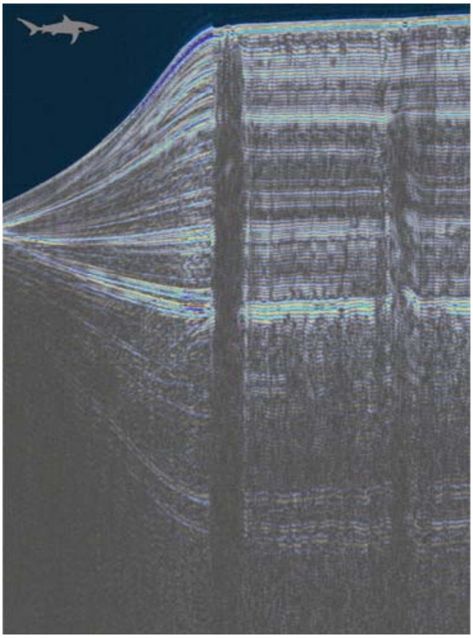
UNIVERSITY OF TROMSØ UIT

The Faculty of Science and Technology
Department of Geology

Characterization of sub-seabed fluid flow and hydrate systems at Nyegga, offshore mid-Norway:

Integration of seismic imaging and velocity modeling



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A dissertation for the degree of
Philosophy Doctor

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Characterization of sub-seabed fluid flow and hydrate systems at Nyegga, offshore mid-Norway: integration of seismic imaging and velocity modeling.

Preface

The doctoral thesis work was carried out from 2006 to 2010 with three years based at the Department of Geology, University of Tromsø and one year based at IFREMER, Brest. The work was financially supported by the Norwegian Research Council PETROMAKS projects (169514/S30 and 175969/S30), by the European Commission FP6 project HERMES (GOCE-CT-2005-511234) through collaborative work between IFREMER, Birmingham University, NOC Southampton and Tromsø University, and by Statoil.

Single channel seismic, ocean bottom seismic recorders (OBS), 3D high resolution P-Cable seismic and bathymetry data of the study area were acquired during cruises in July 2006 and 2008 on board R/V Jan Mayen, University of Tromsø. These data were used during stages 1 and 3 of the thesis together with a 3D seismic data set kindly provided by Statoil for academic research. The second stage of the thesis comprised a one-year stay at IFREMER in 2008 under the Memorandum of Understanding (MOU No. Ref. 05/1215838) between IFREMER and the Department of Geology, University of Tromsø. I was employed at IFREMER with a CDD (Contrat de durée déterminé). During this period a high resolution seismic velocity experiment around a fluid escape feature (chimney) was carried out. The data for the experiment were collected during TTR-16 leg-3, on board R/V Professor Logachev in June 2006. Ocean bottom seismic recorders (OBSs) were kindly provided by UK Ocean Bottom Instrumentation Consortium and by IFREMER. This seismic experiment was used as a case study for the development of the tomography software Tomoinv®. I benefited from an active, multi-task working environment integrated by colleagues from IFP, PGC, IFREMER, Birmingham and NOC Southampton.

During those four years I participated in workshops within the framework of HERMES and PETROMAKS projects as well as in conferences to present and progress (see appendix). I benefited from the participation in acquisition, processing and interpretation of most of the data used for the research.

This thesis consists of an introduction and four articles. The articles are dedicated to the investigation of fluid distribution and gas hydrate related systems of the mid Norwegian continental margin (figure 1). The scientific articles presented are:

Article 1

Plaza-Faverola, A., S. Bünz, and J. Mienert (2010). **Fluid distributions inferred from P-wave velocity and reflection seismic amplitude anomalies beneath the Nyegga pockmark field of the mid-Norwegian margin**, *Marine and Petroleum Geology*, 27(1): 46-60.

Article 2

Plaza-Faverola, A., G. K. Westbrook, K. Stephan, R. Exley, A. Gailler, T. Minshull and K. Broto, (2010). **Evidence from tomographic investigation of Vp variation for accumulation of substantial methane hydrate in a fluid-escape chimney in the Nyegga pockmark field, offshore Norway.** *JGR solid earth.* v. doi:10.1029/2009JB007078, in press.

Article 3

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert. **Repeated fluid expulsion through sub-seabed chimneys offshore Norway in response to glacial cycles.** Submitted to the journal *Earth and Planetary Science Letters*.

Article 4

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert. **The free gas zone beneath gas hydrate bearing sediments and its link to fluid flow: 3-D seismic imaging offshore mid-Norway.** To be submitted.

Acknowledgments

Many feelings were invested in this project. Many of them shared with family, friends and colleagues, and as such they are reviewed in the following acknowledgements.

I start by acknowledging the one who accepted me for the PhD, Jürgen Mienert, my supervisor. The PhD program offered a unique working place, including access to the best software, participation in international conferences and participation in scientific cruises. All this was guaranteed by Jürgen through his contracts and numerous projects. Jürgen said once that my character reminded him the character of his son. We did have numerous discussions of the "father and son" kind. I appreciate that in spite of our differences I felt I always had Jürgen's support. Moreover, I felt encouraged by him to take risks and to present my ideas in workshops and meetings.

I acknowledge the effort kindly invested by Jean-Paul Fouché to make possible my one year stay at Ifremer. Thanks also to Annbjørg, the administration and technical teams at both Tromsø and IFREMER for kindly helping with practical difficulties.

Thanks to Stefan Bünz for his guidance during the thesis. He transmitted me invaluable knowledge about the seismic methods implemented at the university. He brilliantly made me think about processes and uncertainties that would give shape to the stories and in turn to the papers. He would also cleverly solve practical problems with software and computers. In part it is thanks to Stefan that I survived the first year of thesis. When I felt lost and discouraged Stefan would raise my moral by helping me to see the relevance of my work. I don't acknowledge his stress and busyness though! But I suppose I need to content with the time he managed to dedicate to this PhD project. In any case his participation was invaluable.

To the fantastic team Hervé Nousé, Graham Westbrook, Russell Exley, Tesmi Jose and Tim Minchull who since I met on board my first scientific cruise I owe much to their solidarity and disposition to assist me in accomplishing my part of the tomographic mission. They were not only engaged with their own tasks but engaged with the research experiment as a whole and that resulted in a fantastic period of collaborative work and beautiful results.

Thanks to Hervé, for his disposition to teach and for allowing me to be closely involved in acquisition of ocean bottom seismometer data. Equally, many thanks to Russell, my hero of programming, for sharing his tricks that helped me to perform the modeling. They both were quite inspiring and tremendously facilitated my progress in geophysics.

With sincere admiration I am especially thankful to Graham Westbrook who always challenged me with his sharpness. Whenever I thought I had found the truth he would bring me back from the clouds saying "Andreia, this is wrong". Then more work needed to be done just to make him accept my logic. Most of the time I ended by changing my logic instead…But I simply felt great and enthusiastic when learning from Graham through numerous interesting discussions. Sometimes I was so mentally exhausted that I couldn't deal with all his exigencies. That also taught me when to say "NO MORE" :)

I am grateful to Stephan Ker, from IFREMER, who kindly accepted the responsibility of being my scientific advisor and who had the great idea, and managed to convince IFREMER of buying the tomography software for the experiment. He made possible the professional reunion with Karine Broto, my internship advisor at IFP when I was 22 years old! It was great to work with Karine again and realize that I had improved in geophysics since she first explained me what a tomography was :). Thanks to Dan Herold and Wes Wilson from PGC for that first meeting at IFP, I really felt encouraged and willing to accomplish my work. Wes developed a super friendly interface for the tomo code. I am so pleased that Wes and Karine took me seriously as a helper for the development of the software. I learn a lot and thanks to them I managed to get on time some results for the thesis. More programming heroes!

Thanks to my friends in Venezuela, France, Tromsø, and from wherever, because friendship is the best medicine for the soul. Conversations with my friends from school or reunions with my friends from the master were reminders of the fantastic world outside science which I had tendency to forget while embedded in research. Special thanks to the international friends community here in Tromsø that gave to this experience a taste of Mediterranean, some spices from India, a touch of Russia, sweetness from the Netherlands and Switzerland (chocolates), and a lot from Britain and from Nordic lands…Thanks to Carolina, Monica and Mayte for amazing discussions about geology and glaciology. Thanks to my teachers of Norwegian because they kept me motivated by the challenge of learning a tremendously difficult language. I still don't feel proficient, but that is a battle to win sooner or later!

And some words to Kåre, my admirable partner, my boyfriend, my rational advisor and companion in dramas. I owe him big part of my personal achievements because, being a social scientists, he would always approach the problems from a different perspective. He helped me to reduce the intensity of personal drama that I would often invoke when working on my problems. He even wrote a poem to the now famous Nyegga (just to show me how much he understands about geophysics):

"*A Poem to Nyegga*

As P-waves penetrate the sediment,
we inverse the travel times;
lyrics of Nyegga's sentiment,
appear as picking clears the files

3-d charts and colored graphs
of Nyegga at the margin;
show the pockmarks and the gas;
is not nature but a bargain?"

But everything is about life and life I owe to Haydée and Rodolfo, parents I would never change! They give Ignacia and me a world full of love and freedom where they have been not only educators but confidants in the best as in the hardest times. Thanks to Ignacia my beloved sister, the artist, the creative, for filling my life with company, camaraderie, laughs and support. Gracias totales!

Table of contents

Introduction

Scope of the thesis

The comprehension of submarine fluid flow systems is socially and ecologically important for a range of reasons. *First,* natural fluid emissions, particularly methane, have a significant impact on the composition of the sea water and possibly the atmosphere, influencing in turn the carbon cycle and becoming a potential climate mediator (e.g. Kvenvolden, 1993; MacDonald, 1990). *Second*, the large amount of methane storage as gas hydrates in shallow sediments is considered an unconventional future energy resource (e.g., Kvenvolden and Barnard, 1983; Sloan, 2003; Sloan and Koh, 2008). *Third*, sub seabed fluid flow is associated with geohazards like slope instability, gas venting, mud volcanoes, and blow outs during offshore exploration (e.g. Judd and Hovland, 2007; Judd et al., 2002; Nisbet, 2002), including the recent Gulf of Mexico oil spill (e.g., Robertson, 2010).

In a period of 10 years, marine geological and geophysical investigations revealed approximately 70 new submarine fluid venting sites worldwide (Mazurenko and Soloviev, 2003). Venting sites are recognized mainly by associated seafloor expressions such as pockmarks and mounds appearing in bathymetric data. They are also recognized as sub-seabed vertical acoustic blanking zones, known as pipes or chimneys, imaged by acoustic methods. Many of the fluid venting sites worldwide are inferred to be related to the dynamics of gas hydrate systems (e.g. Ginsburg et al., 1993; Henriet and Mienert, 1998; Hovland and Judd, 1988; Paull et al., 1995; Riedel et al., 2002; Suess, 2001; Vogt, 1997; Westbrook et al., 2008, and references therein). Gas hydrates basically form ice-like features with gas trapped inside. Their crystalline arrangement consists of water molecules, which contain voids where molecules of gas such as methane, ethane and carbon dioxide, are incorporated (White, 1979).

A comprehensive understanding of fluid flow related systems would involve a multidisciplinary understanding of processes affecting shallow and deep strata. These processes include fluid migration from deep to shallow reservoirs, formation of microbial gas at shallow depths, gas hydrate formation and decomposition, fluid venting and pockmarks or carbonate mound formation at the seafloor. It is only possible to access sub-seafloor strata over extended regions by way of non-invasive methods based on wave propagation. Seismic imaging has proved to be a reliable method for assessing the distribution of fluid flow related features based on amplitude and frequency anomalies. However, the compromise between resolution and depth coverage, which relates to the frequency of the used seismic signal, poses a challenge to the integrated investigation of shallow and deep processes associated with these features. In addition, structural elements like fractures and small faults, which play a role in fluid migration within shallow sediments, are hardly resolvable in low seismic resolution records.

