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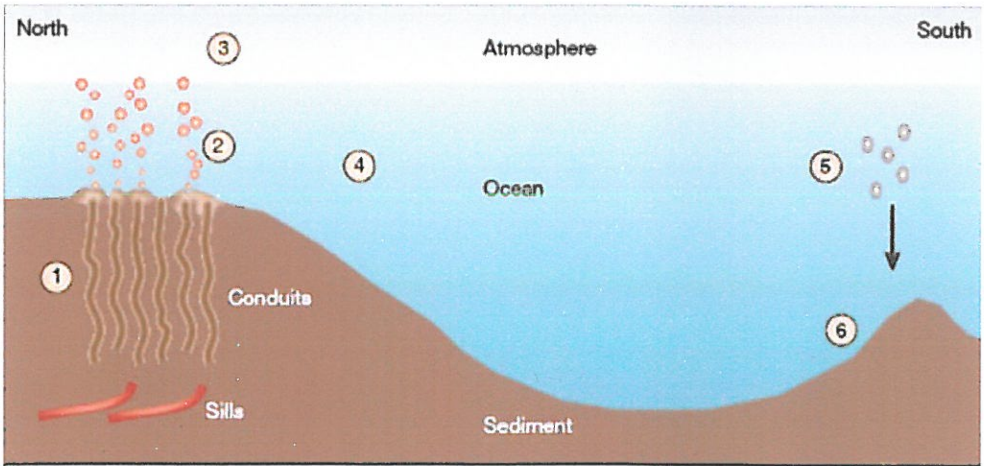
Introduction

Why study hydrocarbon seepage?

The study of present and past seepage of hydrocarbons through the seafloor has been a major focus of interest in several disciplines of Earth Science during the last two decades. The great attraction of this dynamic geological process is, from an academic point of view, driven by the pursuit to understand the impact on today's seafloor environment and the effects of natural greenhouse gas-emissions on global climate. The current understanding of marine geology and subsurface fluid-flow processes has also greatly benefited from hydrocarbon exploration activities. This scientific profit is mainly due to the three-dimensional (3D) seismic technological innovations and the vast amount of data acquired on prolific continental margins, which follows in the wake of a rapidly increasing demand for energy.

Given the enormous content of organic matter accumulated in marine sediments, methane (CH_4) is by far the most common gas in the subsurface [*Schoell*, 1988]. Methane in the atmosphere is about 20 times more efficient greenhouse gas than carbon dioxide (CO_2) [*Khalil and Rasmussen*, 1995]. Thus, if rapidly and significantly released from the solid Earth to the atmosphere, natural emissions of methane may influence global climate [*Dickens*, 1999; *Kennett et al.*, 2003; *Svensen et al.*, 2004].



1. Methanogenesis $2^{12}CH_2O \rightarrow {}^{12}CH_4 + CO_2$. 2. Methane oxidation ${}^{12}CH_4 + 2O_2 \rightarrow {}^{12}CO_2 + 2H_2O$.
3. Methane oxidation ${}^{12}CH_4 + OH^{\cdot} \rightarrow {}^{12}CH_3^{\cdot} + H_2O$.
4. Carbonic acid dissociation ${}^{12}CO_2 + H_2O \rightarrow H^+ + H^{12}CO_3^-$; $H^{12}CO_3^- \rightarrow H^+ + {}^{12}CO_3^{2-}$.
5. Carbonate precipitation ${}^{12}CO_3^{2-} + Ca^{2+} \rightarrow Ca^{12}CO_3$.
6. Carbonate dissolution ${}^{12}CO_2 + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$.

Figure 1. *Simplifying cartoon illustrating the mechanisms involved in massive release of methane to the ocean and atmosphere, which may influence global climate [Adapted from Dickens, 2004].*

About 55 million years ago, a dramatic ocean warming of about 5-7 °C is associated with rapid extinction of benthic organisms [*Kennett and Stott*, 1991]. The short global warming period, known as the initial Eocene thermal maximum (IETM), coincides with a significant input of carbon (carbon dioxide) to the global carbon budget, which preferentially oxidized from catastrophically-released methane [*Dickens et al.*, 1997; *Bains et al.*, 1999]. Although still debated, it is proposed that the IETM initiated due to extensive thermal maturation of organic matter produced by igneous intrusions in the North Atlantic [Fig. 1; *Svensen et al.*, 2004]. Following the initial ocean warming, it is speculated if large amounts of inherently unstable oceanic methane-hydrate dissociated globally because of the rapidly increasing ocean temperatures [*Dickens*, 1999; 2004]. This amplifying feedback mechanism to global warming refers to the 'clathrate gun hypothesis' [*Kennett et al.*, 2003].

Although the present-day natural emissions of methane to the ocean and atmosphere are several orders of magnitudes less than during the IETM, the modern hydrocarbon seeps may possess important clues to the interplay between temporary storage and leakage of methane in the subsurface. We know that active methane degassing occur at many continental margins worldwide [e.g., *Hovland et al.*, 1993; *Suess et al.*, 1999; *Sauter et al.*, 2006; *Chand et al.*, 2008b; *Shakhova et al.*, 2008; Nature News, 26 Sep 2008]. However, the microbial biofilter in near-seafloor sediments and in the water column may consume up to 80% of the methane released when the flux is relatively low [*Heintz et al.*, 2008]. Superimposed onto the increasing amount of anthropogenically released greenhouse gasses, the environmental impact of modern hydrocarbon seeps on global climate remains elusive and speculative. Yet, estimates of the total amount of carbon released during the IETM are comparable to what may enter the global carbon budget over the next few hundred years [*Dickens*, 2004]. Given that the global volume of carbon stored in methane hydrate (3000 to 10 000 gigatonnes) can be twice the amount of carbon stored in conventional petroleum resources on Earth [*Kvenvolden and Lorenson*, 2001], the 'clathrate gun' still remains a potent environmental threat.

Preserved in the planets natural record of geological history – the marine sediments – the various imprints of past and/or present seepage of hydrocarbons are associated with morphological, biological, mineralogical, and chemical anomalies. Methane seeps (or cold seeps) at the seafloor represent vital habitats for deep-marine seafloor ecosystems [*Hovland and Judd*, 1988; *Foucher et al.*, 2009], and if densely populated, such seepage sites may provide a useful guide to hydrocarbon prospecting regions [*Heggland*, 1998].

Subsurface fluid flow and formation of cold seeps are mainly driven by pressure gradients, and therefore closely related with the fluid pressure conditions driving sediments mechanically instable [*Dugan and Flemings*, 2000; 2002; *Kvalstad et al.*, 2005]. Focused fluid flow systems are therefore highly relevant contributors to large submarine slope failures and related tsunamis [*Bugge et al.*, 1987; *Bondevik et al.*, 2005], particularly due to the ocean warming effect on gas hydrate destabilization [*Maslin et al.*, 1998; *Mienert and Posewang*, 1999; *Vogt et al.*, 1999a; *Mienert et al.*, 2005b]. Characterizing the distribution and genesis of spatially and temporally varying fluid flow systems – by means of natural laboratories – may also address important issues of CO_2 injection and long-term storage in the subsurface, because the physical properties of CO_2 are similar to methane [e.g., *Arts et al.*, 2004]. Fluid flow research is therefore one of the fastest growing fields in marine geosciences due to its relevance for today's society.

Scope of thesis

Seismic reflection surveying is the principal method utilized to address geodynamic aspects that govern fluid-sediment interactions at basin scale. Significant progress has been made the last decade, in particular with relation to the technological improvements of 3D seismic imaging, allowing greater spatial resolution and thereby making it possible to identify and map subtler 3D details of complex cold-seep structure and associated stratigraphy.

