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Distribution of subsurface fluid-flow systems in the SW Barents Sea

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ABSTRACT

The SW Barents Sea is a large hydrocarbon-prone epi-continental Sea of the Norwegian Arctic region. A significant portion of the hydrocarbon gases generated in deep source rocks has leaked or migrated into the shallow subsurface and is now trapped in gas hydrate and shallow gas reservoirs. The evolution of sedimentary basins of this region has controlled the leakage of these fluids through marine sediments. Understanding the distribution of various fluid-flow systems may enhance our knowledge of the evolution of different basins in the SW Barents Sea and could help find potential targets for future hydrocarbon exploration. We analyze approximately 3000 2D multi-channel seismic profiles and data from 60 wells covering the entire SW Barents Sea, to identify and classify fluid-flow features, and study their relationship to tectonic elements and geological history. Gas chimneys are the most abundant feature among various other fluid-flow features such as fluid leakage along faults and fractures, seepage pipes, and high amplitude anomalies potentially indicating trapped fluids. Large fluid-flow features, covering areas as large as 600 km^2, occur close to known hydrocarbon fields such as Snøhvit, Skrugard, and Havis. The fluid-flow features occur above major deep-seated faults in the area suggesting a close relation to it. The number of fluid-flow features in the western part of the study area is significantly higher than in the eastern part. The amount of net erosion in the study area shows no direct control over the distribution of fluid-flow features, suggesting that the faults and distribution of mature source rocks control the fluid flow. The strong correlation between the locations of fluid-flow features and structural elements indicates that extensional tectonics, uplift and glaciations could have played major roles in the timing and activity of the fluid leakage, although erosion might have had an added effect.

1. Introduction

The vertical flow of fluids through marine sediments is a widespread and dynamic geological process that occurs on passive and active continental margins worldwide. Fluid migration is associated with excess pore-fluid pressure, and is attributed to temporally and spatially varying processes, such as rapid sediment loading (e.g. Dugan and Flemings, 2000), uplift and erosion (e.g. Doré and Jensen, 1996), dissociation of gas hydrate (e.g. Mienert et al., 2005), polygonal faulting (e.g. Cartwright et al., 2007), and hydrocarbon generation and leakage from deep and shallow source rocks and reservoirs (e.g. Heggland, 1998; Solheim and Elverhøi, 1985; Hovland and Judd, 1988). Presence of shallow gas accumulations associated with fluid leakage are of interest for several reasons: (1) Shallow gas accumulations may reduce the shear strength of sediments, and pose a hazard to hydrocarbon exploration and development (Andreassen et al., 2007a), (2) the occurrence of shallow gas and indications of fluid flow underlying it may point toward deeper prospective reservoirs (e.g. Heggland, 1998) and (3) shallow gas accumulations could be of commercial interest in the future (Carstens, 2005).

Vertical migration of gas through subsurface strata can cause widely distributed acoustic low-velocity zones. These low-velocity zones can deteriorate the seismic signal and create regions of chaotic seismic signals. The nature and shape of this chaotic region of acoustic signals can vary depending on the process of formation of these zones. Chaotic regions in seismic data can also result from mud mobilization triggered by vertical migration of fluids (Løseth et al., 2003). Mud mobilization can modify the structure of sediments to a disrupted succession and form a low-density sediment-fluid mixture. Vertical fluid-flow features and chaotic seismic reflection zones are commonly observed with most types of sediment mobilizations (Graue, 2000; Hurst et al., 2003; Løseth et al., 2003; Jackson and Stoddart, 2005). Fluid flow can also alter the

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formation, cause local sediment remobilization, and appear as chaotic reflections in the seismic profile (Ligtenberg, 2007). Geometry of subsurface fluid-flow systems is hard to constrain by direct observations (Talukder, 2012) and characterization of them is difficult because flow can be highly transient and can vary in time and space along complex and changing conduit systems (Hornbach et al., 2007).

The SW Barents Sea is a part of the Arctic Ocean located north of Norway (Fig. 1). Occurrence of shallow gas, gas hydrates and seafloor expulsion features has been reported from several areas of the SW Barents Sea (e.g. Andreassen et al., 1990; Perez-Garcia et al., 2009; Chand et al., 2009, 2012; Ostanin et al., 2012). Migration of fluids into shallow sediments and seepage into the ocean through the seafloor was probably the result of spillage and migration of hydrocarbons in response to uplift and erosion processes in the Cenozoic (e.g. Doré, 1995; Doré and Jensen, 1996; Henriksen et al., 2011).

Uplift and erosion is known to have affected the SW Barents Sea during Cenozoic times (Faleide et al., 1996; Dimakis et al., 1998; Anell et al., 2009). This process is thought to have a very strong impact on petroleum systems (e.g. Doré and Jensen, 1996; Bjørkum et al., 2001; Cavanagh et al., 2006; Ohm et al., 2008; Henriksen et al., 2011). The negative effects of uplift and associated erosion on hydrocarbon systems include tilting and opening of hydrocarbon-filled traps resulting in spillage of oil and gas (Kjemperud and Fjeldskaar, 1992), gas expansion and ex-solution from oil (Skagen, 1993; Doré and Jensen, 1996; Cavanagh et al., 2006), seal failure (e.g., Sales, 1993), reduction in temperature due to uplift resulting in immature source rocks (Doré et al., 2000; Ohm et al., 2008), and porosity and permeability reduction due to diagenetic processes (Berglund et al., 1986; Walderhaug, 1992).

