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Research paper

Deep-seated faults and hydrocarbon leakage in the Snøhvit Gas Field, Hammerfest Basin, Southwestern Barents Sea

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ABSTRACT

High-quality 3D seismic data are used to analyze the history of fault growth and hydrocarbon leakage in the Snøhvit Field, Southwestern Barents Sea. The aim of this work is to evaluate tectonic fracturing as a mechanism driving hydrocarbon leakage in the study area. An integrated approach was used which include seismic interpretation, fault modeling, displacement analysis and multiple seismic attribute analysis.

The six major faults in the study area are dip-slip normal faults which are characterized by complex lateral and vertical segmentation. These faults are affected by three main episodes of fault reactivation in the Late Jurassic, Early Cretaceous and Paleocene. Fault reactivation in the study area was mainly through dip-linkage. The throw-distance plots of these representative faults also revealed along-strike linkage and multi-skewed C-type profiles. The faults evolved through polycyclic activity involving both blind propagation and syn-sedimentary activity with their maximum displacements recorded at the reservoir zone. The expansion and growth indices provided evidence for the interaction of the faults with sedimentation throughout their growth history.

Soft reflections or hydrocarbon-related high-amplitude anomalies in the study area have negative amplitude, reverse polarity and are generally unconformable with structural reflectors. The interpreted fluid accumulations are spatially located at the upper tips of the major faults and gas chimneys. Four episodes of fluid migration are inferred and are linked to the three phases of fault reactivation and Neogene glaciations. Hydrocarbon leakage in the Snøhvit Gas Field is driven by tectonic fracturing, uplift, and erosion. The interpreted deep-seated faults are the main conduits for shallow hydrocarbon accumulations observed on seismic profiles.

1. Introduction

Fluid-flow or migration is associated with excess pore-fluid pressure which can be attributed to varying processes such as rapid sediment loading, uplift and erosion, dissociation of gas hydrate, polygonal faulting, and leakage from source and reservoir rocks (Doré and Jensen, 1996; Gay et al., 2011; Heggland, 1998; Hovland and Judd, 1988; Mienert et al., 2005). Fluid-flow processes are revealed on seismic reflection profiles as seabed pockmarks, mud volcanoes, and methane derived carbonate mounds, and in the subsurface as seismic blow-out pipes, gas chimneys, paleo-pockmarks and amplitude anomalies (Vadakkepuliyambatta et al., 2013). In the Barents Sea, glacial lineations and iceberg plough marks are also related with the presence of gaseous hydrocarbons (Andreassen et al., 2008; Chand et al., 2008).

The flow mechanism can be triggered by the presence of stratigraphic boundaries, leaking faults and an increase in seafloor temperature during fast deposition of glacio-marine sediments (Chand et al., 2012). Out of all these trigger mechanisms, the role of tectonism or faulting in hydrocarbon migration/leakage on continental margins is still poorly understood. In the special case of the Snøhvit Field, uplift and erosion was proposed as the major factor for fluid leakage at the detriment of tectonics and other mechanisms (Cavanagh et al., 2006; Chand et al., 2008). Cavanagh et al. (2006) and Rodrigues Duran et al. (2013) proposed multiphase erosion including glacial erosion, loading/unloading, and Cenozoic

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exhumation as the main cause of hydrocarbon migration in the Hammerfest Basin. Arvo, 2014 and Ostanin et al., 2013 sparingly discussed the role of fault reactivation and polygonal faulting as mechanisms driving fluid leakage in the area. Hence, there is a pressing need to understand and further investigate the influence of deep-seated faulting as a mechanism for fluid migration in the Hammerfest Basin.

This work is therefore done to elucidate the growth history and displacement character of faults in the Snøhvit field, their mode of reactivation and relationship with fluid migration or leakage. The study area is located in the Hammerfest Basin between the Loppa High to the north and the Finnmark Platform to the south. It is separated from the Loppa High by the Asterias Fault Complex, from the Tromsø Basin to the west by the southern segment of the Ringvassøy-Loppa Fault Complex, and from the Finnmark Platform by the Troms-Finnmark Fault Complex (Fig 1a). In this work, the history of fault growth was investigated using traditional fault displacement plots and the effect of faulting in fluid-leakage is discussed entirely by analyzing several high-amplitude anomalies identified from the seismic cube.

2. Geological setting

The tectonic history of the western Barents Sea can be traced back to the Caledonian Orogeny that strikes through northernmost Norway and northeastwards into the Barents Shelf (Barrère et al., 2009; Gernigon et al., 2014; Gudlaugsson et al., 1998; Ritzmann and Faleide, 2007). The Caledonian fabric is obscured in most parts of the Barents Sea, except on Svalbard, by Late Paleozoic and Mesozoic sedimentary basins (Breivik et al., 2002; Gee et al., 2008). Extensional tectonics during the Late Paleozoic in the western Barents Sea segmented the basins into a fan-shaped array of block-faulted basins separated by highs (Faleide et al., 1984; Gudlaugsson et al., 1998). The Upper Carboniferous to Lower Permian shallow marine carbonate with evaporite deposits are overlain by Upper Permian clastic deposits which formed in response to the Uralian Orogeny (Johansen et al., 1992).