The principal objective of the PETROMAKS project is to understand and quantify geological processes that govern basin-scale fluid flow. As a contribution to the comprehensive and interdisciplinary objective of the PETROMAKS project, this dissertation aims to improve the current understanding of the distribution and driving mechanisms of cold seep development in gas-hydrate provinces. Three-dimensional (3D) and two-dimensional (2D) seismic imaging, inversion of P-wave velocities and forward basin modeling are the main methods utilized in order to achieve insights into the geological preconditions favorable for cold-seep formation.

The main objective is two-tiered, that is, to understand the spatial and temporal evolution of fluid flow features. This dissertation focusses on two target areas, both showing a widespread occurrence of fluid-escape features: (A) the Nyegga area located on the mid-Norwegian margin and (B) the Vestnesa Ridge located on the NW-Svalbard margin (Fig. 2). The two areas represent the largest known gas-hydrate provinces of Europe, for which a comparative study provides a new understanding of their fluid-venting systems because of their strikingly different tectonic, sedimentological, and oceanographic regimes.

The overall objectives of this study are:

- Acoustic characterization of fluid migration pathways (i.e., fluid-escape chimneys) in gas hydrate-bearing sediments,
- Evaluation of the spatial distribution of fluid-escape chimneys with regard to the geological context, and thereby seeking to address their genesis, fluid source, and implications for seal integrity,
- Understanding the temporal evolution, episodic activity and duration of fluid-escape chimneys and associated seafloor vents.

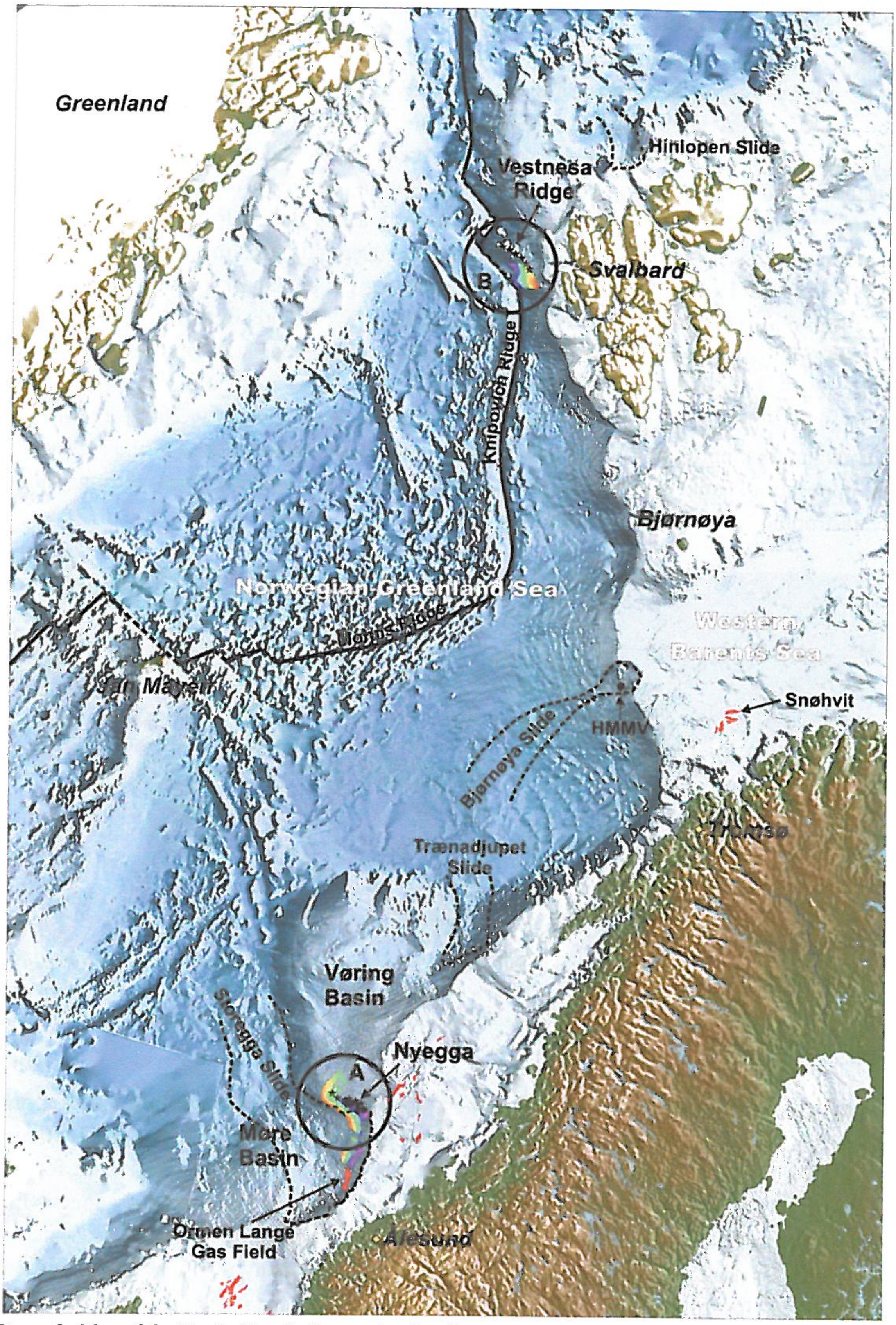


Figure 2: Map of the North Atlantic Ocean showing the two target areas of this research (encircled); (A) the northern flank of the Storegga Slide and (B) the Vestnesa Ridge on the NW-Svalbard margin. Both areas are associated with extensive fluid-escape features (stars, not to scale) and gas-hydrate and free-gas systems [color contours; from Bünz et al., 2003; Vanneste et al., 2005b]. The large submarine slides along the margin are outlined (stippled) and major hydrocarbon reservoirs are shown in red.

"Hotspots" in deep-ocean margins

Pockmarks are near-circular craters formed by localized ejection of water and/or gas in soft and fine-grained sediments at the seafloor [Fig. 3a; *Hovland and Judd*, 1988]. Following the first discovery about four decades ago [*King and MacLean*, 1970], pockmarks have been identified in all water depths from coastal areas to the deepest ocean at high and low latitudes, and consequently they are associated with a range of oceanographic and geologic settings [*Judd*, 2003]. The craters vary in size from a few meters to more than one kilometer in diameter and are generally a few tens of meters deep, although they can reach a significant depth of 80 m. To date, no scientific proof exists for the pockmarks true origin because none has been observed at their time of formation. The flow of fluids in these features is therefore probably episodic in nature, and as such, the flow mode bear a resemblance to a wealth of other focused fluid flow features forming positive seafloor morphologies such as carbonate mounds [e.g., *Trehu et al.*, 2003] and mud volcanoes [e.g., *Dimitrov*, 2002]. However, since the pockmarks represent craters, and as such show no evidence of long term ejection of mud, as opposed to mud volcanoes, it is speculated if pockmarks form during short-lived "catastrophic" events of fluid eruptions [*Hovland et al.*, 2005].