Applying travel-time inversion techniques for velocity analysis and seismic attributes calculations to different resolution seismic data sets, i.e., 3D, 2D single and multi channel and ocean bottom seismometer (OBS) data, the work presented here integrates different scales of geophysical investigations, in order to offer an overall comprehension of fluid flow systems at a specific hydrate province, Nyegga, located north of the giant Storegga slide of the mid-Norwegian continental margin (figure 1).

The thesis work was divided into three stages:

The aim at the first stage was to assess the distribution of shallow gas reservoirs and vertical paths for gas migration from deep sources. This was done by integrating 1D velocity modeling to 3D seismic imaging and mapping. Two areas with the highest concentration of chimneys with seafloor expressions were revealed. Each area was found to be associated with shallow gas layers. Velocity models and 3D imaging at this stage covered the upper 2000 m of sediments. Multi channel seismic profiles provided information about structural features potentially involved in the fluid migration towards shallow strata (article 1).

At the second stage, the aim was to increase the resolution of the investigation looking at anomalous velocities associated to sediments disturbed by fluid escape. A high-resolution tomographic seismic experiment was performed around one vertical fluid escape feature (chimney) in Nyegga associated with authigenic carbonate precipitations at the present seafloor. The experiment used an array of sixteen OBSs distributed around the chimney. The tomography resulted in a 3D velocity model for the upper 500 m of sediments. Possible formation scenarios and internal structures of chimneys in Nyegga were suggested based on the tomographic results (article 2).

Finally, at the third stage the aim was to establish a time-scale for fluid escape in Nyegga. This was attempted through detailed characterization of sediment deformation as responses to fluid flow entering the gas hydrate stability zone. 3D high resolution seismic acquired with the newly developed P-Cable system (Petersen et al., 2010; Planke and Berndt, 2003) provided the necessary resolution. Two articles resulted from this study. Article 3 reports evidences for periodicity in fluid expulsion through chimneys inferred from depositional settings against buried methane vent-related features indicating paleo-seepage. Article 4 characterizes the morphology and distribution of dim-amplitude anomalies, possibly associated with sediment remobilization and hydrate dissociation within sediments beneath paleo-bases of the gas hydrate stability zone. In addition it identifies relationships between deep faults and the distribution of shallow fluid flow related features.

The thesis presents results from 4 articles that together bring us closer to the overall understanding of fluid flow related systems in Nyegga. While each article has separate and specific aims, the problems and results covered by the four articles are nevertheless guided by a single motive: to access geophysical and geological indications of sub-seabed fluid flow processes by the implementation of non-invasive methods.

The following sections of this introduction provide a general overview of focused fluid flow and its relation to gas hydrate associated mechanisms. They also offer an overview of indirect seismic methods implemented for the assessment of fluid and hydrate distribution in continental margins. The sections introduce a series of integrated problems and concepts relevant for understanding the content of the included articles. The articles are referred to within the different sections of this introduction in order to illustrate how each of them contributes to the overall research context.

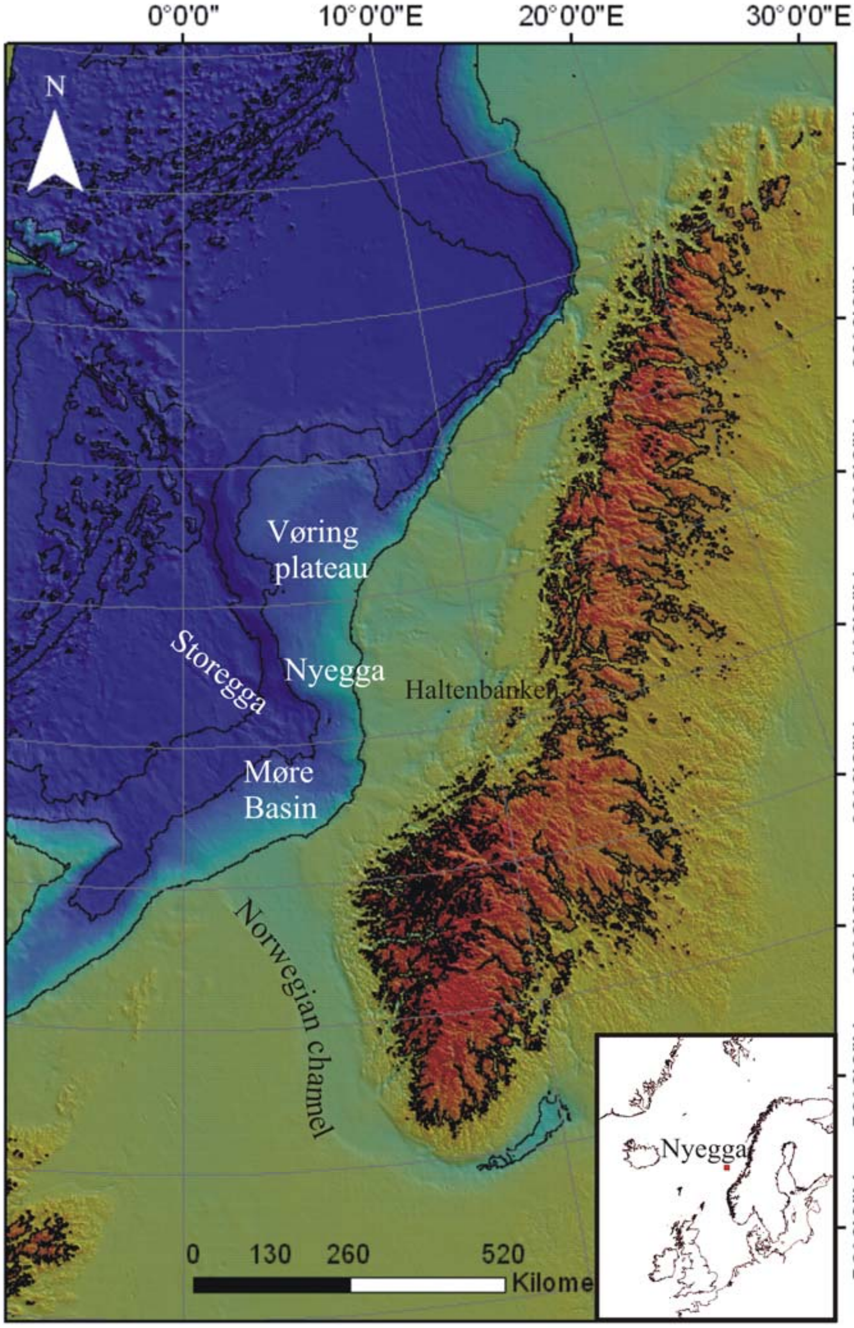

Figure 1: Location of the Nyegga region and major hydrocarbon prone sedimentary basins off the mid-Norwegian continental margin. Located north of the Storegga slide, Nyegga is bounded by the Vøring plateau to the north and the Møre basin to the south.

Insights into focused fluid flow in passive continental margins

It is common to use "fluid" to refer only to liquid. In marine geology and geophysics, however, the term fluid encompasses liquids and gases. Pore water (seawater and groundwater) saturating sedimentary rocks, brine (water with high salt contents) and hydrocarbons (oil and gas) are fluids commonly implicated in focused fluid flow processes in passive continental margins. Particularly methane gas, being highly abundant in the earth's crust, is often found to be related with fluid flow features and gas hydrate formation. Methane concentrations in the earth's crust are primarily formed through reactions of organic matter (e.g. Schoell, 1988). According to its origin methane can in turn be of two types: microbial, where methane is produced and consumed by microbial processes[1]; or thermogenic, where methane results from the transformation of organic matter under the influence of high temperatures (e.g. Galimov, 1988). In opposition to methane of biogenic origin, methane can also derive from processes that do not involve organic matter but thermochemical reactions, i.e., abiogenic methane (e.g., Schoell, 1988).

In porous media fluid flow rates are primarily controlled by Darcy's law, which basically states that the amount of fluids passing through a rock is dependent on the permeability of the rock and on the pore pressure difference between the two ends of the flow system. In systems where permeability is initially low, but faults and fractures are induced by excess pore pressure generation, fluid flow rates become more dependent on the permeability of the generated conduits for fluid migration (e.g. Clennell et al., 1999; Fisher et al., 2003; Jain and Juanes, 2009). Common mechanisms allowing lateral and vertical fluid migration within sediments are diffusion (e.g., when water is not in motion but gas spreads through water) and advection (e.g., when gas is carried upward in solution). The transport of methane through both aqueous diffusion and advection are key mechanism that explain the transport of methane into the gas hydrate stability zone when gas hydrates have already formed and start sealing the porous space (Liu and Flemings, 2007). Methane can also be transported through the sediment column as free gas when its maximum saturation in water is exceed (Liu and Flemings, 2007).

Major driving forces triggering fluid migration in continental margins are overpressure and material buoyancy. Excess pore pressure can be induced by external processes such as sediment compaction

[1] Generally the term biogenic is used to refer to gases produced and consumed by microbial processes. However, it is possible to find in the literature the term "biogenic" used to refer to both microbial and thermogenic gas as opposed to abiogenic.

after rapid burial, emplacement of an efficient seal trapping fluids and/or biogenic gas production being faster than dissipation (e.g. Berndt et al., 2005; Kjeldstad et al., 2003; Rise et al., 2006). Buoyancy of sediments occurs in cases of bulk-density inversion (Anketell et al., 1970; Hovland and Judd, 1988, pp 124-128; Løseth et al., 2003). This happens when a layer composed of low density minerals (e.g. salts) or in which buoyant fluids are accumulating (e.g. gassy mud), is overlain by consolidated sediments with higher bulk density (figure 2). In this context, articles 1 and 4 describe seismic responses (at different resolutions) of sediments affected by remobilization and migration of fluids from deep to shallow strata in the investigated region.

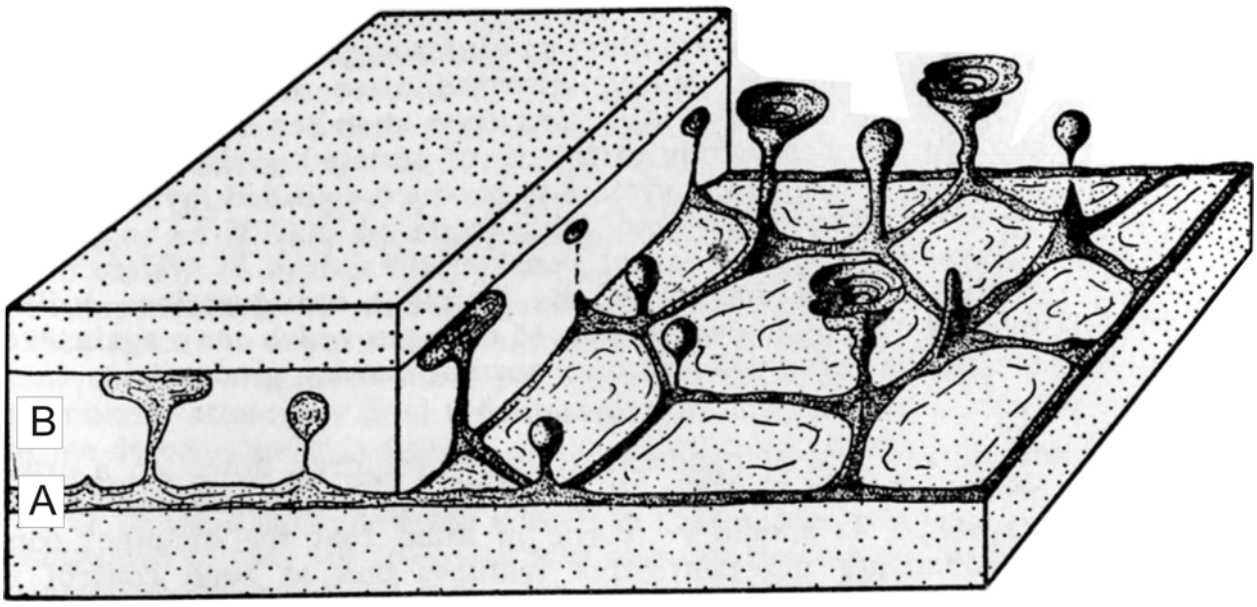

Figure 2: Representation of a system where buoyant material rises through overlying material due to bulk density inversion. Layer A has a lower density compared to layer B (from Anketell et al., 1970).

