FACULTY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF GEOLOGY

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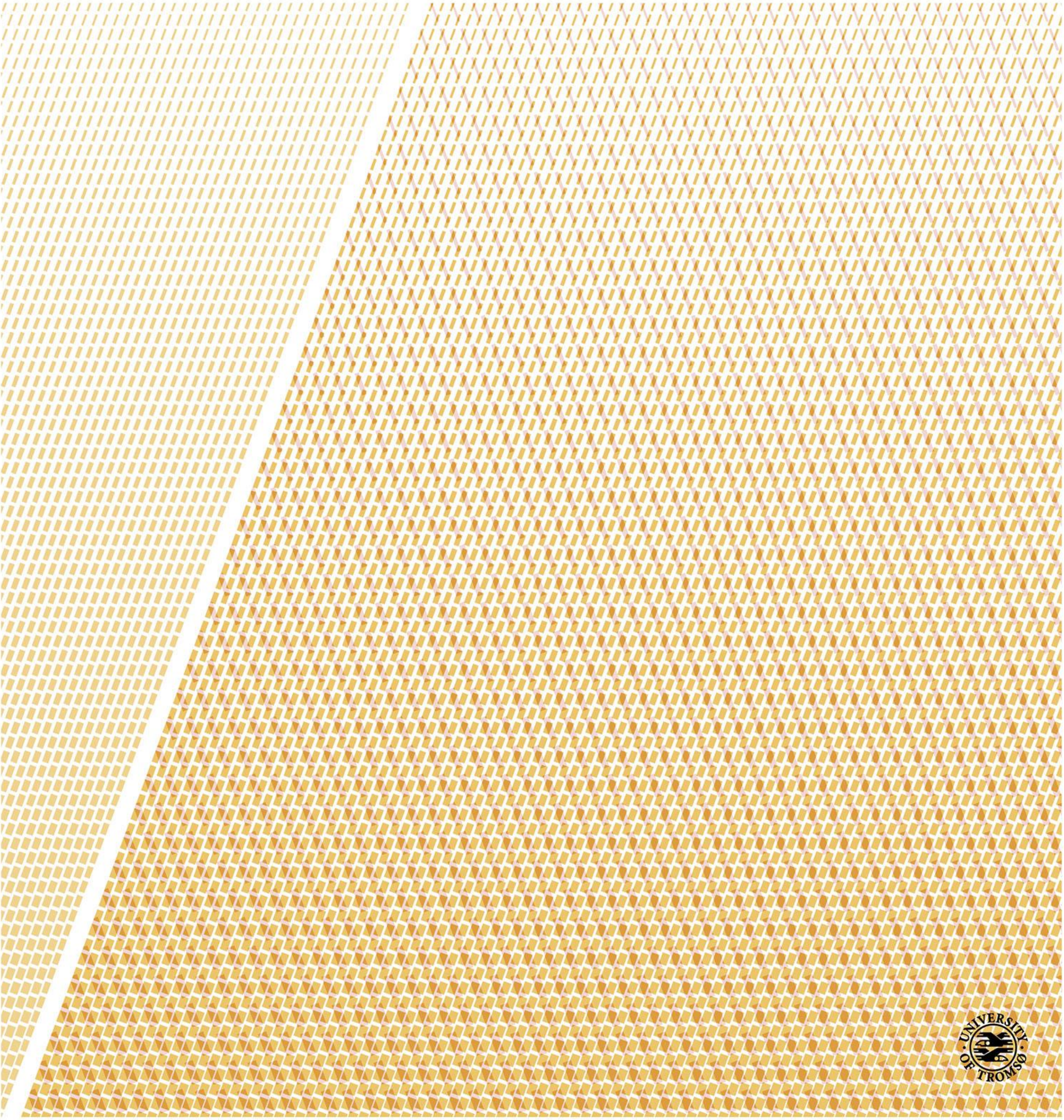
Sunil Vadakkepuliyambatta

A dissertation for the degree of Philosophiae Doctor – March 2014



Sub-Seabed Fluid-Flow Systems and Gas Hydrates of the SW Barents Sea and North Sea Margins

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Preface

This PhD thesis was carried out at the Department of Geology, University of Tromsø from February 2010 to January 2014. This research was financially supported by the Trainee School in Arctic Marine Geology and Geophysics (AMGG) hosted at the University of Tromsø. The main supervisor was Assoc. Prof. Stefan Bünz and co-supervisors were Prof. Jürgen Mienert from the University of Tromsø and Researcher Dr. Shyam Chand from the Norwegian Geological Survey. A part of the research (article 3) in this thesis was conducted at Huffington Department of Earth Sciences, Southern Methodist University (Dallas, USA) in collaboration with Assoc. Prof. Matthew Hornbach. This study was financially supported by Research Council of Norway through the Leiv Eiriksson mobility program (No.216789/F11).

The first two articles of this thesis use multi-channel 2D seismic data and well data from Diskos data repository controlled by the Norwegian Petroleum Directorate (NPD). In addition, TGS-NOPEC geophysical company also kindly provided multi-channel 2D seismic data. 3D high-resolution P-Cable seismic data acquired in 2009 onboard R/V Helmer Hanssen is used for the geophysical research on gas hydrates in the third article. The fourth article uses high-resolution 3D P-Cable seismic data, 2D high-resolution seismic data, and 3D conventional seismic data from the Peon discovery kindly provided by Statoil ASA.

During the period of this study, I had the opportunity to participate in six scientific cruises to the Barents Sea and NW Svalbard. I also contributed to the study of gas seepage from Vestnesa Ridge which was published in Marine Geology (Bünz et al., 2012). In addition to the obligatory courses, I attended four software training courses in seismic interpretation, mapping and seismic modeling. 25% of my PhD period was assigned to work for the department, including teaching and creation of seismic and well databases. Some of the results in this thesis were presented during various international conferences and meetings.

This doctoral thesis includes an introduction and four articles. The scientific articles presented in this thesis are:

Article 1

Vadakkepuliyambatta, S., S. Bünz, J. Mienert, and S. Chand (2013), Distribution of subsurface fluid-flow systems in the SW Barents Sea, *Marine and Petroleum Geology*, *43*(0), 208-221.

Article 2

Vadakkepuliyambatta, S., S. Chand, and S. Bünz. Can ocean warming destabilize gas hydrate accumulations in the SW Barents Sea? *To be submitted*

Article 3

Vadakkepuliyambatta, S., M. Hornbach, S. Bünz, and B. Phrampus. Controls on gas hydrate system evolution in a region of active fluid flow in the SW Barents Sea. *Under review in Geophysical Journal International.*

Article 4

Vadakkepuliyambatta, S., S. Planke, and S. Bünz. Fluid leakage pathways and shallow gas accumulation in the Peon field, northern North Sea, from high resolution P-Cable 3D seismic data. *To be submitted*

Acknowledgements

First of all, I would like to extend my deepest gratitude to Assoc. Prof. Stefan Bünz, who has been a tremendous mentor for me. Thanks for giving me the great opportunity to join the PhD program. This thesis would have been impossible without his immense help at every step. I greatly appreciate his calm demeanor and his willingness to help at all times. It has been a wonderful experience to work under his supervision.

I am indebted to Dr. Shyam Chand for his contribution and valuable guidance during my PhD. We had many interesting scientific and non-scientific debates/discussions over these years, which were always enlightening and made me to think deeper.

Many thanks to Prof. Jürgen Mienert for his support during this research. This thesis has profited from his brilliant comments and suggestions.

I am grateful to Assoc. Prof. Matthew Hornbach who introduced me to heat flow modeling during my research stay at Southern Methodist University, Dallas. I was inspired by his energy and enthusiasm towards research.

Dr. Sverre Planke is acknowledged for assistance during my work with the Peon shallow gas field. I appreciate the time and effort he spent on helping me despite his busy schedule.