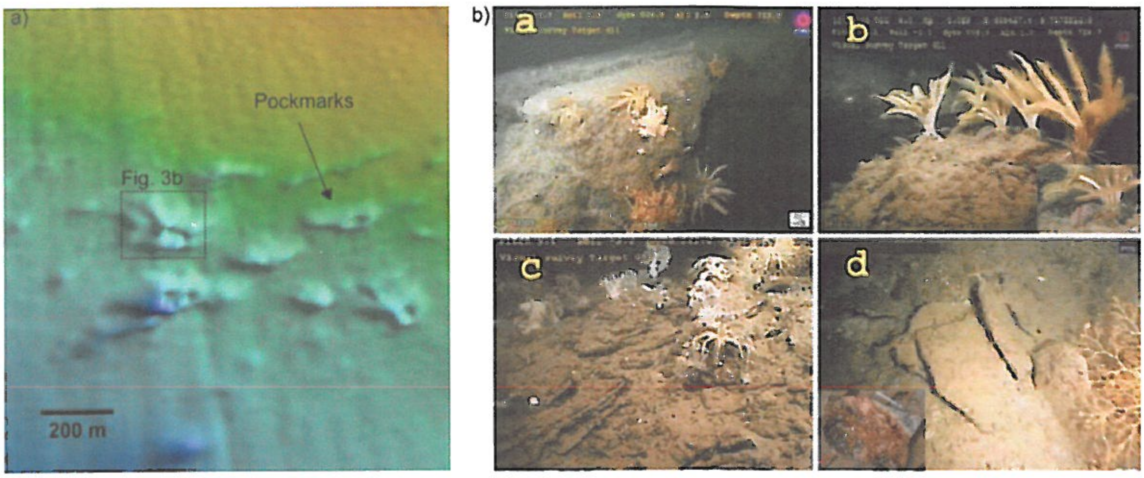


Figure 3. *a) 3D seismic image of the seafloor showing pockmarks in the Nyegga region on the mid-Norwegian margin. b) The photographs taken within a pockmark (framed in Fig. 3a) show a number of macrofaunal organisms attached to large blocks of methane-derived authigenic carbonate [adapted from Hovland et al., 2005].*

A number of indirect indicators suggest seepage of hydrocarbon-rich fluids from cold seeps, except from the direct observations of methane gas bubbling out of the seafloor [e.g., *Tryon et al.*, 2002],. Cold seep ecosystems in the deep ocean were discovered for the first time in 1984 [*Kennicutt et al.*, 1985]. Assemblages of micro- and macro organisms in deep-ocean margins were first surprising because photosynthesis is restricted to water depths typically less than 300 m. Yet, it was soon realized that many chemosynthetic biota derive their energy from methane oxidation, and therefore, their presence at the seafloor crucially depends on a more or less constant supply of hydrocarbon-rich fluids from depth [*Kennicutt et al.*, 1985; *Hovland and Judd*, 1988]. In areas of high methane flux like mud volcanoes, Weaver *et al.* [2004] reported on a benthic biomass production of more than three orders of magnitude greater than the surrounding biomass production resulting indirectly from shallow-water photosynthesis. Consequently, seeps are closely associated with "hotspots" of increased biological activity providing indirect proxies for active hydrocarbon seepage [*Judd and Hovland*, 2007; *Foucher et al.*, 2009]. Observations of dead or buried fauna therefore indicate that the fluid expulsion has come to a halt [e.g., *Paull et al.*, 2008].

Another characteristic feature of many hydrocarbon seeps is the presence of carbonate concretions at the muddy seafloor, which due to their "hard-ground" facilitates growth of macrobenthic fauna (Fig. 3b). These mineralogical seafloor anomalies – called methane-derived authigenic carbonate – are byproducts produced by the consortium of methane-oxidizing archaea and sulphate-reducing bacteria in near-seafloor sediments [*Ritger et al.*, 1987; *Boetius et al.*, 2000]. Carbon isotope analyses typically reveal a significant ^{13}C depletion relative to the marine derived carbonate, suggesting that light hydrocarbons escaped through the seep location [e.g., *Mazzini et al.*, 2004].

Seepage on the Norwegian-Barents-Svalbard margin

Continental shelf areas

The distribution of pockmarks and other seep features show a considerable geographical correlation with geological settings associated with hydrocarbon sources in the subsurface, such as large gas hydrate provinces [*Mienert and Posewang*, 1999; *Bünz et al.*, 2003] and deeper prospective reservoirs [*Heggland*, 1998]. Seafloor pockmarks on the Norwegian-Barents-Svalbard margin were first discovered in the North Sea as a result of extensive hydrocarbon-related surveying [*Josenhans et al.*, 1978; *Hovland*, 1981; 1982; 1983; 1984; 1992; *Hovland and Mienert*, 1992]. Active seepage has been reported from a few North Sea pockmarks [*Dando et al.*, 1991], however, because pockmarks presumably exhibit episodic expulsion such documentations are rather rare even in highly prolific areas. Supported by datings of foraminifera and methane-derived authigenic carbonate, Forsberg *et al.* [2007] recently suggested that the North Sea pockmarks (Troll region) formed about 11 cal. ka BP in response to postglacial dissociation of gas hydrate and subsequent gas release from the shallow sediments. In other regions of the North Sea, like the Skagerrak, pockmarks cluster along outcrops of middle Jurassic sandstones, demonstrating the significance of thermogenic sources in pockmark development [*Rise et al.*, 1999]. However, large parts of the North Sea show widespread occurrences of buried pockmarks, thereby indicating a long history of episodic hydrocarbon expulsion dating back to mid-Oligocene times [*Andresen et al.*, 2008].

A few studies have also documented locally high local concentrations of seafloor pockmarks on the Barents Sea continental shelf [*Solheim and Elverhøi*, 1985; 1993; *Chand et al.*, 2008a; in press]. Gas hydrate has been geophysically inferred in local areas of the SW Barents Sea [*Andreassen et al.*, 1990; *Laberg and Andreassen*, 1996; *Laberg et al.*, 1998], and despite the shallow water depths (<500 m), Chand *et al.* [2008a] suggested that gas hydrate are stable over large areas due to the presence of higher order hydrocarbon gases other than methane. Similar to the proposed genesis of pockmarks in the North Sea, the

Barents Sea pockmarks have been attributed to postglacial dissociation of gas hydrate and subsequent overpressure generation and release of gas [*Solheim and Elverhøi*, 1993].

Notably, about two hundred and fifty gas flares in the water column were recently detected on the shelf offshore NW-Svalbard [Nature News, 26 Sep 2008]. The details are not yet published, however, it signifies that considerable amounts of gas are presently being released from the Arctic seafloor. Active gas venting has also been reported on the continental shelf offshore Vesterålen, northern Norway [*Chand et al.*, 2008b]. It should be noted that the thousands of pockmarks in the North Sea and in the Barents Sea are generally not associated with seismically resolvable leakage pathways such as chimneys [e.g., *Forsberg et al.*, 2007]. This is in strong contrast to the deeper water (~ >500 m) continental slope areas where pockmarks connect with vertical chimneys in the subsurface.

Continental slope areas

The two major areas with high concentration of seafloor pockmarks and fluid venting features along the Norwegian-Barents-Svalbard continental slope occur at the northern flank of the Storegga Slide on the mid-Norwegian margin and at the Vestnesa Ridge on NW-Svalbard margin at water depths between 700 and 1400 m (encircled in Fig. 2). There are also a number of mud mound/diapir fields along the Norwegian-Barents-Svalbard margin [e.g., *Hjelstuen et al.*, 1997; *Vogt et al.*, 1999c]. However, ongoing ejection of mud and gas has only been documented for the Håkon Mosby Mud volcano (HMMV; Fig. 2) [*Milkov et al.*, 2004; *Perez-Garcia et al.*, 2009].

