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Hydrocarbon plumbing systems above the Snøhvit gas field: Structural control and implications for thermogenic methane leakage in the Hammerfest Basin, SW Barents Sea

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ABSTRACT

Based on the analysis of the high-resolution 3D seismic data from the SW Barents Sea we study the hydrocarbon plumbing system above the Snøhvit and Albatross gas field to investigate the geomorphological manifestation and the dynamics of leakage from the reservoir. Fluid and gas escape to the seafloor is manifested in this area as mega-pockmarks 1–2 km-wide, large pockmarks (<100 m wide) and giant pockmarks 100–300 m-wide. The size of the mega pockmarks to the south of the study area may indicate more vigorous venting, whilst the northern fluid flow regime is probably characterised by a widespread fluid and gas release. Buried mega depressions and large-to-giant pockmarks are also identified on the base Quaternary and linked to deep and shallow faults as well as to seismic pipes. A high density of buried and seafloor giant pockmarks occur above a network of faults overlying an interpreted Bottom Simulating Reflector (BSR), whose depth coincides with the estimated base of the hydrate stability zone for a thermogenically derived gas hydrate with around 90 mol% methane. Deep regional faults provide a direct route for the ascending thermogenic fluids from the reservoir, which then leaked through the shallow faults linked to seismic pipes. It is proposed that the last episodic hydrocarbon leakage from the reservoir was responsible for providing a methane source for the formation of gas hydrates. We inferred that at least two temporally and dynamically different fluid and gas venting events took place in the study area: (1) prior to late Weichselian and recorded on the Upper Regional Unconformity (URU) and (2) following the Last Glacial Maximum between ~17 and 16 cal ka BP and recorded on the present-day seafloor.

1. Introduction

Since the onset of petroleum exploration in the Barents Sea, the Snøhvit gas discovery (1984) in the Hammerfest Basin (Figs. 1 and 3) has resulted as the most successful and has been under production since 2006. With the exception of Goliat, recent Skrugard and Havis discoveries as well as a small oil find in well 7120/2-1, almost all of the proven hydrocarbon reserves were found to be gas with uneconomical residual oil (NPD, 2011). The lack of significant oil discoveries and dominance of gas have been attributed to the late Cenozoic exhumation and high latitude glaciations (Doré and Jensen, 1996; Cavanagh et al., 2006; Laberg et al., 2011). In the Barents Sea, uplift and tilting coupled with rapid erosion associated with waning and waxing of the ice sheets led to differential stress distribution, causing (1) depressurization induced reservoir gas expansion and oil-to-gas phase change (Nyland et al., 1992), (2) hydrocarbon spill out of structures due to tilting and uplift (Dore et al., 2002; Cavanagh et al., 2006), (3) Seal failure (Corcoran and Dore, 2002), (4) suppression of hydrocarbon generation due to source rock cooling (Doré and Jensen, 1996) and (5) possible, although still debated, reactivation of faults (Grollimund and Zoback, 2003; Bjørlykke et al., 2005; Brandes et al., 2010).

In sedimentary basins, recognition of active or paleo hydrocarbon seepage is extremely valuable as it provides clues regarding the present-day petroleum system, the risk associated with seal failure, *in situ* hydrocarbon volumes and their possible composition in the deeper prospective reservoirs (Heggland, 1998; O'Brien et al., 2005). Additionally, seabed fluid flow features may be associated not only with shallow gas accumulations but also slope instabilities, which may represent seafloor geohazards and impede successful seabed installations. Hydrocarbon leakage from the Snøhvit, Albatross and Askeladd fields (Fig. 3) has been previously reported as

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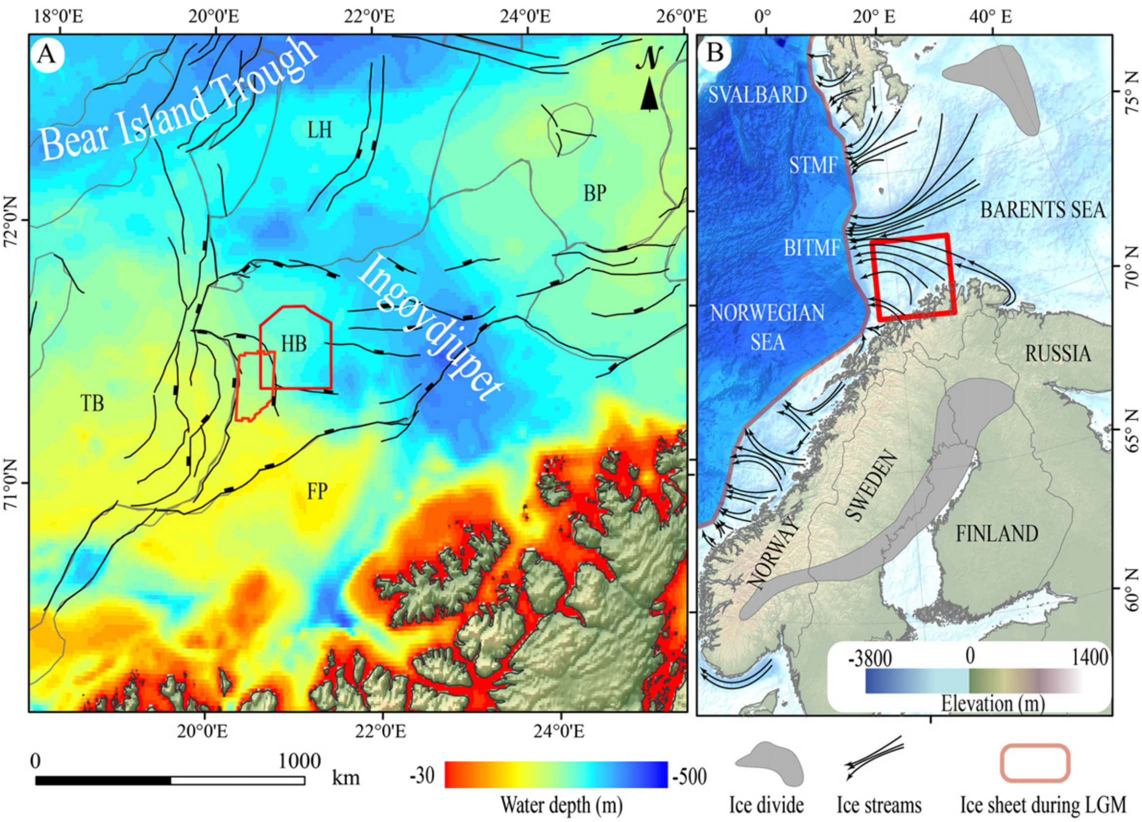

