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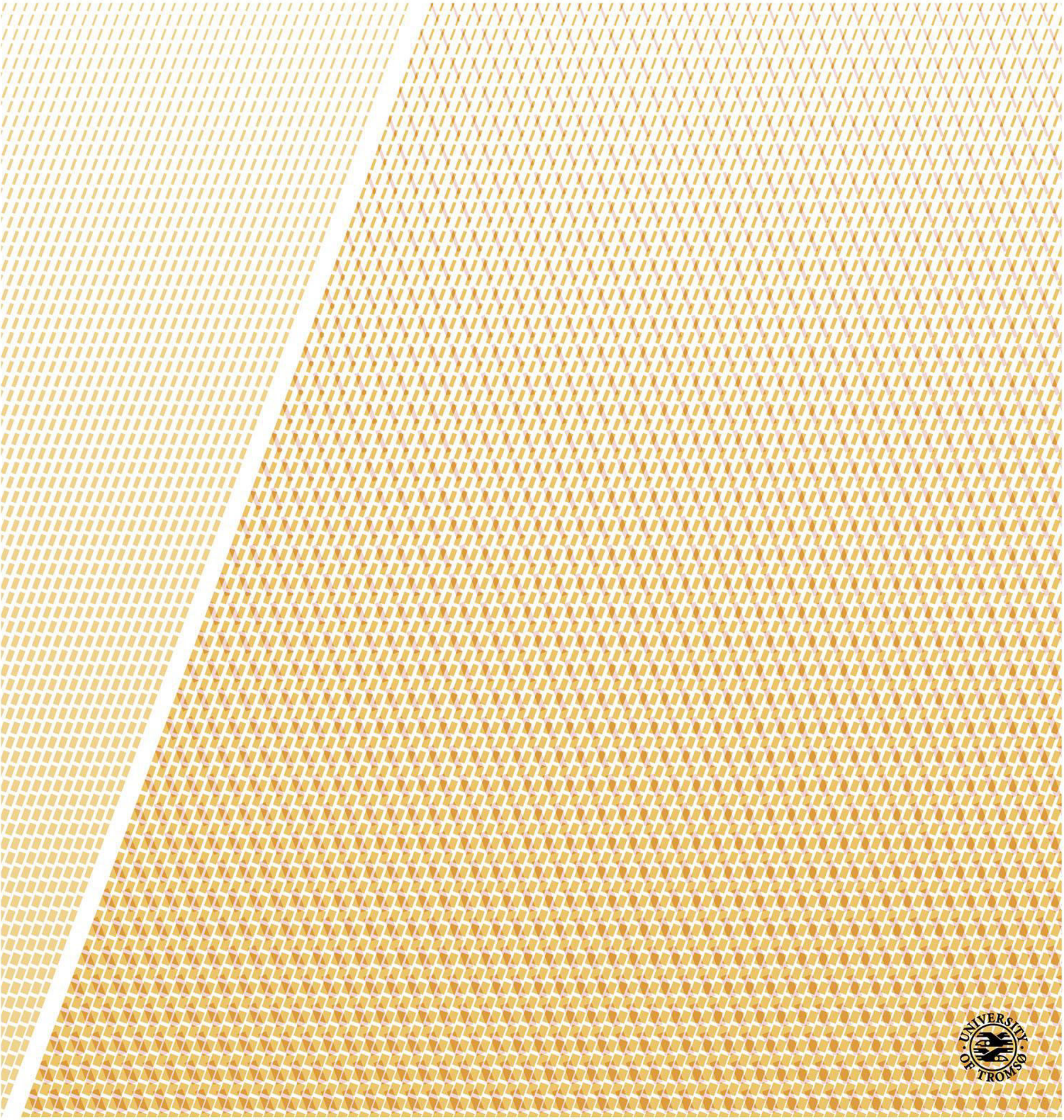
Faculty of Science and Technology, Department of Geosciences

Fluid flow at the Snøhvit field, SW Barents Sea: processes, driving mechanisms and multi-phase modelling

Alexandros Tasianas
A dissertation for the degree of Philosophiae Doctor – May 2017



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PREFACE

I worked on this doctoral degree thesis from 2011 to 2017, initially and mainly at the Department of Geosciences at UiT, the Arctic University of Norway, and towards the end of my thesis at other European institutions. The work was financed through the ECO2 project and is a contribution to the research carried out within this project. The main supervisor was Assoc. Prof. Stefan Buenz and co-supervisor was Prof. Juergen Mienert both from the Arctic University of Norway.

My work mainly focused on the Snøhvit hydrocarbon field and CO_2 storage site in the Hammerfest Basin in the SW Barents Sea. The main basis of my work consisted of an interpretation of conventional 3D and high-resolution P-Cable 3D seismic data that were used to obtain a better understanding of deep-to-shallow fluid flow. The dataset analysis results were used as input for the first and second article. Geological models established by the interpretation also facilitated numerical simulations of fluid flow assuming a number of hypothetical leakage scenarios. These simulations were carried out at the Institute for modeling hydraulic and environmental systems, at the University of Stuttgart in Germany. A third article was then prepared, based on a sensitivity analysis carried out by running these simulations on geological models of the Snøhvit overburden.

The fourth article was the result of a 3-month collaboration, at the beginning of 2014, with CERTH (Center for Research and Technology Hellas) and with Dr. Nikolaos Koukouzas, one of the research directors there. The work focused on carrying out a comparative analysis between Snøhvit and a terrestrial analogue of CO_2 seepage in NW Greece, namely the Florina natural seepage site.

I also contributed, with a published paper about submarine glacial landforms in the Barents Sea, the fifth article of the thesis, to the development of an Atlas by the Geological Society of London. The Atlas itself is entitled "*Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*" and is available in the form of memoirs by the Geological Society of London, UK (Dowdeswell et al. 2016).

During my time at UiT, I had the opportunity to participate in various cruises aboard the Helmer Hanssen; for example to the Vestnessa Ridge, Fram Strait, NW Svalbard and SW Barents Sea. I attended several courses teaching me how to build geological models in Petrel and how to populate them with various petrophysical properties. Other courses allowed me to get familiar with using RMS software, a reservoir characterization and modeling software suite developed by Roxar AS. It is primarily designed to help engineers gather data from a wide variety of sources to efficiently build reliable reservoirs. I was also able to participate in field trips studying outcrops and that focused on better understanding the properties of chalk (Frykman 2001) and the characteristics of petroleum systems in areas where CO_2 is injected and potentially stored.

I participated in seismic survey campaigns offshore, both in 2011 and 2013 at Snøhvit, that led to the acquisition, processing and interpretation of the data that was used in my research. I also participated at the various ECO2 project meetings and workshops and in national and international conferences, as it is illustrated in the appendix, where I had the opportunity to present my work to a large scientific audience.

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

Article 1

Tasianas, Alexandros; Martens, Iver; Bünz, Stefan; Mienert, Jurgen. Mechanisms initiating fluid migration at Snøhvit and Albatross fields, Barents Sea. *Arktos 2016*; Volume 2. ISSN 2364-9453.s doi: 10.1007/s41063-016-0026-z.

Article 2

Tasianas, Alexandros; Bünz, Stefan. High-resolution 3D seismic study of pockmarks and shallow fluid flow systems at the Snøhvit hydrocarbon field in the SW Barents Sea. *Under review in the Journal of Marine Geology.*

Article 3

Tasianas, Alexandros; Mahl, Lena; Darcis, Melanie; Bünz, Stefan; Class, Holger. Simulating seismic chimney structures as potential vertical migration pathways for CO_2 in the Snøhvit area, SW Barents Sea: model challenges and outcomes. *Environmental Earth Sciences 2016*; Volume 75 (504). ISSN 1866-6280.s doi: 10.1007/s12665-016-5500-1.

Article 4

Tasianas, Alexandros; Koukouzas, Nikolaos; Gemeni, Vassiliki; Alexopoulos, Dimitrios; Vasilatos, Charalampos. Geological modelling for investigating CO_2 emissions in Florina Basin, Greece. *Open Geosciences 2015*; Volume 7 (1). ISSN 2391-5447.s 465 - 489.s doi: 10.1515/geo-2015-0039.

Article 5

Tasianas, A., Buenz, S., Vadakkepuliyambatta, S. & J. Mienert. Buried subglacial landforms in the SW Barents Sea imaged using high-resolution P-Cable seismic data. In Dowdeswell, J. A., Canals, M., Jakobsson, M., Todd, B. J., Dowdeswell, E. K. & Hogan, K. A. (eds) 2016. *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. *Geological Society, London, Memoirs*, 46, 183–184, http://doi.org/10.1144/M46.117.

ACKNOWLEDGEMENTS

I would first like to express my gratitude to my supervisor Dr. Stefan Buenz and to thank him for mentoring me, for his commitment and for being there to support me in all stages of my research and throughout the process of preparing my publications. Both his technical skills and knowledge and his qualities as a person have positively influenced my PhD journey.

Special acknowledgements go to the director of the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE), Juergen Mienert for firstly giving me the chance to spend the last few years of my life, here in Tromsø and for providing all that was necessary for having a rewarding stay here.

I am also indebted to Iver Martens for his collaboration in the first paper. His detailed and rigorous initial seismic data interpretation and analysis carried out on the ST0306 dataset, used in the first article, was of tremendous help in getting me started at the beginning of my thesis.

I am very grateful for the help of Melanie Darcis, Lena Walter, Bernd Flemisch and Holger Class and all the other colleagues at the Institute for modeling hydraulic and environmental systems, at the University of Stuttgart, involved in carrying out CO_2 simulations on different scenarios based on the geological models built previously at UiT.

I would like to express my gratitude also to all the administrative staff, both current and those that have left for other places for being always keen to guide me through the university's administrative system and for all practical matters.

My utmost gratitude goes to Steinar Iversen and the rest of the crew, both the engineers, the technical and the scientific staff, onboard the Helmer Hanssen. By taking us to wonderful places during various expeditions, we were able to closely study geological phenomena on the field and better understand the processes involved in forming the various structures that we observed.

Without the help and the support of Statoil ASA, through their provision of data and comments on publications, it would have been difficult to evolve. The company's knowhow and experience on CCS and more particularly for the Snøhvit site was a very precious asset. I would also like to thank the Schlumberger Company for providing the Petrel software and the necessary technical support when carrying out seismic interpretation of the seismic data.