To the north of the giant Storegga Slide, dating back to 8.1 cal. ka BP [*Haflidason et al.*, 2005], pockmarks and mounds occur widespread on the seafloor in water depths of 700-1000 m [*Evans et al.*, 1996; *Mienert et al.*, 1998; *Mienert and Posewang*, 1999; *Gravdal et al.*, 2003; *Bouriak et al.*, 2000]. These seafloor expressions of focused fluid flow have been associated with overpressured free-gas below the gas hydrate stability zone within the Plio-Pleistocene Naust Formation [*Bünz et al.*, 2003; *Hustoft et al.*, 2007; *Westbrook et al.*, 2008a]. It is also suggested that dewatering processes of polygonal fault systems in the siliceous ooze sediments of the deeper Miocene to Early Pliocene Kai Formation contributed to localized overpressure generation and subsequent fluid focusing towards the seafloor [*Berndt et al.*, 2003; *Gay and Berndt*, 2007]. The seafloor pockmarks are frequently associated with methane-derived authigenic carbonate and chemosynthetic fauna [*Hovland et al.*, 2005; *Hovland and Svensen*, 2006; *Mazzini et al.*, 2005; 2006]. The recent discovery of gas hydrate in near-seafloor sediments from several individual pockmarks manifest ongoing micro-seepage of methane [*Ivanov et al.*, 2007; *Haflidason et al.*, 2008]. A few datings of planktonic foraminifera indicate that the authigenic carbonate and clam fields developed within pockmarks between 18.5-13.2 cal. ka BP [*Paull et al.*, 2008], thereby predating many of the North Sea pockmarks [*Forsberg et al.*, 2007].

The Vestnesa Ridge is a large, mounded sediment drift in the Fram Strait [*Eiken and Hinz*, 1993]. The Vestnesa Ridge pockmarks align in a 1 to 3 km wide, and 50-km-long belt at the crest of the sediment drift at 1100-1400 m water depth [*Vogt et al.*, 1994; 1999b]. The Vestnesa Ridge and adjacent slope regions represent the second largest gas hydrate province of Europe [*Eiken and Hinz*, 1993; *Posewang and Mienert*, 1999; *Vanneste et al.*, 2005b; 2005a; *Westbrook et al.*, 2005; 2008b; *Haacke et al.*, 2008; *Bünz et al.*, 2008]. Importantly, a recent cruise (September 2008) discovered a gas flare in the water column above one of the Vestnesa ridge pockmarks (G. K. Westbrook, pers.com on behalf of shipboard party on cruise JR211 of RRS James Clark Ross).

Focused fluid flow in the gas-hydrate hydrate stability zone

The high-pressure and low-temperature conditions in deep-water environments (>300-500 m) cause methane to form ice-like crystals of gas hydrate in the sediment pore space [*Sloan*, 1998]. These requirements, together with appropriate salinity and adequate supplies of methane, confine oceanic gas hydrates to the upper few hundred meters of sediments – the gas hydrate stability zone (GHSZ). The occurrence of hydrate in the pore space reduces the porosity and permeability of the host sediment [*Nimblett and Ruppel*, 2003]. Thus, large gas hydrate deposits like those found on the Blake Ridge (offshore South Carolina), the Hydrate Ridge (Cascadian margin), and on the Norwegian-Barents-Svalbard margin, can form laterally extensive hydrological "seals", which halt buoyant gas escaping vertically to the seafloor. This natural 'hydrate carapace' allows dissolved and free gas to accumulate below the 'base of the gas hydrate stability zone' (BGHSZ).

Seismic reflection profiling show that deep-water pockmarks and mounds frequently represent the seafloor expression of sub-vertical, columnar zones of reduced amplitude and/or highly distorted stratal reflections (Fig. 4). Although a wealth of terms has been used to portray these features, they are nowadays typically called fluid *pipes* or fluid-escape *chimneys* by means of representing confined acoustic imprints of past or presently ongoing cross-stratal, focused fluid flow feeding the seafloor seeps [*Løseth et al.*, 2001; *Berndt et al.*, 2003; *Gay et al.*, 2006; *Cartwright et al.*, 2007]. The chimneys have a circular to sub-circular plan form, generally less than 300 m in diameter, and they may penetrate significant thicknesses of low permeability sediments.

Fluid-escape chimneys are shown to connect seafloor seeps with free gas zones below the BGHSZ [*Suess et al.*, 1999; *Gorman et al.*, 2002; *Riedel et al.*, 2002; *Bünz et al.*, 2003], or deeper polygonal fault systems [*Berndt et al.*, 2003; *Gay et al.*, 2006]. Thus, it is evident that some peculiar processes allow methane to exist in free or dissolved phase as it bypasses the GHSZ without turning into gas hydrate. The processes inhibiting hydrate formation, as methane migrates through the GHSZ, are still highly debated.

Most models for methane migration in the GHSZ assume relatively slowly advecting systems, which self-generate a state of three-phase equilibrium (i.e., reduced hydrate stability) due to vertical focusing of warmer fluids [*Wood et al.*, 2002], or anomalous salinity gradients caused by water depletion subsequent to rapid hydrate growth [*Liu and Flemings*, 2006; 2007]. The high-salinity/temperature models for chimney genesis imply a pockmark formation mode resulting from relatively long-term gas expulsion. For example, Riedel *et al.* [2006] showed that that the flux of methane within a chimney on the Cascadia margin was 3-6 times higher than in the sediments surrounding the chimney. Such enduring low-flux, but long-term, systems are consistent with the development of authigenic carbonate within pockmarks and carbonate mounds, because precipitation of carbonate concretions is a slow process requiring tens to hundreds, or even thousands of years to form extensively.

Løseth *et al.* [2001] utilized 3D seismic data and described a system of chimneys that crossed more than 1000 m of low permeability sediments on the Nigerian continental margin (Fig. 4). The chimneys were circular in plan form and connected large seafloor pockmarks with an overpressured gas reservoir. Løseth *et al.* [2001] proposed a mechanism involving critically pressured reservoir gas, seal-breach at reservoir level by hydraulic fracturing, followed by rapidly ascending gas towards the seafloor in a transient blowout-like event. A few, recent publications have supported the relatively controversial blowout hypothesis as a convenient mechanism for developing this end-member of seismic chimneys, because it agrees with the complex morphology and forceful processes associated with many pockmarks [*Hovland et al.*, 2005; *Cartwright*, 2007; *Cartwright et al.*, 2007]. Although Cartwright *et al.* [2007] classified this type of chimneys as a *blowout* feature, they also emphasized that "...this group of pipes is perhaps the most enigmatic and most difficult to classify".

