UNIVERSITY OF TROMSØ UIT

FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF GEOLOGY

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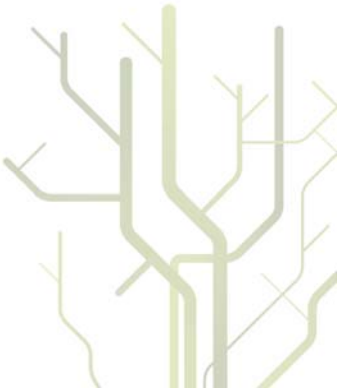
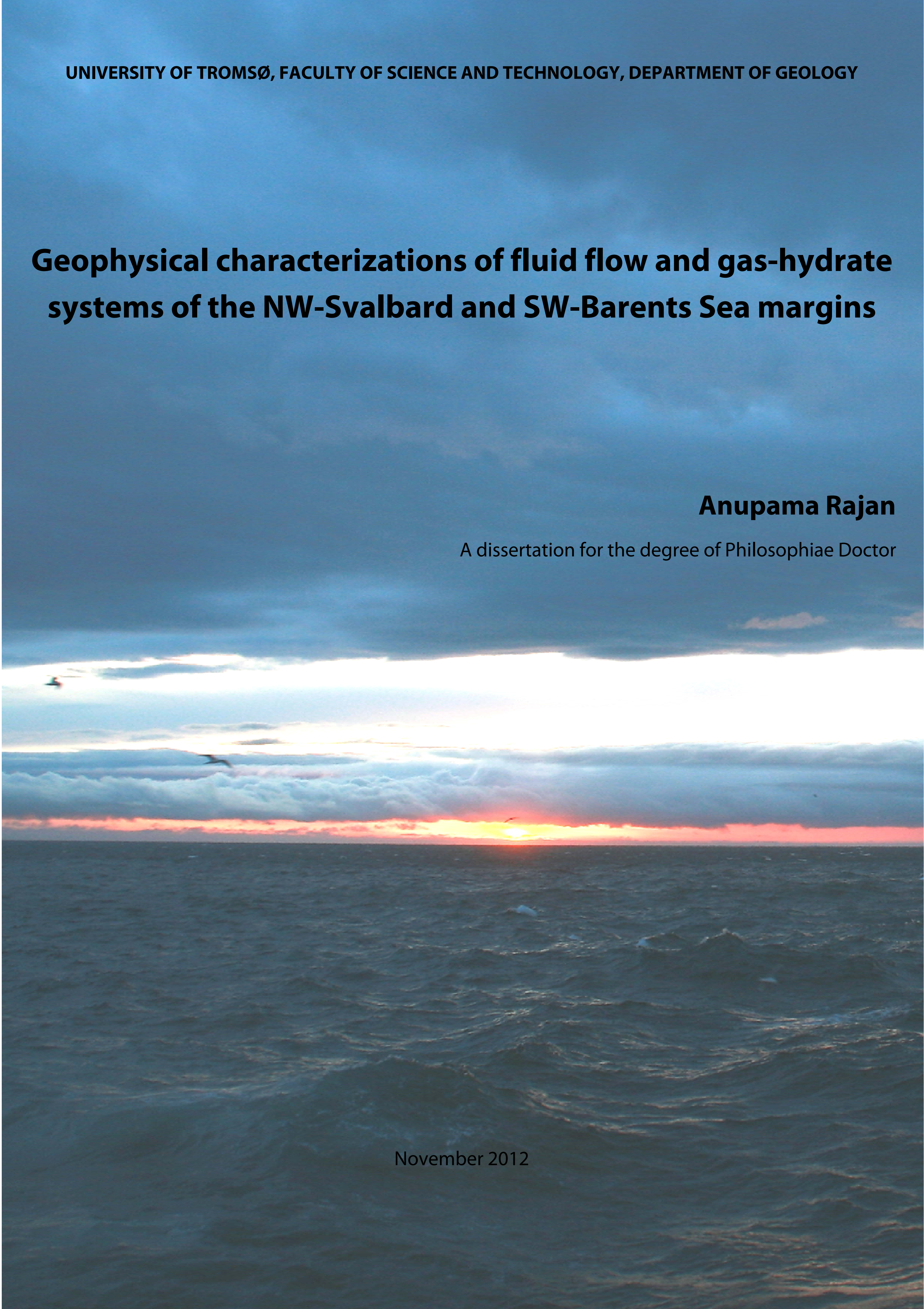
Anupama Rajan

A dissertation for the degree of Philosophiae Doctor
November 2012





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"Fight! They must fall, and thou must live, victor upon this plain!"

-Bhagavad Gita

Preface

This doctoral thesis was carried out from 2008 to 2012 at the Department of Geology, University of Tromsø. The work was financially supported by the Trainee School in Arctic Marine Geology and Geophysics (AMGG) which is hosted by the University of Tromsø (UiT) and is a contribution to the NFR funded Geosystem 3-D seismic imaging (G3) project (195379) and to HERMIONE EU funded project (226354). A part of this thesis has been carried out National Oceanography Centre Southampton (NOCS), Southampton University in collaboration with Prof. Tim A. Minshull and Graham Westbrook.

High resolution 2D seismic, P-Cable 3D seismic and bathymetry data of the study areas were acquired during the June-August scientific cruise in 2009 onboard R/V Jan Mayen (now R/V Helmer Hanssen), UiT. These data were used for the first, second and third article of this thesis together with high resolution 2D multi-channel seismic profiles and conventional 3D seismic dataset kindly provided by University of Bergen and Lundin AS respectively. The fourth article of this thesis comprised a four month stay at NOCS in 2012. During this period, a ray-trace forward modeling at three ocean bottom seismometers (OBSs) sites along the western Svalbard continental margin was carried out that provided compressional-wave velocities for estimating the gas-hydrate and free gas concentration. The data for OBS experiment were acquired during the scientific cruise for a project funded by Natural Environment Research Council, UK, onboard RRS James Clark Ross in August-September, 2011. OBSs were kindly provided by the Ocean-Bottom Instrumentation Facility, part of the NERC’s Geophysical Equipment.

During my tenure at UiT, I had the opportunity to take part in scientific cruises with R/V Helmer Hanssen (NW-Svalbard, Fram Strait, Norwegian Sea and SW-Barents Sea) and RRS James Clark Ross (NW-Svalbard). In addition to marine expeditions, I attended several courses in seismic visualization and geographical mapping. I had the fortuitousness to participate in all the survey campaigns for acquiring, processing and interpreting most of the data used for this research. I also participated in workshops and national and international conferences to present my research study and connect with peers and colleagues.

This doctoral thesis consists of an introduction and four articles. The scientific articles presented are:

Article 1

Rajan, A., J. Mienert, S. Bünz, and S. Chand (2012), Potential serpentinization, degassing, and gas hydrate formation at a young (<20 Ma) sedimented ocean crust of the Arctic Ocean ridge system, *J. Geophys. Res.*, *117*(B3), B03102.

Article 2

Rajan, A., J. Mienert, and S. Bünz (2012), Acoustic evidence for a gas migration and release system in Arctic glaciated continental margins offshore NW-Svalbard, *Marine and Petroleum Geology*, *32*(1), 36-49.

Article 3

Anupama Rajan, Stefan Bünz, Jürgen Mienert and. Andrew J. Smith Tilted bottom-simulating reflectors (TBSRs) provide evidence for active fluid flow from deep hydrocarbon sources in the SW-Barents Sea (submitted to *Journal of Geophysical Research*)

Article 4

Anupama Rajan, Tim A. Minshull and Jürgen Mienert. Heterogeneous distribution of gas-hydrate and free gas in glaciated sediments of the NW-Svalbard continental margin inferred from changes in compressional wave velocity (to be submitted)

In addition to the scientific publications, preliminary results were exhibited in the form of posters and verbal presentations at workshops, national and international conferences (see appendix).

Acknowledgements

This doctoral thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

Foremost, my utmost gratitude to Jürgen Mienert, my supervisor who accepted me for the PhD program. It has been a privilege to work with him under his tutelage. He has been a steady influence throughout my PhD career by providing support in difficult times and encouraging me in developing new ideas, which I appreciate from my heart. He has been a tremendous guru for me and surprised me with his unfathomable patience during our discussions and manuscript preparations!! I have been astounded by his talent in tackling labyrinthine research problems with hard work and high scientific acumen. I thank him for mentoring me and giving me the opportunity to attend various cruises, conferences and courses.

I am also indebted to Stefan Bünz, who contributed immensely with his scientific knowledge during this thesis. He had been critical of my work and had instilled in me the need to think in an unconstrained manner when approaching geological processes. It was while writing manuscripts that his skills in geophysics shone through. The discussions I had with him always prompted me to look at the issue with a different perspective which culminated in our publications. He was always at hand when there was any need of technical assistance with respect to scientific softwares. I appreciate the time he took to review and comment on scientific articles in the midst of his busy schedule in Central European Time (Tromsø) and in New Zealand Daylight Time (Auckland).

I am very grateful to Shyam Chand for his insightful comments and valuable guidance during this thesis and during my research visit at NGU. He taught me gas-hydrate modeling and familiarised me with rock physics which were very decisive in my study and accreted my knowledge in geophysics. He was very responsive and patient when it came to discussions and in answering all the questions that crept up in my mind.

Furthermore, I express my gratitude to Tim A. Minshull who made my four month stint at National Oceanography Centre, Southampton possible and collaborate with his exceptional team comprising Graham Westbrook, Sudipta Sarkar, Hector Moreno and Mark Vardy on

OBS data. I thank them for their cordial temperament in assisting me to carry out the OBS experiment.

Likewise, I am much obliged to T. Ramprasad and M.V. Ramana, from the National Institute of Oceanography, India who introduced me to the vast topic of gas hydrates and instigated me to pursue higher studies.

When I moved to Tromsø from India, It was quite literally a ‘poles-apart’ relocation for me. But, thanks to the administration team, especially Annbjørg, who acted as my translator for my mails during the tenure of my PhD. Special thanks to Bjørn Ivar, Bjørn Runar and Rolf Andersen of IT, Gunnar of Drift and Prof. T.V. Bhuvaneswari of Department of Biology for their help.

Many thanks to Steiner Iversen and the crews of R/V Helmer Hansen and RRS James Clark Ross who played an important role during data acquisition while, simultaneously maintaining their humour in nice, warm, inclement Nordic seas. Thanks also to Jan P. Holm for helping me with printing the posters.