Many thanks also to CERTH staff and Dr. Nikolaos Koukouzas in particular for welcoming me to the center. His guidance and his excellent knowledge of the local CCS activities in Greece were of extreme value. This close collaboration allowed me to apply my knowledge acquired at UiT and make a comparison between the subsea CO_2 sequestration site at Snøhvit and a terrestrial analogue in Florina, Greece.

Finally I would like to thank the various reviewers of my papers submitted to various journals for their patience in reading them and for providing valuable and constructive feedback and helping me to improve them.

My friends and colleagues at the faculty have also been of immense support by giving some of their valuable time, for helping me with technical issues and discussing with me about various topics, related to my PhD.

Finally, if I have missed someone out due to ignorance, please excuse me.

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INTRODUCTION

Fluid flow in sedimentary basins is an important process governing the transport of heat and dissolved mass (Ingham and Pop 1998), much of which may involve large amounts of hydrocarbons. The flow of fluids is mostly driven by compaction and obeys Darcy's law. However, permeability distribution and pressure gradients resulting e.g. from tectonic stress may lead to local focusing of fluids and overpressure entrapments (Bjørlykke and Avseth 2010). Focused fluid flow might take place through parts of or the entire extent of the overburden. Identification and understanding of such potential migration pathways, known as gas chimneys and leaky faults, and their extent in the subsurface can provide insights into the origin of fluid flow and their mechanisms (Ligtenberg 2005). Such understanding provides key knowledge in leakage assessment and migration potential in areas where CO_2 shall be stored in underground sedimentary formations (Berndt 2005; Cartwright et al. 2007; Chiaramonte et al. 2008).

Developing a viable strategy to reduce the amount of greenhouse gases in the atmosphere, such as through CO_2 storage projects, is essential. Since CO_2 migrates through the shallow subsurface before it escapes to the atmosphere, understanding gas migration in the shallow subsurface is of the utmost importance (Andreassen et al. 2007; Hustoft et al. 2007). We accomplished this partly through the development of localized geological models for both the Snøhvit subsurface and, to a lesser extent, the Florina basin, in northern Greece, which allowed us to assess risk to human health and the environment. Leakage assessment is a process by which an understanding of potential leakage scenarios is developed (Duran et al. 2013; Pawar et al. 2015). It is a purely hypothetical process and does by no means imply that storage site integrity is compromised by the sheer presence of leakage structures. There is currently no evidence for leakage from the CO_2 storage operation at Snøhvit (Eiken et al. 2013; Hansen et al. 2011; Linjordet and Olsen 1992; Maldal and Tappel 2004).

FRAMEWORK OF THE PHD PROJECT

The research undertaken in this PhD project was part of a large EU interdisciplinary project named ECO2: “Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2)”. ECO2 was a Collaborative Project funded under the European Commission's Framework Seven Programme Topic OCEAN.2010.3 Sub-seabed carbon storage and the marine environment.

The overall goal of the ECO2 project was to understand the short-term and long-term impacts of CO_2 storage on marine ecosystems. The individual objectives associated with this overall goal are:

1. To investigate the likelihood of leakage from sub-seabed storage sites
2. To study the potential effects of leakage on benthic organisms and marine ecosystems
3. To assess the risks of sub-seabed carbon storage (based on objectives 1 and 2)
4. To develop a comprehensive monitoring strategy using novel monitoring techniques
5. To define guidelines for the best environmental practices in the implementation and management of sub-seabed storage sites (based on objectives 1 to 4)

I was mainly involved in WP1, which concentrated on the architecture and integrity of the sedimentary cover at storage sites and in CCT1, a cross cutting theme aiming at coordinating the development of monitoring techniques and strategies. I also contributed to CCT2, a cross cutting theme aiming to interface between the numerical models and in CCT4 aimed to develop a framework of best environmental practices in the management of offshore CO_2 injection and storage.

WP1 undertook field studies at two operational industrial CO_2 storage sites, i.e. Sleipner in the North Sea and Snøhvit in the SW Barents Sea. ECO2 also investigated two natural CO_2 seepage sites (North Sea, Mediterranean Sea)(Schmidt et al. 2015). Geoscientists working within this WP, like our research team in Tromsø directed by my supervisors, characterized the sedimentary cover at Snøhvit, using existing and novel geophysical data. Our aim was to better assess potential CO_2 migration mechanisms and pathways into the shallow subsurface and the risks associated with storage of CO_2 below the seabed. My contribution specifically consisted of carrying out an analysis of 3D seismic and well logs data, in order to generate and establish geological models for the overburden structure of the Snøhvit industrial CO_2 storage site. The geological models created represent an important input for modeling of fluid and gas flow through the overburden of storage sites and for the risk assessment.

In CCT2, different teams modeled the whole system based on hypothetical leakage scenarios. CCT2 interfaced the different modelling teams from the storage formation through the subsurface to the seabed interface with CO_2 transfer into the ocean and potentially to the atmosphere. In this CCT, my geological models provided the framework for implementation of possible leakage scenarios and allowed to assess model performance and uncertainty for the reservoir leakage part of the study. The models also allowed studying the spatial and temporal evolution of possible CO_2 leakage with respect to size, provenance and variability of CO_2 fluxes, their relation to changes in surrounding environments and their likelihood of occurrence.

My results also helped in the establishment of various deliverables and reports. These include deliverables on the framework of best environmental practices to guide the management of offshore CO_2 injection and storage i.e. deliverable D1.2 entitled “WP1 result summary report relevant for Environmental Best Practice” and the work on risk assessment, i.e. deliverable D1.3 entitled “WP1 summary report relevant for risk assessment”. I also contributed to D1.1, which corresponds to a report on leakage assessment, to D12.3, a synthesis report for CCT2 on predicted impacts and uncertainties and to MS12, a milestone report on geological models for industrial storage sites. For further details concerning my contribution to various project reports and deliverables please refer to the appendix where a complete list is provided.

SCOPE OF THESIS

Objectives

The specific objectives of this PhD project itself are mostly related to the analysis of the overburden structure of the Snøhvit storage site and include:

- To better understand the architecture and to characterize the subsurface geometry of the overburden in the Snøhvit storage site.
- To carry out a baseline study using existing and novel geophysical data to better assess fluid migration mechanisms and pathways into the shallow subsurface.
- To better identify and understand fluid leakage phenomena and potential leakage sites, to assess cap rock integrity throughout the whole overburden and to identify areas of high-priority for future monitoring in the storage site.
- To optimize existing and develop new techniques and tools for monitoring CO_2 migration from the storage formation to the seabed and assess their quantitative efficacy in detecting and measuring a particular CO_2 leakage.
- To provide a catalogue of possible leakage scenarios, their spatial and temporal evolution with respect to size and variability of CO_2 fluxes, their relation to changes in surrounding environments and their likelihood of occurrence.
- To document the key elements for effective risk management of geological storage with respect to overburden structure and leakage rates.

Methods used in the project

New state-of-the-art technology was employed for an enhanced imaging of the seafloor and its sub-surface at unprecedented resolution. New P-Cable high-resolution 3D seismic imaging techniques (UiT, IFM-GEOMAR) provided us with more detailed images of sub-surface architecture and enhanced detection of fluid leakage, which led to a better understanding of the mechanisms of fluid flow through the sedimentary overburden of CO_2 storage sites. The P-Cable 3D high-resolution seismic system consists of a seismic cable towed perpendicular (cross cable) to the vessel's streaming direction (Planke et al.

2009). Up to 24 streamers can be connected to the cross cable and are towed parallel behind the ship. Streamers with hydrophones measure 25m long and contain 8 channels each (Figure 1). The array of multi-channel streamers is used to acquire many seismic lines simultaneously, thus covering a large area with close in-line spacing in a cost efficient way.

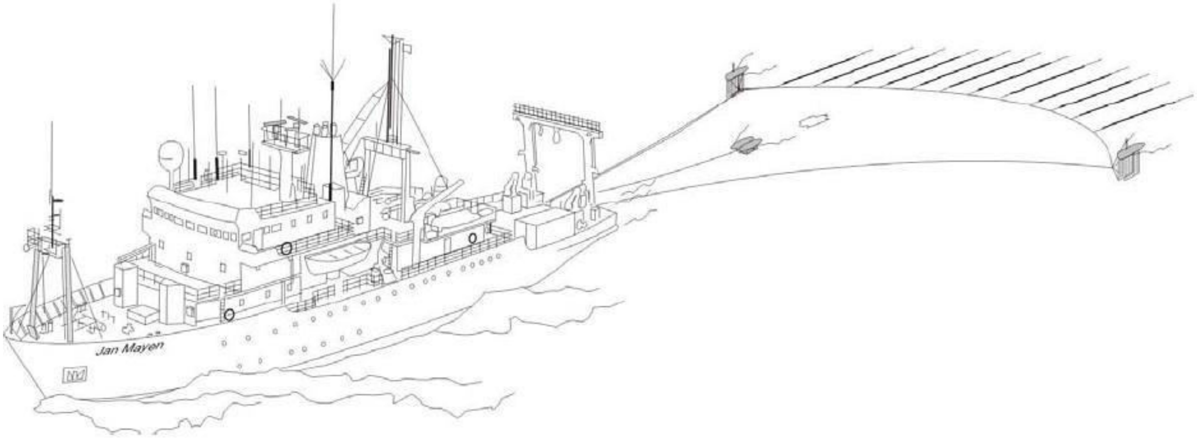

Figure 1. Schematic sketch of the P-Cable high-resolution 3D seismic system

The primary method employed in this thesis is seismic interpretation of both conventional and P-Cable 3D seismic data using Schlumberger's Petrel software. The seismic interpretation consisted of mapping key reflectors located in the Snøhvit subsurface and deriving volume-based attribute information, like RMS amplitude or variance. Interpreted horizons were then used to construct surfaces and layers, which were subsequently populated with geological properties. This so-called geological modeling corresponds to the development and building of 3D models and was undertaken as part of the ECO2 project activities. Potential leakage structures like faults or gas chimneys were implemented into the models. We then used reservoir simulation methods that we applied on the previously constructed geological models in order to understand how fluids would migrate under different conditions and over various periods.