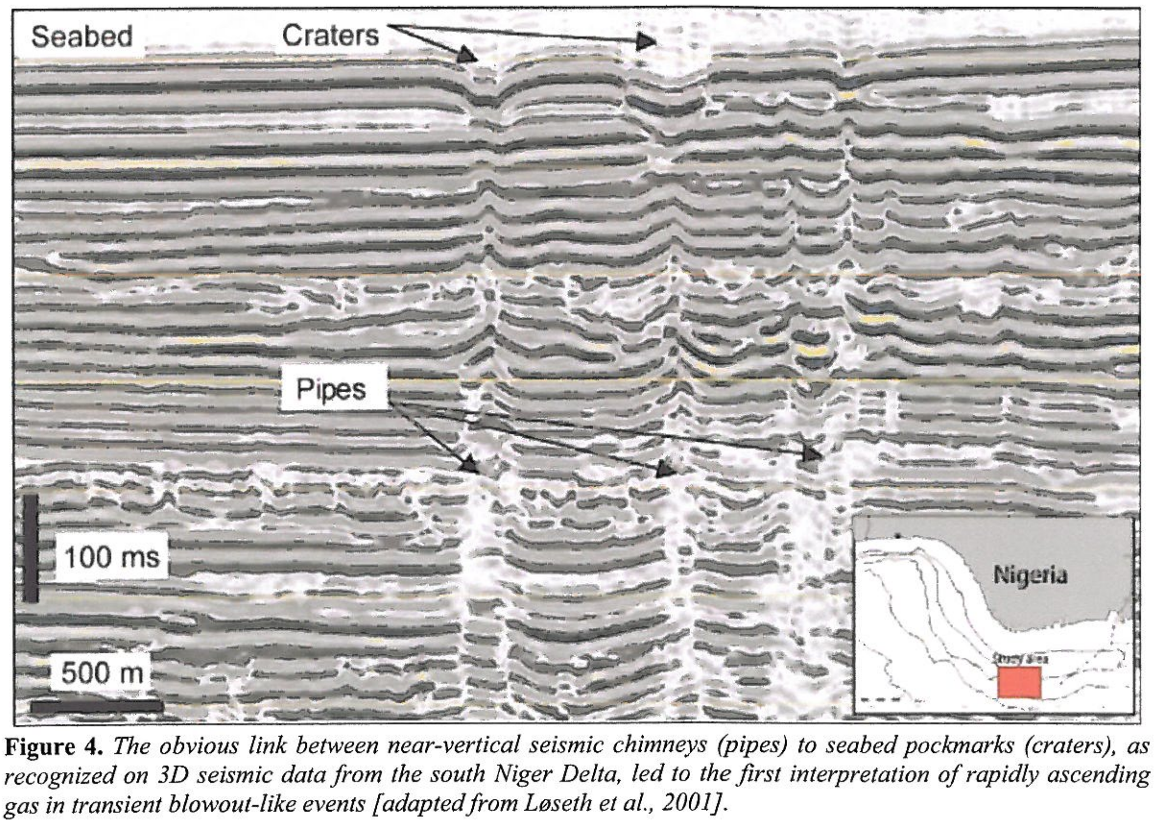


Figure 4. *The obvious link between near-vertical seismic chimneys (pipes) to seabed pockmarks (craters), as recognized on 3D seismic data from the south Niger Delta, led to the first interpretation of rapidly ascending gas in transient blowout-like events [adapted from Løseth et al., 2001].*

Synthesis

3D seismic data analysis and visualization represents the most important tool in marine geoscience because it allows a detailed mapping of the subsurface over tens to hundreds of square kilometers [e.g., *Cartwright and Huuse*, 2005]. 3D seismology is therefore the principal method applied to assess the main objective of this work, that is, *improve our understanding of spatially and temporally varying fluid-escape chimneys and associated seafloor expressions*. Seismic imaging, however, offers a number of challenges because the method provides only a snapshot of the present-day subsurface conditions. There are also obvious limitations related to the resolution of "remote sensing" methods, impeding a rigorous qualitative model to be developed for the object of interest. The object of interest in this case – the fluid-escape chimney – is a near-vertical feature, narrow in diameter, and therefore associated with several acoustic artifacts of various cause, i.e., the chimneys may contain gas hydrate, free gas, or a complex structure that may scatter the seismic energy or cause velocity pull-up/push-down features. It is consequently not possible to elucidate on the very detailed, internal sediment fabric and texture of the fluid-escape chimneys.

However, the great benefit of 3D seismology is the possibility to map associated structure and stratigraphy in detail, and by such allowing a context-based interpretation of the fluid-escape chimneys and their genesis. This approach, as in any basin analysis, is the *sine qua non* of each of the scientific articles of this dissertation. In addition, to elucidate on different aspects such as the interplay between gas hydrate and fluid flow systems, the distribution and specific location of chimneys, and the timing of cold seep development, we integrated conventional seismic interpretation with three other elements. These methods include P-wave velocity analysis followed by quantitative modeling of hydrate and free gas, quantitative spatial analysis of fluid-escape chimneys, and forward basin modeling to investigate the pressure and flow evolution. The workflow applied in respect to the articles is given in Figure 5.

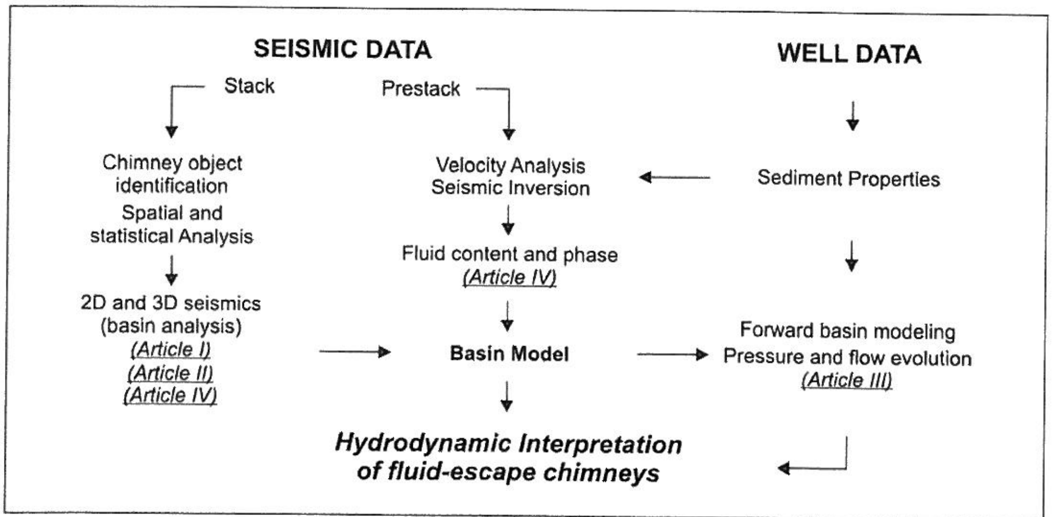


Figure 5. *Workflow illustrating the three principal methods applied in the integrated analysis of fluid-escape chimneys covered by this dissertation.*

Summary of articles

Article I:

Hustoft, S., Mienert, J., Bünz, S. and Nouzé, H., 2007. **High-resolution 3D-seismic data indicate focussed fluid migration pathways above polygonal fault systems of the mid-Norwegian margin.** *Marine Geology 245, pp. 89-106.*

In Article I, we study fluid flow systems on the northern flank of the Storegga Slide by utilizing a high-resolution 3D seismic dataset. The 3D seismic cube is located within an area where gas hydrate and free gas systems have been previously documented in detail from 2D geophysical studies. The high resolution of the 3D seismic data allows subtler structure to be detected, and we find small-scale and elongated fluid flow pathways that originate vertically above polygonal faults in the Kai Formation and connect with the shallower free gas system below hydrated sediments. We suggest these pathways are created by natural hydrofracturing. Thus, the 3D seismic data reveal fluid flow pathways that link dewatering polygonal faults with shallower stratigraphy. These systems have not been previously described in detail for this region. Since these pathways are likely to have a widespread distribution, they may be important structures feeding fluids toward the hydrate/free gas system and thereby contribute to overpressure generation. A few near-vertical fluid-escape chimneys pierce the acoustically well-stratified sediments of the Naust Formation. Most of them terminate at the Eemian interglacial surface, possibly suggesting palaeo-venting activity. Some chimneys terminate at the seafloor as evident from enhanced reflectivity, which may indicate the presence of high velocity material such as authigenic carbonate or gas hydrate. The root zones of these chimneys cannot be determined confidently, because they are not associated with obvious focal structures at depth. However, they are likely rooted with the free gas zone below the hydrate-bearing sediments, or in deeper stratigraphy near the upper termination of polygonal fault systems.