Whereas, positive effects include the occurrence of thermally matured source rocks at shallow levels (Bjørkum et al., 2001), liberation of dissolved methane from formation water (Doré and Jensen, 1996) due to decreases in pressure (e.g. Maximov et al., 1984; Nesterov et al., 1990), ex-solution of light oil or condensate from gas (e.g. Piggott and Lines, 1991), fracture enhancement of less permeable reservoirs (e.g. Aguilera, 1995) and remigration to shallower structures (Waylett and Embry, 1992). In addition, local re-deposition under a heavy overburden associated with erosion can result in rapid maturation of source rocks and generation of hydrocarbons (e.g. Dahl and Augustson, 1993).

Numerous glaciations also affected the SW Barents Sea region during the late Cenozoic. Rapid buildup and removal of ice load, as occurred in the SW Barents Sea, may have less impact on the evolution of the basin (Lerche et al., 1997). However, distortions to the thermal regime of sub-ice sediments caused by spatial and temporal variations of ice thickness influence the generation, migration and present-day accumulation of hydrocarbons (Lerche et al., 1997; Cavanagh et al., 2006). Ice loading can cause structural distortions leading to a redistribution of gas and oil in the reservoir and spill of hydrocarbons (Lerche et al., 1997). Major ice-loading effects are present in the Hammerfest Basin; where many drilled wells found only a small amount of residual oil in rotated and tilted structures (Rasmussen et al., 1993; Nyland et al., 1992).

Often, large gas anomalies overlie hydrocarbon discoveries in SW Barents Sea indicating leakage of gas from the deeper formations (Chand et al., 2008, 2009, 2012; Heggland, 1998, 2004; Meldahl et al., 2001). A recent study from the Loppa High (Chand et al., 2012) reported seepage of gas into the water column indicating that the gas migration is still active through open faults. The locations of these anomalies may indicate possible targets for

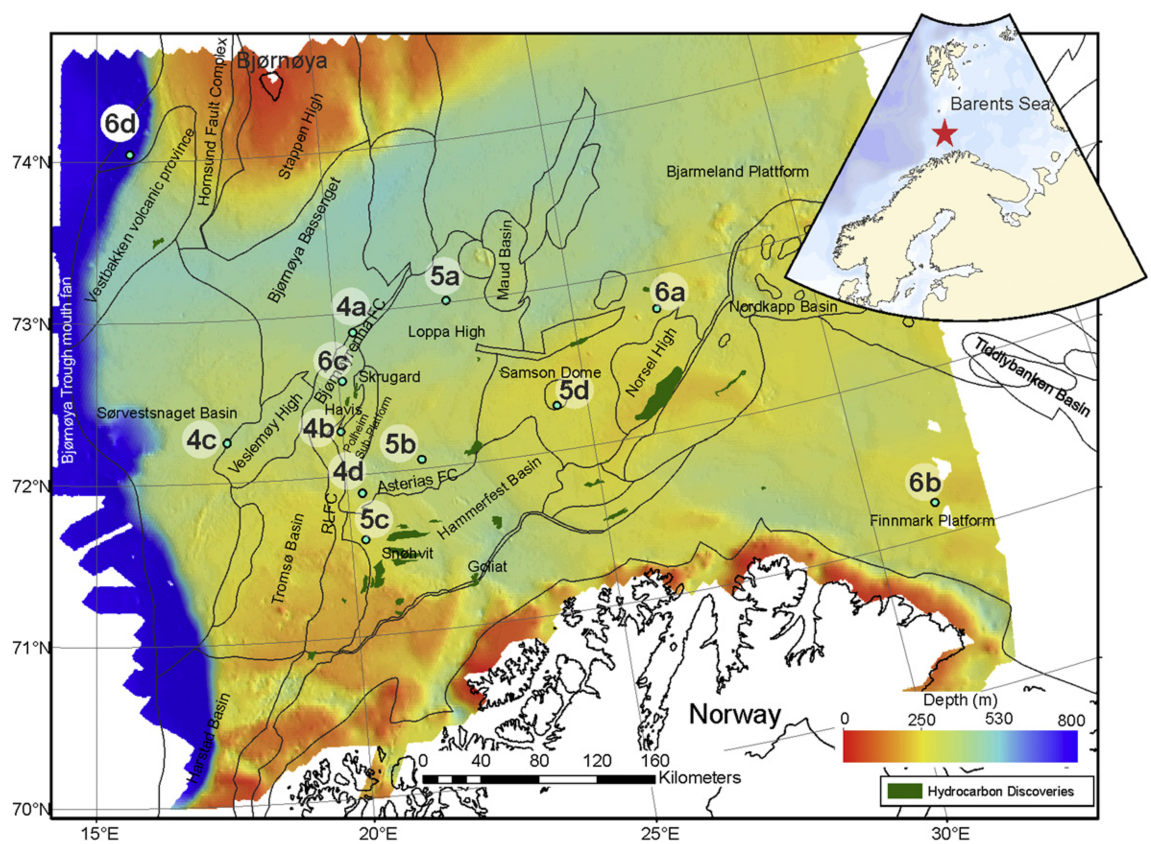

Figure 1. General bathymetric map of SW Barents Sea with major basins and hydrocarbon discoveries. The location of the study area (red star) and seismic lines in the following figures are also shown.