Many tools exist for monitoring geologic storage of CO_2 and modeling of possible fluid migration through the overburden. However, the spatial and temporal resolution of these methods may not be sufficient for storage auditing and leak detection. The use of new state-of-the-art technologies can allow to analyze and propose monitoring schemes that enhance the ability to detect small thresholds of CO_2 leakage from storage formations.

Assessment of risks include identifying potential subsurface leakage modes, the likelihood of an actual leak, leak rate over time, and the long-term implications for safe carbon storage.

IMPORTANCE OF CCS IN REDUCING CO_2 EMISSIONS AND IN MITIGATING CLIMATE CHANGE

There is an overwhelming scientific consensus that climate change is due primarily to the human use of fossil fuels, which releases carbon dioxide and other heat-trapping greenhouse gases into the air (Hansen et al. 2000; Solomon et al. 2007). The gases trap heat within the atmosphere, drive global warming and have a range of effects on ecosystems, including causing rising sea levels, severe weather events and droughts that render landscapes more susceptible to wildfires. Climate change is a complex problem with many dimensions. Responding to climate change involves a mitigation phase (Hepple and Benson 2003) where the aim is to introduce actions to limit the magnitude or rate of long-term climate change. This can be achieved by reducing and stabilizing the levels of heat-trapping greenhouse gases in the atmosphere.

In this context, the role of Carbon Capture and Storage (CCS) becomes important, as it is one of very few options available to us to maintain the value of fossil fuels whilst reducing emissions (Figure 2). It is believed that CCS is the only mature technology that can reduce CO_2 emissions from the burning of fossil fuels significantly (Aarnes 2012). CCS provides us with many opportunities since it is of global interest and allows fossil fuels to continue being part of the energy mix, whilst assuring a high export potential.

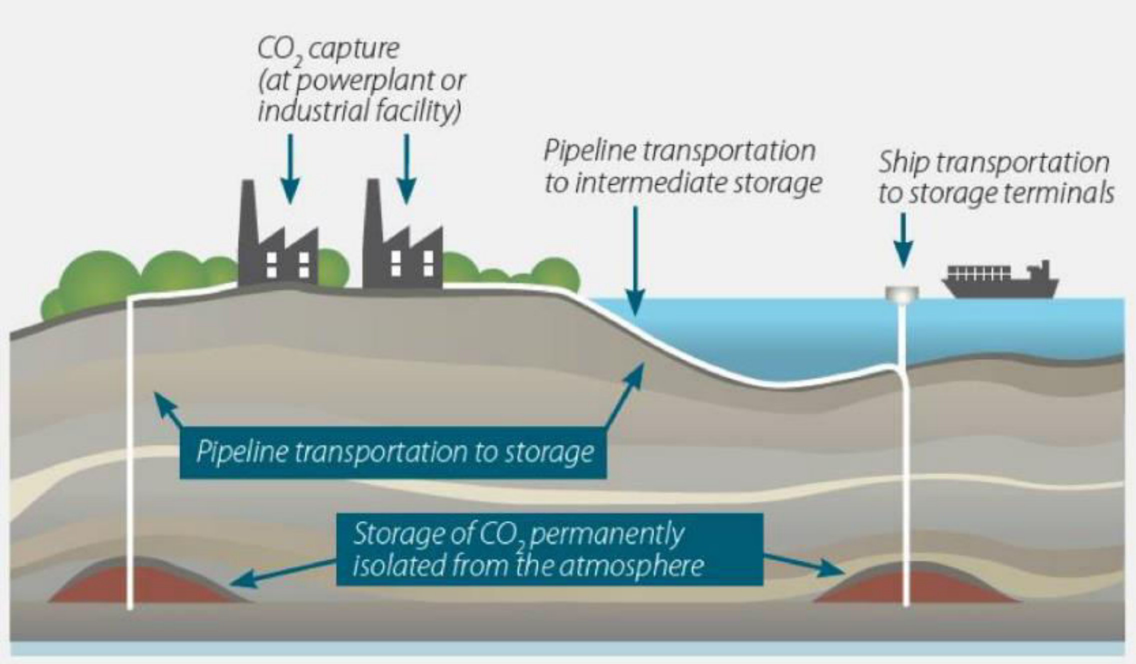

Figure 2. Carbon Capture and Storage (CCS) concept (http://clicinnovation.fi/activity/ccsp/)

By injecting CO_2 back into the earth and not leaving it to accumulate in the atmosphere, through the process of CCS, we can put forward a potential and innovative way of reducing CO_2 emissions and thus mitigate climate change. Although CCS is highly debated (Huijts et al. 2007), it has been used extensively in some countries, such as the USA, Scotland and Norway, thus providing a means to implement this method and remove CO_2 from the atmosphere (Mabon et al. 2014).

CCS technology corresponds to a mature and feasible solution that can be applied in order to more specifically meet the EU objective of reducing greenhouse gas emissions by 85% by 2050 compared to 1990 levels. The storage of CO_2, which is already taking place in various sites around the world, such as Sleipner in Norway, Insalah in Algeria and elsewhere, can be considered as an option in order to contribute to the reduction of greenhouse gas emissions in the atmosphere and an important contribution for providing a solution to Europe's Integrated Energy System. According to the draft Issues released by the SET Plan secretariat in April 2016, CCS is put forward as the only solution for reducing CO_2 emissions from carbon intensive industries that generate CO_2 as part of their production processes.

Many aspects of carbon capture and storage (CCS) are well-understood in chemical engineering and the oil and gas industries. Globally, there appears to be sufficient storage volume for decades to come, with depleted oil reservoirs being obvious targets for CCS projects (Sinayuc et al. 2011). Despite a successful record, CCS remains controversial (Howell et al. 2014). Little is still known about the consequences of CCS and the impacts of CO_2 storage on marine ecosystems even though CO_2 has been stored sub-seabed for over 20 years in the North Sea (Sleipner field) and for over 8 years in the Barents Sea (BS) (Snøhvit field)(Aarnes 2012; Jones et al. 2015). Technical concerns also exist and include issues such as long-term leakage, global capacity, engineering feasibility and the scale of deployment (Gonzalez-Nicolas et al. 2012; Pacala 2003; Pawar et al. 2015). Public opposition exists and often focuses on perceived risks from leakage (Howell et al. 2014; Mabon et al. 2014).

RISK OF GEOLOGICAL STORAGE OF CO_2

Fluid flow features, mechanisms and detection

Expanding geologic storage of CO_2 to a much larger scale worldwide will require a better understanding of sub-surface fluid flow, its subsurface expressions, associated mechanisms and detection methods (Schmidt et al. 2015; Vadakkepuliyambatta et al. 2013).

Submarine fluid flow is a geological process, dynamic in character, which we encounter on all continental margins around the world. Fluid flow refers to the migration of fluids, including oil or gas, through the subsurface. In some cases, the study of fluid flow can include those stages where fluids are able to reach the seafloor and ocean or atmosphere. Fluid flow can be triggered by varying processes that vary in space and time, and is usually driven by hydrodynamic gradients or buoyancy.

Typical fluid pathways that are taken by the migrating fluids in the subsurface include seismic chimneys and pipes, which correspond to vertical seismic anomalies interpreted as focused fluid flow structures, as well as leaking faults (Figure 3).

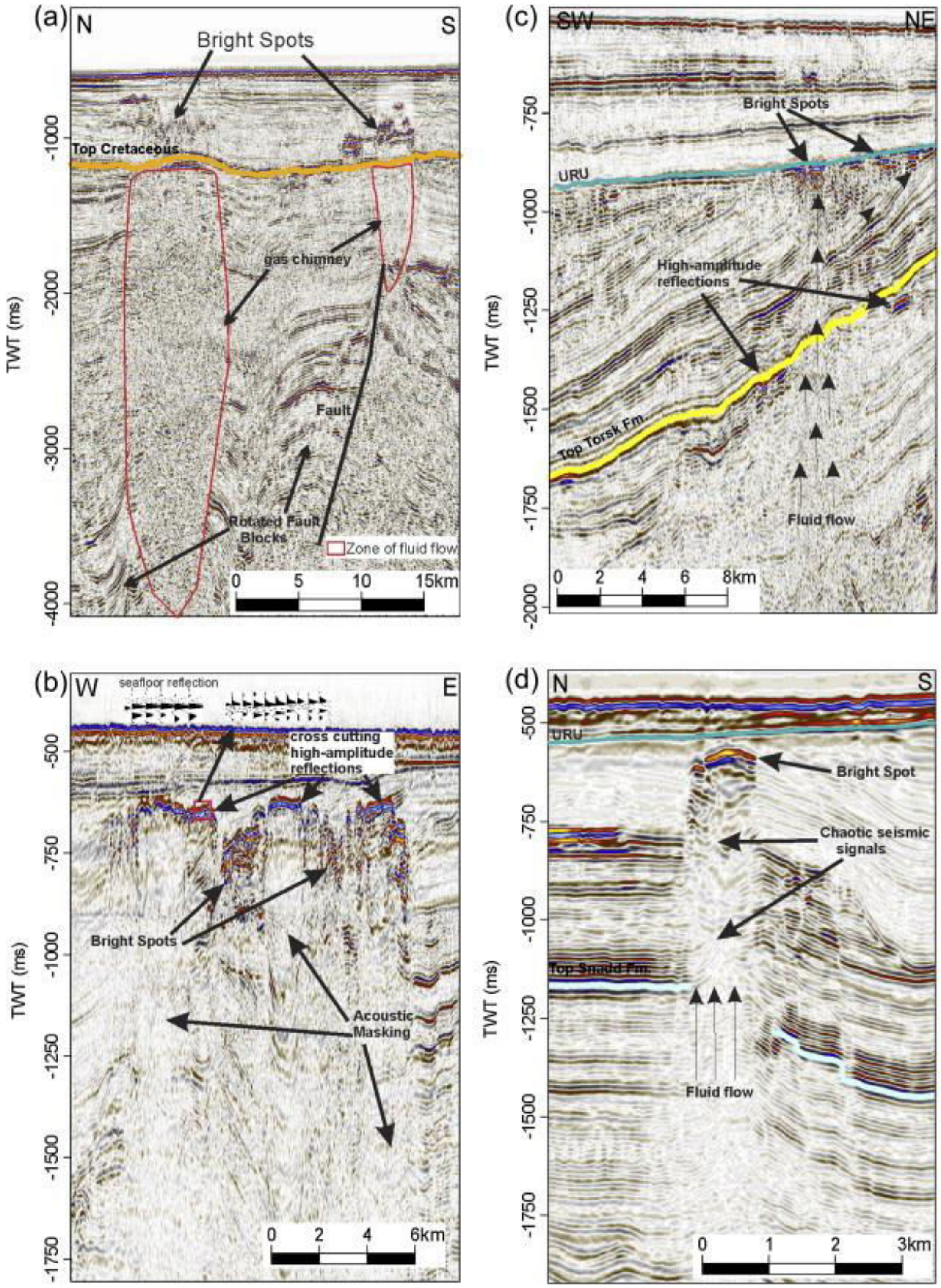

Figure 3. Examples of fluid flow pathways in the SW Barents Sea Basin (Vadakkepuliyambatta et al. 2013)

They hydraulically connect deeper stratigraphic layers with the overburden (Figure 3)(Cartwright et al. 2007; Loseth et al. 2009). The scale of seismic chimney structures varies from meters to hundreds of meter in length and diameter. Seismic chimneys most likely represent a continuum of geological structures including gas filled fracture networks, the remnants of single pulse blowout-like gas expulsions and zones of sediment fluidization as the result of overpressure charged fluid flow. Other examples of fluid flow pathways include fractures and faults. Faults represent areas of weakness with respect to geomechanical processes and can be either permeable or impermeable (Meldahl 2001; Petersen et al. 2010; Vadakkepuliyambatta et al. 2013).