Special acknowledgements go to Jörg Petersen for his congenial personality. This research has additionally profited from discussions with Jan Sverre Laberg, Andreia, Carolina, Steiner Hustoft, Iver Martens and Sunil. I am also thankful to Andrew for proofreading some of the text in a manuscript.

Thanks to my friends Navinder, Jagadish, Deepthi, Pardhasaradhi, Dhivya, Kavitha, Kari, Kasia, Denise, Patrycja, Matthias, Pritham, Steffan, Katrine, Monica, Lindsay, Mayte, Polina, Hilde, Per Inge, Benedict, Lilja and Farah.

Soulful skype conversations (punctuated with growls and howls) with our hounds Kaiser, Gundu and Bruni (now in ectoplasmic form) were a huge relief.

Last but not least, Anoop, my husband for his emotional support, love and encouragement. Thank you for being my pillar of many things!!

Finally, I thank my parents and sister for supporting me throughout my life. I admire our families for their relentlessness in providing much needed ‘maternal language’ support through trans-oceanic dialogues during weekends.

And to God - to whom I owe my existence.

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Introduction

Scope of my thesis

Continental margins, whether tectonically active or passive, are dynamic environments. Many different processes cause fluids to migrate in the sedimentary basins and reach the surface. Gas seepage and fluid escape structures have been reported from continental shelf areas worldwide (e.g. King and MacLean 1970; Solheim and Elverhøi, 1985; Field and Jennings, 1987; Hovland and Judd, 1988; Fader 1991; Kelley et al., 1994; Rise et al., 1999; Judd and Hovland, 2007; Chand et al., 2008, 2012; Westbrook et al., 2009; Bünz e tal., 2012b; Rajan et al., 2012b; Sarkar et al., 2012). Focused fluid flow expresses itself through a wide range of geological phenomena, such as mud volcanoes, pockmarks, pipe structures, diapirs and gas hydrates (e.g. Henriet & Mienert 1998; Judd & Hovland 2007). The fluids that escape from the focused fluid flow systems affect seabed (benthic) ecosystems (e.g. Dando et al., 1991; Hovland et al., 2002; MacDonald et al. 2002; Sibuet and Olu-Le Roy 2003), contribute to climate change (Svensen et al., 2004), and allow prediction of deep hydrocarbon migration patterns in the subsurface (e.g. Gay et al., 2003; MacDonald et al., 2004). Focused fluid flow systems and overpressure have also been cited as a mechanisms contributing to submarine slope instability (e.g. Bugge et al., 1987).

The scale of volcanic activity in the ocean is enormous. Whether or not magma is expelled at the surface, fluids being much more mobile are more likely to escape, and the escape of gases may continue long after other indicators of volcanic activity have ceased. The presence of gas in magma is confirmed by direct observations of bubble expulsion from volcanic vents. The composition and concentration of gas depends on the acidic and basic nature of magma (Judd and Hovland, 2007). All magma contains some gas, and the expansion of gases as they rise towards the surface provides much of the energy required to lift the magma from the subsurface (Judd and Hovland, 2007). As magma cools, the chemical composition of the melts changes as individual minerals crystallize progressively (Judd and Hovland, 2007).

Carbon dioxide and hydrogen sulphide are the most abundant gases released from mafic magmas at spreading centres (Judd and Hovland, 2007). Methane is also produced, but in smaller amounts (Judd and Hovland, 2007). These gases contribute to the fluids emitted by hydrothermal vents. Serpentinization of ultramafic rocks (peridotite) occurs near spreading centres and near subduction zones where diapiric serpentinite bodies have been identified and methane-rich plumes rise into the water column (Judd and Hovland, 2007). For example, the upward migration of fluid at the eastern flank of the Knipovich Ridge offshore Svalbard may be driven by the chemical reaction between seawater and mantle rocks that make up the underlying basement (Rajan et al., 2012a).

We are now facing a situation where global warming may cause another period of gas-hydrate melting (Schmidt and Shindell, 2003). Global warming is advanced over sea-level rise effects because of the shorter time intervals involved (Riebeek, 2010). However, the effect of change in water depth upon the hydrate stability zone is immediate, but a change in temperature at the seabed takes time to propagate down through the sediments (Phrampus and Hornbach, 2012). Temperature appears to lag behind the effects of a change in water depth. Consequently, in order to understand the potential of hydrates as a future energy resource and as a driver of climate change, it is important to better understand today's distribution and dynamics of gas hydrates and fluid flow systems in polar environments of the Svalbard-Barents margin, as well as their response to warming in the Arctic Ocean. Most climate models predict a rapid increase in Arctic air and surface water temperatures within the next decades, and we already realise now that the Arctic has been warming faster than predicted (Kennett et al., 2003; Symon, 2011). For this reason, it is most important to characterize free gas and gas-hydrate systems of the Western Svalbard and Barents margins. The shallow water depths of gas-hydrate related methane seeps and the short distance that methane has to travel through the water column compared to deeper water depths, makes it likely that a much higher percentage of methane will eventually reach the atmosphere (Archer, 2007).

Two key areas were defined before the start of the project: the Western Svalbard margin and the Barents Sea. We characterize the gas-hydrate and fluid flow systems at these areas with high-resolution 2D seismic data, a high-resolution P-Cable 3D seismic reflection survey over the same area, a conventional 3D seismic cube (kindly provided my Lundin Norge AS, Oslo) and ocean bottom seismometer data (OBS).

This thesis consists of four parts:

The aim of the first part was to establish a potential link between inferred areas of serpentinization, transfer of carbon from the deep-seated host rocks through the sediments above diapirism, and methane capture within the gas hydrate stability zone (GHSZ) at the eastern flank of the Knipovich Ridge. This was done using imaging and mapping of two multi-channel seismic reflection profiles. Fluids at the sedimented oceanic ridge may originate from serpentinized mantle and gabbro material and migrate upward causing sediment remobilization. Velocity model at this stage covered the upper 2400 m of sediments. A multi-channel seismic reflection profile provided information about a gas-hydrate related bottom-simulating reflector (BSR) and a saturation of up to 26 % methane hydrate in the pore space of the sediments in the gas-hydrate reservoir (article 1).

In the second part, the aim was to understand the coexistence of free gas and gas-hydrate and to image gas-transport structures, which pass free gas from the base of the gas hydrate stability zone (BGHSZ) along strata to the seafloor. The high-resolution 2D and P-Cable 3D seismic data provided the necessary resolution. Fluid migration towards the upper continental slope of western Svalbard margin appears to be stratigraphically constrained and largely prevails over vertical focused migration. Seismic data provided evidence for the accumulation of gas in the uppermost part of the slope just westward of the shelf break, where it is trapped beneath a prograding glacigenic sequence and also beneath hydrates on the lower continental slope (article 2).

In the third part, the aim was to image fluid migration-path networks for understanding the geo-constraints associated with the fluid flow from deep hydrocarbon reservoir leakage feeding shallow sub-seabed gas and hydrate accumulation zones. 3D high-resolution seismic acquired using P-cable system (Petersen et al., 2010; Planke and Berndt, 2003) and conventional 3D seismic provided the necessary information. Article 3 presents evidence of fluid expulsion through chimneys which seem to be connected to faults and also lateral migration of fluids through the dipping strata overlain by impermeable layers. We image a tilted negative-polarity seismic reflection and interpret it to record the BGHSZ: it is the BSR. We hypothesize that this tilted BSR (TBSR) records lateral variation in the geothermal gradient. The variability of the geothermal gradient could be the result of enhanced heat flow from advection (Wood et al., 2002) or conduction (Hornbach et al., 2005). The gas composition is another important parameter for changes in the GHSZ thickness. Changes in the gas composition would lead to a change in the depth of the BSR. Higher-order hydrocarbons gases would lead to a thicker GHSZ, and confined areas of gradual increase in higher-order hydrocarbons along the BSR could cause a dipping of the BSR. The combination of fluid flow, bringing thermogenic gases upwards is an intriguing one. It allows the formation of a deeper BSR on one side whereas heat flow increases towards the western margin of the Loppa High, which explains the formation of a tilted and cross-cutting reflection.

Finally, in the fourth part the aim was to determine in detail the seismic velocity structure of the regions close to the landward limit of hydrate stability zone, and this was done by integrating 1D velocity modeling to 2D seismic imaging and mapping (article 4). Velocity models and 2D imaging covered the upper 1100 m of sediments. The distributions of acoustically inferred gas-hydrate concentrations show significant variations along the NW-Svalbard. The hydrate saturation generally increases downslope as the seismic facies changes from glacigenic sediments on the upper slope to hemipelagic sediments on the lower slope. The average gas-hydrate concentration within the pore space of sediments is 4% at the uppermost continental slope and 8 - 14% at the lower continental slope. The free gas saturation varies from 0.06% - 0.15% in the investigated area.

The thesis presents results from 4 articles which give an overall understanding of free gas and gas-hydrate systems in the Svalbard–Barents continental margin. The following section of this introduction provides a general idea of focussed fluid flow and gas-hydrate associated mechanisms. It also provides an overview of the seismic methods implemented for the estimation of fluid and hydrate distribution in the investigated sectors of the continental margins.