The Triassic crustal extension in the North Atlantic and locally important differential compaction over the Late Paleozoic grabens has played an important role in accommodation space development (Glørstad-Clark et al., 2010). Intense rifting in the Mid Jurassic to Early Cretaceous occurred in the Southwestern Barents Sea (Faleide et al., 1993; 2008). The westward shift in extensional rifting increased the thicknesses of megasequences with time towards the present day continental-ocean boundary in the Southwestern Barents Sea (Klitzke et al., 2014). In the Late Cretaceous to Paleocene, the breakup between Norway and Greenland was taken up by strike-slip movements along the De Geer Zone. The Southwestern Barents Sea margin developed during the Eocene opening of the Norwegian-Greenland Sea (Faleide et al., 2008). The passive margin evolved in response to subsidence and sediment loading during the widening and deepening of the Norwegian-Greenland Sea. Uplift and glacial erosion during the Pliocene to Pleistocene caused deposition of deep marine fans in the adjacent oceanic domains along the northern and western passive margins (Doré and Jensen, 1996; Henriksen et al., 2011).

The Hammerfest Basin was probably initiated by extensional tectonics in the Carboniferous (Berglund et al., 1986). This caused tilting of the Loppa High and Hammerfest Basin in the Late Carboniferous to Early Permian with reactivation of the underlying basement fault trends. Differential basin subsidence with depocenters in the northeastern and southwestern part of the Hammerfest Basin during the Permian coincided with the reactivation of the Troms-Finnmark Fault Complex and showed that the Asterias Fault Complex was not active during this period. This provides evidence that the Hammerfest Basin was structurally continuous with the Loppa High at this time (Berglund et al., 1986).

Early Triassic sediments onlap onto north to south oriented structural highs and indicate tectonic reactivation during this period. The Late Triassic was a period of quiescence and deposition. Evolution of the margin in the Late Triassic to Mid Jurassic was largely controlled by the interplay of tectonic subsidence, eustatic sea level changes and sediment input. The sea level rise during the Mid Jurassic led to the deposition of the Stø Formation (Berglund et al., 1986). This formation is the main reservoir in the Snøhvit field, and represents a tectonically controlled transgressive wave-dominated estuary (Ottesen et al., 2005). Subsequent erosion of structural highs and deposition was restricted to both shallow and deep marine deltas along the northern and southern margins of the basin (Ottesen et al., 2005). However, the initial sediment distribution was controlled by doming accompanied by E-W trending normal faulting (Faleide et al., 1984) and with the formation of horst and graben structures. During the Late Jurassic, the syn-rift Hekkingen Formation was deposited in a deep marine environment and is the main source rock in the entire Barents Sea (Berglund et al., 1986). Marine sedimentation started as a result of transgression of the central part of the Hammerfest Basin during the Mid Paleocene. A SSW progradation of sediment from the platform areas to NNE of the basin occurred during the Late Paleocene. Subsidence and continued erosion was dominant during the Oligocene and Miocene (Knutsen and Vorren, 1991).

3. Data and methods

This study uses pre-stack time-migrated (PSTM) 3D seismic data covering an area of approximately 486 km^2 in water depths of 250–360 m in the Snøhvit Gas Field. The seismic data consists of 825 inlines and 3775 crosslines, each measuring approximately 47 km and 10 km in length respectively. The inlines are oriented in a NNE-SSW direction perpendicular to fault strike, while the crosslines are oriented parallel to fault strike. During data acquisition, a dual airgun was used working at a sampling rate of 4 ms (Nyquist Frequency of 250 Hz). The interpreted seismic volume has bin spacing of 12.5 × 12.5 m. Vertical resolutions (i.e., $\lambda/4$) of the seismic volume are approximately 10 m for shallow horizons and 15 m for deeper stratigraphic units. The lateral resolution is equal to the bin spacing, which is 12.5 m.

The main methods used in this work include: (1) mapping of the horizons, faults, and high-amplitude anomalies (2) fault and horizon modeling (3) fault displacement analysis and (4) multiple seismic attribute analysis using root mean square (RMS) amplitude, variance and chaos and geobody extraction. The first task in mapping the horizons is well-to-seismic tie in which formation tops from the boreholes were linked to their time-equivalent reflectors on the seismic data. The horizons in this work were interpreted using the 2D and 3D auto-tracking tool in Petrel®2015 across individual seismic profiles. Subsequently, the interpretation was extended into the seed grid at inlines and crossline spacing of 10 (equivalent to 125 m). The complete grids were later converted into surfaces in order to generate thickness maps.

Faults were manually interpreted across seismic profiles perpendicular to fault strikes at intervals of 62.5 m (5 inlines or crosslines). Fault displacement data such as the plot of displacement-distance (t-x), throw-depth (t-z), expansion and growth indices, were used to interpret the history of fault growth, linkage and reactivation. The vertical (throw) dip separations were measured at fault cut-off points on the hanging-wall and footwall sections. In order to make throw-depth (t-z) plots, the throw was determined across the faulted horizons and then plotted against depth to the midpoints between the respective hanging-wall and