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Multiple episodes of fluid flow in the SW Barents Sea (Loppa High) evidenced by gas flares, pockmarks and gas hydrate accumulation

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ABSTRACT

Gas and gas hydrates have gained considerable attention in the last 20 yr due to their possible impact on global climate change from methane escalations. Our study area, the SW Barents Sea, is unique in its evolution due to the effect of glaciations which removed thick layers of sediment from the seabed. Unloading due to erosion and deglaciation resulted in opening of pre-existing faults and creation of new ones, facilitating fluid migration and eventually escape into the water from the subsurface. Expressions of hydrocarbon gas accumulation and fluid flow such as gas hydrates and pockmarks are widely distributed in the Barents Sea. Several gas flares, some of them 200 m high in echograms, occur along a segment of the Ringvassøy Loppa Fault Complex, indicating open fractures and active fluid flow. Observation of gas flares along regional fault complexes outside pockmark regions indicates that present gas escape occurs along faults only. The pockmark formation and gas flares belong to different episodes of fluid flow. The pockmarks are absent outside soft sediment depocentres indicating that their existence is related to the presence of recording medium. The thin sediment cover in pockmarks and their penetration down into glaciomarine sediments indicate that they formed after deposition of these sediments and that fluid escape was active to the very recent past. Methane hydrate stability zone (MHSZ) modelling shows that after the last glacial maximum 18000–20000 ^{14}C years ago, the MHSZ has thinned from 600 m to zero in most parts of the SW Barents Sea. The fluid expulsion probably happened after retreat of the glaciers causing release of methane from dissociation of methane hydrates through fluid escape processes which lasted until recently. Bottom simulating reflectors (BSR) observed are probably due to structure II hydrates formed from gas containing higher order hydrocarbon components such as ethane, propane, etc. along with methane. The study area falls close to the new gigantic oil discoveries, Skrugard and Havis, and north of the Snøhvit hydrocarbon field.

1. Introduction and geological setting

Fluid flow processes have been proposed to bring large quantities of greenhouse gases such as methane from the deeper geo-sphere to the water column (Pohlman et al., 2010) and to the atmosphere which could cause global scale climate change (Hansen et al., 2000; Shakova et al., 2010). Methane is a green house gas causing 23 times more effect than CO_2 (Forster et al., 2007). Locating the occurrences of gas flares and quantifying the discharge of CH_4 from the seabed and its fate in the water column are still a very new area of research (Reeburgh, 2007). Also, methane emissions are observed to have effects on seabed morphology and benthic ecosystems (Judd et al., 1997). The morphology and nature of the cold seeps worldwide vary significantly from one area to the other, reflecting different mechanisms of fluid generation and tectonic or the stratigraphic frameworks creating fluid pathways (Klaucke et al., 2008; Linke et al., 2010; Naudts et al., 2006).

Many areas of active seepage are associated with sub-seafloor oil and gas reservoirs, trapped gas under gas hydrates, and also dissociation of gas hydrate itself (Milkov and Sassen, 2003; Sassen et al., 1999). Numerous gas flares were identified along the Arctic shelf associated with changes in gas hydrate stability conditions (Westbrook et al., 2009) and focussed fluid flow (Hustoft et al., 2009). Occurrences of gas hydrates in marine areas are often associated with the presence of a bottom simulating reflector (BSR) (Shipley et al., 1979). A BSR is a seismic reflector, representing the base of the gas hydrate stability zone (BGHSZ), and described as one which sub-parallels the seafloor reflection, but which is opposite in polarity (Shipley et al., 1979). The BSR indicates an acoustic impedance change across a high velocity layer of gas hydrate bearing sediments overlying a gas rich layer (Stoll and Bryan, 1979). The nature and properties of BSRs and their occurrences vary depending on the sedimentary environment and fluid flow (Chand and Minshull, 2003; Hobro et al., 2005; Westbrook et al., 2008).

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In many parts of the world BSR depths are altered by the presence of one or more gas hydrate inhibitors (NaCl, N_2, warm fluids, isostatic uplift, deglaciation, sliding) or facilitators (CO_2, H_2S, higher order hydrocarbon gases, increase in sea level, subsidence) (Sloan, 1990). This may result in BSRs occurring at different depths. The detection of BSRs is also complicated due to their variation in properties depending on the frequency used for data acquisition and the type of acoustic boundary formed at the BGHSZ (Vanneste et al., 2001). Often the BGHSZ is controlled by the presence of permeable layers and the presence of a BSR is limited to locations where such layers cross cut the BGHSZ.

The study area lies in the southwestern part of the epi-continental Barents Sea. Mesozoic and early Cenozoic sedimentation in the Barents Sea took place in intracratonic basins. After the early Tertiary opening of the Norwegian Sea, the sediment transport bypassed these basins, and depocentres were established on the continental margin (Spencer et al., 1984). Results from drilling and coring show that erosion took place during the glacial–interglacial periods in the late Plio-Pleistocene (<2.7 Ma) creating the upper regional unconformity (URU) (Solheim and Kristoffersen, 1984). The corresponding sediments hence have a glacial affinity (Eidvin and Riis, 1989; Hald et al., 1990; Sættem et al., 1992). Estimates show that about 1000 m of sediments may have been removed during this erosional episode (Laberg et al., 2011; Nøttvedt et al., 1988; Riis and Fjeldskaar, 1992). An upper glacigenic sediment sequence of varying thickness covers the URU (Solheim and Kristoffersen, 1984). Associated with erosion and isostatic rebound from deglaciation, considerable late Cenozoic uplift took place, modelled by Riis and Fjeldskaar (1992) to be 900–1400 m in the western Barents Sea. The removal of overburden and later uplift resulted in the opening of many pre-existing faults and creation of pathways for fluid flow (Nøttvedt et al., 1988).