Seabed fluid flow indicators such as pockmarks (Figure 4), mud volcanoes, pingos and authigenic carbonate build up, which are related to hydrocarbon migration also exist and can be revealed by the analysis of acoustic and seismic data (Hovland and Svensen 2006; Kulin et al. 2013). Pockmarks correspond to erosive features formed by escape of gas and/or fluids from low-permeability, fine-grained surficial sediments (Figure 4). Pingoes and bacterial mats are consistently found adjacent to carbonate ridges and inside crevasses, between large carbonate blocks. It is thus suggested that the upwardly migrating fluids are channeled around these. The fluids must migrate through distinct conduits, which remain active for long periods, such that pingoes can form and grow (Hovland and Svensen 2006).

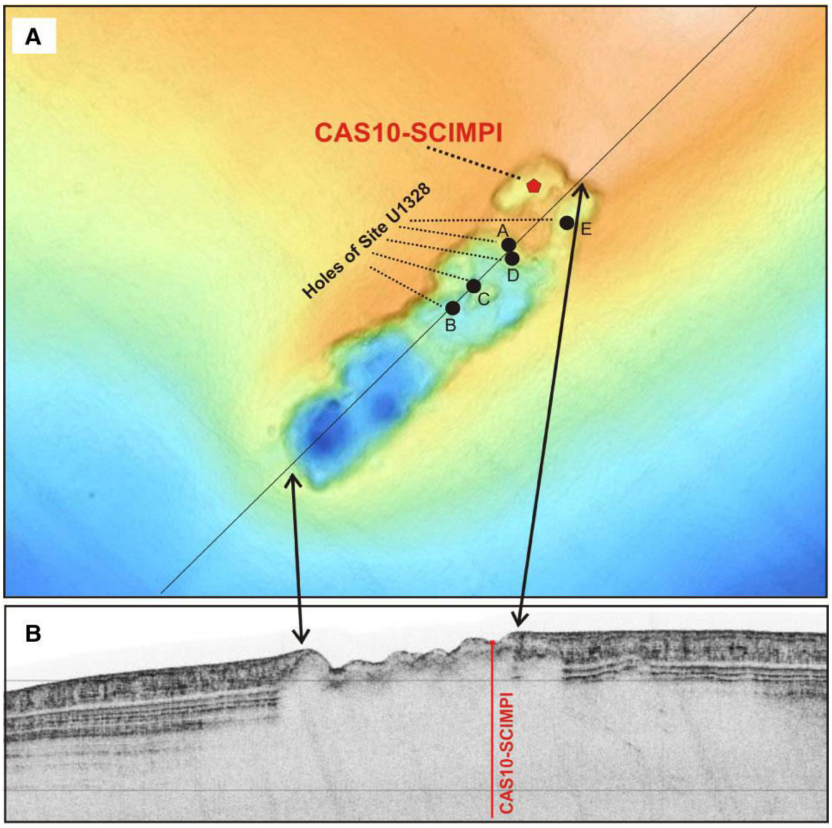

Figure 4. A. Map of Site CAS10 location in the Bullseye Vent system, including holes drilled at Site U1328. B. High-resolution seismic reflection data show the hummocky seafloor with multiple small pockmark-like depressions (Kulin et al. 2013)

Fractures can also exist on the seafloor, but are difficult to detect with the use of conventional 3D seismic. To reveal potential seafloor leakage structures in detail, the use of an autonomous underwater vehicle (AUV) equipped with a high-resolution interferometric synthetic aperture sonar system (HISAS – commercially available) is necessary. Fractures in the seafloor can be connected to a complex fracture network in the subsurface and give rise to active fluid or gas flow from deep geological formations into the seawater (Smith et al. 2011). The most obvious indicators for fluid or gas flow from a fracture are the growth of bacterial mats or bubbles rising from the seafloor.

Methods of subsurface detection and imaging of fluid flow include 2D seismic and 3D seismic (including newly developed high-resolution P-Cable seismic). Seismic investigation can be complemented by sub-bottom profiling in order to fill the resolution gap around the seafloor. Seismic data is very sensitive for imaging seafloor parallel structures, but has limitations in resolving vertical oriented structures. The seismic image of vertical conduits is therefore not very detailed. When interpreting seismic chimneys, it is thus important to rule out that the chimney itself is only a seismic artifact as the result of inadequate processing, data gaps or amplitude blanking beneath seismic anomalies.

The P-Cable high-resolution 3D seismic system has proven useful for mapping fluid leakage systems, shallow gas and gas hydrates. P-Cable 3D seismic allows to image and characterize the top part of the subsurface in much more detail than conventional 3D seismic (Petersen et al. 2010).

Finally, multibeam echosounders (MBES) and single-beam echosounders (SBES) are powerful tools to image both the water column and the seabed. SBES can be used to identify the presence or absence of bubbles within a typical 10-degree beam footprint. MBES systems are used to collect high-resolution seafloor profiles across a swath typically 2-2.5x the water depth. Multibeam systems can also be used to acquire water column information, giving a perception of the full 3D shape of rising bubble plumes.

Fluid flow and leakage assessment

Assessing the risks for CO_2 leakage from a sub-seabed sequestration site is a complex task, which requires detailed knowledge about local geology including the natural fluid flow system and the hydraulic parameters of the seal and the storage formation. It thus becomes necessary to consider the relations between fluid flow and rock integrity, as well as possible leakage scenarios and risks in order to develop, improve, and incorporate current industry operations, government regulations for public safety and environmental impacts from such storage activities (Aarnes 2012; Chiaramonte et al. 2008; Eiken et al. 2011; Jones et al. 2015; Pawar et al. 2015).

Leakage assessment is a process by which an understanding of potential leakage scenarios is developed. It is a purely hypothetical process and does by no means imply that storage site integrity is compromised by the sheer presence of leakage structures.

This leakage assessment process includes four key components:

- the ability to detect a potential leakage pathway;
- the ability to detect small fractions of leaking gas;
- the identification of potential leakage scenarios;
- the qualitative assessment of the likelihood of leakage considering site characteristics and the geological setting.

A significant environmental risk associated with large-scale, sub-seabed CO_2 storage is the potential for leakage from the reservoir, through the overburden and reaching the seabed. Dealing with the effects of leaking CO_2 on the local ecosystem is very unpredictable but past experience can at least provide some guidance as to how such systems will react (Jones et al. 2015; Tannert et al. 2007; Widdicombe et al. 2013).

The evaluation of geological risks for the sub-seabed storage of CO_2 can be built on a set of leakage risks which give rise to the development of leakage scenarios and later on to a set of numerical simulations that predict the plume evolution in space and time. The leakage scenarios are representative of situations where the reservoir and the seabed are connected with a certain leakage structure or migration pathway (Hustoft et al. 2007; Ligtenberg 2005). In addition to man-made structures, e.g. boreholes, several geological structures potentially acting as pathways for leakage of CO_2 can be identified in a certain study area. These geological structures can be classified into 3 types: (a) permeable faults, (b) seismic chimneys, and (c) seismic pipes (Loseth et al. 2011; Meldahl 2001; Petersen et al. 2010; Vadakkepuliyambatta et al. 2013). The leakage scenarios can be either generic or refer to one particular site-specific situation.

Generic leakage scenarios

The proposed ECO2 project's aim was to assess the likelihood of leakage through the seabed and the impact of leakage on marine ecosystems. Observations of commercial field experience and storage projects in progress, do not suggest large-scale leakage will occur. However, at the beginning of the project, there was no definitive assessment of the magnitude of this leakage risk, its spatial and temporal evolution and potential emission rates. The results of the various studies carried out in ECO2 and results from existing storage sites and natural analogues of CO_2 leakage provided information that can help better constrain this risk.

Existence of uncertainty also gives rise to the need of having a risk assessment. ECO2 project collaborators aimed at considering the environmental risks associated with CCS and how these risks may affect the financial, legal, and political considerations surrounding the future geological storage of CO_2. These objectives were met by conducting environmental risk assessments (ERA) and by estimating the potential costs associated with monitoring and intervention in the case of CO_2 leakage and environmental damage resulting from CO_2 leakage (Widdicombe et al. 2013).

In the framework of the ECO2 project a set of numerical simulations were carried out in order to quantify the risk of leakage of CO_2 for different generic leakage scenarios, which have been summarized in D1.1, including the leakage through pre-existing fluid flow systems, faults, abandoned wells and the creation of a blowout scenario.

During the ECO2 modelers meeting in Plymouth in March 2014, the project agreed on four generic leakage scenarios, which should be simulated in order to create first benchmark models with a priority given on scenarios 1 and 2 (Table 1). The proposed leakage scenarios were then successfully implemented into the fluid flow simulations (Blackford et al. 2012).