When pore pressure locally exceeds the lithostatic pressure, and the seal hindering the upward migration of fluids is bypassed (e.g. Cartwright et al., 2007), or when buoyant material starts rising, mud diapirs, mud volcanoes, pockmarks and mounds (figure 2, 3) among other focused fluid flow related features are formed (e.g. Dugan and Flemings, 2000; Hustoft et al., 2009). Cartwright et al. (2007) refer to these as “seal bypass systems” and classify them as fault related, intrusion (sediment remobilization) related and pipe (chimney) related. In addition Hovland and Judd, (1988) and Judd and Hovland, (2007, pp. 45-132) provide a compilation of processes and distribution of seabed fluid flow features worldwide.

The release and vertical transport of fluids due to excess pore pressure is believed to be episodically. Fluids progress towards shallower strata, bypassing seals, as the sedimentary column is built upwards (e.g. Roberts and Carney, 1997). Episodic release of fluids has been inferred by the analysis of mineral deposits (e.g. Cathles and Smith, 1983) and by observational data on present-day seafloors (Roberts and Carney, 1997, and related articles). Nevertheless, estimating the time of activity of relict fluid flow associated features remains challenging due to the limited access to buried evidence of paleo-activity. Article 3 explores the possibility of inferring time scales for venting periodicity using high resolution 3D seismic to find evidence for truncation of sediments against strata deformed by fluid expulsion in the past.

Vertical conduits (chimneys) connecting fluid reservoirs in depth with seafloor fluid flow expressions (e.g., pockmarks and mounds) have been widely described in many sites on continental margins using seismic data (e.g. Cartwright et al., 2007; Haacke et al., 2009; Løseth et al., 2009; Riedel, 2007). However, the exact internal structure of these chimneys, i.e. whether they are dominantly filled with free gas and/or gas hydrates or carbonate concretions, is still among the most challenging questions to be answered. Not least because reflectivity at the chimney's interior is frequency dependent (Wood et al., 2008). Furthermore, both free gas and gas hydrate bearing sediments have been related to both high amplitude events and attenuation in the seismic profiles, depending on the stratigraphic settings and magnitude of fluid venting (Hornbach et al., 2008; Haacke et al., 2009; Riedel et al., 2009; Wood et al., 2008). Articles 2 and 3 approach the problem of chimney internal structures through detailed tomographic modeling and 3D-high resolution seismic characterization. They also discuss possible scenarios of internal composition of chimneys.

In petroliferous systems significant accumulations of hydrocarbons may still occur under the presence of seal bypass systems if the amount of hydrocarbon feeding the reservoir exceeds the speed of depletion through the bypassed seal (Cartwright et al., 2007). Faults can act as conduits for fluids migrating from deep reservoirs to shallow porous strata given that the faults have higher permeability compared to the surrounding sediments and that significant amounts of fluids are to be transported (Fisher et al., 2003). In other cases, such as faulting in porous sandstones, faults can act as barriers to fluid flow due to post-faulting extensive quartz cementation (Fisher et al., 2003). A close relation between faults and fluid escape feature distribution has reiteratively been evoked (e.g. Bünz et al., 2003; Gay and Berndt, 2007; Gay et al., 2006; Hansen et al., 2005; Hustoft et al., 2007;

Pilcher and Argent, 2007; Roberts and Carney, 1997). However, in many cases this relationship has been difficult to prove, in spite of strong intuition, due to the irresolvable character of faults and fractures in seismic resolution. By integrating different resolution seismic data sets (shallow and deep coverage) article 4 offers evidence of the relationship between faults and sediment-gas contact anomalies at shallow gas pockets and an indirect relationship with seafloor fluid escape features distribution.

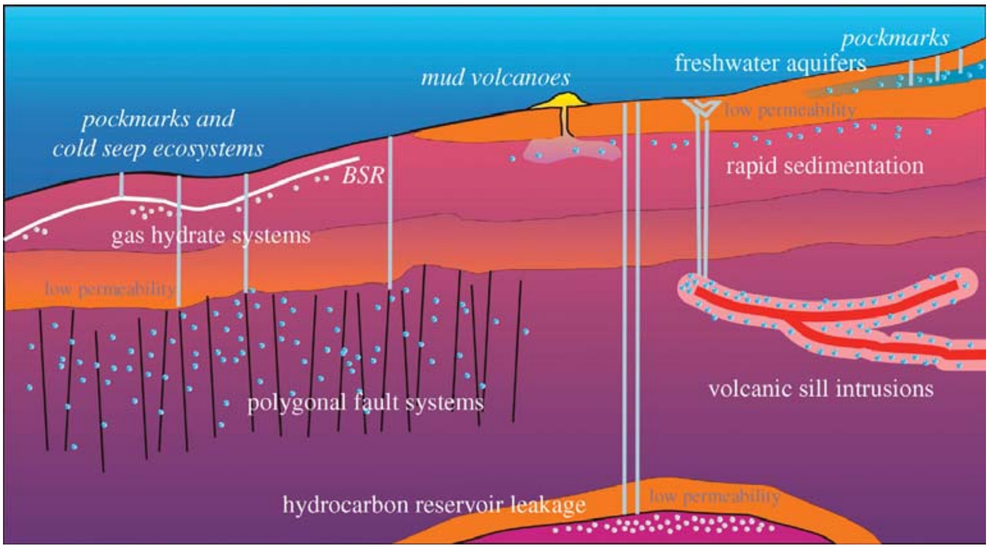

Figure 3: Schematic representation of focused fluid flow systems showing the distribution of fluids and relation between deep and shallow systems in passive continental margins (from Berndt, 2005).

Fluid flow through sediments under gas hydrate stability conditions

In marine environments with water depths generally greater than 300 m, with appropriate configurations of physical conditions such as low temperatures, and sufficient gas and water supply, sediments may enter the gas hydrate stability zone (GHSZ) (e.g. Xu and Ruppel, 1999). Gas hydrate occurrence in continental margins has been confirmed by the deep ocean drilling programs (DSDP, ODP and IODP) (e.g., Riedel et al., 2006a; Trehu et al., 2006; Westbrook et al., 1994).

Gas hydrate kinematics role as future energy in society and their distribution worldwide are not in the scope of this introduction. Some relevant references covering these topics are, among many others, Kvenvolden and Barnard, (1983); Kvenvolden, (1993); Sloan, (1998); Xu and Ruppel, (1999); Buffett, (2000); Sloan and Koh, (2008). Instead, this introduction offers a brief insight into processes that relate fluid flow and gas hydrate emplacement within the GHSZ.

The vertical extension of the GHSZ is limited (figure 4). It is determined by a combination of bottom water temperatures, geothermal gradient, lithostatic and hydrostatic pressure, pore water salinity, amount and composition of available gases, as well as physical properties of the host sediments (e.g. Clennell et al., 1999; Henry et al., 1999). In turn these physical conditions determine whether free gas and water, expelled from reservoirs, will migrate all the way up to the seafloor or whether they will form gas hydrates. Several mechanisms have been proposed to explain the formation of fluid escape chimneys throughout the GHSZ. Although these mechanisms are still in debate, scientists seem to agree in that methane gas hydrates buffer or enable the pass of fluids within the GHSZ towards the seafloor. The fluid migration depends to a large degree on stratigraphic settings, i.e. coarse or fine grained consolidated sediments, and gas/water flow rates, i.e. high or low flux (e.g. Flemings, 2003; Haacke et al., 2007; Liu and Flemings, 2007). Article 2 suggests a model where gas hydrates, emplaced mainly in veins and fractures at the interior of chimneys hinder the escape of free gas towards the present day seafloor. Chimneys are inferred to form by vigorous fluid escapes at early stages of fluid flow activity.

An important component of a gas hydrate system is the free gas zone (FGZ) formed directly beneath the base of the GHSZ. Free gas beneath the GHSZ can be sourced from deeper reservoirs, biogenic break down of organic material, or can be derived from gas hydrate dissociation processes such as hydrate recycling (e.g. Haacke et al., 2007; Pecher, 1996). Often a distinctive bottom simulating reflector (BSR) forms close to the base of the hydrate stability zone. The BSR is associated with the acoustic interface between gas hydrate bearing sediments (characterized by increased seismic velocities) and underlying gas bearing sediments (characterized by low seismic velocities). It can be related to very small amounts of gas hydrates above it and small concentrations of gas beneath it (MacKay et al., 1995). Localizing BSRs is a highly implemented non-invasive method for defining gas hydrate distribution (e.g. Berndt et al., 2004; Bünz et al., 2003; Shipley et al., 1979). Unfortunately, a proper BSR cannot always be observed. Instead, the presence of high amplitude zones (HAZ) beneath the estimated depth of the BGHSZ, are indicators of the gas hydrate/free gas transition zone. Articles 1 and 2 show that P-wave velocity modeling, based on inversion of travel-times form multi-offset seismic data, is a robust method for the identification of gas or gas hydrate bearing sediments when lacking proper BSR reflectors. Amounts of free gas in shallow reservoirs and gas hydrates concentration at the interior of one chimney at Nyegga have been quantified implementing velocity modeling.

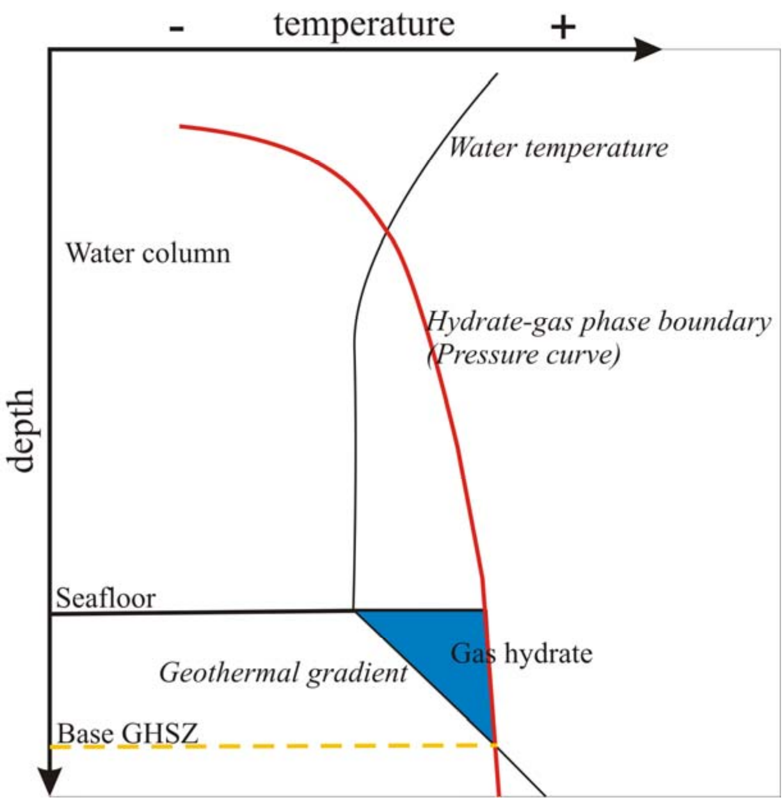

Figure 4: Schematic diagram of the gas hydrate stability zone (GHSZ) extension in marine sediments. The base of the GHSZ is where the geothermal gradient curve intersects the hydrate stability curve. The top of the GHSZ lies in the water column where the hydrothermal gradient curve intersects the hydrate stability curve.