Article II:

Hustoft, S., Bünz, S. and Mienert, J. **3D seismic structure, distribution, and genesis of fluid-escape chimneys at Nyegga, mid-Norwegian margin.** *Submitted to Basin Research.*

In Article II, we use a conventional 3D seismic dataset to assess the spatial distribution of fluid-escape chimneys in the Nyegga region, on the southeastern Vøring Plateau. Previous investigations have documented a high concentration of fluid expulsion features at the seafloor, but their subsurface context is largely unknown. We identified more than 400 near-vertical fluid-escape chimney structures that pierce acoustically well-stratified sediments of the Pleistocene Naust Formation and they extend over a depth range from 200 to 700 meters below seafloor (mbsf). Most of the chimneys terminate at the present-day seafloor where they are recognized as pockmarks or mounds with diameters reaching 350 m. A detailed quantitative analysis of the chimneys, measuring characterizing variables (i.e., height, size in plan form, and strike azimuth of the long axis in plan form), provided unprecedented insights to the geological controls and potential genesis of the fluid-escape chimneys. The results show that the chimneys cluster relative to three principal geological domains; A) above the Helland-Hansen Arch, B) along a buried slide-escarpment, and C) above a mounded "infill contourite". Thus, our investigations show an overall topographic control on fluid focusing and overpressure development. Collectively, about 60% of the fluid-escape chimneys emanate from confined contouritic strata located about 250 to 300 mbsf. The contourites contain free gas as indicated by their highly reflective character and the presence of a cross-cutting bottom-simulating reflection (BSR).

The highest concentrations of chimneys (up to 9 per/km^2) occur in areas where the gas-charged contourite shows significant positive topographic relief, i.e., along the buried slide-escarpment and from the crested geometry of the mounded contourite. Both contexts constitute natural topographic leak-off points, providing clear evidence for fluid focusing and overpressure development in areas of positive subsurface topography. The third cluster of chimneys distribute peripherally above a large Tertiary anticline, the Helland-Hansen Arch. Here, about 50% of the chimneys appear deeper-rooted than the hydrate-related free gas system. Although these deeper-rooted chimneys do not link to obvious focal structure, their deeper origin is statistically justified by the generally shallower root zones elsewhere (chimney domain A and B). The deeper origin is also reasonable in the context of regional flow of deeper fluids focusing towards the crest of the Helland-Hansen Arch. The fluids expelled at the seafloor directly above the Helland-Hansen Arch may therefore have a different composition (thermogenic) compared to the shallower rooted fluid-escape chimneys.

We interpret the fluid-escape chimneys and connecting pockmarks to have formed by transient, forceful fluid-flow in blowout-like events. However, a few of the larger chimneys connect with mounds at the seafloor. This has implications for interpreting chimney genesis, because there is evidently no difference in seismic signature and structural setting between the chimneys associated with pockmarks and those associated with mounds. Previous work suggests that the mounds contain clasts of different material, and we therefore conclude that there is a close link in genesis between blowout chimneys and early stages of mud ejection features. The most active venting period in this region postdates the Late Glacial Maximum (LGM). However, numerous chimneys also terminate at the Eemian interglacial palaeo-surface. This is consistent with our observations in Article I. It is therefore possible that the most active fluid-expulsion periods on the mid-Norwegian margin are associated with the rapid climatic change from glacial to interglacial conditions.

Article III:

Hustoft, S., Dugan, B. and Mienert, J. **Effects of rapid sedimentation on developing the Nyegga pockmark-field; constraints from hydrological modeling and 3D seismic data, offshore mid-Norway**. *Submitted to Geochemistry, Geophysics, Geosystems (G-Cubed).*

Having demonstrated that formation of hundreds of seafloor pockmarks postdate the LGM (~25 cal. ka BP) in Article II, it appears that extensive fluid venting in the Nyegga region was triggered by some specific event. Previous work suggests that the present-day fluid flux is characterized as micro-seepage at most. Previous work also suggests that the sedimentation rate in the Nyegga region was extremely high (up to 35 m/ka) during the last deglaciation. In Article III, we integrate the 3D seismic observations with a forward sedimentation-fluid flow model to quantify the effect of sediment loading and erosion on overpressure generation and fluid expulsion in the Nyegga region. We thereby attempt to constrain the temporal hydrogeological evolution and the timing of pockmark development. The 2D numerical models simulate the temporal evolution of compaction-driven overpressure and fluid expulsion based on sedimentation rates estimated from seismic data and hydrologic and sediment properties obtained from laboratory experiments and petrophysical data. The 2D model predicts rapid overpressure generation in response to high sedimentation rates during the last (Weichselian) deglaciation period (25-18 cal. ka BP). The high pressures significantly increase fluid expulsion, which shows a significant peak between 19 and 16 cal. ka BP. The modeled, millennial scale high-flux period and the following declining flux period exhibit an excellent correlation with existing age dates of methane-derived authigenic carbonate retrieved from Nyegga pockmarks. The model predicts low flux at present, and is therefore consistent with the micro-seepage observed in individual pockmarks today.

The effect of loading (35 m/ka) on pressure in the fluid-source sequence (infill contourite) is equivalent to a 13% reduction in vertical effective stress. Thus, to drive hydraulic fracturing and formation of fluid-escape chimneys through fracture flow, the pre-existing gas pressure must have been probably near critical prior to rapid loading. Based on the modeled hydrodynamic evolution, we therefore conclude that rapid sediment loading represents a mechanism to drive extensive and intensive fluid-expulsion given the preconditions of shallow overpressured free gas. We suggest the Nyegga pockmark-field developed predominantly between 19 and 16 cal. ka BP and therefore several thousand years before the Storegga Slide event. Modeling results suggest that the unloading associated with the Storegga Slide (reduction of lithostatic stress) caused depressuring on the northern flank, which may have halted or at least distinctly decreased the flux on adjacent, formerly active cold seeps. The proposed effects of rapid sediment loading on driving cold seep formation are applicable to a number of passive continental margins where anomalously high sedimentation rates have contemporarily existed. The proposed model is particularly relevant on formerly glaciated margins, because it emphasizes a close interplay between slope sedimentation and methane venting – two effects of rapid climate warming.

Article IV:
Hustoft, S., Bünz, S., Mienert, J. and Chand, S., accepted for publication. **Gas hydrate reservoir and active methane-venting province in sediments on <20 Ma young oceanic crust in the Fram Strait, offshore NW-Svalbard.** *Earth and Planetary Science Letters.*

In Article IV, we focus on a specific sediment drift, the Vestnesa Ridge (~79°N). Here, gas hydrate and free gas has not previously been studied in detail. We document active methane degassing from seafloor pockmarks at this mounded sediment drift on the NW-

Svalbard margin. Located in the eastern Fram Strait, the Vestnesa Ridge represents one of the northernmost methane hydrate provinces worldwide, and the second largest known hydrate province off Europe. Active, vigorous degassing from the pockmark was evident from a 750-m-high and ~150-m-wide gas flare observed in the water column during a cruise with R/V Jan Mayen in October 2008. However, venting activity is highly episodic in nature because we did not detect indications for gas bubbling vigorously out of the seafloor during cruises in 2006 and 2007. Nevertheless, it shows that this type of venting system is far more dynamic than documented elsewhere along the northeastern North Atlantic margin, e.g., mid-Norwegian margin (Articles I, II, III).