Table 1. Leakage scenarios based on the March 2014 modelers meeting (Blackford et al. 2012)

Scenario	**Max flux rate (at seafloor)**	**Footprint (at seafloor)**
1) Seismic Chimney	~150T/d	500m diameter circle
2) Fault/Fracture	~15T/d	200x2000m^2 fracture zone
3) Blowout	~150T/d	50m diameter circle
4) Well/borehole	~20T/a	few meters diameter

The different leakage scenarios were implemented into various geological models that included one of the above-mentioned geological or man-made features to be modeled. The models were then populated by petrophysical properties that were approximated from real-world petroleum systems. This input comes mainly from indirect (3D seismic) or direct observations (well log data, well cores, outcrops) but often not complete geophysical data. The missing data had to be calculated from available petrophysical principles. The spread of values for each individual physical property provided some means of an uncertainty range.

We thus took into account the possible variability in the property values whether they be porosity (Phi) or permeability (K) or other. Based on the standard deviation, calculated for both Phi and K it was possible to determine a range of property values per zone of the model. The results obtained were classified into a Low, Medium and High scenarios, which resulted in a range of fluxes and mass balances for each scenario.

CCS AT SNØHVIT

The Snøhvit site is located in the SW Barents Sea, on the Norwegian continental shelf, and more specifically in the ENE-WSW oriented Hammerfest Basin (HFB), which is about 130km off the coast of Finnmark, northern Norway (Figure 5). The Barents Sea is a large epicontinental sea and part of the Arctic Ocean located north of Norway and Russia. It is bordered by Novaya Zemlya in the east, Franz Josef Land and Svalbard in the north, and the Norwegian Sea to the west. With an area of 1.3 million km^2 and water depths averaging approximately 300 m, it is one of the largest areas of continental shelf in the world (Figure 5).

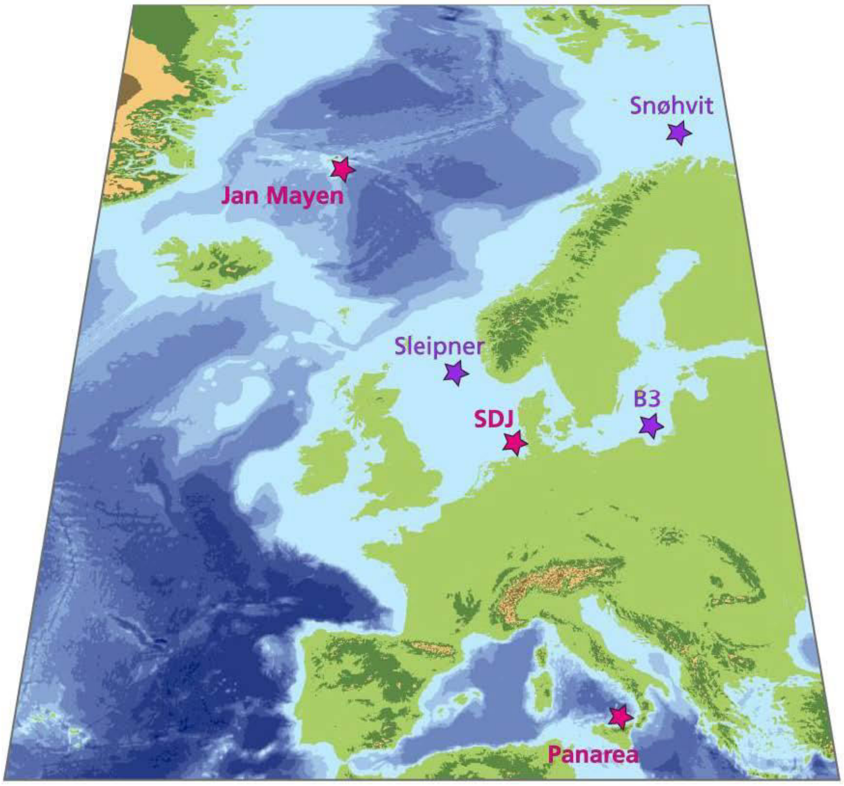

Figure 5. Location of the Snøhvit site in relation to the other storage sites (purple star) and natural seeps (pink star) of the ECO2 project

The HFB contains approximately 5000 m of strata above the basement (Linjordet and Olsen 1992) and was probably established in the Late Carboniferous (Gabrielsen 1990). Important subsidence events had taken place in the Triassic and Early Cretaceous. The main basin development phases took place, however, during the Mid to Upper Jurassic times (Linjordet and Olsen 1992).

Abundant and widespread fluid flow can be observed in the SW BS (Meldahl 2001; Vadakkepuliyambatta et al. 2013). The observed fluid flow features can be of various types, interpreted as gas chimneys, leakage along faults and fractures and other related features (Ostanin et al. 2012; Petersen et al. 2010). Gas chimneys are the most common fluid-flow feature in the BS and appear in most parts with various sizes and shapes. Large gas chimneys cover areas of up to 600 sq.km and feature close to major discoveries. Fluid flow features generally correlate with structural elements. Leakages along faults are present in almost all parts of the SW BS. Large fluid-flow features have peculiar shapes and cover huge areas. Most of them terminate in the shallow strata, with high amplitude reflections at their crest, suggesting shallow gas accumulation.

Focused fluid flow expressions can cover a wide range of geological phenomena ranging from mud volcanoes (Perez-Garcia et al. 2009) to pockmarks, pipe structures, diapirs and gas hydrates (Chand et al. 2012; Judd and Hovland 2007) with pockmarks being the most common feature encountered in the BS study area (Chand et al. 2008; Chand et al. 2009). Several gas flares occur along various segments of Fault Complexes in the BS, indicating open fractures and active fluid flow (Chand et al. 2012). The proximity of geological features such as salt domes and a shallow basement and the presence of faults cause also focused fluid flow (Chand et al. 2008).

Snøhvit, receives ~0.7 Million tons of CO_2 per year and has been in operation since late 2008 (Aarnes 2012). CO_2 is captured at Melkoya LNG terminal near Hammerfest and is transported roughly 153 Km out at sea towards a subsea location where it is injected and stored in a saline sandstone formation. This corresponds to the Tubåen Formation and is located at ~330 m water depth and ~2.6 Km sediment depth (Aarnes 2012). Injection into the Tubåen formation stopped in 2011 and a new injection point was facilitated in the lower Stø Formation. The carbon dioxide injected is first separated from feed gas.

The oil produced from Snøhvit is from the first offshore oil field that functions without offshore installations. Statoil, the field's operator, has already acquired experience with CO_2 storage from Sleipner, and thus Snohvit is its second large-scale CO_2 storage project. Furthermore, the Hammerfest LNG plant is the first plant for liquefying natural gas in Europe and the first petroleum production plant in Northern Norway.

SUMMARY OF THE ARTICLES

Article 1: Tasianas, Alexandros; Martens, Iver; Bünz, Stefan; Mienert, Jurgen. **Mechanisms initiating fluid migration at Snøhvit and Albatross fields, Barents Sea**. *Arktos 2(1), 1-18 (2016).* ISSN 2364-9453.s doi: 10.1007/s41063-016-0026-z.

Article 1 presents and discusses aspects of the fluid leakage system in the SW Barents Sea, which is characterized by an abundance of large gas chimneys, leaking faults and seabed pockmarks. These large focused fluid flow structures occur in close vicinity to the major hydrocarbon reservoirs and are proof that hydrocarbon leakage has taken place in the past. This paper analyses conventional 3D seismic data from the Snøhvit hydrocarbon field in the Hammerfest basin in order to determine the origins and mechanisms initiating fluid flow in the area. This was achieved by looking at the possibility of occurrence of fluid expulsion and migration out of proven reservoirs in the past. It is thought that the denudation of the Barents Sea during the glacial cycles and the major episodes of uplift and erosion were responsible for having caused such fluid flow in the past. We identified potential spill point locations by mapping the trap of the hydrocarbon reservoirs. The spill points coincide with two major gas chimneys and several faults that extend into shallow strata. Mechanisms initiating fluid flow that we proposed are related to uplift and erosion causing an expansion of gas in hydrocarbon reservoirs. This in turn allowed the gas to reach below the spill point. Fluid flow from these reservoirs then initiated at the spill points of the reservoirs, at the bottom of the closure corresponding to the gas-water contact. Fluids may have thus escaped, through the spills points, leading to the emplacement and development of the gas chimneys in the area. Similarly, other migration pathways were also taken into consideration and these include migration of fluids along faults. A mechanism might also have led to migration of fluids along faults that were reactivated by glaciotectonic processes and connect with spill points at reservoir depth. Any faults, whether they may be normal, reverse or strike-slip, close to the lateral ends of the reservoirs are thus likely to have been reactivated as a result of the glacial erosion in the Barents Sea. Both gas chimneys and faults have thus allowed gas to migrate into shallow strata, mostly below the upper regional unconformity but also within glacial sediments.

Article 2: Tasianas, Alexandros; Bünz, Stefan. **High-resolution 3D seismic study of pockmarks and shallow fluid flow systems at the Snøhvit hydrocarbon field in the SW Barents Sea**. *Under review in the Journal of Marine Geology.*

In Article 2 we analyse high-resolution P-Cable 3D seismic data from the Snøhvit area in order to unveil the fluid flow pathways in the shallow overburden and at the seabed in the vicinity of the Snøhvit gas field. The 3D seismic analysis provides a better understanding of the driving mechanisms and fluid flow dynamics in the shallow overburden that have led to the formation of pockmarks in the area. The paper not only concentrates on pockmark formation at the seabed around the Snøhvit gas field but also assesses the age and duration of pockmark development. In this paper we present two different types of pockmarks occurring at the seafloor, namely the "Normal pockmarks" (NPs), with elliptical shape and width up to a few hundred meters, and the "Unit pockmarks" (UPs), that are only up to 20 m wide. Fluid leakage from deep-seated hydrocarbon accumulation is a widespread phenomenon in the Barents Sea. Fluid flow pathways in the shallow overburden at Snøhvit are controlled by the presence of small-scale fault systems and updip migration along bedding strata of a small clinoform system below the glacial sediments. We present and discuss a model for the formation of the pockmarks that likely started to form during deglaciation when gases may have been released from free gas and dissociating gas hydrates that were trapped under the ice sheet. Active seepage likely occurred over a long period of time subsequent to the retreat of the ice sheet. Although fluid migration has taken place in the past in the study area, we clarify that at present, there is no active seepage of gas in the Snøhvit area.