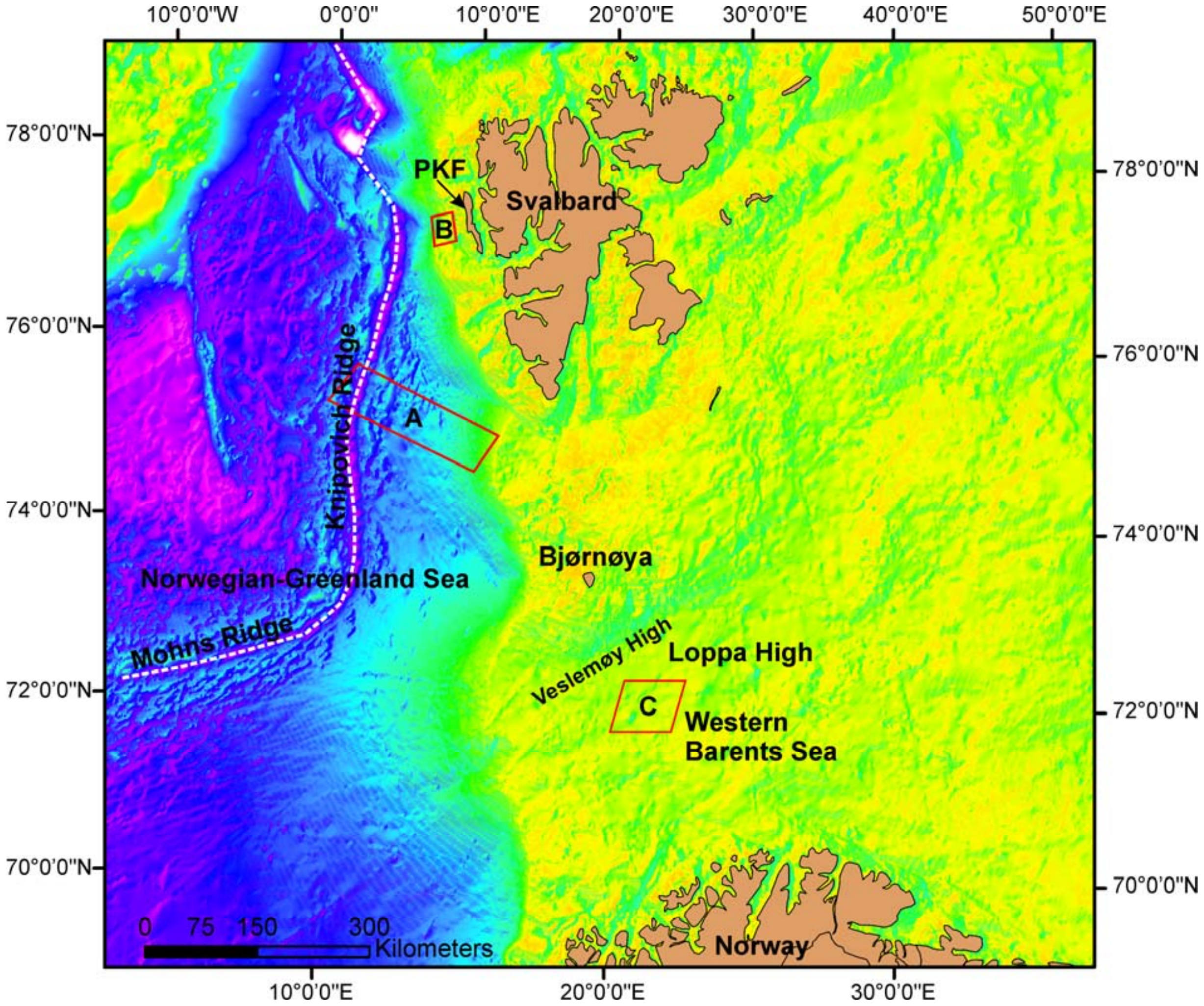


Figure 1: Map showing the target areas of this research (red rectangular boxes); (A) off Svalbard along the eastern flank of the Knipovich Ridge, (B) west of Prins Karls Forland (PKF) on the NW-Svalbard margin and (C) SW-Barents Sea, is bounded by structural highs and major hydrocarbon prone sedimentary basins.

Setting of the study area

The continental margin of Norway hosts numerous large deep-seated and shallow accumulations of gas. Fluid and gas are constantly migrating from these reservoirs to the seabed. In some areas, vertical pipes and pockmarks provide evidence of past episodes of gas migration while in other areas these structures are still active (e.g. Hovland et al., 1998; Vogt, 1999; Bouriak et al., 2000; Bünz et al., 2003; Hansen et al., 2005). Natural gas hydrates are present in the Storegga area offshore mid-Norway, off Svalbard and in the Barents Sea, and their occurrence are associated with shallow gas accumulation.

The Svalbard continental margin formed as a result of several rifting episodes throughout the Tertiary (Faleide et al., 1993) (Figure 1). Opening of the Norwegian-Greenland Sea started in the early Eocene (Engen et al., 2008) with a change in plate configuration and spreading direction in earliest Oligocene. Changes of plate movement in the Oligocene resulted in the development and activation of the Knipovich Ridge forcing continental separation of Greenland and Svalbard (Lundin and Doré, 2002). The opening of the northern Norwegian-Greenland Sea caused the Knipovich Ridge to propagate from south into the Spitsbergen Shear zone (Crane et al., 1988).

A prominent BSR occurs in the NW-Svalbard area determined from travel time inversion of OBS data and multi-channel seismic data (Posewang and Mienert, 1999; Westbrook et al., 2005; Hustoft et al., 2009). The BSR is caused by a large reduction in P-wave velocity and is thought to be caused by the presence of free gas occupying the pore volume, if uniformly distributed (Hustoft et al., 2009).

The Late Cenozoic post-rift evolution of sedimentary basins in the Arctic region is closely linked to the glacial activity. The fast flowing ice streams caused major erosion on the shelf, sediment transport, and deposition in prograding glacigenic sequences (e.g. Sættem et al., 1992; Laberg and Vorren, 1995; Solheim et al., 1998) on the adjacent continental slopes building up the glaciated margin. Glacigenic debris flows (GDF) originated during peak glaciations by sediment release along ice stream fronts at the shelf break (e.g. Laberg and Vorren, 1995). Trough mouth fans on the continental slope are the result of these glacier-driven sedimentary processes (Vorren et al., 1998, Sarkar et al., 2011). Furthermore, the study area is highly influenced by the West Spitsbergen current (WSC), warm North Atlantic current (e.g. Slubowska-Woldengen et al., 2007; Spielhagen et al., 2011), which transport heat into the Arctic Ocean.

The Barents Sea shelf areas have been eroded and compacted, and their morphology has been shaped by major ice sheet advances and retreats particularly during the last 1.5 Ma (Faleide et al., 1996; Andreassen et al., 2004; 2007) (Figure 1). High pressures and cold temperatures existed at the base of the Barents Sea ice sheets at the Last Glacial Maximum (LGM), when the ice sheet reached a thickness exceeding 1500 m (Cavanagh et al., 2006). The resulting pressure and temperature regimes during the glaciations and the melting of the ice sheet accompanied by sea level rise during the deglaciation must have influenced the gas-hydrate, fluid flow and free gas systems of this enormous epi-continental sea. The geological setting is special in that glacial sediments of the Barents Sea are highly compacted and separated from underlying pre-glacial sedimentary rocks by a major regional unconformity (URU = Upper Regional Unconformity) (Andreassen et al., 2008). The glacigenic sediments provide the most upper cap rock for fluids rising from deep source rocks into the GHSZ.

Gas hydrates of the southern Barents Sea were first inferred by the identification of a BSR (Løvø et al., 1990; Laberg and Andreassen, 1996). From these data it is conceivable that the gas-hydrate/free gas reservoirs could be an unconventional energy resource or if released by natural processes a concern for the environment. Consequently, it is becoming important that the mobility of these reservoirs is understood during a global warming scenario. Globally, an increase in ocean temperature of ~3°C would cause gas-hydrate melting and gas release (Kennett et al., 2003). Heat flow data in the area are highly variable due to changes in lithology and the presence of salt diapirs (Chand et al., 2008). Both at the Barents Sea and off Svalbard, evidence for gas-hydrate reservoirs exists based on reflection seismic data. Seabed craters or pockmarks were identified by using multibeam acoustic imaging techniques. Solheim and Elverhøi, 1993 reported that large seabed pockmarks in the Barents Sea were formed by rapid degassing or blow-outs as a result of the destabilization of gas hydrates during the last deglaciation.

Perception of gas seepage and focused fluid flow regime on the Svalbard-Barents margin

High concentration of methane in water column offshore Svalbard is likely caused by the release of sub-seabed methane at seepage sites on the SW-Svalbard shelf (Damm et al., 2005). In the Svalbard shelf and slope area deep-seated hydrocarbon sources (Knies and Mann, 2002), shallow gas hydrates (Vogt et al., 1994; Posewang and Mienert, 1999; Hustoft et al., 2009) and natural seabed seeps (Solheim and Elverhøi, 1985; Vogt et al., 1999; Knies et al., 2004; Westbrook et al., 2009; Rajan et al., 2012b) all may contribute via natural seep processes at still unknown rates over time to elevated dissolved methane concentrations in the water column. More than 222 flares are concentrated on the NW-Svalbard continental margin (Westbrook et al., 2009). The highest concentration of flares lies in the northern area of the outer shelf clearly outside and east of the pinch out of the projected GHSZ (article 2).

The term fluid includes both liquids and gas. Leakage of liquid and gaseous hydrocarbons through focused fluid flow systems is a process identified in most sedimentary basins and on continental margins. Studying the abundance, distribution and drivers for this process is important in understanding its role in geological phenomena, such as submarine slope stability and gas-hydrate dynamics. Moreover, since natural gas seepage is a significant source of methane to the ocean and atmosphere (Archer, 2007), it may impact ocean chemistry and might have played a role in Earth’s past maximum-thermal events (Kvenvolden and Rogers, 2005). Furthermore, as this process is usually linked with distribution of subsurface hydrocarbon accumulations, it is of economic importance. As a result, a great deal of work has been performed to identify gas chimneys, mud volcanoes, seabed pockmarks, and carbonate mounds along continental margins, which are known to be indicators of active natural gas migration and leakage from deeper sources and reservoirs (e.g., Hovland and Judd, 1988; Orange et al., 1999; Loncke et al., 2004; Berndt, 2005; Leon et al., 2006; Gay et al., 2007; Hornbach et al., 2007; Anka et al., 2009).

Fluid migration is the movement of fluids through formations with sufficient permeability. The main driving force of fluid is explained using Darcy’s law, where the fluid flow rate is dependent on the permeability of the fluid flow medium, the hydraulic potential, and the fluid viscosity (Freeze, 1979). The information about fluid migration to shallower subsurface gives a better insight to the possible origin of hydrocarbons, migration pathways, sealing quality of faults, leakage from prospects and indicators for overpressure and geohazards (Ligtenberg and Connolly, 2003).

Fluid-rock interactions between the crust, mantle, and oceans can cause serpentinization processes (Kelly and Früh-Green, 1999; Früsh-Green et al., 2003; Kelly et al., 2005; Vance et al., 2007; Proskurowski et al., 2008). In recent years, studies at mid-ocean ridge systems have detected the presence of elevated methane concentrations from the host rocks due to either the circulating fluid or through magmatic degassing that is undergoing serpentinization reactions (Kelly and Früh-Green, 1999; Proskurowski et al., 2008). These discoveries demonstrated that the abiotic synthesis of hydrogen and hydrocarbons may occur in deep-sea environments in the presence of ultramafic rocks, water, and moderate amounts of heat. As a consequence of the formation of magnetite, hydrogen gas (H_2) is produced from the reduction of seawater during serpentinization. Carbon dioxide (CO_2) rich fluids and the excess hydrogen gas (H_2) combine to form methane (CH_4) and some other hydrocarbons in a Fischer-Tropsch reaction. This reaction occurs abiotically in hydrothermal systems in serpentine and low temperature beneath oceans and continents (Figure 2). The presence of hydrogen gas, hydrogen sulfide and methane in fluids that seeps out of the rocks provide important energy sources for different microbial species found at hydrothermal vents (Sleep et al., 2004; Judd and Hovland, 2007; Proskurowski et al., 2008).