Background of the study area: fluid flow offshore mid-Norway

Pockmarks, mounds, mud volcanoes and other features indicating vertical fluid flow have been found at several locations offshore Norway (i.e. Vøring basin, Vema Dome, Gjallar ridge, northern flank of the Storegga slide) at water depths up to 1000 m and deeper (e.g. Bouriak et al., 2000; Bünz et al., 2003; Hansen et al., 2005; Hovland et al., 1998; Vogt, 1999). The occurrence of gas hydrate in the region was first inferred in the 80s by the observation of a BSR at the northern flank of the Storegga slide (Bugge et al., 1988), one of the world's biggest submarine slides discovered so far. Since then the inference of gas hydrate occurrence has been extended to adjacent areas north, west and south of the Storegga slide, through the implementation of non-invasive methods, i.e. wide-angle seismic data velocity analysis and BSR mapping (Bouriak et al., 2000; Bünz et al., 2003; Bünz et al., 2005; Mienert et al., 2005; Mienert et al., 1998; Posewang and Mienert, 1999; Westbrook et al., 2008).

At the Gjallar Ridge, north of the Vøring basin, buried fluid flow related mounded-features seemingly formed during the Paleogene, and reactivated during late Pliocene (Hansen et al., 2005). They are confined to Kai, Brygge and deeper formations (Hansen et al., 2005) and thus are considerably older than the fluid escape related features in Nyegga. In Nyegga most of the chimneys connecting shallow gas reservoirs with pockmarks and mounds are confined to the shallowest Pleistocene formation, called Naust (Hjelstuen et al., 2010; Hustoft et al., 2010; Hustoft et al., 2007). Sampling at different sites at the Nyegga pockmark field have confirmed the occurrence of shallow gas hydrate (Akhmetzhanov et al., 2008; Ivanov et al., 2007; Vaular et al., 2010), micro seepage of methane gas (e.g. Nouzé and Fabri, 2007) and authigenic carbonate precipitation at the interior of mounds and pockmarks at the present day seafloor (Hovland and Svensen, 2006; Hovland et al., 2005; Mazzini et al., 2006; Paull et al., 2008). These observations together with the lack of evidence for vigorous venting at present suggest that the fluid escape features in Nyegga formed as vigorous vents in the past but are at present of very low activity or inactive.

Concerning the timing of fluid escape, a Weichselian major period of overpressure and chimney formation has been suggested (Hustoft et al., 2009). Differential loading and compaction induced by rapid deposition of the Plio-Pleistocene sedimentary succession on the mid-Norwegian margin is believed to play a major role in the generation of overpressure and fluid flow escape in the margin (Hustoft et al., 2009; Kjeldstad et al., 2003). It has been a debate whether the chimneys are the result of a single fluid escape period or if more than one period of overpressure and chimney formation has occurred associated to glacial cycles. With repeated ice sheets advances to the shelf edge during the last 0.5 Ma (Hjelstuen et al., 2005; Hohbein and Cartwright, 2006; Rise et al., 2005) in mind, this thesis tackles the problem of fluid escape-timing. Article 3 shows fluid escape periods are seemingly associated to last stages of Elsterian, Saalian and Weichselian glaciations. Particularly the end of the Saalian seems to be an important period in the history of chimney formation in Nyegga.

To which extent can iceberg-scouring be considered a process that reduce the overburden and induce fluid escape by depressurization or whether the infill of relic iceberg ploughmarks with fine grained sediments have acted as seal for escaping fluids in the investigated Nyegga site are aspects that remain poorly investigated. Article 3 shows smaller scale relic ploughmarks that have an age of approximately 400 ka. Ploughmarks density and estimated water depths of 430-450 m suggest that Elsterian glaciations had a moderate influence on the Nyegga region. Interestingly, this paleo-seafloor with abundant iceberg ploughmarks in Nyegga correlate in depth and character with an iceberg-carved paleo-seafloor towards the Haltenbanken region found to be an efficient seal to underlying gas-charged sands (Gallagher et al., 1989; Heggland et al., 1996)[2]. An extended investigation based on this similarity may provide us with new insights to better understand the nature of the seal of shallow reservoirs at Nyegga.

The base of the gas hydrate stability zone as indicated by a BSR was mapped in an extended region at the northern escarpment of the Storegga slide comprising Nyegga (Bünz et al., 2003). Polygonal faults has been mapped within the fine-grained, hemi-pelagic sediments of the Kai (Berndt et al., 2003), and lower Naust Formations (Gay and Berndt, 2007) as well as the upper Brygge formation (Hansen et al., 2005) towards the Vøring Plateau. Polygonal faults seem to provide pathways for fluids towards shallow strata and influence the distribution of mounds and pockmarks in the area (Berndt et al., 2003; Bünz et al., 2003; Gay and Berndt, 2007; Hustoft et al., 2007). If polygonal faults are important controllers of fluid flow distributions and overloading has been an important trigger of excess pore pressure build up in the margin, the question arises why are pockmarks and mounds not observed everywhere between Vøring and Nyegga or south of Storegga where highly polygonal faulted sediments and glacial sediment loads exists along the mid-Norwegian margin (Berit Hjelstuen, personal communication)? An answer may be given by considering a third factor in addition to overloading and polygonal faulting, which is the existence of deep hydrocarbon reservoirs at specific locations as a source of fluids towards shallow reservoirs (article 4).

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[2] The iceberg-carved paleo seefloor at Haltenbanken and its sealing property was found during one of the Statoil projects dedicated to find explanations for the West-Vanguard blowout in 1985 (Judd and Hovland, 2007, p 178). The Haltenbanken region extends only a few km east from Nyegga (figure 1).

Non-invasive seismic methods for assessing fluid and hydrate distribution

So far, widespread and relatively low cost detection of hydrate and gas distribution has relied on indirect, non-invasive methods (e.g. Riedel et al., 2006b). Detection of BSRs in seismic profiles and high-resolution seismic velocity analysis are methods commonly implemented (e.g. Bünz et al., 2005; Westbrook et al., 2008). In this framework the doctoral thesis combine seismic velocity modeling techniques, geophysical signal attribute analysis and seismic mapping applied on different seismic data resolution (i.e. multi-offset ocean bottom seismometer recordings, 2D single channel, multi-channel and 3-D seismic data) (figure 5) to improve the comprehension of fluid flow and gas hydrate formation processes.

Complex geological formations characterized by lateral and vertical velocity changes and intrusions of sediment bodies of anomalous low or high compressional wave velocities (e.g. gas chimneys, gas hydrate or carbonate concretions) can be inferred through forward or inverse velocity modeling (Zelt, 1999, and references therein). In forward modeling travel times are calculated for inferred interval velocities and depths of interfaces (figure 6). Velocity and depth values are manually and iteratively optimized so that residual times (calculated minus observed travel times) are minimized. Inverse modeling searches simultaneously, through an iterative resolution of least-squared functions, for all variables (i.e. depth and velocity) that best satisfy the observed traveltimes. That is, depths and velocities that minimize residual times.

This study implemented, in a first approach, 1D inverse P-wave velocity modeling (Zelt, 1999) integrated into a 3D seismic interpretation to infer the gas distribution within shallow reservoirs in the Nyegga region (article 1). In a second approach the resolution of the P-wave velocity investigation was increased by building a detailed 3D velocity model around a particular gas chimney (article 2) through the implementation of a reflection tomography algorithm (Jurado et al., 1996). The implemented reflection tomography technique computed the velocity model (composed of P-wave velocity function and interface geometry of sub-seafloor layers) that better explains travel-times recorded by ocean bottom seismometers (figure 5) deployed around the chimney (figure 6). The mathematical expression of the tomography (figure 6) is composed of three terms: **(1)** comparison of calculated minus observed travel-times; **(2)** control of the roughness of the interfaces during inversion; **(3)** control of the roughness of the velocity functions during inversion. Geological constraints based on a priori information (borehole data, available velocity estimations, geometry of reflectors on stacked data, etc) are often included in the inversion.

Homogenous and patchy distribution of gas produces anomalous decreases in compressional waves (P-waves) passing through gas bearing sediments. Low velocity anomalies are in general good indicators of free gas in sediments. In contrast, both pure gas hydrate, having P-wave velocities around 3.5 km/s (Sloan Jr, 1998) and carbonate concretions, with P-wave velocities of 3.4-6.5 km/s (Anselmetti and Eberli, 1993) would induce anomalous increases of compressional wave velocities. In addition, thick sequences of glacigenic debris flows (GDF) deposited along the mid-Norwegian margin (e.g. Berg et al., 2005; Hjelstuen et al., 2005), characterized by high density material, show P-wave velocities comparable to gas hydrate bearing sediments (Bünz et al., 2005). Article 2 suggests a model for the internal structure of chimneys in Nyegga in which high velocities are explained by the occurrence of mainly gas hydrates. However, a formation scenario that includes authigenic carbonate build ups formed at a paleo-seafloor cannot be ruled out. Article 3 explores this formation scenario by looking at stratigraphic indicators of paleo-vent-related authigenic carbonate dome-like and pockmark-like features at different depths within the GHSZ.

The resolution of seismic investigations is dependent on the dominant frequency of the acoustic signal generated and recorded (Yilmaz and Doherty, 2001, pp 1801-1807). High frequency signals have short vertical coverage but high resolution. Inversely, low frequency signals penetrate deeper but have a lower resolution. For a better understanding of processes involved in fluid vents and hydrate formation, the relationship between fluid escape features, i.e. chimneys and shallow gas pockets, generally affecting the upper hundreds of meters of the sedimentary column, and underlying deeper formations one needs to integrate seismic data from low to high resolution (article 4). The present study benefited from the access to different resolution seismic data sets from both, industry and academia, to explore the role of deeper sources and faults that connect to and sustain shallow gas accumulations and hydrate formations in the Nyegga region (article 4). This thesis exploits the benefits of different resolution seismic data sets to improve the overall understanding of fluid flow systems in continental margins.