Article 3: Tasianas, Alexandros; Mahl, Lena; Darcis, Melanie; Bünz, Stefan; Class, Holger. **Simulating seismic chimney structures as potential vertical migration pathways for CO_2 in the Snøhvit area, SW Barents Sea: model challenges and outcomes**. *Environmental Earth Sciences 75(6), 1-20 (2016).* ISSN 1866-6280.s doi: 10.1007/s12665-016-5500-1.

Article 3 provides an analysis determining the parameters that affect the migration process of CO_2 from the gas reservoir at Snøhvit. It provides an evaluation of the effects of applying a broad but realistic range of reservoir, fault and gas chimney properties on potential CO_2 leakage at various depths throughout the subsurface and an assessment of the potential of CO_2 reaching the seabed. Using the Snøhvit gas reservoir and overburden in the Barents Sea, the geological models that were built allowed for numerical simulations of CO_2 migration in focused fluid flow structures to be run. In the simulations, the CO_2 is injected over a 20 year period at a rate of 0.7 Mt/year and migration is allowed to take place over a 2000 year time frame for domains of various dimensions depending on the geological feature modelled, namely faults and realistic or generic gas chimneys. The total mass of CO_2 injected in the reservoir during the 20-year injection period amounted to 14 Mt. The parameter that had the most influence on the CO_2 migration process was probably the permeability of the reservoirs, especially the average permeability (k). CO_2 migration was also very sensitive to the uncertainty from the permeability of fluid flow pathways. Depending on the gravitational number, the plume shape changes and the leakage rates are strongly affected. In the caprock fault models, fault thickness and the contrast between average permeability and fault permeability are important parameters at Snøhvit. When the average permeability is low, there is a difficulty to start the CO_2 migration process, and the variation in fault permeability and thickness has greater effect than for medium and high average permeabilities. In addition, for the faulted caprock scenarios, we came to the important conclusion that at near surface depths the permeability of 765 mD is already large enough for a significant CO_2 flow; therefore, there is no influence of a further increase. However, at the chimney top level (600 m) a further increase from 765 to 3000 mD has an additional effect on improving CO_2 flow. In the realistic chimney scenarios, the average permeability parameter strongly influences the CO_2 migration at 370 m depth. At all depths and at low permeability of zone 9, average permeability becomes a determining factor in the CO_2 migration process. Finally, in the generic gas chimney scenarios, also, the average permeability strongly influences the maximum flux and the total amount of CO_2 migrated. The total amount of CO_2 that migrates strongly depends on the interaction between average permeability, which strongly influences the plume shape and the velocity for the CO_2 movement, the diameter of the chimney, which influences the capturing area, and the storage capacity due to the residual saturation in the chimney, which is increased with increasing diameter. For the worst-case scenario, it only takes 3.4 years for the CO_2 to start to leak from the top of the reservoir and another 22.1 years for it to reach the seabed. In this case, 33,7 % of the initial CO_2 injected, leaks at the seabed. Despite the above-mentioned results, no leakage of CO_2 is actually taking place from the Snøhvit reservoir today.

Article 4: Tasianas, Alexandros; Koukouzas, Nikolaos; Gemeni, Vassiliki; Alexopoulos, Dimitrios; Vasilatos, Charalampos. **Geological modelling for investigating CO_2 emissions in Florina Basin, Greece**. *Open Geosciences 7(1), 465–489 (2015)*. ISSN 2391-5447.s 465 - 489.s doi: 10.1515/geo-2015-0039.

Article 4 presents an investigation of naturally occurring CO_2 emissions from the Florina natural analogue site in Greece as a comparison to the CCS activities carried out at the industrial site at Snøhvit. The main objective was to interpret previously collected depth sounding data and use them to develop 3D geological models of the Florina basin. By also locating the extent of the aquifer, the location of the CO_2 source, the location of other natural CO_2 accumulations, and the points where CO_2 reaches the surface, we were able to assess the potential for CO_2 leakage and compare the mechanisms of natural seepage occurring here to the mechanisms of CO_2 migration at the overburden at Snøhvit. The geological models provided a better understanding of the 3D structure of the Florina Basin and allowed us to determine possible directions of groundwater flow and the pathways the CO_2 can take to migrate throughout the basin. They provided important insight into the lateral and vertical extent of the aquifer in specific formations throughout the basin by illustrating the basin wide extent of the upper and lower limits of the aquifer. The geological models also provided and confirmed the existence of around 1000 m of sediments above the basement in the area around the Mesochorion village. The NE-SW oriented faults, which acted as fluid flow pathways, are still functioning today, allowing for localized leakage at the surface. The surface indications of CO_2 seepage around Florina city have also been observed in Neogene marls and clays. The faults developing in the Neogene sediments, for example, can facilitate the vertical migration of CO_2. Carbon dioxide accumulations in the Mesochorion area are characterized by an absence of an upper cap rock layer, as indicated by the model. CO_2 can therefore leak due to the absence of a cap rock in these specific locations, not only laterally but also directly upwards. CO_2 can flow in the pores of the permeable sediments or dissolved in water either in the same direction or against the direction of groundwater flow. CO_2 could thus have flowed from the Mesochorion geological reservoir, located at approximately 300 m depth, through the

Neogene aquifers and faults to the near surface using several different migration pathways, as indicated in the geological model. Initiation of CO_2 flow at Florina Basin could have taken place between 6.5 Ma and 1.8 Ma ago. CO_2 leakage may be spatially variable and episodic in rate with the episodicity being linked to the timing of Almopia volcanic activity in the area.

Article 5: Tasianas, Alexandros, Buenz, Stefan, Vadakkepuliyambatta, Sunil. & Mienert, Juergen. **Buried subglacial landforms in the SW Barents Sea imaged using high-resolution P-Cable seismic data**. *In*: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K. & Hogan, K.A. (eds) *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. Geological Society, London, Memoirs, **46**, 183–184 (2016). http://doi.org/10.1144/M46.117.

Article 5 presents an interpretation carried out on high-resolution P-Cable seismic data, characterized by a frequency bandwidth of up to 300 Hz and a spatial resolution of 6 × 6 m, acquired along the border between the Ringvassøya Fault Complex and the Loppa High in the SW Barents Sea. A large, grounded ice sheet covered the epicontinental Barents Sea multiple times during the Late Pleistocene. The glacier eroded away large amounts of sediments from the Tertiary and Cretaceous sedimentary successions of the Barents Sea. In this paper, we present the palaeo-landforms from the erosional base for continental-shelf glaciations, namely the Upper Regional Unconformity (URU). The URU consists of sub-parallel lineations running in two different directions almost normal to each other and truncates the underlying westwards-dipping Tertiary sediments. We observe some east-west trending set of ridges and depressions observed on the URU, called mega-scale glacial lineations, which we interpret to be the result of soft-sediment deformation that has recorded the palaeo-ice-flow direction of the advancing ice sheet. The seismic data is also characterized by a presence of shallow gas accumulating in beds that are more permeable and distributed in a homogeneous way. The gas might have further promoted the weakening of the sedimentary rock allowing for the overriding glacier to erode deeper into some of the beds thus leading to the formation of depressions that are orientated almost normal to the ice-flow direction.

FUTURE RESEARCH

The second P-Cable 3D seismic cube obtained at Snøhvit was partially interpreted but the interpretation and analysis should continue. The first cube, that led to the writing of the 2nd article, was partially repeated in summer 2013. The objective of the time-lapse survey in 2013 was mainly to develop the P-Cable technology into an effective monitoring technology at CCS sites. The 2011 and 2013 surveys should be compared visually by obtaining subcrop volumes and then subtracting these 2 from each other in order to determine if any changes have taken place.

Regarding article 3, further geological modeling and simulations could lead to studying the variation of other parameters in the sensitivity analysis that were not taken into consideration here. The time limit that we had didn’t allow to vary all the parameters that we would have liked to vary or that it could have been possible to vary. We mainly varied one parameter at a time, but in future research we could try varying 2 parameters at a time. The strategy for determining what parameters are more influential was applied to gas chimneys and faults but it could also be applied to other structures such as wells, etc. or to other geological settings e.g. to the Sleipner site or to generic scenarios or to scenarios somewhere in between real world and generic settings.

Future leakage assessment activities have to focus on quantifying the hydraulic properties of seal bypassing fluid conduits by studying field analogues, using multi-frequency acoustic surveys and ideally drilling into these gas chimney structures. Only a detailed knowledge about the hydraulic properties may help to quantify their actual leakage potential and thus potentially minimize the probability of CO_2 leakage in the modelled scenarios. Such knowledge, as well as better reservoir characterization, can also be integrated in monitoring strategies to mitigate the risk of CO_2 leakage (Edlmann et al. 2013; Schutze et al. 2012).

Regarding article 4, the results from the Florina site can form the basis for the development of novel monitoring techniques in future research. More specifically, we could undertake research activities that develop terrestrial leakage detection techniques and then compare them to monitoring strategies developed for seabed or sub-seabed leakage detection (Schmidt et al. 2015). The results from this research work can also be used as a basis to better understand CO_2 generation, migration and entrapment and give insight into the geochemical and mineralogical effects of carbon dioxide in the CO_2 natural analogue areas in Europe.

In both the conventional and P-Cable seismic data, clinoforms have been formed, but the full extent of clinoforms should be mapped. In the first paper, further studies that could be carried out include analysing fault throws as a structural framework study and the spill points at the top of the structure. It would be interesting to see whether we see any evidence of fluid flow structures/anomalies on seismic above the mapped spill points. In addition, the question concerning what impact the glaciations may have had on the leakage from thermogenic reservoirs could be further studied.

REFERENCES

Aarnes J (2012) Carbon Capture and Storage and the London Protocol. The regulation of continental shelf development, Halifax, Nova Scotia http://wwwvirginiaedu/colp/pdf/Halifax-Aarnespdf

Andreassen K, Nilssen EG, Odegaard CM (2007) Analysis of shallow gas and fluid migration within the Plio-Pleistocene sedimentary succession of the SW Barents Sea continental margin using 3D seismic data Geo-Mar Lett 27:155-171 doi:DOI 10.1007/s00367-007-0071-5

Berndt C (2005) Focused fluid flow in passive continental margins Philos Trans A Math Phys Eng Sci 363:2855-2871 doi:10.1098/rsta.2005.1666

Bjørlykke K, Avseth P (2010) Petroleum geoscience : from sedimentary environments to rock physics. Springer, Heidelberg ; New York

Blackford J, Haeckel M, Wallmann K (2012) Report on range of long-term scenarios to be simulated ECO2 Deliverable, D122, ECO2 Project, Plymouth Marine Laboratory 6pp doi:DOI 10.3289/ECO2_D12.2.