Previous studies from the Barents Sea have indicated patchy high amplitude reflections, which are interpreted as BSRs (Andreassen and Hansen, 1995; Chand et al., 2008; 2009; Laberg et al., 1998). They are interpreted to be due to the presence of structure II gas hydrates containing a few percentages of higher order hydrocarbon gases or CO_2 along with methane (Chand et al., 2008; Laberg et al., 1998). Modelling has shown that pure methane hydrates cannot be stable where these anomalies occur. A similar study carried out along the western flank of Ingøydjupet indicated patchy subsurface reflections which again are not conform to pure methane hydrate (Chand et al., 2009). No drilling has been carried out for hydrate sampling along the Barents Sea margin, but a surface gravity core from the Nordkapp Basin indicated presence of hydrate nodules which vaporised when exposed to atmospheric conditions (Chand et al., 2008).

The present study is focussed on a small region along the southwestern Barents Sea covering parts of the western margin of the Hammerfest Basin, the Loppa High, Tromsøflaket and Ingøydjupet. It is close to the new gigantic oil discoveries, Skrugard and Havis, and north of the Snøhvit hydrocarbon field (Figs. 1 and 2). The study is aimed to achieve a better understanding of fluid flow processes and their relation to shallow geological and seabed conditions created by the Plio-Pleistocene erosion/deposition processes and tectonic activity in this region.

2. Materials and methods

Multibeam echosounder (MBE) data were collected by the Norwegian Defence Research Establishment (FFI) using Kongsberg Maritime EM710 mounted on FFI's research vessel HU Sverdrup II (Fig. 1). It is a $0.5 \times 1.0°$ system with operating frequency of 70–100 kHz. With typical water depths of ca 350 m in the study area the MBE data gives 1 to 2 m spatial resolution for the terrain model. The MBE data also include seafloor reflection (backscatter) properties, which indirectly gives an indication of sediment type/grain size and hardness/ruggedness of the seabed. The EM710 system can also record the water column which is very useful for detecting gas bubbles in the water column (gas flares). The EM710 data were processed using Fledermaus Geocoder for backscatter and Fledermaus Midwater for water column gas anomalies.

A parametric subbottom profiler seismic system mounted on HU Sverdrup II, (Kongsberg Defence Systems TOPAS PS18) was used to

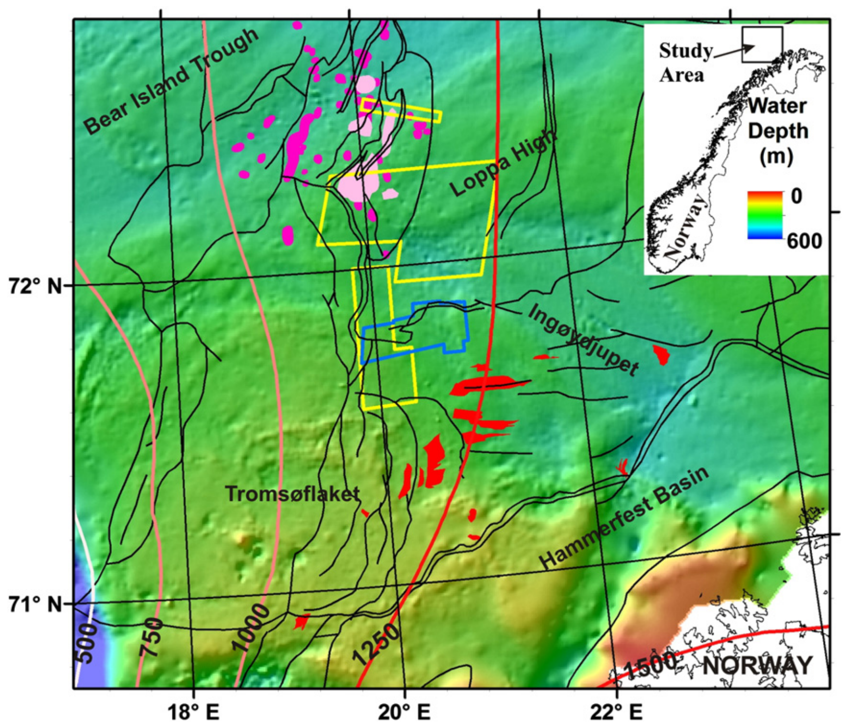

Fig. 1. Regional bathymetry of the Barents Sea showing the location of multibeam bathymetry (yellow polygons) and the 3D seismic block (blue polygon). Also shown are gas anomalies (purple), BSRs (pink) (Andreassen and Hansen, 1995), hydrocarbon discoveries (red), faults (black lines) (Gabrielsen et al., 1990) and ice thickness contours from the Last Glacial Maximum (Siegert et al., 2001).