The serpentinization process occurring in the oceanic basement leads to a volumetric fluid increase. The heat produced during the serpentinization process results in an accelerated maturation of biogenic material and also drives hydrocarbon to shallower strata where it is consumed by hydrate formation. The major driving forces triggering fluid migration in continental margins are overpressure and buoyancy.

Studies of glacial landforms at continental margins of the Nordic Seas (Vorren et al., 1989) demonstrated that during the time when glaciers reached the shelf edge high sedimentation rates prevail due to glacigenic sediment input in the form of debris flows (Figure 3). If sedimentation rates are high enough, the speed of sediment burial exceeds the rate of compaction. Rapid sedimentation rates ($> 1\text{mm yr}^{-1}$) are documented as a source of ovepressure in basins worldwide (Rubey and Hubbert, 1959; Fertl, 1976; Dugan and Flemings, 2000). If the pressure cannot be reduced and increases further, the overpressure build up within sediment layers may initiate lateral fluid migration and/or vertical focused fluid migration through micro fracturing (Judd and Hovland, 2007). When buoyant material starts rising mud diapirs, mud volcanoes, pockmarks and mounds among other focused fluid flow related features are formed (e.g. Hustoft et al., 2009) and also allow gas to come out of solution, resulting in the formation of bubbles (Figure 4). As gas ascends through the sediment column and pressure decreases, the free bubbles will expand and reduce the bulk density of the material even further. Articles 1, 2 and 4 describe seismic response of sediments affected by remobilization and migration of fluid from deep to shallow strata in the investigated region.

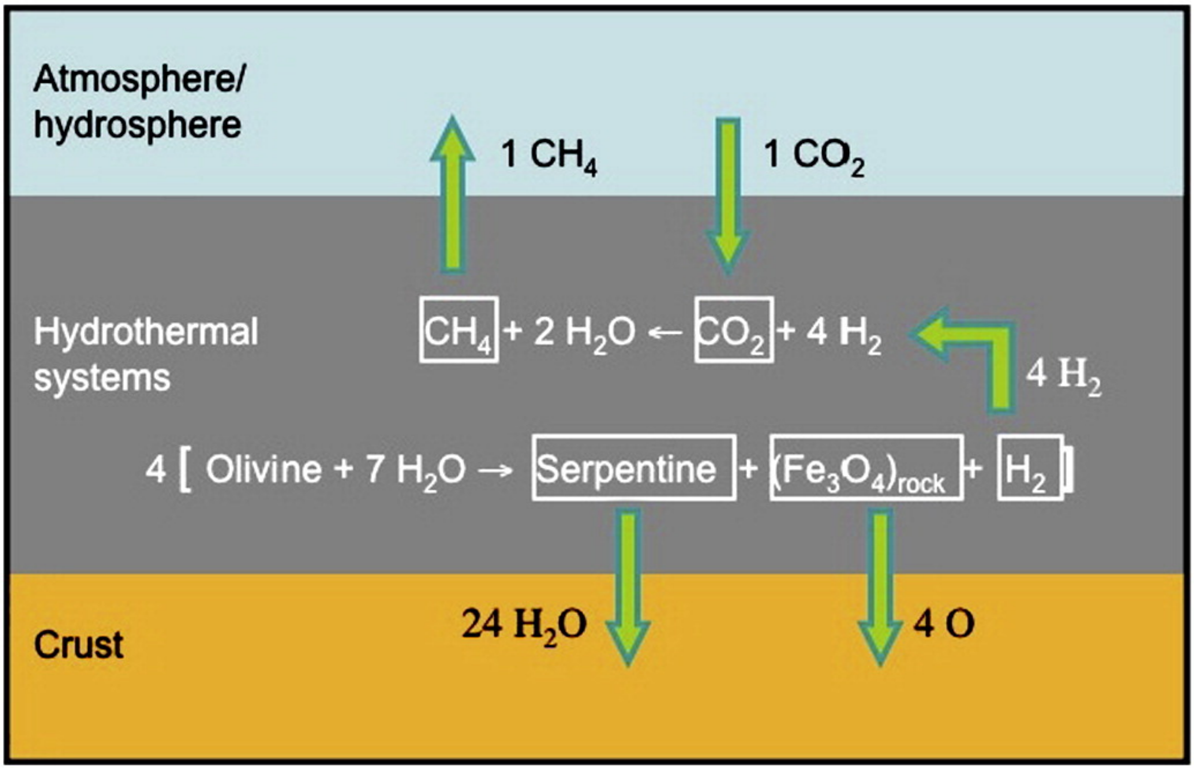


Figure 2: Schematic view of the H_2O–CO_2 cycle through serpentinization and methane formation, and related water, oxygen and carbon exchange fluxes between the crust, the hydrothermal systems and the active hydrosphere (from Chasserfière and Leblanc, 2011)

High concentrations of seabed pockmarks have been documented on the Barents Sea continental shelf (Solheim and Elverhøi, 1985, 1993; Chand et al., 2008, 2012). Gas hydrates have been geophysically inferred in many areas of SW-Barents Sea (Andreassen et al., 1990; Laberg and Andreassen, 1996; Laberg et al., 1998, Bünz et al., 2012a) and are stable over large areas due to the presence of higher-order heavier hydrocarbon gases than methane (Chand et al., 2008). The formation of Barents Sea pockmarks are due to postglacial dissociation of gas hydrates and the resulting overpressure generation and gas release (Solheim and Elverhøi, 1993).

Vertical conduits have been widely described in details at many sites of continental margins using seismic data (e.g. Berndt et al., 2003; Cartwright et al., 2007; Hustoft et al., 2007; Haacke et al., 2009; Løseth et al., 2009). Acoustic pipes or fluid escape chimneys by means of representing confined acoustic imprints of past or presently ongoing cross-strata, focused fluid flow feeding the seafloor seeps (Berndt et al., 2003; Gay et al., 2006; Cartwright et al., 2007; Løseth et al., 2009, 2011; Plaza Faverola et al., 2010) (Figure 5). However, the exact cause of this acoustically detected disturbance is unknown, although it is believed that small amounts of trapped gas and slightly displaced sediments may be involved (Wood et al., 2008). Furthermore, both free gas and gas-hydrate bearing sediments have been associated with both high-amplitude seismic anomalies 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). Faults play a major role when it comes to fluid flow and migration since they can act as both a seal and trap.

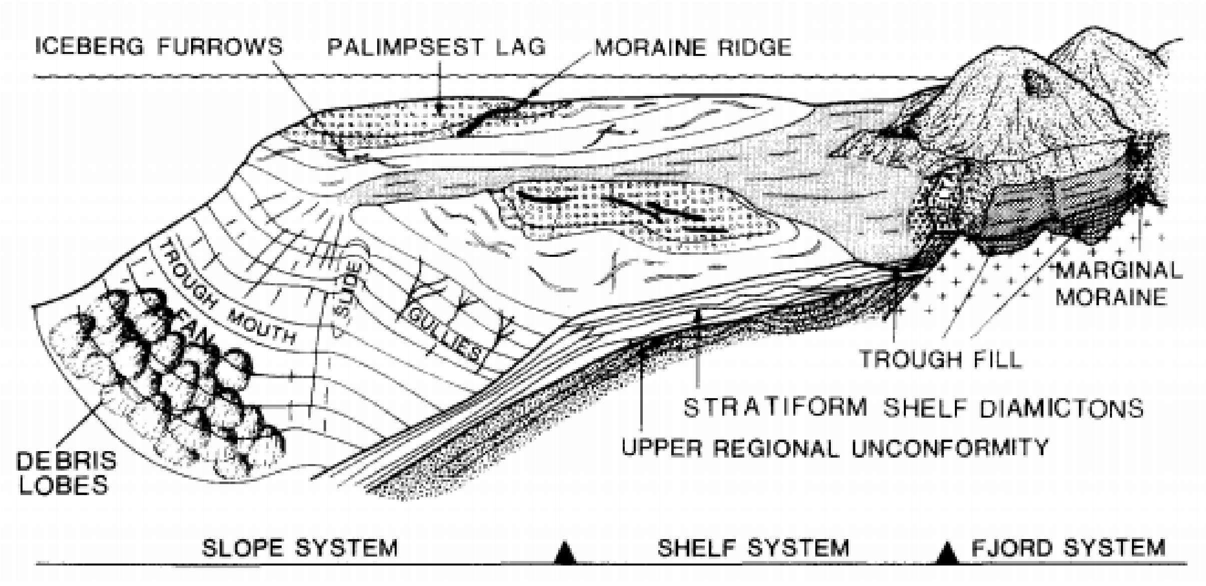


Figure 3: Above model illustrates the main glacigenic morphology elements and lithofacies of the passive continental margin of northern Norway (from Vorren et al., 1989).

