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# Fluid distributions inferred from P-wave velocity and reflection seismic amplitude anomalies beneath the Nyegga pockmark field of the mid-Norwegian margin

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ABSTRACT

Travel-time inversion of wide-angle ocean-bottom seismic (OBS) data results in detailed P-wave velocity models of the shallow sub-seabed beneath the Nyegga pockmark field. The area lies on the northern flank of the Storegga Slide on the mid-Norwegian margin. Velocity anomalies indicate two low P-wave velocity zones (LVZs) providing evidence for the presence of gas-rich fluids in the subsurface at Nyegga. Integrating the velocity results with 2D and 3D reflection seismic data demonstrates that LVZs coincide with zones of high-amplitude reflections that allow mapping the extent of the fluids in the subsurface. The upper fluid accumulation zone corresponds to a velocity inversion of ~250 m/s and occurs at a depth of about 250 mbsf. The lateral extent is documented in two distinct areas. The westward area is up to 40 m thick where gas-rich fluids beneath a bottom-simulating reflection indicate that fluids may be trapped by gas hydrates. The eastward zone is up to 60 m thick and comprises a contourite deposit infilling a paleo-slide scar. On top, glacigenic debris flow deposits provide a locally effective seal for fluids. The second velocity inversion of ~260 m/s extends laterally at about 450 mbsf with decreasing thickness in westward direction. Based on effective-medium theory the gas saturation of pore space in both layers is estimated to be between 0.5 and <1% assuming a homogeneous distribution of gas. Fluids probably originate from deeper strata approximately at the location of the top of the Helland-Hansen Arch. Fluids migrate into the second LVZ and are distributed laterally. Fluids migrate into shallower strata or are expelled at the seabed through the formation of vertical fluid migration features (VFMFs), so-called chimneys. The distribution of the chimneys is clearly linked to the two fluid accumulation zones in the subsurface. A conceptual model draws on the major controlling factors for fluid migrations at specific locations within Nyegga. Fluid migrations vary according to their actual position with respect to the prograding Plio–Pleistocene sedimentary wedge.



## 1. Introduction

The flow of fluids through marine sediments is one of the most dominant and pervasive processes in continental margins (Berndt, 2005; Carson et al., 2003). These processes control the evolution of sedimentary basins and their seafloor environment, and have implications for hydrocarbon exploration and seabed ecosystems (Berndt, 2005). Many seep sites at the seafloor are associated with large but complex faunal communities that have received significant attention in recent years (e.g. Wheeler et al., 2007). However, there is a need for a better understanding of the driving mechanism of fluid flow in various geological settings, the accumulation of fluids in the subsurface and their focused flow through conduits and/or faults to the seabed.

One of the main indicators of fluid flow on continental margins is the occurrence of pockmarks at the seabed (Hovland et al., 2002; Judd, 2003). Pockmarks have been described from many areas of active and passive continental margins (Hovland, 1982; Rise et al., 1999). They often connect to active chimneys or pipes in the subsurface that are vertical, cylindrical structures, which often pierce through more than 1000 m of sediments (Løseth et al., 2001). The chimneys show a transparent acoustic character that interrupts reflections. Up-bending reflections at the chimney outer limits may be the result of mechanical strata deformations due to

*Abbreviations:* Area I, refers to the most distal area respect to the Storegga slide; Area II, refers to closest area respect to the Storegga slide; BGHSZ, Base gas-hydrate stability zone; CD, contourite deposits; GDF, glacigenic debris flow; GHSZ, gas-hydrate stability zone; HAZ 1, refers to the shallower high amplitude zone; HAZ 2, refers to the deeper high amplitude zone; HHA, Helland-Hansen Arch; INT, refers to Intra Naust T reflector; LVZ 1, refers to the shallower low velocity zone; LVZ 2, refers to the deeper low velocity zone; LVZ/HAZ 1, refers to the shallower level for fluid accumulation; LVZ/HAZ 2, refers to the deeper level for fluid accumulation; OBS, ocean-bottom seismometer; VFMF, vertical fluid migration feature.

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upward-migrating fluid within the chimney or may be due to higher velocity material inside the chimney (e.g. Westbrook et al., 2008b).

The fluid composition is often unknown but depends to a large degree on source areas from which gases such as biogenic (shallow source) and/or thermogenic methane (deep source) migrate upwards (Kelley et al., 1994; Rise et al., 1999; Solheim and Elverhoi, 1993). Though large uncertainties do exists regarding their composition and the timing of fluid flow, pockmark and chimney formations in continental margins allow for one common assumption that is, they mark focussed fluid-flow features indicative of overpressurised formations in the sub-seabed (Rise et al., 1999).

More than four hundred pockmarks exist at the seabed in the region of Nyegga at the northern flank of the Storegga Slide on the mid-Norwegian margin (Bünz et al., 2003; Hovland and Svensen, 2006; Mazzini et al., 2006) (Fig. 1). They occur in water depths between 500 and 1500 m along the north-eastern flank of the Storegga slide. The majority of pockmarks connect to chimneys that pierce through glacigenic debris flows deposited during the last glacial maximum (LGM), which argues for a postglacial activity of vertical fluid flow (Bouriak et al., 2000; Bünz et al., 2003; Hustoft et al., 2007; Mienert et al., 2005b; Paull et al., 2008). Potential source areas of fluids and occurrence of overpressurised formations from which fluids migrate are less known and consequently under debate (Berndt, 2005; Hustoft et al., 2007; Mazzini et al., 2006).