I would like to thank all the staff in the department of geology who helped in one way or another and with whom I had fruitful discussions. Especially I would like to thank Karin Andreassen, Jan Sverre Laberg, Tore Vorren, Erling Ravna, and Holger Stunitz. I would also like to thank Annbjorg, Margrethe, Kai, and Inger for their amazing administrative support. Many thanks to Evje and Rolf for keeping my computer fit and running. The captain and crew of RV Helmer Hanssen are acknowledged for the amazing experiences onboard.

I express my gratitude to all my friends in the department for the interesting company and being part of many exciting scientific/non-scientific conversations. Special thanks to Anupama, Andreia, Pritam, Sergey, Andrew, Aleksey, Kamila, Ulrike, and Steffen. Thanks to Ben, Sara, Zach, and many others for making my stay in Dallas a pleasant experience.

Special thanks to Pritam, Subash, Anoop, Pardha, and Anup for the company and all the interesting discussions during our Saturday evenings.

Thanks to my friends in Kerala, especially Jose, Bijin Manu, Mohanan and his family.

Many thanks to my dear Sash for supporting me through some difficult times.

Without the support of my family, I wouldn’t be here. I thank my parents and sisters for their absolute confidence in me, and motivating me through every walk of life. I dedicate this thesis to my parents, especially my father whose greatest wish was to provide his children the highest education possible. Words fail me to thank them for their contribution in my life.

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Introduction

Why fluid-flow systems are important?

Submarine fluid flow is a dynamic geological process occurring on all continental margins worldwide (Berndt, 2005). The research for understanding fluid-flow systems has gained increasing interest over the last two decades mainly due to a wide range of reasons. Fluid flow can result in shallow gas accumulations, which can pose serious geological hazard to hydrocarbon exploration and development (e.g., Bryant and Roemer, 1983; Prince, 1990; Judd and Hovland, 2007; Tjelta et al., 2007). On the other hand larger shallow gas accumulations can be considered as an economically viable natural gas resource (e.g., Peon field, northern North Sea (Carstens, 2005)). Also, fluid flow can contribute to form gas hydrate accumulations if the region is within gas hydrate stability conditions. An enormous amount of hydrocarbons are trapped in gas hydrate accumulations in the shallow sub-surface, which also makes them a potential unconventional energy resource (Dobrynin et al., 1981; MacDonald, 1990b; Max et al., 2006; Boswell and Collett, 2011; Wallmann et al., 2012). These gas hydrate accumulations are often fed by and developed from fluids migrating from deep-seated sediments, thus gas of thermogenic origin may contribute to shallow biogenic gas sources. Both fluid-flow features and gas hydrate accumulations may indicate the presence of deeper hydrocarbon reservoirs (Heggland, 1998; O'Brien et al., 2005). Fluid flow is also considered to contribute to slope instability creating massive submarine landslides (Bugge et al., 1987; Paull et al., 2000; Bünz et al., 2005; Vanneste et al., 2006; Judd and Hovland, 2007; Berndt et al., 2012) and thereby, tsunamis (Bondevik et al., 1997), particularly due to gas hydrate destabilization (Mienert et al., 1998; Maslin et al., 2004; Mienert et al., 2005; Maslin et al., 2010). Areas of fluid escape can also enhance the diversity of marine life, developing specific ecosystems around the seepage area (Kennicutt et al., 1985; Greinert et al., 2010).

Natural gas seeps deliver methane, the most common gas in the subsurface into the ocean and perhaps in to the atmosphere. If it reaches appreciable levels it has the potential enhancing global warming (Nisbet, 2002; Kennett et al., 2003). Methane is ~20 times more efficient as a greenhouse gas than CO_2 (Khalil and Rasmussen, 1995; Ruppel, 2011), and methane emissions may have contributed to past warming events: Permian– Triassic boundary (Krull and Retallack, 2000), in the Jurassic (Hesselbo et al., 2000), the Cretaceous (Jenkyns and

Wilson, 1999), at the Paleocene–Eocene Thermal Maximum (Dickens et al., 1997; Dickens, 2011) and in the Pleistocene (Ruppel, 2011). Increasing ocean temperatures could contribute to gas hydrate destabilization, thus increasing the methane output in to the Ocean (Kvenvolden, 1988; MacDonald, 1990a; Biastoch et al., 2011; Phrampus and Hornbach, 2012; Marín-Moreno et al., 2013). However, methane gas rarely survives dissolution and microbial oxidation within the ocean creates limitations on what portion may finally reach the atmosphere (McGinnis et al., 2006; Mau et al., 2007; Ruppel, 2011).

The study of subsurface fluid-flow systems in the SW Barents Sea is of particular interest due to the fact that this area has been uplifted and eroded multiple times thereby releasing huge quantities of oil and gas from deeper reservoirs (Doré and Jensen, 1996; Henriksen et al., 2011). Recent increase in petroleum exploration activities in the SW Barents Sea has required the need for a better understanding of the distribution and evolution of fluid-flow systems and associated gas hydrate accumulations. Moreover, ongoing warming of Arctic waters in contact with the seabed may cause gas hydrate dissociation and increase in methane release (Biastoch et al., 2011). Gas hydrate systems in polar latitudes are of particular importance due to the fact that environmental changes will be felt here first and most likely are more extreme than elsewhere (Kennett et al., 2003; Symon, 2011). A better understanding of the distribution of gas hydrates and their sensitivity to environmental changes in the SW Barents Sea, a shallow shelf sea, is therefore necessary.

Shallow gas accumulations may become economically important. The North Sea Peon shallow gas discovery, situated at ~165 m below seafloor, may constitute a hydrocarbon reservoir with economic significance (Carstens, 2005; Ottesen et al., 2012). Knowledge of the development of this shallow gas reservoir, its structure and migration pathways of gas in to the reservoir, could thus provide a better understanding of new play concepts in glacigenic sediments and nonetheless, also provide important inputs in to the planning and development of this reservoir for exploitation.

The regional distribution of fluid-flow features and gas hydrates in the SW Barents Sea was unknown at the beginning of this study, and very little information existed about the nature of these hydrate accumulations and their constraining parameters (e.g., Andreassen et al., 1990; Laberg et al., 1998; Chand et al., 2008). Similarly, no published articles documented characteristics of the Peon shallow gas reservoir and the fluid migration system associated with it. Further studies in potential exploration risks and environmental impact associated with submarine fluid flow and gas hydrates require a much better understanding of the distribution and evolution of these features and their geological controls.

The principal objective of this thesis has therefore been to understand the distribution and evolution of subsurface fluid-flow features and gas hydrate systems in the SW Barents Sea and northern North Sea (Fig. 1). In detail, they are:

- Classification of subsurface fluid-flow systems in the SW Barents Sea and study their distribution in relation to structural elements and geological history;
- Integration of gas hydrate stability models with seismic data to understand their distribution in relation to structural elements, and to study their response to ocean warming;
- In-depth analysis of controls on the formation of gas hydrate accumulation in an area of active focused fluid flow;
- Characterization of fluid migration pathways and reservoir structure in the Peon shallow gas field.