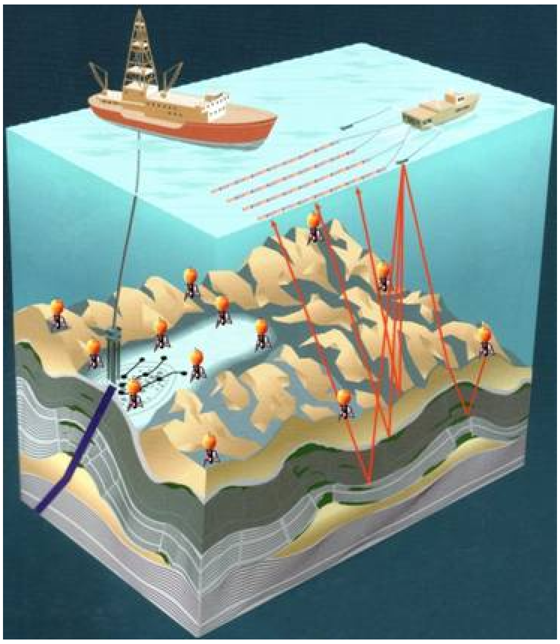
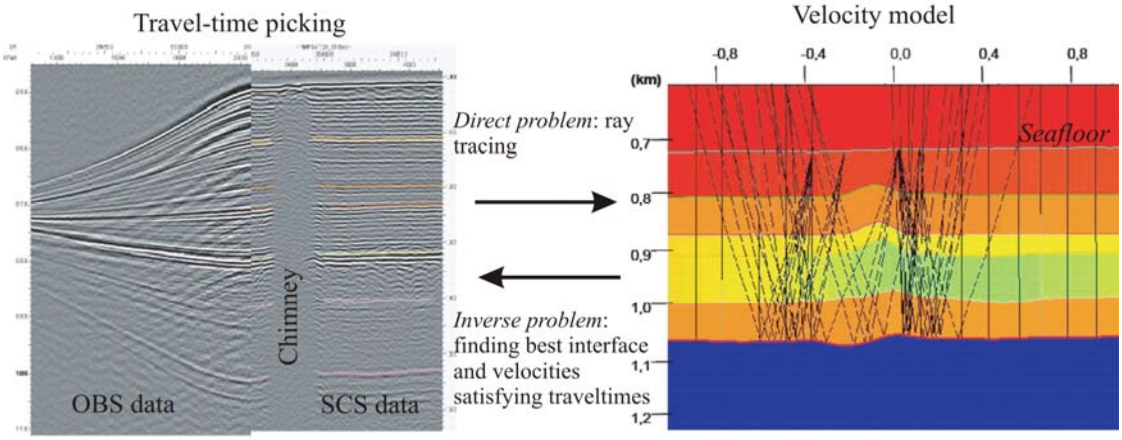


Figure 5: Representation of a marine deployment of ocean bottom seismic recorders (OBS) manufactured by SEND Off-Shore Electronics (www.send.de)

Image from: http://www.send.de/pics/obsinwater.jpg



$$C(m)=\sum_{i=1}^{NT}\sigma_i^{-2}(t_i(m)-t_i^{obs})^2+\sum_{i=1}^{NZ}\int_{\Omega}\varepsilon_{i,Z}^2(x,y)\left\|D^2(Z^i(x,y)-(Z^i(x,y))_{prior})\right\|^2 dxdy+\sum_{i=1}^{NV}\int_{\Omega}\varepsilon_{i,v}^2(x,y)\left\|D^2(v_0^i(x,y)-(v_0^i(x,y))_{prior})\right\|^2 dxdy$$

Term 1: calculated - observed traveltimes

Term 2: control of the roughness of the interfaces

Term 3: control of the roughness of the velocity functions

Figure 6: Tomography principle. The tomography consists in solving the direct (ray tracing) and indirect (inverting to search for the best interface and velocity coupling satisfying observed travel times) problems. Input data consists of travel time picked on multi offset (OBS) and single channel seismic (SCS) data (term 1 of the equation). Regularization factors and geological constraints from a priori information are included to control the roughness of the search interface and velocity functions (terms 2 and 3 of the equation respectively).

Summary of the articles

Article 1: Fluid distributions inferred from P-wave velocity and reflection seismic amplitude anomalies beneath the Nyegga pockmark field of the mid-Norwegian margin.

Andreia Plaza-Faverola, Stefan Bünz, Jürgen Mienert

The distribution of fluids in the subsurface at Nyegga was investigated through the assessment of anomalous low P-wave velocity zones and anomalous high amplitude zones in 2D and 3D seismic data. Two levels for fluid accumulation were characterized and mapped within the shallowest 500 m of sediment in the whole studied area. The shallower level is at approximately 250 mbsf and it is laterally discontinuous. Towards the east fluids accumulate in a contourite body sealed by glacigenic debris flow. Towards the west fluids accumulate beneath the BSR seemingly trapped by gas hydrate bearing sediments. The deeper level for fluid accumulation extends laterally at approximately 450 mbsf. Gas saturations were estimated based on effective medium theory. Fluids are inferred to spread laterally from major paths for deep sourced fluid vertical migration and vertically towards the seafloor through fluid flow escape features, so called chimneys. The distribution of chimneys was proved to be related to the lateral distribution of fluids within the shallower level for fluid accumulation. A conceptual model was presented to suggest major controlling factors for fluid migration at specific locations within Nyegga.

Article 2: Evidence from 3D seismic tomography for a substantial accumulation of gas hydrate in a fluid-escape chimney in the Nyegga pockmark field, offshore Norway.

Andreia Plaza-Faverola, Graham K. Westbrook, Stephan Ker, Russell J.K. Exley, Audrey Gailler, Tim A. Minshull and Karine Broto.

A high resolution P-wave velocity investigation around one of the chimneys in Nyegga, associated to a dome like structure at the seafloor, was carried out through tomographic modeling. The seismic experiment consisted of an array of sixteen 4-component ocean-bottom seismic recorders deployed at approximately 100-m separation and a dense network of shots to define the 3D variation of the chimney's structure and seismic properties. A reflection tomography of the upper 350 m of sediments revealed an anomalous high velocity zone at the interior of the chimney within the gas hydrate stability zone and confirmed the presence of the previously inferred two layers for gas accumulation beneath the base of the gas hydrate stability zone and deeper. A model of the internal structure of the chimney based on the emplacement of gas hydrate in fractures and veins explains the observed velocity anomalies and positive relief of interfaces at the chimney flanks and interior. Assuming a fracture-filling model as likely, maximum hydrate concentrations were estimated to 11-

27 % of the total volume applying time average relationships depending on how host-sediment properties are affected by hydrate formation.

Article 3: Repeated fluid expulsion through sub-seabed chimneys offshore Norway in response to glacial cycles.

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert

One of the less understood mechanisms of fluid flow through chimneys in sedimentary basins is the timing of fluid flow. This paper uses high-resolution 3D seismic data to search for stratigraphical settings possibly evidencing burial of paleo-fluid escape related features. Seismic attribute maps show lateral amplitude anomalies that characterize the location of truncated strata at certain depths against chimneys flanks. The depositional pattern and activity of chimneys is inferred from these seismic geomorphologic data and an established seismic stratigraphy. The results suggests at least three major periods of fluid flow activity in the Nyegga region with major fluid expulsions that are possibly driven by excess overpressure build up within the late stages of the Elsterian, Saalian and Weichselian glaciations. By analogy with observations at the present day seafloor a model is presented to explain the truncation of seismic reflectors by deposition of sediments against buried and preserved carbonate domes or by strata truncation due to sediment wash-out during pockmark formation.

Article 4: The free gas zone beneath gas hydrate bearing sediments and its link to fluid flow: 3-D seismic imaging offshore mid-Norway.

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert

The free gas zone (FGZ) beneath the present day base gas hydrate stability zone (BGHSZ), assessed in articles 1 and 2 by seismic velocity modelling, was investigated using high-resolution 3D P-Cable seismic data. The characterization of the FGZ focuses on determining the morphology and distribution of dim-amplitude anomalies confined to sediments within the 80 m thick FGZ immediately beneath the BGHSZ. The identified dim-amplitude anomalies are interpreted as evidence of sediment remobilization possibly aided by hydrate dissociation at focused fluid flow zones beneath bases of the GHSZ. Estimations of paleo-depth locations of bases of the GHSZ for the last 160 ka suggests that the shape and vertical extension of the anomalies has been controlled by less permeable interfaces, likely related to gas hydrate bearing sediments, at gas-gas hydrate phase boundaries. Deeper structures indicate that faulting controls the distribution of gas feeding the free gas zone beneath the BGHSZ forming zones of focused fluid flow prone to excess pore pressure generation. The distribution of mounds and pockmarks seems, to some extent, to be associated with these areas of localized excess pore pressure.

Future research

Sampling deep within at least one chimney structure in Nyegga, i.e. drilling through it, would be the most straight forward method to test models about the internal geological structure and possible gas hydrate and/or authigenic carbonate build ups within chimneys. Why this hasn’t been done so far probably has economical and ecological reasons. It has been through the implementation of non-invasive seismic techniques that characterization of gas hydrate provinces at the Norwegian margin has been achieved. The integration of different seismic data sets available for this study can still be exploited to get relevant information for the understanding of fluid flow systems in gas hydrate provinces. There are four main topics of interest that can be approached as a continuation of the work done during this doctoral thesis.

1- Depth or time migration of the 3D P-Cable data using available interval velocities from articles 1 and 2. Having the required disk memory capacity and running interfaces would allow testing different 3D migration algorithms and study the effect of migration at chimney flanks. If the quality of the migrated data allows detailed imaging it may be even possible to find evidence for brecciation, indicating fracturing of hard material at the interior of chimneys.

2- 3D mapping and inversion of the amplitude field of diffractions associated to the chimneys is of interest to determine chimney wall structures. Diffractions at the flanks and front of the chimneys are indicators of strong acoustic impedance contrast at the chimney interior respect to the hosting sediments or indicators of structural relief at the flanks. Automatic picking of diffractions shows two different patterns of distribution of diffraction hyperboles (figure 7). The one pattern is concentric to the chimneys centers, being likely related to structural relief, and the other one is chaotic at the interior of chimneys likely related to the presence of diffracting bodies such as brecciated carbonate built ups or gas hydrate bearing sediments. Inversion of diffraction amplitude fields can help to infer geometries of diffracting bodies inside the chimneys. An experiment based on the work by Mahapatra and Mahapatra (2009) was started as part of this thesis. Diffractions at the flanks of diverse chimneys form the 3D P-cable data set are used as input for inversion. Some results of the inversion are already available but analysis of the results suggests that the parameters of inversion and the scale of the inverted amplitudes need to be revised.

3- The resolution and coverage of the 3D P-Cable data sets are ideal for characterizing with a unique degree of detail structures and seismic morphology within Quaternary/Pliocene sedimentary sequences. Iceberg-scour features have been found at different depths within Nyegga. Some of these features are included in the present thesis as part of discussions about the relationship between fluid flow activity and glacial cycles. However, some observations remain to be investigated in detail. Some depression-like features, bigger than traditionally observed pockmarks, have been mapped at the base of the high amplitude zone underneath the GHSZ (figure 8). The depressions may provide evidence of fluid venting from deep reservoirs during the past or may be relevant for the reconstruction of grounded ice blocks and the local glacial history.

4- Comparison of geophysical attributes from an active vent site at present (e.g. Vestnesa Ridge) with a non active vent site (e.g. Nyegga) using similarly processed 3D P-cable data sets may provide valuable guidelines for seismic interpretation and characterization of active and inactive venting systems.