Cartwright J, Huuse M, Aplin A (2007) Seal bypass systems Aapg Bull 91:1141-1166 doi:Doi 10.1306/04090705181

Chand S, Mienert J, Andreassen K, Knies J, Plassen L, Fotland B (2008) Gas hydrate stability zone modelling in areas of salt tectonics and pockmarks of the Barents Sea suggests an active hydrocarbon venting system. Mar Petrol Geol 25:625-636

Chand S, Rise L, Ottesen D, Dolan MFJ, Bellec V, Boe R (2009) Pockmark-like depressions near the Goliat hydrocarbon field, Barents Sea: Morphology and genesis Mar Petrol Geol 26:1035-1042 doi:DOI 10.1016/j.marpetgeo.2008.09.002

Chand S et al. (2012) Multiple episodes of fluid flow in the SW Barents Sea (Loppa High) evidenced by gas flares, pockmarks and gas hydrate accumulation Earth Planet Sc Lett 331:305-314 doi:DOI 10.1016/j.epsl.2012.03.021

Chiaramonte L, Zoback MD, Friedmann J, Stamp V (2008) Seal integrity and feasibility of CO(2) sequestration in the Teapot Dome EOR pilot: geomechanical site characterization Environ Geol 54:1667-1675 doi:DOI 10.1007/s00254-007-0948-7

Dowdeswell JA, Canals M, Jakobsson M, Todd BJ, Dowdeswell EK, Hogan KA (2016) Atlas of Submarine Glacial landforms: Modern, Quaternary and Ancient. Geological Society, London, Memoirs 46 doi:doi.org/10.1144/M46

Duran ER, di Primio R, Anka Z, Stoddart D, Horsfield B (2013) 3D-basin modelling of the Hammerfest Basin (southwestern Barents Sea): A quantitative assessment of petroleum generation, migration and leakage Mar Petrol Geol 45:281-303 doi:10.1016/j.marpetgeo.2013.04.023

Eiken O, Gilding D, Hansen H, Nazarian B, Osdal B, Ringrose P (2013) Snøhvit: The history of injecting and storing 1 Mt CO2 in the fluvial Tubåen Fm. Proc GHGT11

Eiken O, Ringrose P, Hermanrud C, Nazarian B, Torp TA, Hoier L (2011) Lessons Learned from 14 years of CCS Operations: Sleipner, In Salah and Snohvit Enrgy Proced 4:5541-5548 doi:DOI 10.1016/j.egypro.2011.02.541

Frykman P (2001) Spatial variability in petrophysical properties in Upper Maastrichtian chalk outcrops at Stevns Klint, Denmark Mar Petrol Geol 18:1041-1062 doi:Doi 10.1016/S0264-8172(01)00043-5

Gabrielsen RH (1990) Structural elements of the Norwegian continental shelf. Part 1, The Barents Sea Region. NPD bulletin, vol no 6. Oljedirektoratet,

Gonzalez-Nicolas A, Cody B, Bau D (2012) STOCHASTIC ANALYSIS OF FACTORS AFFECTING THE LEAKAGE OF CO2 FROM INJECTED GEOLOGICAL BASINS XIX International Conference on Water Resources CMWR 2012, University of Illinois at Urbana-Champaign, June 17-22, 2012

Hansen J, Sato M, Ruedy R, Lacis A, Oinas V (2000) Global warming in the twenty-first century: An alternative scenario P Natl Acad Sci USA 97:9875-9880 doi:DOI 10.1073/pnas.170278997

Hansen O, Eiken O, Østmo S, Johansen RI, Smith A (2011) Monitoring CO2 injection into a fluvial brine-filled sandstone formation at the Snøhvit field, Barents Sea. SEG San Antonio 2011 annual meeting

Hepple RP, Benson SM (2003) Implications of surface seepage on the effectiveness of geologic storage of carbon dioxide as a climate change mitigation strategy Greenhouse Gas Control Technologies, Vols I and Ii, Proceedings:261-266

Hovland M, Svensen H (2006) Submarine pingoes: Indicators of shallow gas hydrates in a pockmark at Nyegga, Norwegian Sea Marine Geology 228:15-23 doi:10.1016/j.margeo.2005.12.005

Howell R, Shockley S, Mabon L, Ashworth P, Jeanneret T (2014) Engaging the public with low-carbon energy technologies: Results from a Scottish large group process Energ Policy 66:496-506 doi:10.1016/j.enpol.2013.11.041

Huijts NMA, Midden CJH, Meijnders AL (2007) Social acceptance of carbon dioxide storage Energ Policy 35:2780-2789 doi:DOI 10.1016/j.enpol.2006.12.007

Hustoft S, Mienert J, Bunz S, Nouze H (2007) High-resolution 3D-seismic data indicate focussed fluid migration pathways above polygonal fault systems of the mid-Norwegian margin Marine Geology 245:89-106 doi:DOI 10.1016/j.margeo.2007.07.004

Ingham DB, Pop I (1998) Transport phenomena in porous media. 1st edn. Pergamon, Oxford ; Danvers, MA

Jones DG et al. (2015) Developments since 2005 in understanding potential environmental impacts of CO2 leakage from geological storage Int J Greenh Gas Con 40:350-377 doi:10.1016/j.ijggc.2015.05.032

Judd AG, Hovland M (2007) Seabed Fluid Flow: The impact on Geology, Biology and the Marine Environment. Cambridge University Press, Cambridge

Kulin I, Riedel M, Klaus A (2013) Simple Cabled Instrument for Measuring Parameters In situ (SCIMPI) and Hole 858G CORK replacement IODP Sci Prosp 341S doi: doi:10.2204/iodp.sp.341S.2013

Ligtenberg JH (2005) Detection of fluid migration pathways in seismic data: implications for fault seal analysis Basin Res 17:141-153 doi:DOI 10.1111/j.1365-2117.2005.00258.x

Linjordet A, Olsen RG (1992) The Jurassic Snohvit Gas-Field, Hammerfest Basin, Offshore Northern Norway Aapg Memoir 54:349-370

Loseth H, Gading M, Wensaas L (2009) Hydrocarbon leakage interpreted on seismic data Mar Petrol Geol 26:1304-1319 doi:DOI 10.1016/j.marpetgeo.2008.09.008

Loseth H, Wensaas L, Arntsen B, Hanken NM, Basire C, Graue K (2011) 1000 m long gas blow-out pipes Mar Petrol Geol 28:1047-1060 doi:DOI 10.1016/j.marpetgeo.2010.10.001

Mabon L, Shackley S, Bower-Bir N (2014) Perceptions of sub-seabed carbon dioxide storage in Scotland and implications for policy: A qualitative study Mar Policy 45:9-15 doi:10.1016/j.marpol.2013.11.011

Maldal T, Tappel IM (2004) CO2 underground storage for Snohvit gas field development Energy 29:1403-1411 doi:DOI 10.1016/j.energy.2004.03.074

Meldahl P (2001) Identifying faults and gas chimneys using multiattributes and neural networks The Leading Edge

Ostanin I, Anka Z, Primio RD, Bernal A (2012) Identification of a large Upper Cretaceous polygonal fault network in the Hammerfest basin: Implications on the reactivation of regional faulting and gas leakage dynamics, SW Barents Sea. Marine Geology doi:10.1016/j.margeo.2012.03.005

Pacala SW (2003) Global constraints on reservoir leakage Greenhouse Gas Control Technologies, Vols I and Ii, Proceedings:267-272

Pawar RJ et al. (2015) Recent advances in risk assessment and risk management of geologic CO2 storage Int J Greenh Gas Con 40:292-311 doi:10.1016/j.ijggc.2015.06.014

Perez-Garcia C, Feseker T, Mienert J, Berndt C (2009) The Hakon Mosby mud volcano: 330 000 years of focused fluid flow activity at the SW Barents Sea slope Marine Geology 262:105-115 doi:DOI 10.1016/j.margeo.2009.03.022

Petersen CJ, Bunz S, Huston S, Mienert J, Klaeschen D (2010) High-resolution P-Cable 3D seismic imaging of gas chimney structures in gas hydrated sediments of an Arctic sediment drift Mar Petrol Geol 27:1981-1994 doi:DOI 10.1016/j.marpetgeo.2010.06.006

Planke S, Eriksen FN, Berndt C, Mienert J, Masson D (2009) P-Cable High-Resolution Seismic Oceanography 22:85-85

Schmidt M, Linke P, Sommer S, Esser D, Cherednichenko S (2015) Natural CO2 Seeps Offshore Panarea: A Test Site for Subsea CO2 Leak Detection Technology Mar Technol Soc J 49:19-30

Sinayuc C, Shi JQ, Imrie CE, Syed SA, Korre A, Durucan S (2011) Implementation of horizontal well CBM/ECBM technology and the assessment of effective CO2 storage capacity in a Scottish coalfield Enrgy Proced 4:2150-2156 doi:DOI 10.1016/j.egypro.2011.02.100

Smith J, Durucan S, Korre A, Shi JQ, Sinayuc C (2011) Assessment of fracture connectivity and potential for CO2 migration through the reservoir and lower caprock at the In Salah storage site Enrgy Proced 4:5299-5305 doi:DOI 10.1016/j.egypro.2011.02.510

Solomon S et al. (2007) Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 Cambridge University Press, Cambridge

Tannert C, Elvers HD, Jandrig B (2007) The ethics of uncertainty - In the light of possible dangers, research becomes a moral duty Embo Rep 8:892-896 doi:DOI 10.1038/sj.embor.7401072

Vadakkepuliyambatta S, Bünz S, Mienert J, Chand S (2013) Distribution of subsurface fluid-flow systems in the SW Barents Sea Mar Petrol Geol doi:http://dx.doi.org/10.1016/j.marpetgeo.2013.02.007

Widdicombe S, Blackford JC, Spicer JI (2013) Assessing the environmental consequences of CO2 leakage from geological CCS: Generating evidence to support environmental risk assessment Mar Pollut Bull 73:399-401 doi:10.1016/j.marpolbul.2013.05.044

Article 1

Mechanisms initiating fluid migration at Snøhvit and Albatross fields, Barents Sea

Tasianas, A., I. Martens, S. Buenz and J. Mienert

Arktos, 2(1), 1-18 (2016)

Article 2

High-resolution 3D seismic study of pockmarks and shallow fluid flow systems at the Snøhvit hydrocarbon field in the SW Barents Sea

Tasianas, Alexandros; Bünz, Stefan.