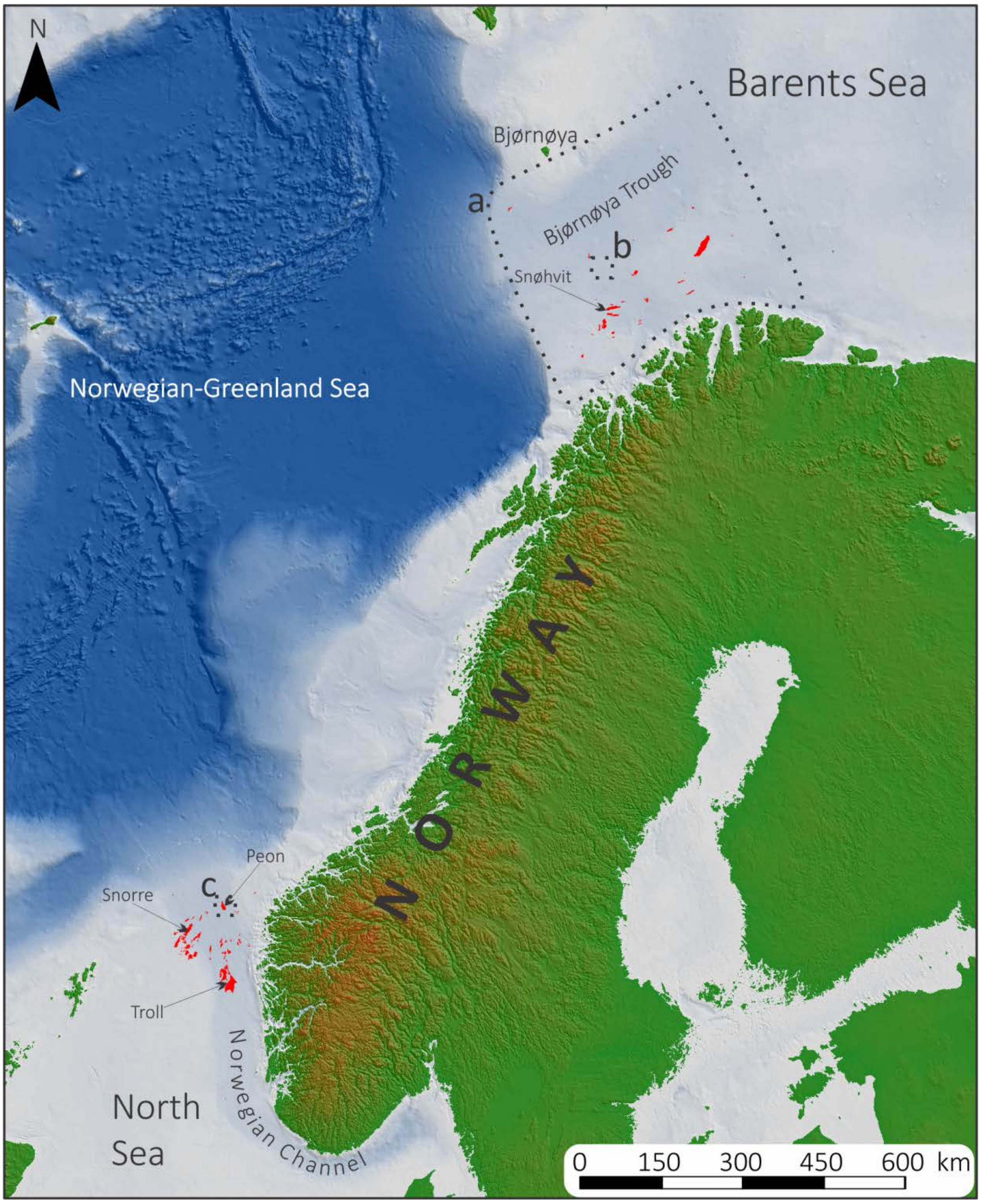

Figure 1. Map of the North Atlantic Ocean showing the location of target areas of this research; a) Southwestern Barents Sea (article 1 and 2) b) Polheim Sub-Platform (article 3) and c) Peon shallow gas field, northern North Sea (article 4). Some of the well-known oil and gas discoveries are also shown (red shaded area).

Focused fluid flow in passive continental margins

Fluid flow refers to the migration of fluids, especially hydrocarbons in this study, from the subsurface and potentially through the seafloor in to the ocean and atmosphere. Focused fluid flow is widespread and fluid-flow features have been observed on continental margins worldwide (King and MacLean, 1970; Hovland, 1981; Bugge et al., 1987; Hovland and Judd, 1988; Vogt et al., 1994; Lammers et al., 1995; Gorman et al., 2002; Berndt et al., 2003; Hornbach et al., 2003; Løseth et al., 2003; Berndt, 2005; Judd and Hovland, 2007; Westbrook et al., 2009; Løseth et al., 2011; Chand et al., 2012; Rajan et al., 2012a; Wadham et al., 2012; Vadakkepuliyambatta et al., 2013). Fluid flow can be triggered by temporally and spatially varying processes, such as rapid sediment loading (Dugan and Flemings, 2000), uplift and erosion (Doré and Jensen, 1996; Henriksen et al., 2011), dissociation of gas hydrates (Mienert et al., 2005), polygonal faulting (Berndt et al., 2003; Cartwright et al., 2007), hydrocarbon generation and leakage from deep and shallow source rocks and reservoirs (Heggland, 1998; Vadakkepuliyambatta et al., 2013), earthquakes (Fischer et al., 2013), and is almost always driven by hydro-dynamic gradients or buoyancy.

The density and pressure gradients between sedimentary layers play a major role in the nature and rate of fluid migration. In porous media, rate of fluid flow is controlled by the intrinsic permeability of the medium, the pressure gradient, and fluid viscosity as stated by Darcy’s law (Darcy, 1856). Low-permeability formations can, thus, inhibit flow of fluids resulting in excess pore pressure generation. When the overpressure exceeds the lithostatic pressure, the excess pressure is released through mechanical failure of the low-permeability formation resulting in vertical migration of fluids through fractures (Grauls and Cassignol, 1992; Cartwright and Dewhurst, 1998; Cartwright et al., 2007). Excess pore pressure release in low-permeability systems can also occur along tectonic-induced fractures, naturally existing micro fractures, or fracture pipes (Brown, 2000; Løseth et al., 2011). Through a series of experiments, Anketell et al. (1970) demonstrated that buoyant materials (e.g., salt, gas-rich sediments) could rise through overlying formations in sedimentary systems where a low density material is trapped between high density layers.

Methane gas (CH_4) generated through organic matter reactions in marine sediments forms the most common hydrocarbon associated with fluid flow (Schoell, 1988). Methane can be generated in the subsurface through biogenic or abiogenic processes. Biogenic methane involves conversion of organic matter in to methane either by microbes (biogenic) or by high-temperatures (thermogenic) (Galimov, 1988). Abiogenic methane do not involve organic matter and is formed exclusively through inorganic chemical reactions, either surficial or deep-seated (e.g., mantle)(Schoell, 1988; Chassefière and Leblanc, 2011; Rajan et al., 2012b).

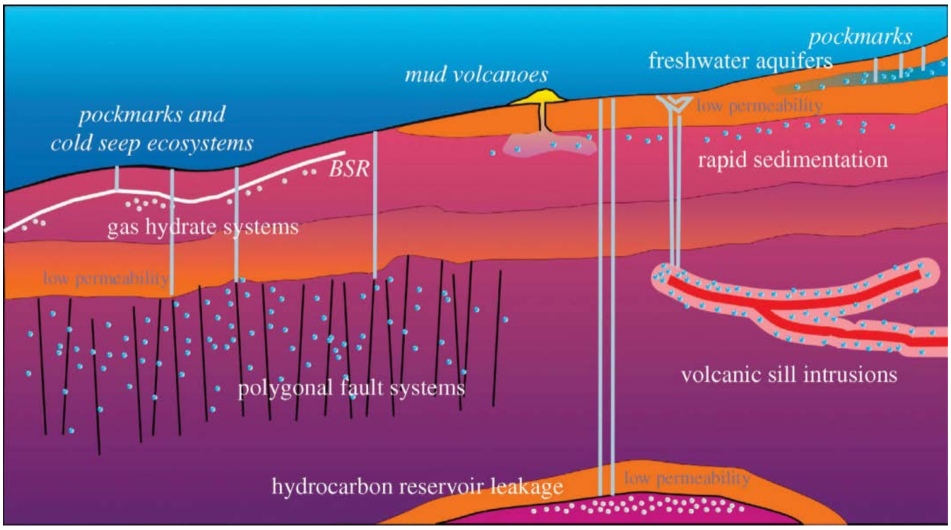

Figure 2. Illustration of various fluid flow systems on passive margins (figure from (Berndt, 2005)

Submarine fluid flow leaves multitude of expressions on the seafloor and in the subsurface (Fig. 2). It has three major components; the source, the plumbing system, and the venting structures (Fig. 3). When there is enough overpressure for the fluids to breach overlying sediments, fluid venting structures such as mud volcanoes, mud diapirs, pockmarks and mounds can form on the seafloor (Hovland, 1981; Berndt, 2005; Greinert et al., 2006; Sauter et al., 2006; Judd and Hovland, 2007; Paull et al., 2008) (Fig.2). First discoveries of fluid-flow features involved direct observations of pockmarks on the seabed (King and MacLean, 1970; Hovland, 1981).