We identified more than hundred pockmarks that systematically align the apex of the Vestnesa Ridge. The pockmarks are up to 600 m wide and therefore considerably larger than the Nyegga pockmarks. The difference in scale is probably attributable to the higher level of degassing at the Vestnesa Ridge. High-resolution single-channel 2D seismic data show that pockmarks connect with fluid-escape chimneys, which pierce acoustically well-stratified sediment to more than 200 mbsf and cause significant disruption on the otherwise prominent bottom-simulating reflection (BSR). Travel time inversion of multi-channel 2D seismic data reveals anomalously high P-wave velocities (1700-1850 m/s) above the BSR and significantly lower velocities below (1350-1500 m/s). We use a differential effective medium approach to quantify the concentration of gas hydrate and free gas in the sediment across the Vestnesa Ridge. The model predicts saturations of up to 11% in the hydrate reservoir, which due to the seafloor topography forms a large anticlinal permeability-barrier. Under the assumption of uniformly distributed gas, the model suggests a pore space saturation of 1-3% of free gas below the BSR. Peak saturations of both gas hydrate and free gas, however, occur at the crest of the ridge and in immediate vicinity of extensional faults. Thus, inversion of P-wave velocity data suggests that the presence of 5-10% of gas hydrate in the pore space of the sediment forms an effective anticlinal hydrological seal that deflects fluids updip, allowing overpressuring and episodic release of pressure through chimneys at the crest of Vestnesa Ridge. This is justified by the fact that pockmarks are only present at the apex of the ridge.

The dynamic and active fluid flow system of Vestnesa probably applies to the interplay between its peculiar tectonic setting on young (<20 Ma) and hot ocean crust, and the stratigraphic/topographic architecture of the mounded and elongated sediment drift. Compiling our results with previously published data, we find that extensional faulting may play a key role in the supply and distribution of free gas and methane hydrate across the Vestnesa Ridge. This hydrated sediment drift in the Arctic will therefore be an important location for future studies on the complex interplay between hydrate, free gas, methane venting, and probably also cold-seep ecosystems.

Discussion

Nyegga vs. Vestnesa

The second largest gas-reservoir on the Norwegian margin, the Ormen Lange field, is located within the Storegga Slide. The slide is one of the largest Holocene submarine landslides yet discovered (Fig. 2). In the wake of safe exploitation of the deep-water gas field, the entire region has been subjected to numerous integrated studies focusing on geohazards and triggering mechanisms [*Solheim et al.*, 2005b, and references therein]. The last ten years of investigations have therefore resulted in a huge database with emphasis on the shallow overburden of the Vøring and Møre basins, and the Plio-Pleistocene margin evolution is largely well-constrained [e.g., *Sejrup et al.*, 2005]. Likewise, the large-scale distribution of gas hydrate systems, polygonal fault systems, and fluid flow features on the northern flank of the Storegga Slide have been identified [*Mienert et al.*, 1998; 2005a; *Bouriak et al.*, 2000; 2003; *Andreassen et al.*, 2003; *Berndt et al.*, 2003; *Bünz et al.*, 2003; 2005; *Hovland et al.*, 2005; *Mazzini et al.*, 2005; 2006; *Gay and Berndt*, 2007]. However, no studies have previously pinpointed the specific spatial distribution of fluid-escape chimneys and their explicit relationship with subsurface structure and stratigraphy by use of 3D seismic data analysis. The fluid source, evolution and timing of chimneys, and why they locate exactly where they do, have so far remained largely unknown.

Our seismic investigations of the northern flank of the Storegga Slide (Articles I, II, and III) show indications of possibly two main epochs of extensive seafloor fluid venting. The first coincides with the last interglacial palaeo-surface (Eemian interglacial) dated approx. 120 ka [*Haflidason et al.*, 2003; *Hjelstuen et al.*, 2005]. The second evidently postdates the LGM, and we speculate whether there is a correlation between intense periods of subsurface degassing and glacial cyclicity. It is previously indicated a relationship between the frequency of major advances of the Fennoscandian ice sheet during the last 0.5 Ma and major sliding along the Norwegian margin, i.e., large-scale sliding occurs at intervals of approximately 100 ka [*Sejrup et al.*, 2000; *Nygård et al.*, 2005; *Solheim et al.*, 2005a]. The slide scars, in turn, stimulate significant deposition of infilling contourites, because of the combined effects of rough seafloor topography and increased accommodation space [*Laberg et al.*, 2001; *Bryn et al.*, 2005; *Leynaud et al.*, in press]. We find that these sediments have relatively higher porosity because they are slightly coarser grained than hemipelagic and glaciomarine clays, and their mounded geometry and lithology is therefore crucial to the distribution of free gas and overpressure (Articles II, and III). From our studies in the Nyegga area, we conclude that sliding and subsequent drift deposition represents local prerequisites for high concentrations of fluid expulsion features. Occasionally, this type of sediment has also shown to facilitate remobilization in the Sklinnadjupet Slide area because they are often overlain by higher density glacial debris flows [*Laberg et al.*, 2001]. The Nyegga area shows a similar sedimentary succession (Fig. 6), as well as indications for small-scale remobilization at some of the seep locations (Article II). This indicates that large-scale dynamic slope-sedimentary processes, resulting indirectly from rapid climatic shifts, control the distribution of fluid venting features over large parts of the mid-Norwegian margin. In

Article III, we hypothesize if rapid sediment loading associated with disintegration of the last Weichselian ice sheet triggered extensive fluid venting within a millennial scale time window. In view of the glacial cyclicity and associated slide frequency, the "sediment dump fluid-pump" may therefore also apply to former deglaciations of the Middle and Late Pleistocene. Nevertheless, compiling our results with previous work it appears that the Nyegga fluid flow system, by large, is in a dormant state, and one may speculate if a new glaciation is required to cause vigorous and extensive degassing.

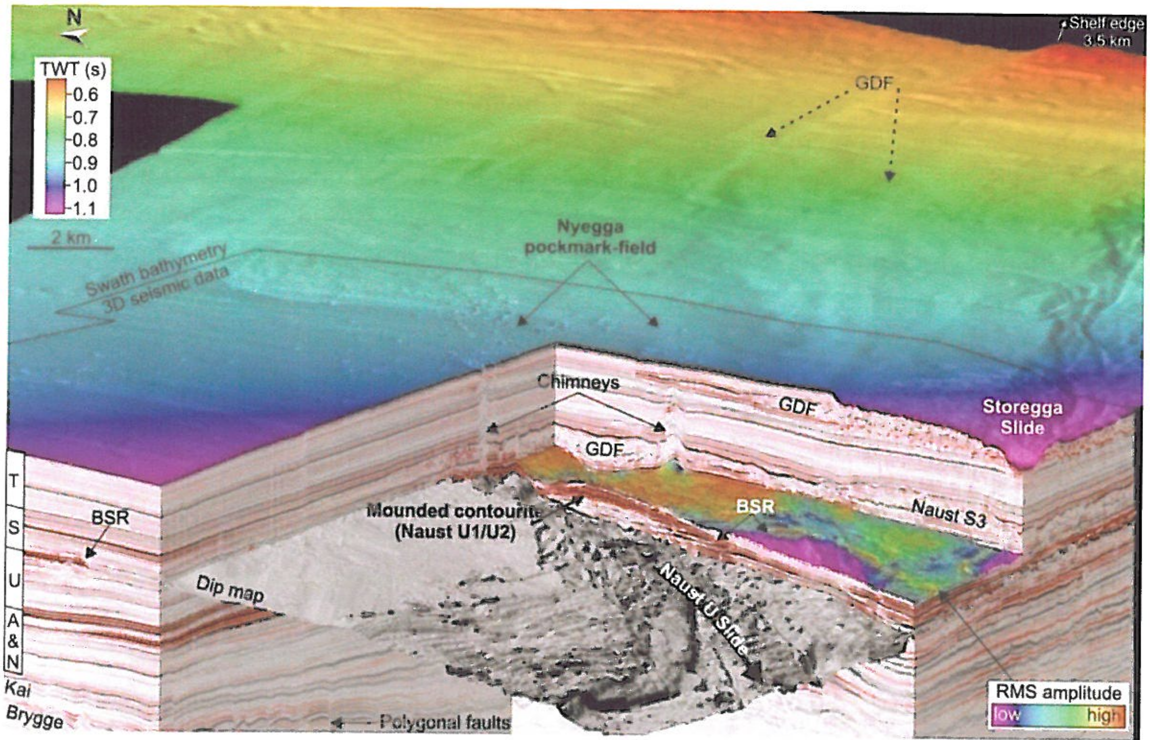


Figure 6. *Perspective view showing the Nyegga pockmark-field and connecting fluid-escape chimneys in the subsurface, which originate from an infill contourite deposited within a palaeo slide-scar. Note that the contourite is overlain by a glacial debris flow (GDF). The bottom-simulating reflection suggests the high reflectivity at the crest of the mounded contourite is caused by free gas.*