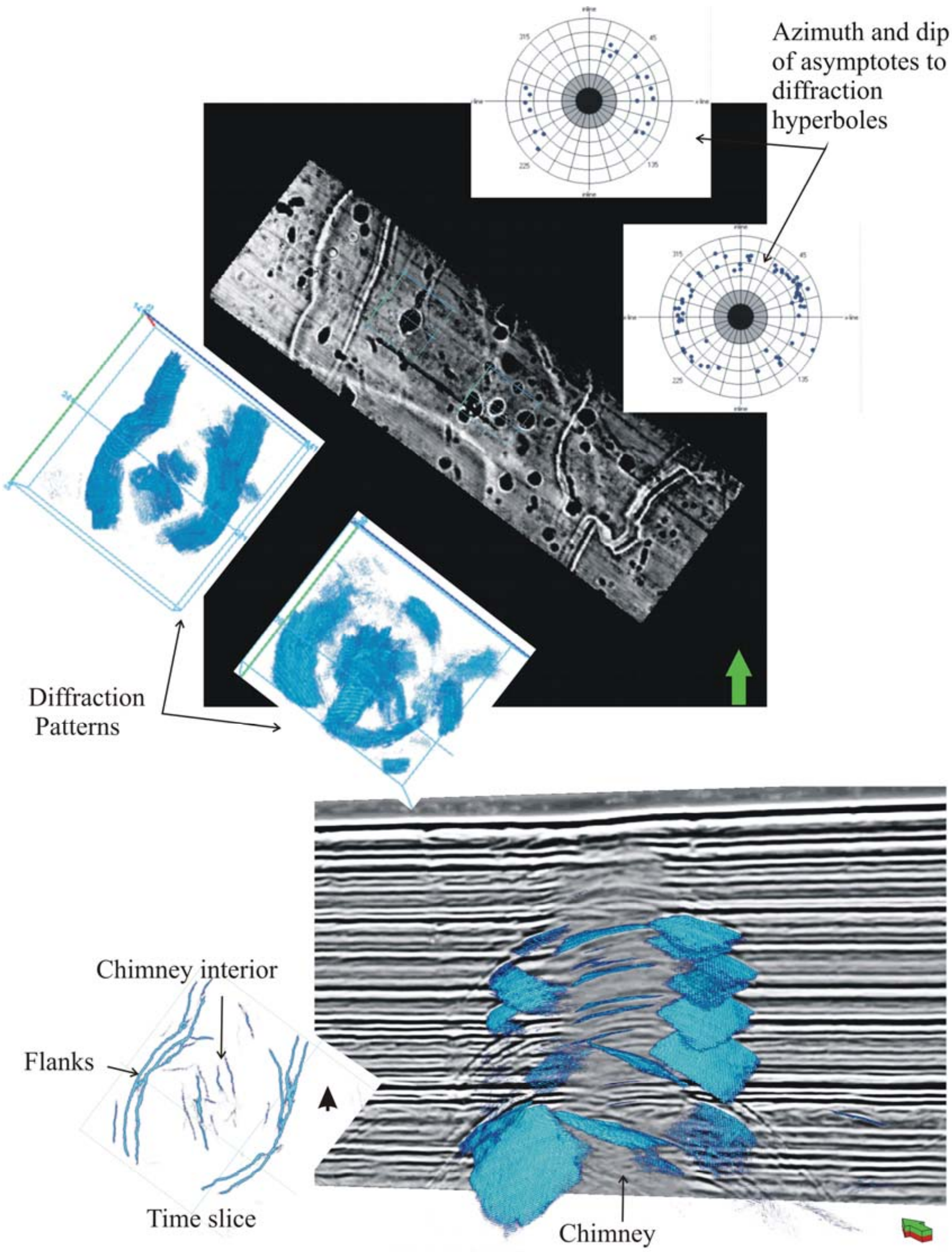


Figure 7: 3D distribution of asymptote planes to diffraction hyperboles associated to different chimneys in Nyegga. Diffractions appear at the flanks and at the interior of the chimneys. Calculation of azimuth of asymptotes to diffraction hyperboles reveals patterns of closed (diffractions all around) and open (diffractions interrupted along a fault) chimneys.

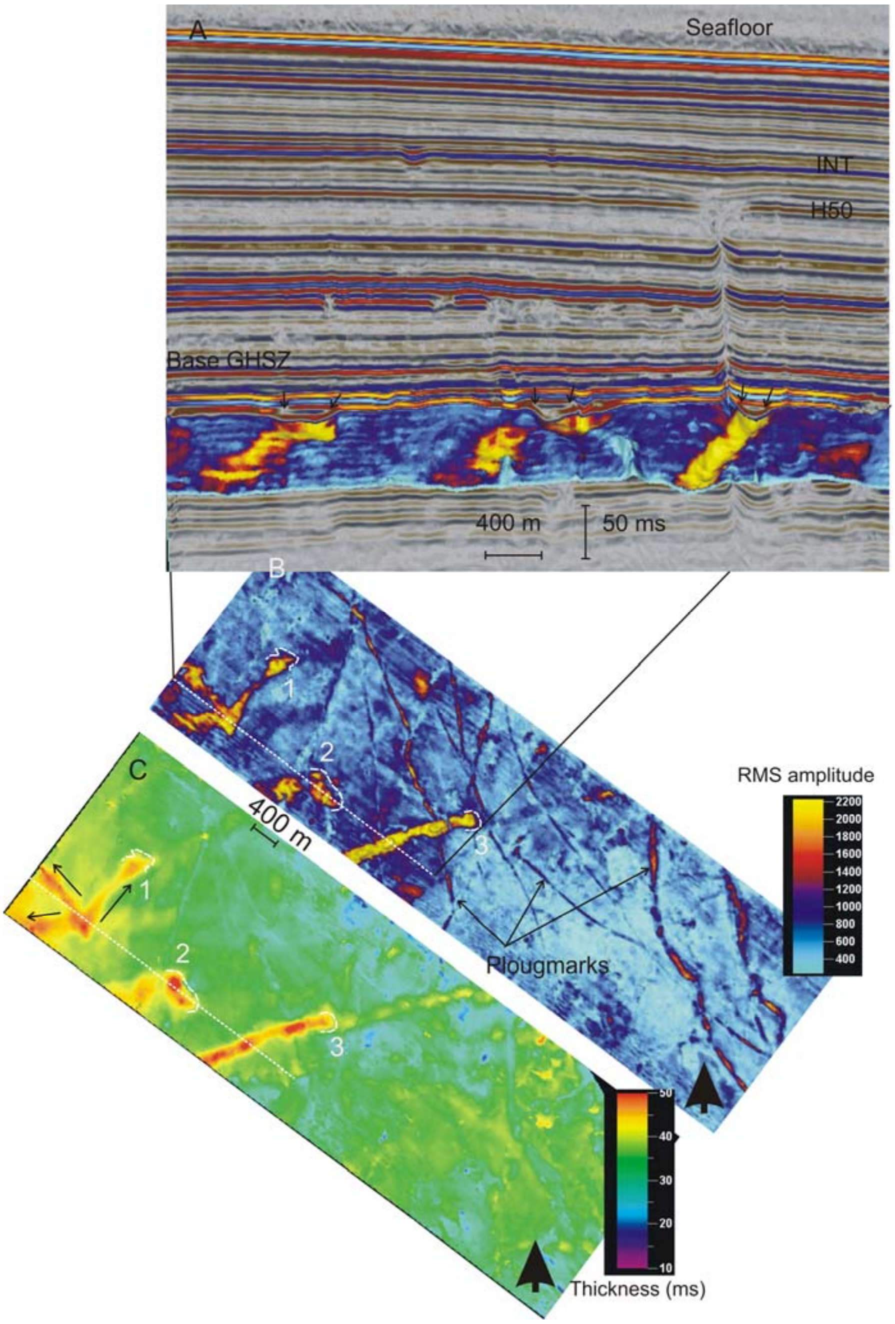


Figure 8: Seismic properties of depressions (1, 2, 3) at the base of the high amplitude zone beneath the gas hydrate stability zone (GHSZ) in the investigated Nyegga site. The black small arrows (A) are indicating onlap fill of the depressions in the cross-sectional view. The RMS map (B) allows comparing the size of the depressions with the size of iceberg ploughmarks mapped a few meters above, i.e. at the depth of the base of the GHSZ. The thickness map (C) is calculated respect the base of the GHSZ. The depressions are 11-20 m deep.

References

Akhmetzhanov, A.M., Kenyon, N.H., Ivanov, M.K., Westbrook, G., and Mazzini, A., 2008, Deep-water depositional systems and cold seeps of the Western Mediterranean, Gulf of Cadiz and Norwegian continental margins. IOC Technical Series No. 76, UNESCO, 2008.

Anketell, J.M., Cegla, J., and Dzulynski, S., 1970, On the deformational structures in systems with reversed density gradients: Rocznik Polskiego Towarzystwa Geologicznego, v. 40, p. 3-30.

Anselmetti, F.S., and Eberli, G.P., 1993, Controls on sonic velocity in carbonates: Pure and Applied Geophysics, v. 141, p. 287-323.

Berg, K., Solheim, A., and Bryn, P., 2005, The Pleistocene to recent geological development of the Ormen Lange area: Marine and Petroleum Geology, v. 22, p. 45-56.

Berndt, C., Bunz, S., Clayton, T., Mienert, J., and Saunders, M., 2004, Seismic character of bottom simulating reflectors: examples from the mid-Norwegian margin: Marine and Petroleum Geology, v. 21, p. 723-733.

Berndt, C., Bünz, S., and Mienert, J., 2003, Polygonal fault systems on the mid-Norwegian margin: a long-term source for fluid flow: Subsurface Sediment Mobilization, p. 283-290.

Berndt, C., Mienert, J., Vanneste, M., and Bunz, S., 2005, Gas hydrate dissociation and sea-floor collapse in the wake of the Storegga Slide, Norway: Onshore-Offshore Relationships on the North Atlantic Margin, v. 12, p. 285-292.

Bouriak, S., Vanneste, M., and Saoutkine, A., 2000, Inferred gas hydrates and clay diapirs near the Storegga Slide on the southern edge of the Voring Plateau, offshore Norway: Marine Geology, v. 163, p. 125-148.

Buffett, B.A., 2000, Clathrate hydrates: Annual Review of Earth and Planetary Sciences, v. 28, p. 477-507.

Bugge, T., Belderson, R.H., and Kenyon, N.H., 1988, The Storegga Slide: Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, v. 325, p. 357-388.

Bünz, S., Mienert, J., and Berndt, C., 2003, Geological controls on the Storegga gas-hydrate system of the mid-Norwegian continental margin: Earth and Planetary Science Letters, v. 209, p. 291-307.

Bünz, S., Mienert, J., Vanneste, M., and Andreassen, K., 2005, Gas hydrates at the Storegga Slide: Constraints from an analysis of multicomponent, wide-angle seismic data: Geophysics, v. 70, p. B19-B34.

Cartwright, J., Huuse, M., and Aplin, A., 2007, Seal bypass systems: AAPG bulletin, v. 91, p. 1141.

Cathles, L.M., and Smith, A.T., 1983, Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis: Economic Geology, v. 78, p. 983.

Clennell, M.B., Hovland, M., Booth, J.S., Henry, P., and Winters, W.J., 1999, Formation of natural gas hydrates in marine sediments 1. Conceptual model of gas hydrate growth conditioned by host sediment properties: Journal of Geophysical Research, v. 104, p. 22985.

Dugan, B., and Flemings, P.B., 2000, Overpressure and fluid flow in the New Jersey continental slope: Implications for slope failure and cold seeps: Science, v. 289, p. 288.

Fisher, Q.J., Casey, M., Harris, S.D., and Knipe, R.J., 2003, Fluid-flow properties of faults in sandstone: the importance of temperature history: Geology, v. 31, p. 965.

Flemings, P.B., Liu, X. L., Winters, W. J., 2003, Critical pressure and multiphase flow in Blake Ridge gas hydrates: Geology, v. 31, p. 1057-1060.