Depending on the subsurface geology, source of fluids, and differential pressure, upward rising fluids generate various subsurface features (Fig. 2). They deliver fluids to the shallow subsurface and are difficult to characterize due to lack of direct observations and their highly transient nature in both space and time (Hornbach et al., 2007; Talukder, 2012). Most of the current knowledge on plumbing systems is obtained from seismic data interpretation. Known features of sub-seabed fluid flow can be broadly classified in to fluid flow faults and fractures, gas chimneys, blowout pipes, intrusions, and sediment mobilization. A detailed account on classification of fluid flow features based on their seismic signature is given by Cartwright et al. (2007) and Løseth et al. (2009). Article 1 of this thesis embarks on a similar objective, to classify the fluid plumbing systems in the SW Barents Sea.

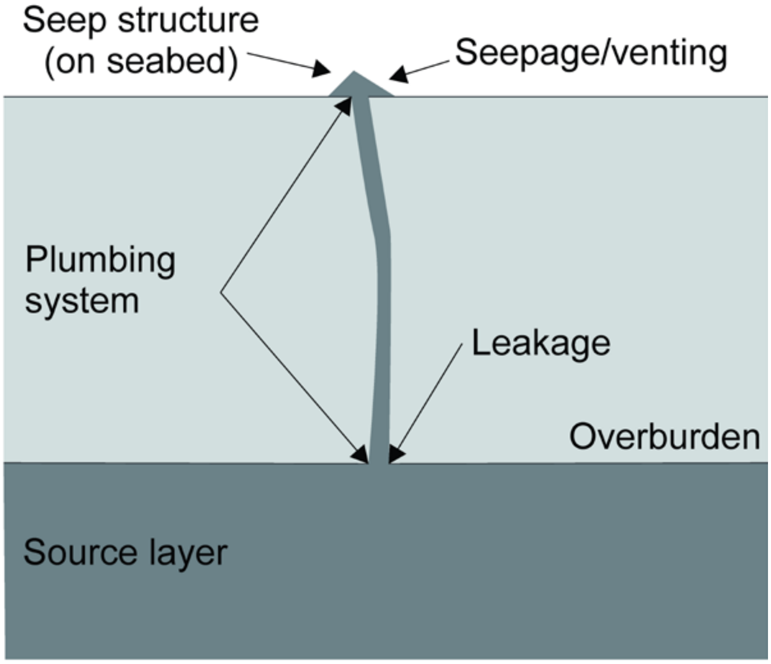

Figure 3. Simplified illustration of a fluid flow system and its components (Talukder, 2012)

Vertical migration of fluids through sedimentary formations can result in heterogeneous distribution of small gas accumulations leading to attenuation and scattering of seismic energy. These zones of noisy, low-amplitude seismic signals can appear on the seismic data in different shapes based on the nature of their formation (Fig. 4a). Such seismic features are observed with mud mobilizations (Graue, 2000; Løseth et al., 2003), gas chimneys (Løseth et al., 2002; Hustoft et al., 2009a; Vadakkepuliyambatta et al., 2013) and blowout pipes (Berndt et al., 2003; Cartwright et al., 2007; Løseth et al., 2011) (Fig. 4b). Mud mobilization can modify the structure of sediments to a disrupted succession and form a low-density sediment-fluid mixture resulting in noisy and chaotic seismic signals. Gas blow-out pipes and gas chimneys are vertical fluid conduits which often connect to surface venting features (Løseth et al., 2009; Plaza-Faverola et al., 2010a; Løseth et al., 2011; Bünz et al., 2012). Very little information exists on internal structure of the chimneys and this is still one of the challenging questions in fluid flow research. Plaza-Faverola et al. (2010b) documents the presence of gas hydrates within gas chimneys at Nyegga, offshore Norway whereas in the North Sea, drilling in to one of the chimneys showed remobilized sediments (Ligtenberg, 2007). Arntsen et al. (2007), with the help of modeling, showed that gas chimneys might essentially be a system of interconnected fracture networks. Due to the heavy attenuation of seismic signals inside a chimney, identifying the source of fluids is often difficult. The root of gas chimneys could be a wide zone or a focused point, such as faults (Løseth et al., 2009).

Faults and fractures offer low-resistance pathways for fluids across low-permeability sedimentary formations. Fractures are very common fluid conduits and are prone to develop above overpressured reservoirs (Arntsen et al., 2007; Cartwright et al., 2007). Petroleum systems bound by fault traps can turn to non-sealing faults due to tectonic activities and transport fluids to the shallow subsurface or in to the ocean (Henriksen et al., 2011). Such leaking faults are usually associated with high-amplitude acoustic anomalies, which indicate the presence of small gas accumulations, along their fault plane or the adjacent sedimentary bedding (Løseth et al., 2009). Non-tectonic faults, known as polygonal faults, can be formed in fine grained sediments due to sediment contraction and fluid expulsion (Cartwright, 1994) and can act as migration pathways for fluids (Berndt et al., 2003; Bünz et al., 2003; Berndt, 2005) (Fig. 4b).

Shallow gas accumulations are a feature that is generally observed in association with fluid plumbing systems. They are represented in the seismic data by a high-amplitude anomaly and a reverse polarity with respect to the seafloor. They can be associated with all kinds of fluid plumbing systems and are formed when vertically migrating fluids encounter low-permeability formations and/or when the excess pore fluid pressure is dissipated before reaching the seafloor. They are known to cause blowouts during drilling (Prince, 1990). However, their presence often lead to deeper hydrocarbon reservoirs (Heggland, 1998).

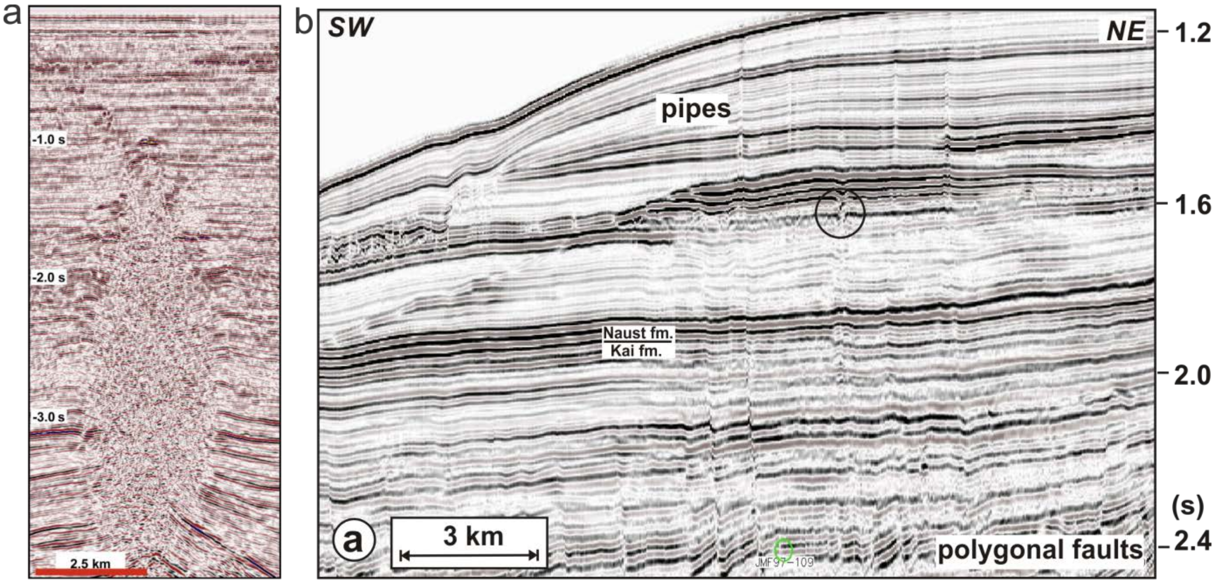

Figure 4. a) Seismic expression of a gas chimney. The zone of chaotic signals is interpreted as the fluid leakage zone (from Løseth et al., 2009). b) Seepage pipes and its co-existence with polygonal faults from the mid-Norwegian margin. The source of fluids might be within the polygonal faulted sequence (from Berndt et al., 2003).