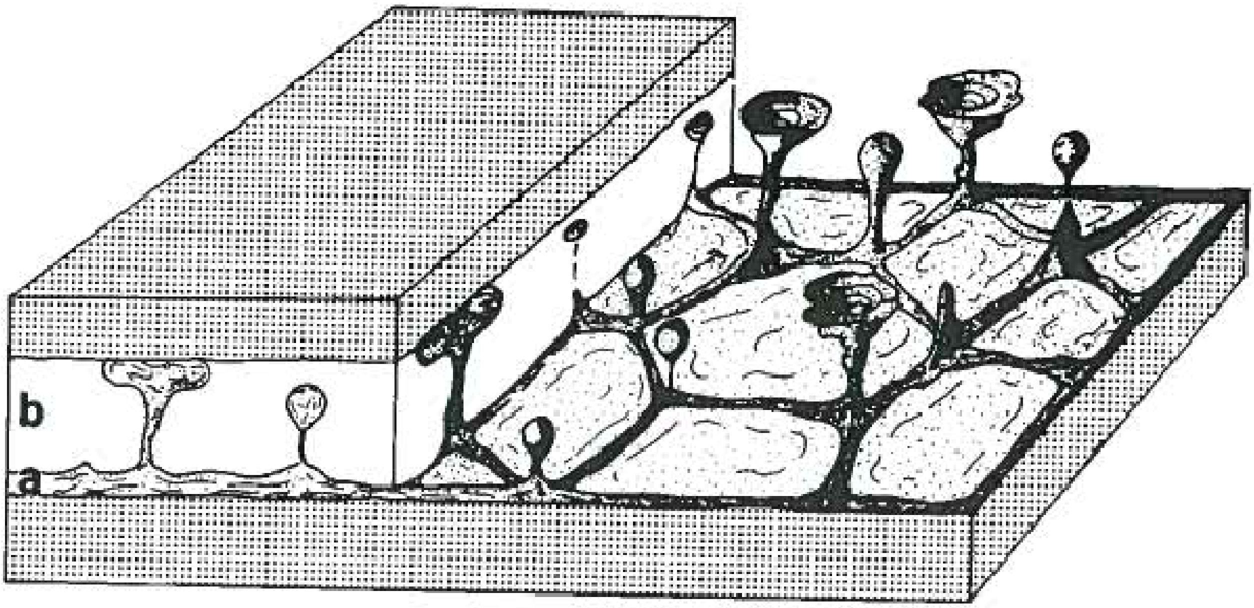


Figure 4: Experimental demonstration of plumes or diapirs of buoyant material rising through overlying material. Layer a is of low density and viscosity compared to layer b. (From Hovland and Judd, 1988; redrawn from Anketell et al., 1970)

Focussed fluid flow through the GHSZ

In the sub-seabed, methane can form hydrate, an ice-like crystalline solid, formed from water molecules and natural gas (mainly methane) under low temperature and high pressure conditions (Sloan, 1998). Favorable stability conditions are not the only requirements. Gas composition, ionic strength of the water and availability of excessive gas (methane) are other controlling factors for the formation of gas hydrates in a region (Kvenvolden, 1993). Gas-hydrate occurrence in continental margins has been confirmed by the deep ocean drilling programs (DSDP, ODP and IODP) (e.g., Westbrook et al., 1994; Riedel et al., 2006; Tréhu et al., 2006). The thickness of the GHSZ depends on the seafloor depth, geothermal gradient, composition of gas, bottom water temperature, lithostatic and hydrostatic pressure, pore water salinity as well as the physical properties of the host sediments (e.g., Clennell et al., 1999; Henry et al., 1999). Moreover these physical conditions determine whether free gas and water, expelled from reservoirs, will migrate through the GHSZ or if they will form gas-hydrate (Trehu et al., 2004). The presence of higher hydrocarbons such as ethane, propane and others gases along with methane alters the position and thickness of the GHSZ (e.g. Chand et al., 2008).

Gas-hydrate formation appears to be closely linked to fluid flow because, in most settings, it is predicted to require supply of gas from below into the GHSZ (Ruppel and Kinoshita, 2000). Models for gas-hydrate formation based on single-phase fluid flow (Zatsepina and Buffet, 1997; Xu and Ruppel, 1999; Ruppel and Kinoshita, 2000; Xu, 2004) assume that gas is transported into the hydrate stability zone in solution in upward migrating pore water. Multiphase-flow models (Haeckel et al., 2004; Liu and Flemings, 2006; Liu and Flemings, 2007) predict that in regions with high gas supply, hydrate formation is rapid enough to exclude salt and elevate salinity to the point that further hydrate formation is inhibited. These models provide a mechanism by which free gas can migrate through the GHSZ and also explain the presence of high salinities observed at venting locations (e.g. Milkov et al., 2004; Ruppel et al., 2005; Wright et al., 2005; Liu and Flemings, 2006). It appears that a lithological variation, e.g. the transition from hemipelagic sediments to GDF, has an effect on gas-hydrate formation (Bünz et al., 2003). Observations from the major gas-hydrate field of the mid Norwegian margin north of the giant Storegga submarine slide (Haflidason et al., 2004; Bryn et al., 2005; Mienert et al., 2005) show that GDF may hinder gas-hydrate growth because it clearly interrupts a continuous BSR at the BGHSZ (Bünz et al., 2003).

Vertical acoustic pipes or fluid escape chimneys are commonly associated with focused migration of fluids (e.g. Hustoft et al., 2007). Acoustic pipes show pull up effects which may be associated with the locally high velocity zones caused by either authigenic carbonate build up or gas-hydrate plugs (e.g. Hustoft et al., 2007; Plaza-Faverola et al., 2010). In regions where there is high fluid flux through the seabed, masses of gas hydrates may form within the sediments. Evidence for gas-hydrate in ocean-floor sediments come from anomalous reflections, BSRs (Lancelot and Ewing, 1973). The BSR is anomalous firstly due to its highly reflective impedance; this reflection is a result of relatively high acoustic velocity hydrate-bearing layer overlying gassy (low acoustic velocity) sediment and is normally of reverse polarity. Secondly, the BSR lies at a constant depth beneath the seabed, mimicking seabed topography. Seismic reflections below BSR are usually more strongly defined i.e. higher amplitude than those above it, where sediment layers tend to generate only weak reflections. In some cases, this upper zone is seismically transparent, possibly as a result of being cemented by hydrate and of having relatively high acoustic velocity (Paull and Dillon, 1981; Dillon and Paull, 1983; Paull et al., 2002).

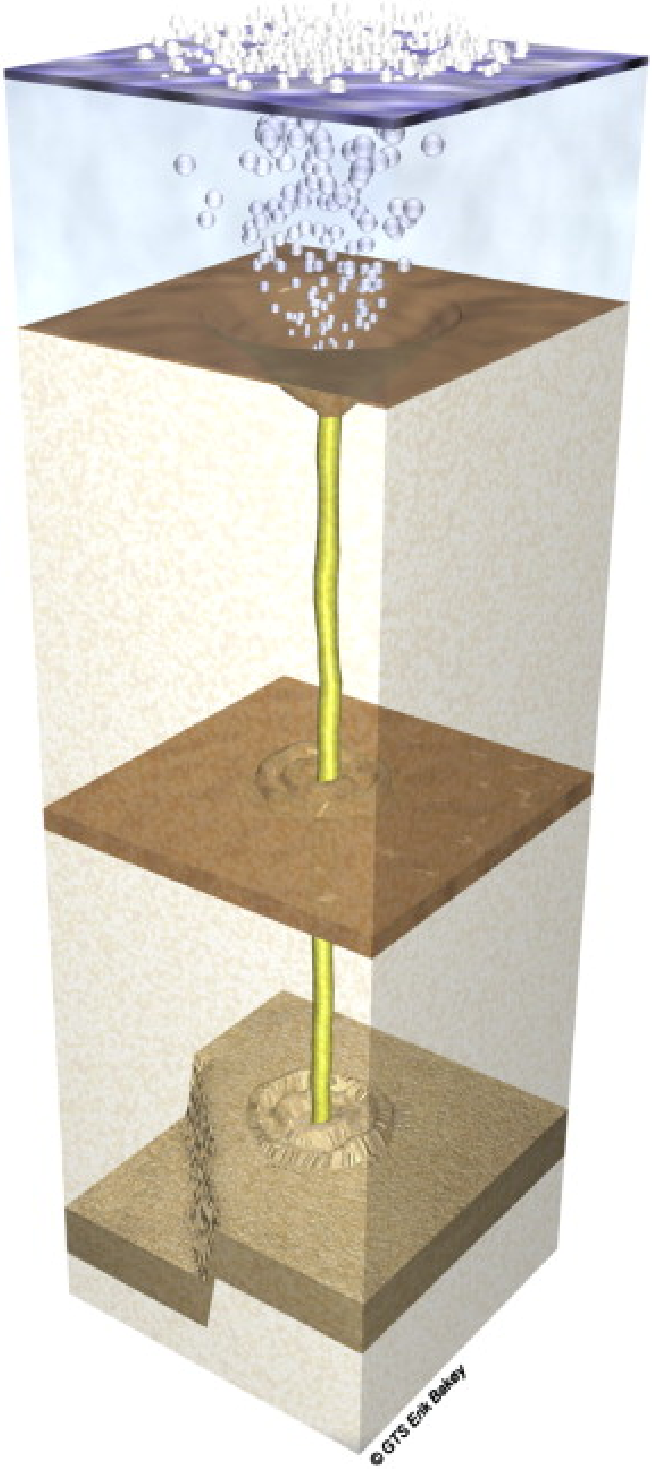


Figure 5: Sketch of a typical blow out pipe (from Niger area, Løseth et al., 2011)

A BSR may therefore be indicative of both gas hydrates above the BSR, and free gas beneath the BSR. It also may indicate the diffusive migration of gas through the whole sediment package, from below the GHSZ to the seabed (MacKay et al., 1994; Solovie and Ginsburg, 1997; Clennell et al., 1999). However, gas hydrates may also exist without a BSR as documented by Blake Ridge drilling results (e. g. Holbrook et al., 2002).

In addition to pressure and geothermal gradient other variable affecting the stability of gas-hydrate is the hydrothermal gradient, thermal conductivity, heat flow and geological heterogeneity (Macleod 1982). The geothermal gradient is also affected by the heterogeneities in the local geological configuration and associated thermal conductivity, for example as observed in Gulf of Mexico in areas of salt tectonics (Ruppel et al., 2005) and in the Barents Sea (Bugge et al., 2002). The proximity specific geological features such as mud diapirs, shale diapirs and salt domes, shallow basement and the presence of faults cause focused fluid flow (Chand et al., 2008). It has been observed worldwide that shallow salt structures can enhance the temperature of the nearby sediments up to 30^0 C due to the high conductivity of salt (Thomsen and Lerche, 1991). Vertical fluid migration due to diapirism brings in the gases along with heat to shallower level thereby disturbing the local stability conditions (Chow et al., 2000).

Advective heat flow from expulsion of warm fluids may lead to local up-warping of the BGHSZ, similar to possible gas chimneys on the Cascadia margin (Wood et al., 2002). Pecher et al., 2010 suggested enhanced advective heat flow from focused fluid migration through the sediments caused local up-warping of the BGHSZ which explained the presence of gas above the level of the region of BGHSZ (e.g., from southern Hikurangi margin) (Figure 6). Article 3 approaches this problem of TBSR through detailed gas hydrate stability modeling and 3D visualization of high-resolution seismic data. It also discusses the possible scenarios of focused fluid migration.