In contrast, the Vestnesa Ridge plumbing system is far more active than previously thought, and thus deviates from the low flux systems typical of rifted margins (Article IV). With exceptions documented for the Håkon Mosby Mud Volcano [*Sauter et al.*, 2006], we provide one of the rare documentations of vigorous degassing from a deep-water pockmark/chimney structure along the entire northeastern North Atlantic margin. This site in the Arctic will therefore be an exciting location for future investigations to understand better the migration of methane in the GHSZ, as well as associated seafloor ecosystems that are likely to occur. The episodic venting system suggests that the free-gas zone is exceptionally more dynamic at the Vestnesa Ridge than the steady-state systems representative for tectonically passive environments [e.g., *Haacke et al.*, 2008]. Although we predicted the concentration of free gas to be in the order of 1-3% of the pore space, we emphasize that this estimate is under the assumption of hydrostatic pore pressure conditions. If the vigorous gas ejection observed at October 28, 2008 (gas flare in the water column) was rooted directly in the free-gas zone, 200 mbsf, then the pore pressure evidently exceed hydrostatic. Thus, as the gas modulus increases with pressure [*Mavko et al.*, 1998], it is possible that our predicted concentration of free gas is too conservative and a significant underestimate.

The location of pockmarks and connecting chimneys is ultimately controlled by the stratigraphic architecture of the sediment ridge and the anticlinal "hydrate carapace". However, the Vestnesa plumbing system differs significantly from other passive margin settings, because it is located on oceanic crust with an age of less than 20 Ma [*Engen et al.*, 2008]. The NW-Svalbard margin is therefore characterized by a high geothermal gradient (up to 115 °C/km) due to the close distance to the mid-ocean ridge [*Vanneste et al.*, 2005b], and thereby exceeding the mid-Norwegian margin geothermal gradient by a factor of two or three. The high temperatures of the Vestnesa region have therefore major implications for thermal maturation of organic matter, as the distance from "kitchen" to the shallow free gas accumulation at the ridge crest is significantly reduced. The tectonic setting of a young and hot oceanic basin also facilitates thermal subsidence, which in addition to the northward propagation of the Knipovich Ridge [*Crane et al.*, 2001], cause ongoing extensional faulting of the entire sedimentary cover. These faults may provide efficient flow paths from deeper stratigraphy. Thus, it is clear that the exceptionally active plumbing systems at Vestnesa is significantly influenced by its tectonic environment, and thereby differs strongly from the mid-Norwegian margin.

Our seismic investigations reveal high amplitude segments in the upper approx. 50 m of a few fluid-escape chimneys at the Vestnesa Ridge. We speculate if these relate to massive layers of gas hydrate and/or authigenic carbonate. If these amplitude anomalies are caused by the presence of carbonate cement, it is evident that they record a long history of methane venting because precipitation of carbonate is restricted to the sulphate-reducing zone (upper few meters below seafloor). The chronology is poorly constrained for this region, but if applying a sedimentation rate of 9.61 cm/ka for the last 25 ka and 105 cm/ka for prior periods as constrained from the only published gravity core at the Vestnesa Ridge [*Howe et al.*, 2008], it suggest that precipitation of carbonate (i.e., methane venting) initiated about 70 ka BP. In view of the tectonic environment and the geometry of the Vestnesa Ridge, it is reasonable that vigorous methane venting has occurred relatively frequently during the latest Pleistocene. This type of venting system is therefore in significant contrast to the present-day dormant flow system in the Nyegga region, where venting intensification may relate to glacial/interglacial cyclicity.

Future Research

In general, enhanced understanding of the larger scale distribution of fluid-escape chimneys, their contexts, and origins can only be achieved through continued description and interpretation. Although seismic chimneys have been recognized as representing flow paths for a decade or two, only few studies have described these enigmatic features in unprecedented 3D detail. As larger deep-water areas are continuously explored by the industry and academia, providing a growing database, new subsurface contexts of fluid-escape chimneys will most certainly be discovered. In addition, 3D seismic surveys acquired by the industry are nowadays processed with special emphasis on the overburden allowing subtler details of fluid-sediment dynamics to be described on basin-scales. Research topics that may shed new light on fluid venting in gas hydrate environments, and associated seismic imaging are outlined below.

- Integrated chimney structure analysis. A comparative high-resolution 3D seismic (P-Cable) study between fluid-escape chimneys from Nyegga and Vestnesa is currently in progress. The P-Cable 3D seismic data provide a higher lateral (6x6 m bin) and temporal resolution compared with industry-acquired conventional 3D seismics, allowing chimney structures to be imaged in greater detail. These investigations are particularly important because the two fluid flow systems are governed by different dynamics, and they host chimney structures of presumably dormant (Nyegga) and active (Vestnesa) state.

- 4D seismic time-lapse imaging of the active venting system at Vestnesa Ridge may gain insights to i) short-term changes in the interiors of the chimney structures, ii) changes in gas hydrate stability within the chimneys, and iii) changes in the free gas system feeding the vents. Additionally, time-lapse monitoring may provide new constraints on basin evolution in terms of ongoing extensional faulting and fracturing and its impact on the overall plumbing system.

- Forward basin modeling of the NW-Svalbard margin would be an interesting aim in order to address the effects of high basin temperatures on the flux from deeper stratigraphy, the gas hydrate stability, and seafloor venting. However, crucial information such as sediment properties and chronology is currently lacking for this particular region.

- Interdisciplinary studies of several pockmarks at the Vestnesa Ridge transect should be assessed to provide information on fluid compositions, and potential benthic ecosystems, as well as ages of potential methane-derived authigenic carbonate.

- Datings of methane-derived authigenic carbonate retrieved from multiple pockmarks in the Nyegga region represent the key parameter to test our hypothesized trigger mechanism for pockmark development and widespread fluid venting on the southern Vøring Plateau.

- Considering the likelihood of several thousand fluid-escape chimneys (sub-seismic scales included) on the mid-Norwegian margin, it is important to understand properly whether they are "reservoirs" for gas hydrate, and if these are the first to dissociate in response to pressure and temperature changes. This can only be proved by drilling. However, high-resolution electromagnetic surveying, accompanied with seismic experiments may be able to unravel issues regarding the acoustic properties of chimneys. An applicable workflow may include acquisition of 2D seismic multi-channel data, using a dense shooting interval to obtain the highest possible fold across the chimney, followed by pre-stack time/depth migration. Ray trace modeling and generation of synthetic seismograms are fundamental to address the complex wavefield propagation associated with fluid-escape chimneys' sediment and/or velocity heterogeneity. It is important to assess the acoustic properties of chimneys because it concerns seismic chimney imagery in many basins and how they are interpreted.

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