Sea region (Estublier and Lackner, 2009). In the study area the hydrocarbon source rocks correspond to the Upper Jurassic Hekkingen Formation, the Lower Jurassic Nordmela Formation and the Triassic Ingøydjupet Group. The Hekkingen Formation shales are mature for oil and gas generation at the western margin of the Hammerfest Basin and along the western fringe of the Loppa High and at the same time also correspond to the local cap rock (Dore, 1995; Mørk et al., 1999; Ohm et al., 2008).

The underlying lithostratigraphic formations, namely the Fruholmen, Tubåen, Nordmela and Stø formations, consist mainly of sandstones interbedded with thin shale layers (Estublier and Lackner, 2009). The lower unit of the Nordmela Formation forms the cap rock of the underlying Tubåen Formation, whereas the upper Nordmela Formation unit and the gas bearing Stø Formation are the main reservoirs in the area (Estublier and Lackner, 2009). The reservoir zone is located at depths of between ~2700–2800 m below sea surface (Linjordet and Olsen, 1992; Maldal and Tappel, 2004; Shi et al., 2013) and consists of Triassic to Jurassic delta plain deposits. Furthermore, the Tubåen Formation has been deposited in a marginal-marine fluvio-deltaic depositional environment. It is in the Tubåen and the Stø Formations where CO_2 has been injected as part of the CCS activities at the Snøhvit plant.

3. Data and methods

This paper uses high-resolution 3D seismic data acquired approximately 600 m from the southern edge of the Snøhvit gas field in the Hammerfest Basin (Fig. 1). In 2011, UiT the Arctic University of Norway acquired high-resolution P-Cable 3D seismic data aboard the R/V Helmer Hanssen research vessel (Fig. 2a). Time was converted into meters using a velocity of 1500 m/s. Structure maps generated by the P-Cable technique have a higher resolution when compared to the multibeam swath bathymetry data (MBE) (Fig. 2). The latter (Fig. 2b) were acquired simultaneously to the 3D seismic data using a SIMRAD EM300 system (30 kHz) onboard the vessel. The final processed multibeam data, due to the close line spacing, have a bin spacing of 5 m also providing a high-resolution image of the seabed morphology.

The P-Cable system of this study consists of 14 streamers with a spacing of 12.5 m along a cross cable. Streamers measured 25 m long and contained eight channels each. The array of multi-channel streamers was used to acquire many seismic lines simultaneously, thus covering a large area with close in-line spacing in a cost efficient way. Due to the curvature of the cross cable, the streamers were slightly closer together (~10–12 m). One mini-GI gun (15 in^3) was used as