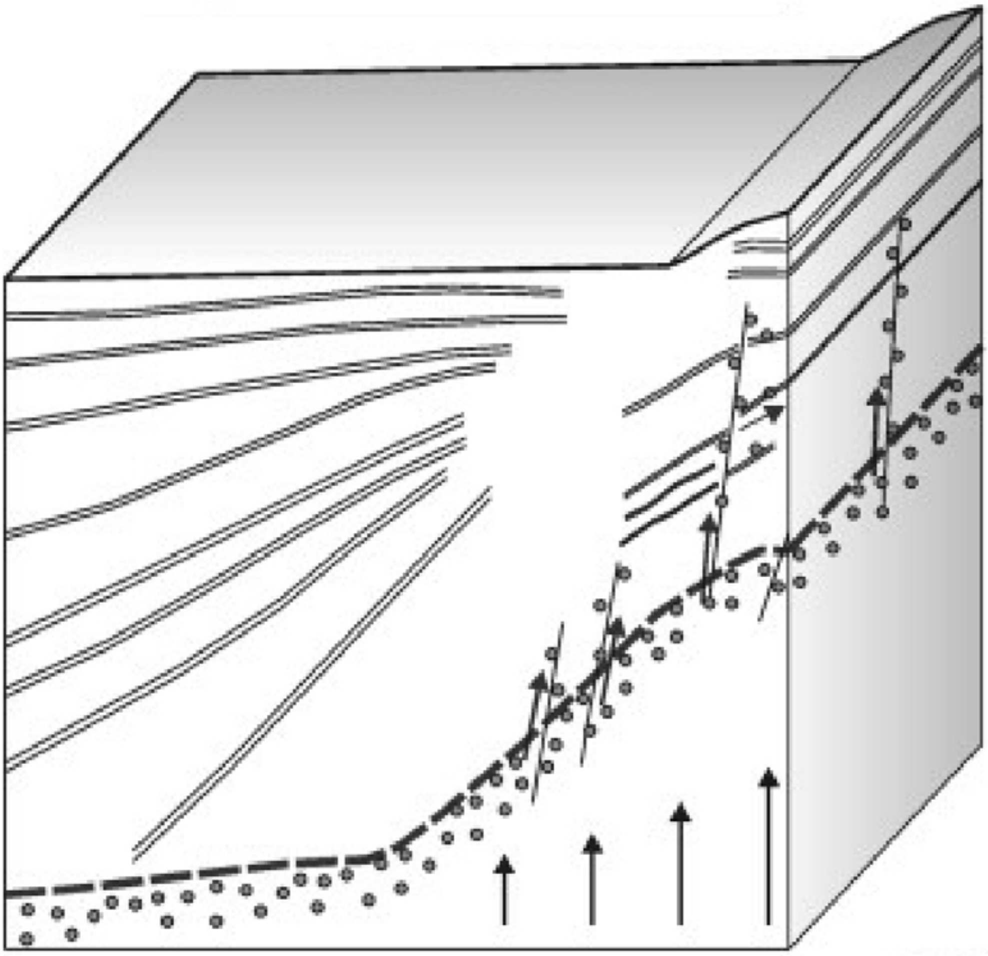


Figure 6: Schematic representation of focused fluid flow where the BGHSZ is locally up-warped in response to a local heat flow anomaly. Faults and fractures generate secondary permeability that allow the fluid to breach the BGHSZ and extend into the GHSZ (from Crutchely et al., 2011)

There is a clear association between gas-hydrate occurrence and fault zones, as well as other tectonically active related features (Hyndman and Davis, 1992; Soloviev and Ginsburg, 1994). For example, the Blake Ridge, a passive margin is characterized by the presence of extensive fault zones. If we assume a basic proportionality between porosity and permeability, the higher porosity would suggest a greater capability to transport fluids. Simplistically high porosity and permeability favor the accumulation of gas-hydrate. Because permeability tends to be anisotropic in the consolidating sediments, more porous beds may also favor gas-hydrate accumulation (Takur and Rajput, 2011).

The dissociation of accumulated oceanic gas-hydrate deposits and the release of large quantities of methane—a powerful greenhouse gas—in a short period of time could have dramatic climatic consequences (MacDonald, 1990). Figure 7 shows a schematic sketch of the GHSZ in the seafloor environment and its relationship to ocean temperature changes. Many deep oceanic hydrate deposits are stable under the influence of significant temperature variations; shallow deposits, such as those found in arctic regions or in the Gulf of Mexico, can undergo rapid dissociation and release large quantities of carbon. In arctic regions in particular, temperature changes are expected to be more pronounced, increasing the risk of hydrate destabilization even further (Reagan and Moridis, 2007; 2008).

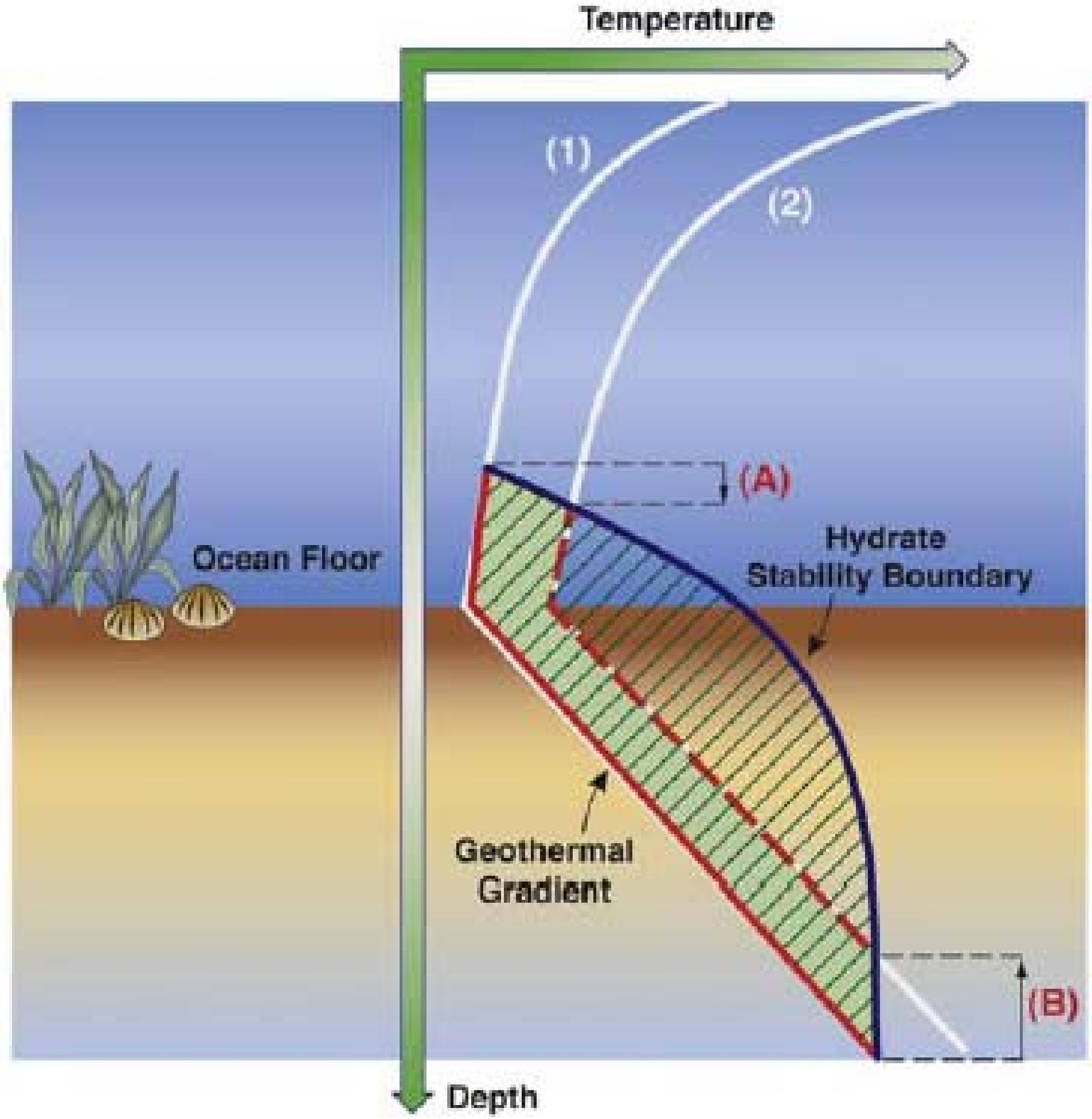


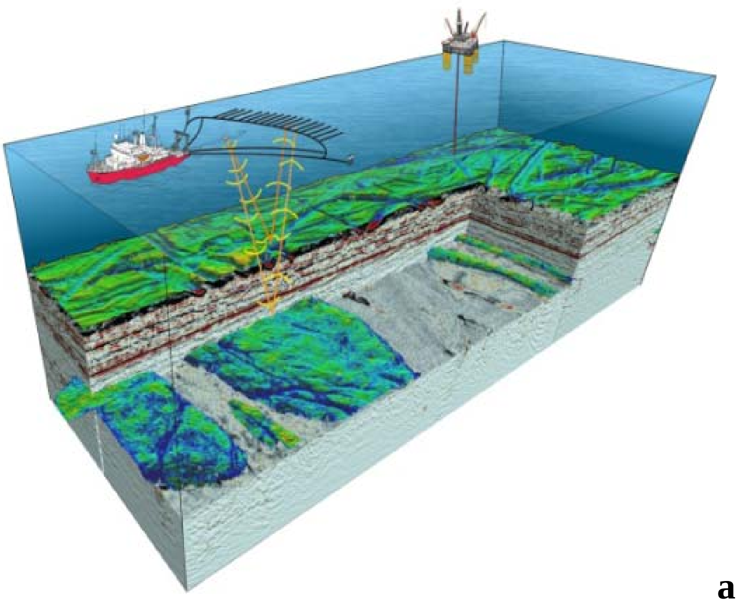
Figure :7 presents a general schematic of the hydrate phase boundary (blue line) and GHSZ for oceanic hydrates (shaded area). An increase in water temperature at the seafloor (a shift from temperature profile (1) to profile (2) lowers the position of the top of the GHSZ (A) and raises the position of the bottom of the GHSZ (B). Such a shift could induce hydrate dissociation and lead to the release of methane into the ocean and atmosphere (Reagan and Moridis, 2008)

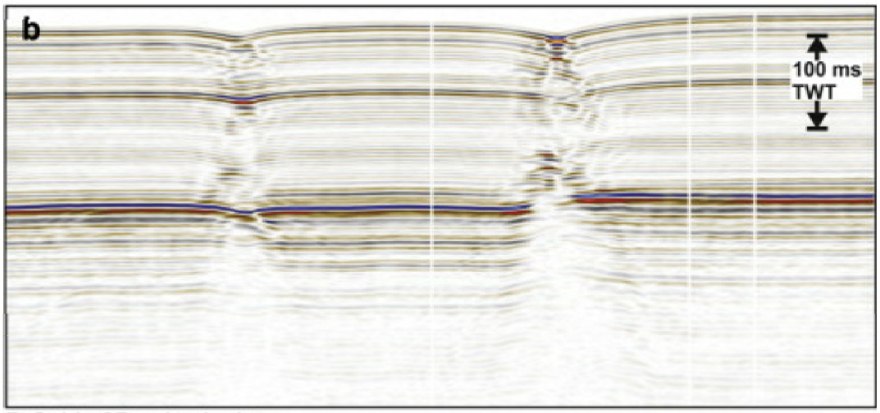
Seismic methods for evaluating fluid flow and gas-hydrate system

This doctoral thesis combines seismic imaging and mapping, geophysical attribute analysis, seismic velocity modeling, and gas-hydrate concentration modeling technique applied on different seismic data (i.e. 2D single channel, multi-channel, high-resolution P-Cable 3D, conventional 3D and OBS) to understand and improve the knowledge of fluid flow and gas-hydrate system.