Figure 1. A) Regional framework of the study area showing the IBCAO bathymetry (Jakobsson et al., 2008) topography and structural elements: HB = Hammerfest basin, FP = Finnmark Platform, LH = Loppa high, BP = Bjarmeland Platform, TB = Tromso basin, modified from Ostanin et al. (2012). (B) Ice stream and ice divide locations (Ottesen et al., 2005) and maximum ice sheet extent during the LGM (Svendsen et al., 2004). BITMF = Bear Island trough mouth fan, STMF = Sorfjorden trough mouth fan. Red boxes show locations of the 3D seismic data (see Fig. 3 for a detailed view).

large gas anomalies causing acoustic wipe-out zones (Ostanin et al., 2012), whilst a paleo oil–water contact suggested that reservoirs were once filled with significantly larger volumes of hydrocarbons than today (Linjordet and Grung-Olsen, 1992). Leakage has been postulated to have taken place along the major tectonic faults, bounding the reservoir structures (Linjordet and Grung-Olsen, 1992; Ostanin et al., 2012), whilst seabed pockmarks and acoustic flares manifest possible recent fluid leakage into the hydrosphere (Judd and Hovland, 2007; Chand et al., 2012). Nonetheless, a detailed analysis of all the elements of the hydrocarbon plumbing system dynamics has not been carried out before.

In general, evidence of fluid flow is manifested on the seabed as metre- to- kilometre scale pockmarks, seep mounds, acoustic flares (Judd and Hovland, 2007), mounded structures (Anka et al., 2012) as well as gas chimneys and seismic pipes (Cartwright et al., 2007; Løseth et al., 2009). The fluid and gas seeps also attract diverse benthic and chemosynthetic communities, making them an integrated part of the deep sea ecosystems (Judd and Hovland, 2007). In the subsurface, ascending gas and fluids may also be temporarily or permanently trapped en route to the surface, leaving imprints of their former flow within the stratigraphic successions. They can be inferred from geophysical datasets in form of amplitude anomalies caused by the acoustic impedance contrasts associated with the velocity and density changes compared to the surrounding rock (Brown, 2004; Løseth et al., 2009). Shallow gas accumulations can cause scatter and attenuate seismic waves while disrupting seismic records causing chaotic, acoustic turbidity, wipe-out zones, and artificial sagging of the reflections due to gas presence in the overlying strata (Løseth et al., 2009). Gas saturations as low as 10% in the sediment pore space can potentially cause a significant drop in P wave velocity and may be detected by seismic methods, depending on the impedance contrast and the data resolution (Brown, 2004; Andreassen et al., 2007).

Disturbances having a stacked or columnar nature are termed “seismic pipes” and are considered to be vertical fluid and gas migration pathways affecting at times over 1 km of sediments (Cartwright et al., 2007; Huuse et al., 2010; Moss and Cartwright, 2010; Løseth et al., 2011). Seismic pipes are usually circular to sub-circular in plan-view and have vertical to sub vertical geometries, characterised by vertical zones of deteriorated seismic signal. They have been postulated to be caused by hydraulic fracturing of the sealing stratigraphy by rapidly ascending gas and fluids escaping from overpressured hydrocarbon accumulations (Cathles et al., 2010). Inside the seismic pipes intense fracturing dominates, thus increasing permeability and reducing seal integrity, allowing fluids to flow (Cartwright et al., 2007; Huuse et al., 2010). However, some seismic pipes may be plugged by hydrate cementation, releasing methane at slow rates (Plaza-Faverola et al., 2010). Seismic pipes may also terminate in blow-out events on the seabed, forming pockmarks, depending on their intensity and overpressure regime (Cartwright et al., 2007). They are discriminated from seismic processing artifacts as they exhibit both structural and stratigraphic control upon their development, such as their location above structural traps or faults (Cartwright et al., 2007; Huuse et al., 2010). Seismic pipes are differentiated from gas chimneys, which are wide zones of deteriorated seismic signal (wipe-out, chaotic reflections, velocity pull-downs), associated with low velocity zones caused by shallow gas accumulations or vertical gas migration (Løseth et al., 2009). Stacked pockmarks can be also related to tectonically induced changes in the stress field (Baraza and Ercilla,