Gas Hydrates

Gas hydrates are ice-like substrates consisting mainly of light hydrocarbons (mostly methane) entrapped by a rigid cage of water molecules (Sloan and Koh, 2008). Gas hydrate formation in marine sediments requires natural gas and water existing at very specific pressure and temperature conditions (Claypool and Kaplan, 1974; Kvenvolden, 1988) (Fig. 5). The stability of hydrates is also affected by the composition of gas and ionic impurities in the water (Kvenvolden, 1998; Sloan and Koh, 2008). These constraints on hydrate formation define the gas hydrate stability zone (GHSZ) —the limited depth/pressure range in which gas hydrates are stable. Anomalous reflections in the seismic data, known as ‘bottom simulating reflectors’ (BSRs), mark the bottom of the GHSZ and are still the best indirect indicator for the presence of hydrates in marine sediments (Holbrook et al., 1996; Bünz et al., 2003; Vanneste et al., 2005) (Fig. 6). This reflection is usually the result of relatively dense hydrate-bearing layer (high acoustic velocity) overlying gassy sediment (low acoustic velocity). As such, the BSR has high reflection amplitude and reversed polarity compared to the seafloor reflection. In an environment where the gas composition, water composition, sediment composition, and regional heat flow are relatively homogenous and stable, the BSR mimics the seabed topography and cuts across normal seismic reflections produced by lithological changes in the sedimentary bedding (e.g., Shipley et al., 1979). Many hydrate accumulations on continental margins worldwide are closely associated with focused fluid flow systems that provide the gas for hydrate formation (e.g., Tréhu et al., 2004; Hornbach et al., 2008; Hustoft et al., 2009a). However, many such focused fluid flow pathways exist because hydrate efficiently traps gas leading to overpressure beneath the hydrate-bearing sediments and the ensuing formation of vertical fluid flow structures due to natural hydraulic fracturing (Bünz et al., 2003; Hustoft et al., 2007; Plaza-Faverola et al., 2011).

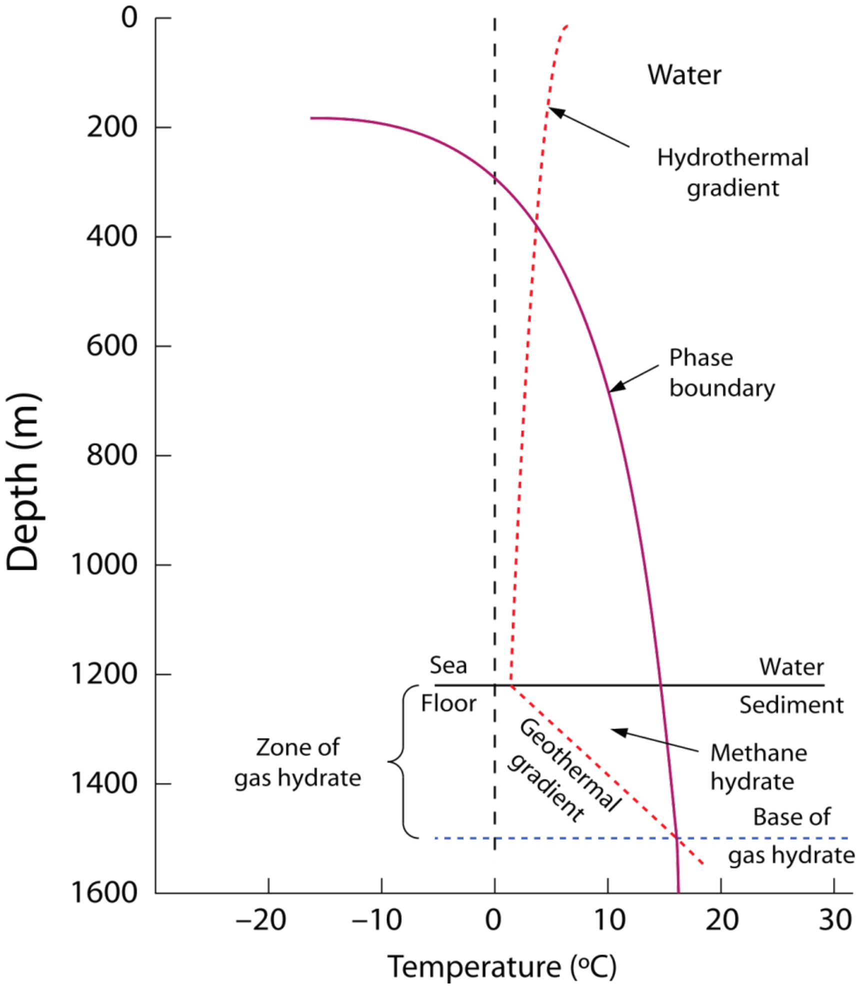

Figure 5. a) A typical phase diagram for gas hydrates showing the region of hydrate stability, modified from Kvenvolden (1988) and Collett et al. (2009).

Gas hydrates have been sampled from many parts of the world (Tréhu et al., 2003; Claypool, 2006)and are known to exist in almost all continental margins and permafrost regions of the world (Kvenvolden, 1998; Collett et al., 2011; Wadham et al., 2012). Being the largest carbon reservoir on the planet, gas hydrates are considered as an unconventional resource, which may, in future, sate the world's ever-increasing energy requirement (Boswell and Collett, 2011). Gas hydrates may also play a role as a geohazard, in relation to being an agent in climate change and in submarine mass wasting (Kvenvolden, 1988; Yakushev and Collett, 1992; Mienert et al., 1998; Maslin et al., 2010; Biastoch et al., 2011). Changes in hydrate stability conditions could destabilize the gas hydrates and release massive amounts of methane gas in to the ocean and atmosphere (Kvenvolden, 1988; Biastoch et al., 2011) . In doing so, they also reduce the sediment strength which may lead to submarine landslides (Bugge et al., 1987; Maslin et al., 2010).