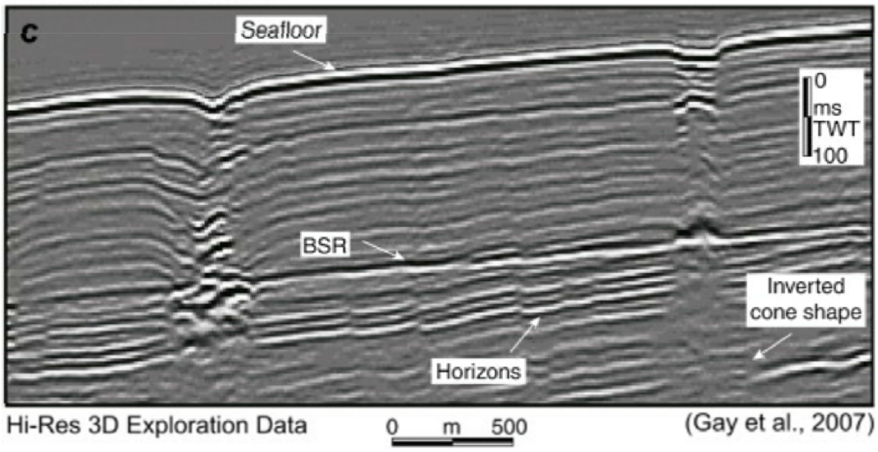
In the recent past, 3D seismic data analysis, imaging and visualizations became an increasingly important tool for studies of geofluids (Bünz et al., 2005; Gay et al., 2006; 2007; Hustoft et al., 2007; Riedel, 2007; Sultan et al., 2007; Hornbach et al., 2008) and the GHSZ However, 3D seismic research studies are mostly restricted to areas of hydrocarbon exploration. Moreover, conventional 3D seismic technology is intended to image targets at larger depths focusing on hydrocarbon reservoirs. The processing of this type of conventional data does not account for shallow subsurface structures. Many areas of scientific interest in the field of marine geosciences are outside any conventional 3D seismic coverage, e.g. the Arctic regions. The poor resolution of conventional 3D seismic data doesn't allow the researchers to resolve many scientific questions. Therefore, the University of Tromsø (Petersen et al., 2008) in cooperation with Volcanic Basin Petroleum Research (VBPR, Oslo), National Oceanographic Centre Southampton (Southampton University) and IFM-GEOMAR (Kiel University) developed a lightweight high-resolution 3D seismic system, the P-Cable system (Planke and Berndt, 2003) (Figure 8a).

In comparison to several 3D seismic studies, which used a set of parallel, closely spaced high-resolution 2D lines to construct a 3D seismic data volume (e.g., Zuhlsdorff and Spieß, 2004; Hornbach et al., 2008; Wagner-Friedrichs et al., 2008), the P-Cable system offered full 3D seismic data acquisition using a set of parallel streamers with high-resolution seismic sources (Air gun), which make this system unique in academic research (Petersen et al., 2010).





P-Cable 3D seismic data



Hi-Res 3D Exploration Data (Gay et al., 2007)

Figure 8: (a) Diagram of high-resolution P-Cable 3D seismic system (UiT), (b) and (c) comparison between high-resolution P-Cable 3D seismic data and high-resolution 3D conventional data (from Gay et al., 2007)

The spatial resolution of this system is higher than the conventional 3D seismic as well as the temporal resolution. Moreover, this increase in resolution allows a much better target identification and imaging of shallow subsurface structures and fluid flow systems (Figure 8b and c).

Seismic data processing was performed by using Landmark's ProMAX software, Deco Geophysical RadExpro 3.9 and seismic UNIX which allowed multiple attenuation and enhancement of the basement reflector. Standard processing (Yilmaz, 1987) was applied and consisted of navigational correction, binning, static and tidal correction, bandpass filtering, amplitude correction, trace editing, normal move out (NMO) correction, dip move out (DMO) correction, stacking, 3D stolt migration, pre stack time migration in FK domain (Stolt, 1978) using NMO velocities. Detailed velocity analysis was conducted for the seismic profiles presented in article 1.

OBS data provides constraints on the seismic velocities of the underlying sediments. The reflected waves were modeled using a forward modeling technique (Zelt and Smith, 1992) by fitting the calculated reflections in a user defined model to the observed reflections on the OBS sections. P-wave reflections were modeled using a layer-stripping approach from the top to the bottom and the different interfaces are adjusted until a good fit was found with the calculated data (e.g. Chabert et al., 2011). The P-wave velocity modeling was integrated with the 2D high-resolution seismic interpretation to infer the occurrence of free gas and gas-hydrate within the shallow area on the continental slope of western Svalbard region.

Summary of the articles

Article 1: *Potential serpentinization, degassing, and gas hydrate formation at a young (<20 Ma) sedimented ocean crust of the Arctic Ocean ridge system* (***published in Journal of Geophysical Research***)

Anupama Rajan, Jürgen Mienert, Stefan Bünz and Shyam Chand

Seismic data acquired across a sedimented segment of the ultraslow spreading Knipovich Ridge offshore NW-Svalbard established a suggesting potential link between inferred areas of serpentinization, methane release from the deep-seated host rocks through the sediments above by diapirism and the capture of free gas within the GHSZ marked by a distinct BSR. The southeastern area is controlled by the presence of glacial debris flow (GDF) that explains the location of high interval P-wave velocities. High variation in P-wave velocity above the BSR document the presence of appreciable amount of gas hydrates within the pore space of the sediments. Gas saturation was estimated using the partial hydrate-cementing model. The average concentration of the gas hydrates is predicted to be up to 26% of the pore space of the sediments with considerable variability and uncertainty in a 60 to 240 m thick zone that varies with depth significantly towards the BSR. The serpentinization process in the oceanic basement, led to a volumetric fluid increase. This volume increased the sediment remobilization of the sequences overlying the basement and due to the overpressure and buoyancy the mobilized sediments move upward through the sedimentary column which resulted in the formation of diapiric structures. Gas-hydrate and free gas accumulates in a mini basin between two buried diapirs. A model was offered to show the mechanism of migration and accumulation of gas and gas-hydrate above the area of serpentinization of the ultraslow spreading Knipovich Ridge.

Article 2: *Acoustic evidence for a gas migration and release system in Arctic glaciated continental margin offshore NW-Svalbard* **(published in Marine and Petroleum Geology)**

Anupama Rajan, Jürgen Mienert, Stefan Bünz

High-resolution P-Cable 3D and 2D seismic investigation were carried out in water depth from 200 m on the shelf to 800 m on the upper continental slope west of Prins Karls Forland, elucidated the presence of geophysical evidence for geologically controlled fluid migration pathways, gas-hydrate occurrence and an active seabed gas expulsion system. More than 220 gas flares were identified from outer shelf while past methane release activity at mid-shelf area was evident from pockmarks without flares. The integration of 2D and 3D seismic data reveals the presence of active fluid escape from sediments of the W-Svalbard continental margin. The westward prograding shelf consists of glacigenic sequences and a glacial debris flow (GDF), which are spatially confined. The physical properties of GDFs are not seen to be favorable for gas-hydrate growth and their reduced permeability may provide an effective trapping mechanism for gas. Because of this reason, the location of gas leakage zones at the seafloor on the shelf. Gas migration occurs along the permeable strata towards the upper slope thereby eluding the theoretical GHSZ, which pinches out at the uppermost part of the slope at 370 m water depth. A BSR is only evident at the lower continental slope in water depth exceeding 800 m and the thickness of the GHSZ in this area is 190 m. Vertical focused fluid flow indicators are limited. A conceptual model was presented based on the seismic observations, which explain and summarize the geologically controlled gas migration system in the glaciated margin of western Svalbard.

Article 3: *Tilted bottom-simulating reflectors (TBSRs) provide evidence for active fluid flow from deep hydrocarbon sources in the SW-Barents Sea* ***(submitted to Journal of Geophysical Research)***

Anupama Rajan, Stefan Bünz, Jürgen Mienert and Andrew J. Smith

This paper uses high-resolution P-Cable 3D seismic and conventional 3D seismic data to access the deep control of shallow gas accumulation and gas-hydrate zones in the SW-Barents Sea. The presence of prominent TBSR indicates active fluid migration from deep sources. Seismic anomalies such as acoustic chimneys indicate fluid migration pathways, gas accumulation, and/or gas-hydrate occurrences. Extensive shallow gas accumulation occurs at the Intra-Glacial and URU horizons at 470 – 520 ms TWT below the seafloor. The acoustic chimneys vary in size and are connected to faults, and none of the chimneys reach the seafloor. The upper termination of the chimneys occurs in rocks of Cenozoic age. The results suggest that the fluid migration pathways to the shallow gas accumulation area are mainly vertical fluid conduits, which are located in the vicinity of faults. Lateral migration of fluids is controlled by dipping strata. TBSRs indicated the BGHSZ suggest variation in geothermal gradients and/or thermogenic gas composition. Heat flow variations from the centre to the rim of the chimney potentially cause disturbance in hydrate bearing sediment giving the nature of the TBSR. Also, changes in the gas composition would lead to a change in the depth of the BSR. Presence of higher-order hydrocarbons gases would lead to a thicker GHSZ, and confined areas of gradual increase in higher-order hydrocarbons along the BSR could cause a dipping of the BSR. The stability model using thermogenic gas composition (type I and II) show gas hydrates are stable at ~225 m to ~345 m depth, with different geothermal gradients for upper level (28.7°C/km and 37°C/km) and lower level (23.4°C/km and 28.3°C/km) at the BGHSZ.