Galimov, E.M., 1988, Sources and mechanisms of formation of gaseous hydrocarbons in sedimentary rocks: Chemical Geology, v. 71, p. 77-95.

Gallagher, J.W., Braaten, A.M., Hovland, M., and Kemp, A., 1989, Use of an interpretation Station for the Study of Shallow Gas Sands on Haltenbanken," paper presented at the 1989 NPF Conference "Shallow Gas and Leaky Reservoirs," Stavanger, April, 10-11.

Gay, A., and Berndt, C., 2007, Cessation/reactivation of polygonal faulting and effects on fluid flow in the Voring Basin, Norwegian Margin: Journal of the Geological Society, v. 164, p. 129-141.

Gay, A., Lopez, M., Cochonat, P., Seranne, M., Levache, D., and Sermondadaz, G., 2006, Isolated seafloor pockmarks linked to BSRs, fluid chimneys, polygonal faults and stacked Oligocene-Miocene turbiditic palaeochannels in the Lower Congo Basin: Marine Geology, v. 226, p. 25-40.

Ginsburg, G.D., Soloviev, V.A., Cranston, R.E., Lorenson, T.D., and Kvenvolden, K.A., 1993, Gas hydrates from the continental slope, offshore Sakhalin Island, Okhotsk Sea: Geo-Marine Letters, v. 13, p. 41-48.

Hansen, J.P.V., Cartwright, J.A., Huuse, M., and Clausen, O.R., 2005, 3D seismic expression of fluid migration and mud remobilization on the Gjallar Ridge, offshore mid-Norway: Basin Research, v. 17, p. 123-139.

Heggland, R., Nygaard, E., and Gallagher, J., 1996, Techniques and experiences using exploration 3D seismic data to map drilling hazards, Proceedings of the Offshore Technology Conference Houston, TX, OTC, paper 7968.

Henriet, J.P., and Mienert, J., 1998, Gas hydrates: relevance to world margin stability and climate change., Geological Society, London, Spetial Publication N. 137, pp. 338.

Henry, P., Thomas, M., and Clennell, M.B., 1999, Formation of natural gas hydrates in marine sediments 2. Thermodynamic calculations of stability conditions in porous sediments: Journal of Geophysical Research, v. 104, p. 23005.

Hjelstuen, B., Haflidason, H., Sejrup, H., and Nygård, A., 2010, Sedimentary and structural control on pockmark development—evidence from the Nyegga pockmark field, NW European margin: Geo-Marine Letters, v. 30, p. 221-230.

Hjelstuen, B.O., Sejrup, H.P., Haflidason, H., Nygard, A., Ceramicola, S., and Bryn, P., 2005, Late Cenozoic glacial history and evolution of the Storegga Slide area and adjacent slide flank regions, Norwegian continental margin: Marine and Petroleum Geology, v. 22, p. 57-69.

Hohbein, M., and Cartwright, J., 2006, 3D seismic analysis of the West Shetland Drift system: Implications for Late Neogene palaeoceanography of the NE Atlantic: Marine Geology, v. 230, p. 1-20.

Hornbach, M.J., Saffer, D.M., Holbrook, W.S., Van Avendonk, H.J.A., and Gorman, A.R., 2008, Three-dimensional seismic imaging of the Blake Ridge methane hydrate province: Evidence for large, concentrated zones of gas hydrate and morphologically driven advection: J. geophys. Res, v. 113.

Hovland, M., and Judd, A.G., 1988, Seabed Pockmarks and Seepages. Impact on Geology, Biology and the Marine Environment. Graham & Trotman Ltd., London., 293 p.

Hovland, M., Nygaard, E., and Thorbjørnsen, S., 1998, Piercement shale diapirism in the deep-water Vema Dome area, Vøring basin, offshore Norway: Marine and Petroleum Geology, v. 15, p. 191-201.

Hovland, M., and Svensen, H., 2006, Submarine pingoes: Indicators of shallow gas hydrates in a pockmark at Nyegga, Norwegian Sea: Marine Geology, v. 228, p. 15-23.

Hovland, M., Svensen, H., Forsberg, C.F., Johansen, H., Fichler, C., Fossa, J.H., Jonsson, R., and Rueslatten, H., 2005, Complex pockmarks with carbonate-ridges off mid-Norway: Products of sediment degassing: Marine Geology, v. 218, p. 191-206.

Hustoft, S., Bünz, S., and Mienert, J., 2010, Three-dimensional seismic analysis of the morphology and spatial distribution of chimneys beneath the Nyegga pockmark field, offshore mid-Norway: Basin Research, v. 22, p. 465-480.

Hustoft, S., Dugan, B., and Mienert, J., 2009, Effects of rapid sedimentation on developing the Nyegga pockmark field: Constraints from hydrological modeling and 3-D seismic data, offshore mid-Norway: Geochemistry Geophysics Geosystems, v. 10, p. Q06012.

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, v. 245, p. 89-106.

Haacke, R.R., Hyndman, R.D., Park, K.P., Yoo, D.G., Stoian, I., and Schmidt, U., 2009, Migration and venting of deep gases into the ocean through hydrate-choked chimneys offshore Korea: Geology, v. 37, p. 531-534.

Haacke, R.R., Westbrook, G.K., and Hyndman, R.D., 2007, Gas hydrate, fluid flow and free gas: Formation of the bottom-simulating reflector: Earth and Planetary Science Letters, v. 261, p. 407-420.

Ivanov, M., Westbrook, G.K., Blinova, V., Kozlova, E., Mazzini, A., Nouzé, H., and Minshull, T.A., 2007, First Sampling of Gas Hydrate From the Vøring Plateau: Eos Trans. AGU, v. 88, p. 209.

Jain, A.K., and Juanes, R., 2009, Preferential Mode of gas invasion in sediments: Grain-scale mechanistic model of coupled multiphase fluid flow and sediment mechanics: J. Geophys. Res., v. 114, B08101, doi: 10.1029/2008jb006002.

Judd, A.G., and Hovland, M., 2007, Seabed fluid flow: the impact of geology, biology and the marine environment., Cambridge University Press, Cambridge, 475 p.

Judd, A.G., Sim, R., Kingston, P., and McNally, J., 2002, Gas seepage on an intertidal site: Torry Bay, Firth of Forth, Scotland: Continental Shelf Research, v. 22, p. 2317-2331.

Jurado, F., Sinoquet, D., and Lailly, P., 1996, jerry: a 3D reflection tomography designed for complex structures: KIM 1996 Annual Report. http://consortium.ifp.fr/KIM/KIM_BIBLIOGRAPHY/Jurado/jerry.pdf: IFP, Pau, France.

Kjeldstad, A., Skogseid, J., Langtangen, H.P., Bjorlykke, K., and Hoeg, K., 2003, Differential loading by prograding sedimentary wedges on continental margins: An arch-forming mechanism: Journal of Geophysical Research-Solid Earth, v. 108, p. NO. B1, 2036.

Kvenvolden, K.A., 1993, Gas hydrates—geological perspective and global change: Rev. Geophys, v. 31, p. 173–187.

Kvenvolden, K.A., and Barnard, L.A., 1983, Hydrates of natural gas in continental margins: Studies in Continental Margin Geology, v. 34, p. 631-640.

Liu, X.L., and Flemings, P.B., 2007, Dynamic multiphase flow model of hydrate formation in marine sediments: Journal of Geophysical Research-Solid Earth, v. 112, p. B03101.

Løseth, H., Gading, M., and Wensaas, L., 2009, Hydrocarbon leakage interpreted on seismic data: Marine and Petroleum Geology, v. 26, p. 1304-1319.

Løseth, H., Wensaas, L., Arntsen, B., and Hovland, M., 2003, Gas and fluid injection triggering shallow mud mobilization in the Hordaland Group, North Sea: Geological Society London Special Publications, v. 216, p. 139.

MacDonald, G.J., 1990, Role of methane clathrates in past and future climates: Climatic Change, v. 16, p. 247-281.

MacKay, M.E., Jarrard, R.D., Westbrook, G.K., and Hyndman, R.D., 1995, the Shipboard Scientific Party, Leg 146, 1995. Origin of bottom-simulating reflectors: Geophysical evidence from the Cascadia accretionary prism: Geology, v. 22, p. 459-462.

Mahapatra, M., and Mahapatra, S., 2009, Seismic diffraction tomography technique using very fast simulated annealing method for delineating small subsurface features: Journal of Applied Geophysics, v. 67, p. 125-129.

Mazurenko, L.L., and Soloviev, V.A., 2003, Worldwide distribution of deep-water fluid venting and potential occurrences of gas hydrate accumulations: Geo-Marine Letters, v. 23, p. 162-176.

Mazzini, A., Svensen, H., Hovland, M., and Planke, S., 2006, Comparison and implications from strikingly different authigenic carbonates in a Nyegga complex pockmark, G11, Norwegian Sea: Marine Geology, v. 231, p. 89-102.

Mienert, J., Bünz, S., Guidard, S., Vanneste, M., and Berndt, C., 2005, Ocean bottom seismometer investigations in the Ormen Lange area offshore mid-Norway provide evidence for shallow gas layers in subsurface sediments: Marine and Petroleum Geology, v. 22, p. 287-297.

Mienert, J., Posewang, J., and Baumann, M., 1998, Gas hydrates along the north-eastern Atlantic Margin: possible hydrate bound margin instabilities and possible release of methane, in: Henriet, J.-P., Mienert, J. (Eds.), Gas Hydrates: Relevance to World Margin Stability and Climatic Change: Geological Society of London, Special Publication v. 137, p. 275-291.

Nisbet, E.G., 2002, Have sudden large releases of methane from geological reservoirs occurred since the Last Glacial Maximum, and could such releases occur again?: Philosophical Transactions: Mathematical, Physical and Engineering Sciences, v. 360, p. 581-607.

Nouzé, H., and Fabri, M.-C., et l'équipe scientifique embarquée, 2007, Vicking cruise report –Cold Seeps on the Norwegian Margin. Associated Ecosystem – R/V Pourquoi pas ? May 19th – June 18th, 2006. Alesund- Alesund. Report no. GM/07- 02, Ifremer, Département des Géosciences Marines, Ifremer.

Paull, C.K., Ussler, W., Borowski, W.S., and Spiess, F.N., 1995, Methane-rich plumes on the Carolina continental rise: associations with gas hydrates: Geology, v. 23, p. 89.

Paull, C.K., Ussler, W., Holbrook, W.S., Hill, T.M., Keaten, R., Mienert, J., Haflidason, H., Johnson, J.E., Winters, W.J., and Lorenson, T.D., 2008, Origin of pockmarks and chimney structures on the flanks of the Storegga Slide, offshore Norway: Geo-Marine Letters, v. 28, p. 43-51.

Pecher, I., Van Huene, R., Ranero, C., Kukowski, N., Minshull, T., Singh, S., 1996, Formation mechanisms of free gas beneath the hydrate stability zone at convergent margins: geophysical evidence from bottom simulating reflectors at the Peruvian and Pacific Costa Rica margins, p. 593-600.

Petersen, C.J., Bünz, S., Hustoft, S., Mienert, J., and Klaeschen, D., 2010, High-resolution P-Cable 3D seismic imaging of gas chimney structures in gas hydrated sediments of an Arctic sediment drift: Marine and Petroleum Geology, v. doi: 10.1016/j.marpetgeo.2010.06.006, p. 1-14.

Pilcher, R., and Argent, J., 2007, Mega-pockmarks and linear pockmark trains on the West African continental margin: Marine Geology, v. 244, p. 15-32.

Planke, S., and Berndt, C., 2003, Apparatus for seismic measurements, Norwegian patent no. 317652.