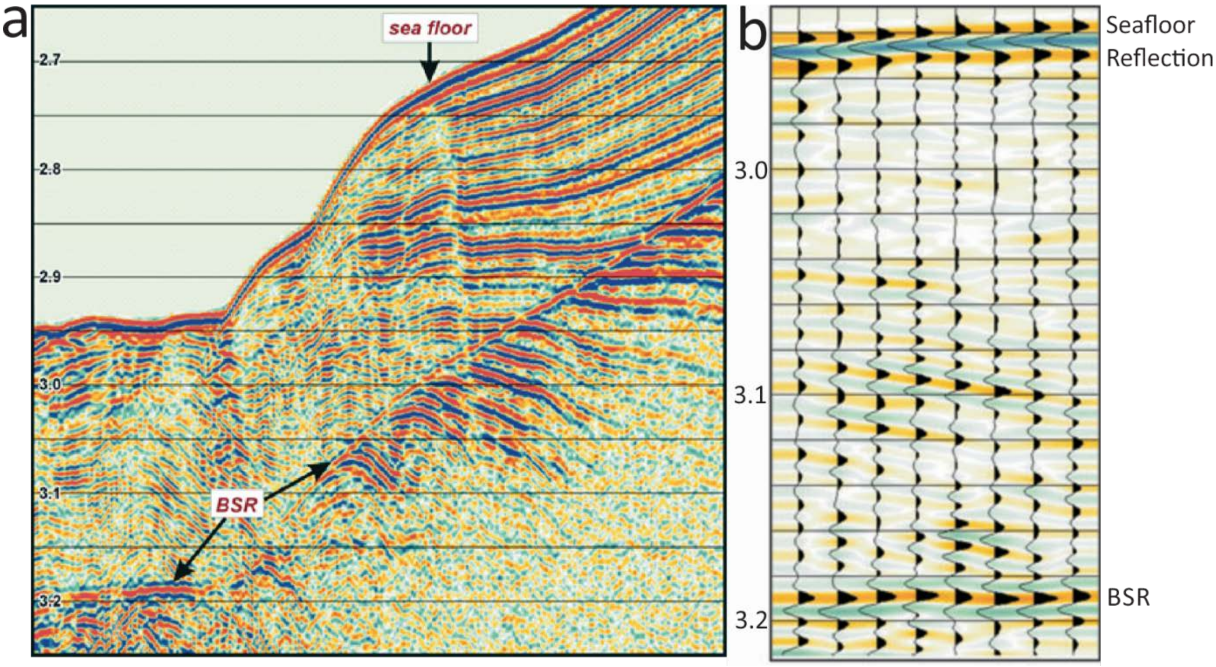

Figure 6. a) Typical seismic expression of a BSR (example from western Svalbard margin). b) Wiggle trace display illustrating high-amplitude of the BSR and its reverse polarity with respect to the seafloor. (Figure modified from Vanneste et al. (2005)).

Being a compound with socio-economic importance, the environments in which gas hydrate form and destabilize are of major interest in scientific research. Gas hydrate stability and distribution can be controlled by a variety of parameters such as sediment properties, pore-water salinity, geothermal gradient, bottom water temperature, gas composition, lithostatic pressure, and presence of inhibitor compounds (Sloan and Koh, 2008). Geological conditions could alter one or many of these parameters and alter the hydrate stability conditions in a particular area. Salt intrusions can increase both shallow sediment temperatures and water salinity resulting in a thinner GHSZ (Dickens and Quinby-Hunt, 1997; Bugge et al., 2002; Hornbach et al., 2005; Ruppel, 2005). Focused fluid flow and faults are known to increase heat flow locally and create shallower BSRs (Ruppel, 2005; Pecher et al., 2010). Article 3 analyzes the factors affecting gas hydrate accumulation associated with a focused fluid flow system in the SW Barents Sea. Composition of the gas forming hydrates can affect the hydrate stability significantly, as even a moderate (5-10%) variation in gas composition can shift the base of GHSZ by tens-to-hundreds of meters (Chand et al., 2008; Sloan and Koh, 2008; Collett et al., 2009). In addition, sea level changes, uplift and erosion, ocean temperature variations, and glaciations are known to influence gas hydrate stability (Chand et al., 2012; Phrampus and Hornbach, 2012). Article 2 focuses on addressing major factors affecting hydrate stability in the SW Barents Sea and their potential impact in destabilizing gas hydrates in the near future.

Insights into fluid flow in SW Barents and northern North Seas

Occurrence of various fluid-flow features such as shallow gas, gas hydrates, sediment mobilization, and fluid venting features has been reported from several parts of the SW Barents Sea (Andreassen et al., 1990; Løvø et al., 1990; Laberg and Andreassen, 1996; Laberg et al., 1998; Sauter et al., 2006; Andreassen et al., 2007; Chand et al., 2008; Chand et al., 2009; Chand et al., 2012; Ostanin et al., 2012; Safronova et al., 2012; Ostanin et al., 2013; Rajan et al., 2013). The SW Barents Sea consists of a mosaic of basins, platforms, and structural highs (Gudlaugsson et al., 1998). The late Cenozoic history of the SW Barents Sea area is of particular interest as the uplift and erosion during this period (Nøttvedt et al., 1988; Vorren et al., 1988; Vorren et al., 1991) is thought to have resulted in the spillage and migration of hydrocarbons from reservoirs in the region (Doré and Jensen, 1996; Henriksen et al., 2011). Moreover, various glaciations during this period have shaped the present geomorphology of the area (Riis and Fjeldskaar, 1992) and an up to 1.7 km thick ice cap during the late Weichselian glaciation (Svendsen et al., 2004) could have had an impact on the petroleum systems and gas hydrates in the SW Barents Sea (Lerche et al., 1997; Chand et al., 2008; Chand et al., 2012; Ostanin et al., 2013).

Pockmarks are observed near the Goliat and Snøhvit fields, their distribution seemingly controlled by the availability of soft sediments (Chand et al., 2009; Ostanin et al., 2013). They are supposed to be inactive Indications of polygonal faults, vertical fluid migration and paleo pockmarks within the glacial sediments were also observed in the Snøhvit gas field (Ostanin et al., 2012, 2013). Andreassen et al. (2007) reported a multitude of shallow gas accumulations and fluid migration features within the Plio-Pleistocene succession and suggested multiple cycles of hydrocarbon migration and gas hydrate destabilization. The results from Goliat and Snøhvit fields also seem to concur with this idea. Active fluid seepage in to the ocean near the Loppa High (Chand et al., 2012) suggest the fluid migration is still active in some areas of the SW Barents Sea.

Gas hydrates are inferred in the SW Barents Sea from BSR observations in the seismic data (Andreassen et al., 1990; Løvø et al., 1990; Laberg and Andreassen, 1996; Chand et al., 2012; Ostanin et al., 2013; Rajan et al., 2013). Gas hydrate stability modeling suggests a highly variable GHSZ in the region, owing to variations in heat flow, gas composition, and structural elements (Chand et al., 2008). Pure methane hydrates are unstable in most parts of the SW Barents Sea (Chand et al., 2008) and deeper BSRs in the seismic data indicate presence of higher order hydrocarbons (C_2 and higher) from deep sources (Laberg et al., 1998). Piercement structures such as salt domes in the Nordkapp Basin affect gas-hydrate stability leading to thinning of the GHSZ by significantly altering the subsurface heat flow (Bugge et al., 2002; Chand et al., 2008). The bottom water temperatures in the area also have a major impact on the hydrate stability of the region. Different water masses control the bottom water temperatures in the Barents Sea region (Løvø et al., 1990). In general, the northern part of the SW Barents Sea is significantly colder than the southern part due to the influence of cold Arctic water masses, and the bottom water temperature in our study area (320 m) may in some extreme cases vary between -1.5 ^{0}C to 6.5 ^{0}C (World Ocean Database, 2009). Given that methane hydrates were stable during the glacial periods (Chand et al., 2012), significant amounts of hydrates could have destabilized during interglacial periods. Few heat flow measurements exist in the SW Barents Sea (Bugge et al., 2002) and measurements of shallow gas samples are non-existent. Considering the geological complexity of the SW Barents Sea area and lack of information on the major parameters affecting hydrate stability, it is rather difficult to constrain GHSZ models in the area.

The North Sea has been major location for studying fluid expulsion features for the last three decades. Various types of fluid-flow features have been identified in this area including gas seepages (Hovland et al., 1985; Hovland and Judd, 1988), pockmarks (Van Weering et al., 1973; Hovland, 1981; Forsberg et al., 2007; Judd and Hovland, 2007), sediment mobilization (Løseth et al., 2003), polygonal faults (Cartwright, 1994; Lonergan et al., 1998; Løseth et al., 2003), gas chimneys (Judd and Hovland, 2007), and shallow gas accumulations (Tjelta et al., 2007). The North Sea region is particularly famous for its high density of pockmarks on the seafloor with as much as 60 per sq. km occurring in the Norwegian Channel (Judd and Hovland, 2007). In addition to the pockmarks on the seafloor, buried 'fossil' pockmarks that have ceased venting and subsequently covered by sediments are also observed (Long, 1992). Seismic evidence of gas in shallow sediments has been recorded from various parts of the North Sea in which pockmarks are known to exist (Judd and Hovland, 2007). It is suggested that shallow gas is widespread but their origin (thermogenic or biogenic) is still debated (Gevirtz et al., 1985; Brekke et al., 1997).