Under review in the Journal of Marine Geology

Article 3

Simulating seismic chimney structures as potential vertical migration pathways for CO_2 in the Snøhvit area, SW Barents Sea: model challenges and outcomes

Tasianas, A., L. Walter, M. Darcis, S. Buenz, and H. Class

Environmental Earth Sciences, 75(6), 1-20 (2016)

Article 4

Geological modelling for investigating CO_2 emissions in Florina Basin, Greece

Tasianas, A., N. Koukouzas, V. Gemeni, D. Alexopoulos and C. Vasilatos

Open Geosciences, 7(1), 465–489 (2015)

Article 5

Buried subglacial landforms in the SW Barents Sea imaged using high-resolution P-Cable seismic data

Tasianas, A., S. Buenz, S. Vadakkepuliyambatta & J. Mienert

Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient. Geological Society, London, Memoirs, 46, 183–184 (2016)

APPENDIX

The current appendix lists all the ECO2 reports and meetings to which I have contributed. For further details please consult the lists below and the following links to the relevant locations on the ECO2 web page:

http://www.eco2-project.eu/deliverables-and-publications.html

http://www.eco2-project.eu/meetings.html

ECO2 Reports and deliverables

2015

Wallmann, K., Haeckel, M., Linke, P., Haffert, L., Schmidt, M., Buenz, S., James, R., Hauton, C., Tsimplis, M., Widdicombe, S., Blackford, J., Queiros, A. M., Connelly, D., Lichtschlag, A., Dewar, M., Chen, B., Baumberger, T., Beaubin, S., Vercelli, S., Proelss, A., Wildenborg, T., Mikunda, T., Nepveu, M., Maynard, C., Finnerty, S., Flach, T., Ahmed, N., Ulfsnes, A., Brooks, L., Moskeland, T. and Purcell, M. *Best Practice Guidance for Environmental Risk Assessment for offshore* *CO_2* *geological storage*. ECO2 Deliverable, D14.1., 53 pp. DOI 10.3289/ECO2_D14.1.

2014

Baumberger, T., Bünz, S., Pedersen, R. B., Blomberg, A. E., Landschulze, K., Tasianas, A., Berndt, C., Karstens, J., Class, H., Ahmed, W., Flemisch, B., Chadwick, A., Holloway, S., White, J. C., Cevatoglu, M., Bull, J. and Orlic, B. *WP1 result summary report relevant for "Environmental Best Practice"*. ECO2 Deliverable, D1.2., 32 pp. DOI 10.3289/ECO2_D1.2.

Karstens, J., Berndt, C., Bünz, S., Tasianas, A., Class, H., Ahmed, W. and Orlic, B. *WP1 summary report relevant for risk assessment*. ECO2 Deliverable, D1.3., 23 pp. DOI 10.3289/ECO2_D1.3.

Haeckel, M. and Blackford, J., eds. *CCT2 Synthesis report on predicted impacts & uncertainties.* ECO2 Deliverable, D12.3., 42 pp. DOI 10.3289/ECO2_D12.3.

2013

Pedersen, R. B., Baumberger, T., Berndt, C., Blomberg, A. E., Bünz, S., Chadwick, A., Class, H., Darcis, M., Flemisch, B., Holloway, S., Karstens, J., Landschulze, K., Tasianas, A., Thorseth, I. H. and White, J. C. *Report of Leakage Assessment*. ECO2 Deliverable, D1.1., 77 pp. DOI 10.3289/ECO2_D1.1.

Bünz, S. *R/V Helmer Hanssen Cruise No. 2013007 - Part I, University of Tromsø cruise report, Tromsø – Longyearbyen, 08-07-13 to 21-07-13*. Institutt for Geologi, Univ. i Tromsø, Tromsø, 33 pp. DOI 10.3289/CR_ECO2_24445.

2012

Stefan Bünz, Alexandros Tasianas, Jens Karstens, Christian Berndt, Melanie Darcis, Bernd Flemisch. *Geological models for industrial storage sites.* Milestone Report (MS12), 103 pp.

2011

Bünz, S. and Institutt for Geologi, Universitetet i Tromsø. *UNIVERSITY OF TROMSØ cruise report Tromsø – Longyearbyen, 01-07-11 to 14-07-11, R/V Helmer Hanssen; Part 1*. Institutt for Geologi, Universitetet i Tromsø, Tromsoe, Norway, 28 pp. DOI 10.3289/CR_ECO2_20595.

Conferences, workshops and meetings

Oral presentations:

2016 AMGG Workshop, Tromsø, Norway, Alexandros Tasianas, *Simulating seismic chimney structures as potential vertical migration pathways for CO_2 in the Snøhvit area, SW Barents Sea: model challenges and outcomes*.

2014 AMGG Workshop, Tromsø, Norway, Alexandros Tasianas, *Investigation of CO_2 migration potential through a "sensitivity" analysis at Snøhvit, Barents Sea.*

3rd annual ECO2 meeting, Salina, Sicily, Italy, Alexandros Tasianas, *Sensitivity analysis on the parameters affecting* CO_2 *flow through generic and realistic geological features such as gas chimneys and faults at Snøhvit in the Barents sea.*

ECO2 Young scientist workshop, Salina, Sicily, Italy - *2 June 2014*

ECO2 young scientists' excursion, Aeolian Islands, Italy - *29 May to 1 June 2014*

2013 AMGG Workshop, Tromsø, Norway, Alexandros Tasianas, CO_2 *storage, fluid flow and assessment of the leakage potential at Snøhvit in the Barents Sea using P-Cable high resolution seismic data.*

AGU annual meeting, San Francisco, USA, Alexandros Tasianas and Stefan Buenz, *High resolution P-Cable 3D seismic study of pockmarks and shallow fluid conduits at the Snøhvit reservoir in the SW Barents Sea.* [Talk] In: AGU Fall Meeting 2013, 09.-13.12.2013

Statoil/Uit meeting, Trondheim, Norway, Alexandros Tasianas, CO_2 *storage and fluid flow at Snøhvit in the Barents Sea using Conventional 3D and P-Cable 3-D high-resolution seismic data.*

P-Cable Workshop, Oslo, Norway, Alexandros Tasianas, CO_2 *storage, fluid flow and assessment of the leakage potential at Snøhvit in the Barents Sea.*

2nd ECO2 annual General Assembly meeting, Bergen, Norway, Alexandros Tasianas, *Fluid flow mechanisms and imprints at Snøhvit, Barents Sea.*

2012 AMGG Workshop, Tromsø, Norway and Work Package 1 (WP1) meeting, Kiel, Germany, Alexandros Tasianas, *Geological Interpretation and Modelling of the Snøhvit Reservoir and Overburden Rocks.*

NFiP Seminar, Stavanger, Norway, Alexandros Tasianas, *Fluid flow and assessment of the leakage potential at Snøhvit in the Barents Sea.*

1st ECO2 annual General Assembly meeting, NOC, Southampton, UK

2011 Environmental risk assessment workshop, DNV, London, U.K, 1 – 2 Sep 2011

Planning of numerical modeling activities workshop, GEOMAR, Kiel, Germany, 18 May 2011

Poster presentations:

- 2014 ECO2 annual meeting poster presentation, Salina, Italy, Alexandros Tasianas, Lena Walter, *Investigation of CO_2 migration potential through a "sensitivity" analysis at Snøhvit, Barents Sea*.
- 2012 AGU annual meeting, San Francisco, USA, Alexandros Tasianas, *Fluid flow and assessment of the leakage potential in the Snøhvit reservoir and overburden in the Barents Sea.*

Scientific cruises

- R/V Jan Mayen (now R/V Helmer Hanssen), SW Barents Sea, Norway, July 2011, P-Cable, OBS data acquisition.
- R/V Jan Mayen (now R/V Helmer Hanssen), SW Barents Sea, Norway, July 2012, Student cruise.
- R/V Jan Mayen (now R/V Helmer Hanssen), SW Barents Sea, Norway, July 2013, P-Cable repeat survey data acquisition.

Publications

- Tasianas, Alexandros; Martens, Iver; Bünz, Stefan; Mienert, Jurgen. **Mechanisms initiating fluid migration at Snøhvit and Albatross fields, Barents Sea**. *Arktos 2(1), 1-18 (2016).* ISSN 2364-9453.s doi: 10.1007/s41063-016-0026-z.

- Tasianas, Alexandros; Mahl, Lena; Darcis, Melanie; Bünz, Stefan; Class, Holger. **Simulating seismic chimney structures as potential vertical migration pathways for CO_2 in the Snøhvit area, SW Barents Sea: model challenges and outcomes**. *Environmental Earth Sciences 75(6), 1-20 (2016).* ISSN 1866-6280.s doi: 10.1007/s12665-016-5500-1.

- Tasianas, Alexandros, Buenz, Stefan, Vadakkepuliyambatta, Sunil. & Mienert, Juergen. **Buried subglacial landforms in the SW Barents Sea imaged using high-resolution P-Cable seismic data**. *In*: Dowdeswell, J.A., Canals, M., Jakobsson, M., Todd, B.J., Dowdeswell, E.K. & Hogan, K.A. (eds) *Atlas of Submarine Glacial Landforms: Modern, Quaternary and Ancient*. Geological Society, London, Memoirs, **46**, 183–184 (2016). http://doi.org/10.1144/M46.117.

- Tasianas, Alexandros; Koukouzas, Nikolaos; Gemeni, Vassiliki; Alexopoulos, Dimitrios; Vasilatos, Charalampos. **Geological modelling for investigating CO_2 emissions in Florina Basin, Greece**. *Open Geosciences 7(1), 465–489 (2015).* ISSN 2391-5447.s 465 - 489.s doi: 10.1515/geo-2015-0039.