Article 4: *Heterogeneous distributions of gas-hydrate and free gas in glaciated sediments of the NW-Svalbard continental margin inferred from changes in compressional wave velocity* ***(to be submitted)***

Anupama Rajan, Tim A. Minshull and Jürgen Mienert

This manuscript in preparation presents preliminary results and is the base for a paper to be submitted from the authors as a contribution to the James Clark Ross cruise work JR269-A.

The continental slope of NW-Svalbard was investigated using a high-resolution seismic reflection profile and OBS wide-angle seismic data. It allowed to image in detail the strata controlled gas transport towards areas of active escape of methane gas at the outer continental shelf. A clear decrease in compressional wave velocity (V_p) is observed ~180 m below the seafloor, where the velocity decreases from 1.78 to 1.6 km/s. This low velocity zone (LVZ1) is ~ 25 m thick suggesting appreciable amounts of free gas in the pore space of sediments. A low velocity zone (LVZ2) up slope confirms the presence of shallow gas pocket within the GHSZ. The OBS sites within the GHSZ do not show any presence of a BSR. However, anomalously low velocity V_p indicating the presence of free gas was modeled for all the three sites. Two-dimensional concentration models of methane hydrate using the differential effective medium theory predict saturation of up to 14 % of methane hydrate and 0.15% of free gas in the pore space of glacigenic sediments. The OBS data in connection with seismic reflection profiles show discontinuous, chaotic reflectors of generally high-amplitude, characteristic of glacigenic sediment sequence above LVZ1, which lies within and is underlain by more continuous, lower amplitude reflectors, typical of hemipelagic sediments.

The presence of hemipelagic sediments causes greater attenuation of high frequencies in this area indicating the presence of gas.

Future research

Understanding large scale distribution of free gas and gas-hydrate systems and their origins can only be achieved through continued imaging and interpretation. The integration of different seismic datasets available for this study can still be exploited to get relevant information for the understanding of fluid flow systems in gas-hydrate provinces. Some subjects of interest that can be continued as part of this doctoral thesis are as follows:

Serpentinization strongly affects the rheology, gravity and seismic structure of ocean crust formed by slow-spreading. Hydration of olivine-rich rocks has a major effect on the magnetic signature of the ocean floor because of the production of magnetite during the process of serpentinization. The geochemical consequences of serpentinization are also important to seafloor studies. Serpentinite-hosted hydrothermal vents are common along slow and ultraslow spreading ridges. Ocean drilling in the serpentinized area will give an opportunity to understand peridotite-water interaction and highly unusual compositions of interacting fluids and thus the nature of fluid flow from the deep-seated host rock. Serpentinization provides a direct link between mantle and microbes and is an ideal topic for interdisciplinary science in a new drilling program.

The multicomponent data (article 4) can be further made available for the identification of P-S converted waves. The S-wave reflections should be matched to the modeled P-wave reflections by an error/trial method until the best fit (i.e. lower travel time residuals) between the observed and calculated data. The relation between P- and S- wave velocities together with the Poisson Ratio provide further constraints on the presence of hydrate and free gas in the sediments. The amount of hydrate and gas can be quantified by comparing the observed deviation of the physical properties (i.e. the seismic velocities). Some rock-physics-based approaches such as self-consistent approximation/differential effective medium (SCA/DEM) (Chand et al., 2006; Jakobsen et al., 2000) and the three-phase effective medium model (TPEM) (Ecker et al., 1998; Helgerud et al., 1999) can be used to estimate the concentration of gas-hydrate in the sediments. Depth migration of the high-resolution P-Cable 3D seismic (article 2) using the interval velocities from article 4 also provide a better and detailed mapping of fluid flow in the gas-hydrate system.

It is no doubt that gas-hydrate/free gas reservoirs may be a new future energy resource and a concern for the environment if released by natural processes. It is necessary to understand the mobility of this reservoir during a global warming scenario. At the SW-Barents Sea, evidence for shallow gas accumulation and gas-hydrate reservoirs exists based on seismic reflection data. Identification of pockmarks and the related blow outs provide clear evidence for a highly dynamic gas and gas-hydrate systems in postglacial times. It is vital that we quantify how much gas hydrates and methane can be expected in the western Barents Sea based on the accessible P-cable 3D seismic data and how much methane a major greenhouse gas may reach the atmosphere if bottom water warming continues. The distribution of free gas/gas-hydrate in the western Barents Sea and their fluid flow systems in the gas-hydrated zone were discussed in article 3. A possible further step is to calculate gas-hydrate dissociation and methane release for a range of possible bottom-water temperature and sea level change scenarios. This allows us to understand the constraining effect of Arctic warming on hydrate reservoirs. Detailed heat flow studies in the Arctic will be important in determining whether the observed BGHSZ is in agreement with the modelled BGHSZ (e.g. Phrampus and Hornbach, 2012, Mienert, 2012). This will help us in determining whether gas-hydrate systems are in steady-state or if hydrates are melting as a result of warming ocean temperatures in the Arctic. It is also important to estimate the concentration and the stability of free gas/gas-hydrate in the western Barents Sea. In order to achieve this, an array of long-term OBS wide angle seismic nodes can be deployed to provide constraints on the seismic velocities of the underlying sediment over several years.

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Article 1

Potential serpentinization, degassing, and gas hydrate formation at a young (<20 Ma) sedimented ocean crust of the Arctic Ocean ridge system

Anupama Rajan, Jürgen Mienert, Stefan Bünz and Shyam Chand

Journal of Geophysical Research

Article 2

Acoustic evidence for a gas migration and release system in Arctic glaciated continental margins offshore NW-Svalbard

Anupama Rajan, Jürgen Mienert and Stefan Bünz

Marine and Petroleum Geology

Article 3

Tilted bottom-simulating reflectors (TBSRs) provide evidence for active fluid flow from deep hydrocarbon sources in the SW-Barents Sea

Anupama Rajan, Stefan Bünz, Jürgen Mienert and Andrew J. Smith

Submitted to Journal of Geophysical Research

UNIVERSITY OF TROMSØ

Article 4

Heterogeneous distributions of gas-hydrate and free gas in glaciated sediments of the NW-Svalbard continental margin inferred from changes in compressional wave velocity

Anupama Rajan, Tim A. Minshull and Jürgen Mienert

To be submitted

UNIVERSITY OF TROMSØ

Appendix

Conferences and workshops

Verbal:

2011 AMGG, Tromsø. Anupama Rajan, *Methane expulsion and associated migration pathway system offshore Prins Karls Forland, NW-Svalbard*.

2011 AMGG Workshop, Tromsø. Anupama Rajan, *Fluid flow pathways and Emissions*.

2008 AMGG, Tromsø-Svalbard. Anupama Rajan, *Seafloor morphology and submarine landforms of glaciated shelves and slopes elucidated by seismic data from the West Svalbard Margin*.

2008 AMGG, Tromsø. Anupama Rajan, *Dynamics of gas-hydrate and fluids in polar shelf environments of the Barents Sea.*

Posters:

2011 AGU annual meeting, San Francisco. Anupama Rajan, Jürgen Mienert, Stefan Bünz, Shyam Chand, *Imaging fluid migration-path networks for understanding the geo-constraints associated with fluid flow and venting mechanism in gas-hydrated sediments of SW-Barents Sea*.

2011 ICGH, Edinburgh, UK. Anupama Rajan, Stefan Bünz, Jürgen Mienert, Shyam Chand, *Methane expulsion and associated migration pathway systems offshore Prins Karls Forland, NW-Svalbard*.

2010 Arctic Conference, Tromsø, Anupama Rajan, Stefan Bünz, Jürgen Mienert, Shyam Chand, *Preliminary results of P-wave velocity reference curve for glacigenic and highly compacted sediments and velocity analysis for the estimation of gas hydrate along the profiles in the Knipovich ridge, Offshore SW-Svalbard.*

2010 EGU general assembly, Vienna. Anupama Rajan, Stefan Bünz, Jürgen Mienert, Shyam Chand, *P-wave velocity reference curves for glacigenic and highly compacted sediments and P-wave velocity analysis for estimating gas hydrate concentrations in sediments of the Knipovich ridge, Offshore SW-Svalbard.*

Scientific cruises

RRS James Clark Ross, NW-Svalbard, July 2012. SCS, OBS and CSEM data acquisition.

RRS James Clark Ross, NW-Svalbard, August-September 2011. SCS, OBS and CSEM data acquisition.

R/V Jan Mayen (now R/V Helmer Hanssen), SW-Barents Sea, August 2009. P-Cable 3D seismic and OBS data acquisition.

R/V Jan Mayen (now R/V Helmer Hanssen), Fram Strait and NW-Svalbard, August 2008. Soil sampling and Chirp profiling.

R/V Jan Mayen (now R/V Helmer Hanssen), Storegga-mid Norwegian margin, July 2008. P-Cable 3D seismic data acquisition.

R/V Jan Mayen (now R/V Helmer Hanssen), mid Norwegian margin, March 2008. Test trials on P-Cable 3D seismic system.

Honors and Award

Awarded the prestigious American Geophysical Union 2011 "Outstanding student paper award"

Publications

Rajan, A., J. Mienert, S. Bünz, and S. Chand (2012), Potential serpentinization, degassing, and gas hydrate formation at a young (<20 Ma) sedimented ocean crust of the Arctic Ocean ridge system, *J. Geophys. Res.*, *117*(B3), B03102.

Rajan, A., J. Mienert, and S. Bünz (2012), Acoustic evidence for a gas migration and release system in Arctic glaciated continental margins offshore NW-Svalbard, *Marine and Petroleum Geology*, *32*(1), 36-49.

Extended Abstract

Rajan, A., J. Mienert, S. Bünz, and S. Chand (2012), Methane expulsion and associated migration pathways systems offshore Prins Karls Forland, NW-Svalbard, *Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011.*

ISBN xxx-xx-xxxx-xxx-x