Glaciations have played a significant part in the hydrocarbon migration history in this area (Fichler et al., 2005). A proposed mechanism for the formation of pockmarks in the Troll field suggests gas release through the seafloor from dissociating of gas hydrates in response to deglaciation about 11000 years before present (Forsberg et al., 2007). One of the largest shallow gas fields ever discovered, the Peon gas field, is located north of the Troll field (Carstens, 2005). Article 4 presents the first report on the associated fluid migration pathways and reservoir structure of this gas accumulation with potential economic value.

Seismic and numerical methods for characterizing submarine fluid-flow systems

Advances in the field of seismic exploration technology have led to a significant reduction of dry wells all over the world and enhanced the study of shallow subsurface. 3D seismology and vast increase in computing power enables better visualizations and attribute analyses with a resolution of few tens of meters over large areas (Cartwright and Huuse, 2005). Being the most effective tool to study subsurface fluid-flow features, this thesis has made use of 2D and 3D seismic data of various resolutions and penetrations. Articles 1 and 2 utilizes conventional 2D seismic data whereas article 3 uses 3D high-resolution P-Cable data (Planke et al., 2009). Article 4 provides a comparison of the various seismic data (2D high-resolution, 3D conventional, high-resolution 3D P-cable) and the use of each data in studying the Peon shallow gas reservoir and its fluid migration system. Apart from the seismic data, the CSMHYD program developed by Sloan and Koh (2008) is used to estimate gas hydrate stability in articles 2 and 3. Exploration well logs and ocean temperature measurements from World Ocean Database 2009 are used in all articles. Article 3 uses a newly developed, finite-difference numerical solution of the heat flow equation to improve the estimation of gas-hydrate stability. The methodology is described below in detail.

The heat generated at the bottom of the crust is transported upwards through the sediments in two major fashions: diffusion and advection. Diffusive heat transport is slow and can be a significant factor in heat flow through all types of rocks. Advection is fast and the medium of heat transport is fluids. Heat flow is one of the most significant parameters controlling gas hydrate stability, particularly in the SW Barents Sea (Chand et al., 2008). Gas hydrate systems associated with fluid flow features, such as gas chimneys, could thus show anomalous heat flow signatures when compared with the regional heat flow. Estimation of accurate heat flow values at a location is therefore essential in reducing the errors in the modeling of gas hydrates stability. Numerical methods can be used to model the heat flow either by diffusion or advection. Hornbach et al. (2012) and Phrampus and Hornbach (2012) successfully applied these models in constraining gas hydrate stability off the US coast.

Fourier's law forms the basis of heat conduction, which states that the heat flow (q) per unit area and per unit time, at a point in the medium is directly proportional to the temperature gradient at the point (Turcotte and Schubert, 2002). In one dimension it can be written as

$$q = -k \frac{dT}{dx} \quad (1)$$

where T is the temperature, k is the co-efficient of thermal conductivity, and x is the coordinate in the direction of temperature variation. The minus sign in equation 1 represents direction of heat flow from higher temperature to lower temperature.

From equation 1, the general differential equation for rate of heat diffusion with time in three dimensions in a non-deforming medium with constant diffusivity (K) can be written as (Spiegelman, 2004; Gerya, 2010)

$$\frac{\partial T}{\partial t} = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (2)$$

where ∂ is the partial derivative, T is the temperature, t is time, x, y, and z are the coordinates in each direction. $\partial T/\partial t$ is the rate of change of temperature with time and $\partial T/\partial x$ is the rate of change of temperature with space.

For simultaneous heat and fluid flow, involving both advection and diffusion (assuming constant diffusivity), through isotropic, homogeneous, and fully saturated porous mediums, the differential equation 2 changes to (Bredehoeft and Papadopulos, 1965)

$$\frac{\partial T}{\partial t} = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) - \left(\frac{\partial}{\partial x}\left(V_x \bullet T\right) + \frac{\partial}{\partial y}\left(V_y \bullet T\right) + \frac{\partial}{\partial z}\left(V_z \bullet T\right)\right) \quad (3)$$

where V_x, V_y, and V_z represent fluid flow rates in x, y, and z directions respectively.

To solve equations 2 and 3 numerically, a finite-difference technique, where the space derivatives are approximated and expanded to fourth order, can be used (Spiegelman, 2004; Gerya, 2010). Article 3 uses the finite-difference numerical solution of equation 2 and 3 (considering only vertical flow, $V_y=V_x=0$) in conjunction with CSMHYD program (Sloan and Koh, 2008) to estimate the base of GHSZ.

Summary of articles

Article 1: Vadakkepuliyambatta, S., S. Bünz, J. Mienert, and S. Chand (2013), Distribution of subsurface fluid-flow systems in the SW Barents Sea, *Marine and Petroleum Geology, v43, pp 208-22.*

As many as 3000 2D multi-channel seismic profiles and well log data from 60 exploration wells covering the entire SW Barents Sea are analyzed to characterize fluid-flow systems. Various fluid-flow features are identified, classified and their distribution is studied with respect to major structural elements, uplift and erosion history of the region. Gas chimneys are the most abundant fluid-flow feature in the region among a variety of subsurface fluid-flow features such as fluid leakage along faults, seepage pipes, shallow gas accumulations, and gas hydrate indications. Some of the gas chimneys covered extremely large areas as big as 600 km^2. Fluid-flow features occur above major deep-seated faults in the area indicating a close relationship. Faults may be acting as fluid leakage pathways in most parts of the SW Barents Sea. Most of the fluid-flow features are concentrated on a small area close to Ringvassøy-Loppa Fault Complex, Bjørnøyrenna Fault Complex, Loppa High, and Polheim Sub-Platform regions. In general, the number of fluid flow features in the western part of the study area is significantly higher than in the eastern part. This could be mainly due to higher concentration of faults and gas-mature source rocks on the western part. The amount of net erosion in the region shows no direct control over the distribution of fluid-flow features, suggesting that the faults and distribution of mature source rocks control the fluid flow. The strong correlation between major faults and fluid-flow features suggests that extensional tectonics, glaciations and uplift could have played major roles in the timing and activity of fluid leakage.

Article 2: Vadakkepuliyambatta, S., S. Chand, and S. Bünz. Can ocean warming destabilize gas hydrate accumulations in the SW Barents Sea? *To be submitted*

Article 2 provides an improved estimation of the gas hydrate stability field in the whole SW Barents Sea taking in to account spatial variations in geothermal gradient, bottom water temperature and gas composition. Geothermal gradients are estimated using bottom-hole measurements from 73 individual exploration wells. Information on gas composition is extracted from gas sample analyses conducted on various exploration wells, and bottom water temperature is constrained by CTD casts obtained from World Ocean Database 2009. The estimated hydrate stability field exhibits high sensitivity to gas composition and geothermal gradient and shows a very high variability within the SW Barents Sea basin. Methane hydrates are stable in small areas in the SW Barents Sea, but particularly in the Bjørnøya Trough area. Hydrates containing higher-order hydrocarbons are stable over a much larger area. Generally, the thickness of the GHSZ increases towards the continental slope area. The gas hydrate stability modeling was integrated with an analysis of approximately 3000 2D multi-channel seismic profiles covering the whole SW Barents Sea. The hydrate-stability model is used to identify potential BSRs providing indirect evidence for the presence of gas hydrates. Most BSR occurrences can be associated with gas chimneys and leaking faults and occur patchily in the whole study area. BSR patches vary in their size and distribution with all observed BSRs falling within the Structure II hydrate-stability field. BSR related to pure methane hydrate accumulations were not observed in the area. The distribution of gas hydrates seem to be controlled by availability of gas sources and gas composition. The effect of LGM on present day shallow subsurface thermal gradient is negligible and thus has little effect on the hydrate stability field in the area. The timing of gas hydrate formation in the SW Barents Sea may coincide with various uplift and erosion episodes, which might have triggered leakage of hydrocarbons from deeper reservoirs. We estimate that increasing global ocean temperatures could cause destabilization of hydrates located within 100 meters of the seafloor in ~200 years. However, hydrates in the SW Barents Sea are relatively stable as most observed BSRs are located deeper (assuming a major part of gas hydrate forming close to BSR).