Posewang, J., and Mienert, J., 1999, High-resolution seismic studies of gas hydrates west of Svalbard: Geo-Marine Letters, v. 19, p. 150-156.

Riedel, M., 2007, 4D seismic time-lapse monitoring of an active cold vent, northern Cascadia margin: Marine Geophysical Researches, v. 28, p. 355-371.

Riedel, M., Bellefleur, G., Mair, S., Brent, T.A., and Dallimore, S.R., 2009, Acoustic impedance inversion and seismic reflection continuity analysis for delineating gas hydrate resources near the Mallik research sites, Mackenzie Delta, Northwest Territories, Canada: Geophysics, v. 74, p. B125.

Riedel, M., Collett, T., and Malone, M., 2006a, Stages of Gas-Hydrate Evolution on the Northern Cascadia Margin. IODP Expedition 311 Scientists, Scientific Drilling, p. 18-24.

Riedel, M., Novosel, I., Spence, G.D., Hyndman, R.D., Chapman, R.N., Solem, R.C., and Lewis, T., 2006b, Geophysical and geochemical signatures associated with gas hydrate-related venting in the northern Cascadia margin: Geological Society of America Bulletin, v. 118, p. 23-38.
Riedel, M., Spence, G.D., Chapman, N.R., and Hyndman, R.D., 2002, Seismic investigations of a vent field associated with gas hydrates, offshore Vancouver Island: Journal of Geophysical Research-Solid Earth, v. 107, p. NO. B9, 2200, doi:10.1029/2001JB000269.
Rise, L., Ottesen, D., Berg, K., and Lundin, E., 2005, Large-scale development of the mid-Norwegian margin during the last 3 million years: Marine and Petroleum Geology, v. 22, p. 33-44.
Rise, L., Ottesen, D., Longva, O., Solheim, A., Andersen, E.S., and Ayers, S., 2006, The Sklinnadjupet slide and its relation to the Elsterian glaciation on the mid-Norwegian margin: Marine and Petroleum Geology, v. 23, p. 569-583.
Roberts, H.H., and Carney, R.S., 1997, Evidence of episodic fluid, gas, and sediment venting on the northern Gulf of Mexico continental slope: Economic Geology, v. 92, p. 863.
Robertson, C., 2010, New Setback in Attempt to Contain Gulf Oil Spill, The New York Times: New York, http://www.nytimes.com/2010/05/09/us/09rig.html?_r=1.
Schoell, M., 1988, Multiple origins of methane in the earth: Chemical Geology, v. 71, p. 1-10.
Shipley, T.H., Houston, M.H., Buffler, R.T., Shaub, F.J., McMillen, K.J., Ladd, J.W., and Worzel, J.L., 1979, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: AAPG Bull, v. 63, p. 2204–2213.
Sloan, E., 2003, Fundamental principles and applications of natural gas hydrates: Nature, v. 426, p. 353-363.
Sloan, E.D., and Koh, C.A., 2008, Clathrate hydrates of natural gases: Boca Raton, CRC, 703 p.
Sloan Jr, E.D., 1998, Physical/chemical properties of gas hydrates and application to world margin stability and climatic change: Geological Society London Special Publications, v. 137, p. 31.
Suess, E., Torres, M. E., Bohrmann, G., Collier, R. W., Rickert, D., Goldfinger, C., Linke, P., Heuser, A., Sahling, H., Heeschen, K.,, 2001, Sea floor methane hydrates at Hydrate Ridge, Cascadia margin: GEOPHYSICAL MONOGRAPH-AMERICAN GEOPHYSICAL UNION, v. 124, p. 87-98.
Trehu, A., Torres, M., Bohrmann, G., and Colwell, F., 2006, Leg 204 Synthesis: Gas hydrate distribution and dynamics in the Central Cascadia Accretionary Prism Complex: Ocean Drilling Program: Scientific Results, v. 204, p. 40.
Vaular, E.N., Barth, T., and Haflidason, H., 2010, The geochemical characteristics of the hydrate-bound gases from the Nyegga pockmark field, Norwegian Sea: Organic Geochemistry, v. 41, p. 437-444.
Vogt, P.R., Cherkashev, G., Ginsburg, G., Ivanov, G., Milkov, A., Crane, K., Lein, A., Sundvor, E., Pimenov, N., Egorov, A.,, 1997, Haakon Mosby mud volcano provides unusual example of venting: Eos Trans. AGU, v. 78, p. 549.
Vogt, P.R., Gardner, J., Crane, K., Sundvor, E., Bowles, F., Cherkashev, G.,, 1999, Ground-truthing 11-to 12-kHz side-scan sonar imagery in the Norwegia–Greenland Sea: Part I: Pockmarks on the Vestnesa Ridge and Storegga slide margin: Geo-Marine Letters, v. 19, p. 97-110.
Westbrook, G.K., Carson, B., and Musgrave, R.J., 1994, Summary of Cascadia Drilling Results. Proceedings of the Ocean Drilling Program, Initial Reports, Volume 146, p. 389-396.
Westbrook, G.K., Chand, S., Rossi, G., Long, C., Bünz, S., Camerlenghi, A., Carcione, J.M., Dean, S., Foucher, J.P., and Flueh, E., 2008, Estimation of gas hydrate concentration from multi-component seismic data at sites on the continental margins of NW Svalbard and the Storegga region of Norway: Marine and Petroleum Geology, v. 25, p. 744-758.
White, R.S., 1979, Gas hydrate layers trapping free gas in the Gulf of Oman: Earth and Planetary Science Letters, v. 42, p. 114-120.

Wood, W.T., Hart, P.E., Hutchinson, D.R., Dutta, N., Snyder, F., Coffin, R.B., and Gettrust, J.F., 2008, Gas and gas hydrate distribution around seafloor seeps in Mississippi Canyon, Northern Gulf of Mexico, using multi-resolution seismic imagery: Marine and Petroleum Geology, v. 25, p. 952-959.

Xu, W., and Ruppel, C., 1999, Predicting the occurrence, distribution, and evolution of methane gas hydrate in porous marine sediments: Journal of Geophysical Research-Solid Earth, v. 104, p. 5081-5095.

Yilmaz, O., and Doherty, S.M., 2001, Seismic data analysis: Tulsa, OK, Society of Exploration Geophysicists, 2024 p.

Zelt, C.A., 1999, Modelling strategies and model assessment for wide-angle seismic traveltime data: Geophysical Journal International, v. 139, p. 183-204.

Article 1

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

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert

Marine and Petroleum Geology

Article 2

Evidence from 3D seismic tomography for a substantial accumulation of gas hydrate in a fluid-escape chimney in the Nyegga pockmark field, offshore Norway.

Andreia Plaza-Faverola, Graham K. Westbrook, Stephan Ker, Russell J.K. Exley, Audrey Gailler,Tim A. Minshull and Karine Broto.

Journal of Geophysical Research

Article 3

Repeated fluid expulsion through sub-seabed chimneys offshore Norway in response to glacial cycles.

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert

Submitted to Earth and Planetary Science Letters

Article 4

The free gas zone beneath gas hydrate bearing sediments and its link to fluid flow: 3-D seismic imaging offshore mid-Norway.

Andreia Plaza-Faverola, Stefan Bünz and Jürgen Mienert

To be submitted

Appendix

Conferences, workshops and meetings

Oral:

*2010- AMGG, Tromsø. Andreia Plaza-Faverola, *Fluid distribution and hydrate systems in Nyegga: research summary. Integration of seismic methods*.

2009- AGU annual meeting, San Fracisco. Graham Westbrook, Andreia Plaza-Faverola, Stephan Ker, Russell Exley, Audrey Gailler, Tim Minshull, Karine Broto. *A large body of hydrate defined by 3D seismic tomography in a chimney beneath the CNE03 pockmark on the Vøring plateau, offshore Norway .*

*2009- GANS workshop, Tromsø. Andreia Plaza-Faverola, *Fluid distribution in Nyegga and hydrate concentrations in CNE03 inferred from P-wave travel-time inversion methods.*

*2007- PETROMAKS fluid flow meeting, Bremen. Andreia Plaza-Faverola, *Seismic chimney experiment: Nyegga.*

*2007- AMGG, Tromsø. Andreia Plaza-Faverola, *Seismic constraints for the study of fluid-gas migration systems at the Norwegian margin.*

Posters:

*2010- EGU general assembly, Vienna. 1/ Andreia Plaza-Faverola**,** Stefan Bünz, Juergen Mienert, *Periods of activity and internal structures of sub-seafloor methane escape features in the Nyegga pockmark field, offshore Norway;* 2/ Andreia Plaza-Faverola, Graham Westbrook, Stephan Ker, Russell Exley, Audrey Gailler, Tim Minshull, Karine Broto, *Evidence from 3D seismic tomography for hydrate accumulation in a fluid-escape chimney in the Nyegga area on the Vøring plateau.*

*2008- AGU annual meeting, San Francisco. Andreia Plaza-Faverola, Graham Westbrook, Stephan Ker, Russell Exley, Audrey Gailler, Karine Broto , *Reflection Tomography for the Investigation of Vp Variation within the CNE03 chimney in the Nyegga region of the mid-Norwegian Margin.*

*2008- EAGE conference, St Petersburg. Andreia Plaza-Faverola**,** Stefan Bünz, Juergen Mienert, Wiktor Weibull*, Fluid distribution within the Nyegga area, mid-Norwegian margin.*

*2007- Statoil conference, Trøndheim. Andreia Plaza-Faverola**,** Stefan Bünz, Juergen Mienert, *Fluid distribution within the Nyegga area, mid-Norwegian margin.*

*2007- HERMES-AGM, Carvoeiro. Andreia Plaza-Faverola**,** Stefan Bünz, Juergen Mienert, Seismic constraints for the study of fluid-gas migration systems at the Norwegian margin.

Seismic cruises

- R/V Jan Mayen, West Barents Sea; August 2009. P-cable 3D seismic data acquisition.
- R/V Jan Mayen, West Svalbard; July 2007. 2D SCS and OBS data acquisition.
- R/V Jan Mayen, West Svalbard; October 2006. 2D SCS and OBS data acquisition.
- R/V Jan Mayen, Nyegga-mid Norwegian margin; July 2006. 2D SCS and OBS data acquisition.
- R/V Professor Logachev, TTR16, leg 3. Brest-Bergen; June-July 2006. Seismic data acquisition and sediment coring.

Publications

- **Plaza-Faverola, A**., G. K. Westbrook, K. Stephan, R. Exley, A. Gailler, T. Minshull and K. Broto, (2010). Evidence from tomographic investigation of Vp variation for accumulation of substantial methane hydrate in a fluid-escape chimney in the Nyegga pockmark field, offshore Norway. J. Geophys. Res, doi:10.1029/2009JB007078, in press.
- **Plaza-Faverola, A**., S. Bünz, and J. Mienert (2010). Fluid distributions inferred from P-wave velocity and reflection seismic amplitude anomalies beneath the Nyegga pockmark field of the mid-Norwegian margin, *Marine and Petroleum Geology*, 27(1): 46-60.
- Westbrook, G. K., R. Exley, T.A. Minshull, H. Nouzé, A. Gailler, T. Jose, S. Ker, and **A. Plaza-Faverola** (2008), High-resolution 3D seismic investigations of hydrate-bearing fluid-escape chimneys in the Nyegga region of the Vøring plateau, Norway. *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008)*, Vancouver, British Columbia, CANADA, July 6-10, 2008, 12pp. [https://circle.ubc.ca/handle/2429/1022].