The main objective of this study is to determine the lateral distribution of fluids in the subsurface and its relationship to vertical fluid venting in Nyegga. A combined use of multi-component ocean-bottom seismometer (OBS), single channel reflection seismic (SC) and 3D seismic data (3D) allows to constrain the occurrence of low velocity zones (LVZs) and high amplitude zones (HAZs) in the upper 800 mbsf (meters below the seafloor). Integrating P-wave velocity models with 2D and 3D seismic stratigraphic interpretations allow us to assess the fluid and/or gas distributions and migration pathways in the subsurface and their geological controlling factors.

## 2. Geological setting

The tectonic and stratigraphic evolution of the mid-Norwegian margin contains phases that largely control pathways and accumulation of fluids. The tectonic and stratigraphic evolution of the Vøring and the Møre basins (Fig. 1) began with late-Jurassic/Early Cretaceous rifting that continued in three phases until Late Paleocene/Early Eocene continental break-up (Brekke, 2000). Two NW–SE trending lineaments: the Bivrost to the north and the Jan Mayen to the south, partly control the development of sedimentary basins in this region. The lineaments divide the mid-Norwegian margin into three main structural provinces consisting of the NE–SW trending Vøring and Møre basins and the Trøndelag Platform (Brekke, 2000). The Nyegga study area is situated at the border between the two sedimentary basins (Fig. 1).

Tertiary domes developed after the Palaeocene–Eocene continental break-up (Gomez and Verges, 2005; Vagnes et al., 1998) (Fig. 1). These structures have the potential for possible petroleum traps and hydrocarbon exploration proved their existence (Berg et al., 2005; Bryn et al., 2005b). Particularly, the Helland-Hansen Arch and the Ormen Lange Dome comprise hydrocarbon reservoir candidates that extend from the south-eastern end of the Jan Mayen Lineament towards the Vøring Basin (Gomez and Verges, 2005) (Fig. 1). Deep seismic investigations of the Helland-Hansen Arch show a long and gentle anticline that is approx. 60 km wide in east west orientation and more than 240 km long in north–south direction. Its eastern flank is slightly steeper than the western flank (Kjeldstad et al., 2003). Some authors explain the formation of the Helland-Hansen Arch and other anticlines of Tertiary age of the mid-Norwegian margin as inversion structures after episodes of

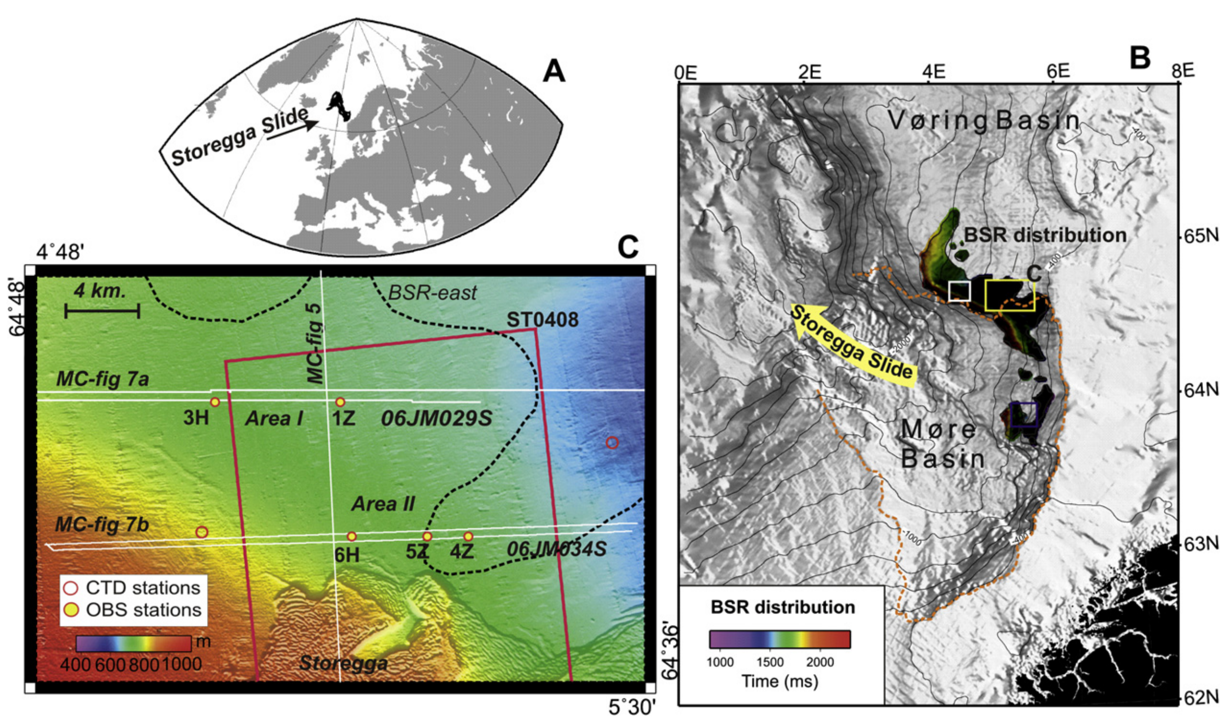


**Fig. 1.** A) Location of the Storegga slide at the mid-Norwegian margin. B) Location of the Nyegga pockmark field at the northern flank of the Storegga slide. The BSR distribution from Bünz et al., (2003) is displayed. The Nyegga area is indicated by a C (yellow box). Two adjacent areas where Vp models are available for comparison are displayed: hydrated province (white box) to the north-east (Bünz et al., 2003); Ormen Lange (purple box) to the south (Mienert et al., 2005a). C) Bathymetry of the study area showing the location of the OBSs and seismic surveys. Multi-channel (MC) and single channel (SCS) seismic lines (white solid lines) and the STO408 3D seismic block (red box) are shown. The dashed black line indicates the eastern border of the BSR distribution in B.