Article 3: Vadakkepuliyambatta, S., M. Hornbach, S. Bünz, and B. Phrampus. Controls on gas hydrate system evolution in a region of active fluid flow in the SW Barents Sea. *Under review in Geophysical Journal International*.

High-resolution 3D P-Cable seismic data from the Loppa High, SW Barents Sea show gas hydrate related BSRs and indications of vertical fluid migration. The seismic data is used in conjunction with 3D heat flow and fluid flow models to place constraints on hydrate stability in this complex environment. A 3D steady-state, finite difference thermal model is developed incorporating bottom water temperature from CTD casts, geothermal gradients from bottom-hole temperature measurements, and gas composition from analysis of gas sample from nearby exploration well, to constrain heat flow, fluid flow and gas hydrate stability at the location. In general, observed BSRs occur shallower than modeled BSRs. This discrepancy can be explained either by an increase in methane concentration of 0.7% or a salinity value of 51 ‰. Alternatively, it can also be explained by vertical fluid migration rate of ~3.8 mm y^{-1}. From these calculations we propose that shoaling of BSR is mainly due to fluid/heat flow variations at the site and to some extent, possibly, variations in fluid geochemistry. Our analysis indicates focused fluid migration along specific irregular-shaped conduits in a large chimney complex. Also, recent observations of gas seepage near this location and meter-scale variations in the BSR depth indicate that the fluid flow system is currently active and most likely, very dynamic. Our study provides new insight into regional heat flow, geochemistry, and end-member vertical fluid flux rates in the Barents Sea.

Article 4: Vadakkepuliyambatta, S., S. Planke, and S. Bünz. Fluid leakage pathways and shallow gas accumulation in the Peon field, northern North Sea, from high resolution P-Cable 3D seismic data. *To be submitted*

The Peon field is a huge shallow gas discovery located in the northern North Sea. Seismic data of varying resolution including 3D high-resolution P-Cable seismic, 2D high-resolution seismic and 3D conventional seismic are used to characterize the reservoir structure and investigate the fluid migration system in the area. In addition, wire line well logs from exploration well 35/2-1 are also integrated with seismic interpretation. Situated on the upper regional unconformity (URU), a 32 m thick Peon reservoir was interpreted with numerous intra-reservoir reflections indicating significant variations in sediment properties within the reservoir. A non-flat, high-amplitude reflection representing the gas-water contact is identified. Lateral changes in gas saturation within the reservoir may explain the observed variation in the reflection strength of the gas-water contact. Glacial deposits lying above the reservoir exhibited erosional features such as ploughmarks and high-amplitude anomalies suggesting shallow gas accumulations. Glacial deposits seem to be efficiently trapping the upward migrating fluids, which often migrate laterally in between these deposits. However, shallow gas indications just above the reservoir do not rule out the possibility of leakage from the reservoir. Gas-related reflections were non-existent above a particular stratigraphic level, and neither are paleo-indications of fluid leakage. The present day seafloor above the reservoir is devoid of ploughmarks, pockmarks, or other fluid venting features, although a high-density pockmark field is present to the west of reservoir. The Late Pliocene successions below the reservoir dip steeply towards the northwest. The presence of gas in these formations is inferred from numerous high-amplitude reflections. We suggest that lateral fluid migration is dominant in the Pliocene formations. Zones of vertical fluid flow are represented by gas chimneys and pipes. The Oligocene Hordaland Group exhibits polygonal faults and mobilized sediments associated with high-amplitude reflections indicating presence of gas. The polygonal faults act as a major pathway for fluids from deeper formations. Leaking Jurassic faults are supposed to be the source of the fluids, which also triggered the sediments mobilization. Fluid flow in this region is probably long lived leading to the filling of a large shallow gas reservoir with potential economic value.

Future research

The SW Barents Sea is a great natural lab to study submarine fluid flow and associated gas hydrate systems. It exhibits almost all types of fluid-flow features and some of the features have never been observed elsewhere. The studies of fluid flow and gas hydrates in the Barents Sea have so far been using indirect methods. Drilling through one or more of the gas hydrate or shallow gas accumulations will greatly help better understand the development and internal structure of these systems. More heat flow measurements are necessary while studying the stability of gas hydrate accumulations in the SW Barents Sea. Considering the hardness of the seafloor in the area, shallow drilling (using for eg. MARUM-MeBo) would be an effective tool to measure subsurface temperature in addition to various other petrophysical parameters.

Article 1 presented a wide variety of fluid flow features in the SW Barents Sea. The timing and triggering mechanism of these features is still unknown. Being an area with different basins, it would be interesting to focus on individual basins to study the characteristics and timing of emplacement of these features in detail. Integrating seismic data with velocity logs and rock physics modeling could help to estimate the approximate amount of hydrocarbons stored in shallow gas reservoirs in the area. Basin modeling (e.g., Hustoft et al., 2009b) of fluid-leakage systems will give a better understanding of the temporal evolution of fluid-flow systems.

It is well documented by article 2 and previous studies (e.g., Chand et al., 2008; Chand et al., 2012; Ostanin et al., 2013) that glaciations had a major impact on the hydrate accumulations in the SW Barents Sea. Estimating BSR depth oscillations during glacial interglacial periods could provide approximate amount of methane released in to the ocean during this period. Integration of future climate models (e.g., Marín-Moreno et al., 2013) to study the response of hydrate accumulations within the SW Barents Sea can provide feedbacks for improving these models further. Integrating velocity analysis of pre-stack seismic data from these locations and quantifying the amount of hydrates would give a fair idea of amount of gas release that can occur due to climate change.

Numerical heat flow model employed in article 3 can be helpful in quantifying gas hydrates (e.g., Hornbach et al., 2012) in locations with better controls on sediment properties. It can also be used to calculate fluid flux rates and heat flow anomalies in sites of active leakage such as Vestnesa Ridge, NW of Svalbard (Bünz et al., 2012).

The observation of an unusual gas-water contact within the North Sea Peon reservoir, detailed in article 4, is intriguing. A more focused study on the reservoir structure integrating high-resolution seismic and well log data could reveal lateral variability in the thickness of gas zone and gas saturation. Detailed interpretation of the glacial sediments above Peon reservoir is necessary to understand the development history of Peon reservoir and the fluid flow systems. Tying the shallow reflections to nearby geotechnical boreholes (e.g., from Troll field) could provide a better age control for the glacial sediments situated above the reservoir.

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Article 1

Distribution of subsurface fluid-flow systems in the SW Barents Sea

Sunil Vadakkepuliyambatta, Stefan Bünz, Jürgen Mienert, Shyam Chand

Marine and Petroleum Geology, 43(2013)

Article 2

Can ocean warming destabilize gas hydrate accumulations in the SW Barents Sea?

Sunil Vadakkepuliyambatta, Shyam Chand, Stefan Bünz

To be submitted

Article 3

Controls on gas hydrate system evolution in a region of active fluid flow in the SW Barents Sea

Sunil Vadakkepuliyambatta, Matthew J. Hornbach, Stefan Bünz, Benjamin J. Phrampus

Under review in Geophysical Journal International

Article 4

Fluid leakage pathways and shallow gas accumulation in the Peon field, northern North Sea, from high resolution P-Cable 3D seismic data

Sunil Vadakkepuliyambatta, Sverre Planke, Stefan Bünz

To be submitted

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