Impact of Geological Heterogeneity on CO_2 Sequestration

From Outcrop to Simulator

Kim Senger

Dissertation for the degree philosophiae doctor (PhD)
at the University of Bergen

Dissertation date: 16. December 2013

Impact of Geological Heterogeneity on CO_2 Sequestration

From Outcrop to Simulator

Kim Senger

Dissertation for the degree philosophiae doctor (PhD)

Uni Research, Bergen, Norway

Centre for Integrated Petroleum Research (Uni CIPR)

University Centre in Svalbard, Longyearbyen, Norway

Department of Arctic Geology

University of Bergen, Bergen, Norway

Department of Earth Science

"Even if there is only one possible unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe? The usual approach of science of constructing a mathematical model cannot answer the questions of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing?"

- Stephen W. Hawking

"Nobody climbs mountains for scientific reasons. Science is used to raise money for the expeditions, but you really climb for the hell of it."

- Sir Edmund Hillary

Acknowledgements

When I applied for the PhD position that would ultimately lead to the submission of this thesis I was crossing Norway on skis. I was living a dream and, as always happens when you follow a dream, countless people go out of their way to help you out. Such as the receptionist at Tyinkrysset who allowed me to use her personal computer to submit the job application. Similarly, countless people have helped me on the voyage from that job application towards the PhD submission. Too many to list individually here, but I'm particularly grateful to my fellow 'fish-tank' occupants at Uni CIPR (Ola, Christian, Andreas, Toby, Luisa, Bjørn *et al.*) and the northernmost geologists at UNIS (Srikumar, the other Ola, Sten-Andreas and Helge to name a few) for a great spirit, discussion and caffeine intake. And of course Klang the dog for companionship. My family has always supported me and deserves a huge thank-you.

My main supervisor Jan Tveranger earns the sincerest thanks for his constant support, motivation and scientific input at all times of the day and night. Jan also deserves full credit for giving me the freedom to work and play anywhere I chose, be it Bergen, Utah, Karoo or Svalbard, while at the same time always being available for fruitful discussions, either in the office, in the field or over a beer or two.

I was fortunate to be co-supervised by Alvar Braathen, Sverre Planke and Atle Rotevatn, whose scientific input and suggestions greatly improved this thesis, as did the close collaboration with Snorre Olaussen up north and Walter Wheeler and Simon Buckley down south. Åke Fagereng hosted me at the University of Cape Town. Many sincere thanks are also extended to the colleagues who contributed to the various manuscripts. An unofficial supervisor, post-doc Kei 'Dr Fracture' Ogata, became a great friend and taught me what a real geologist is. I shall never forget watching Svalbard-TV together in the Deltaneset cabin or staying with you in Zanego!

Finally, I guess when I went skiing three and a half years ago I was looking for something. Now I know that I have found it, or better put, her, the love of my life. Lilith, thank you for moving together in the adventure known as life.

Kim Senger Bergen, August 2013

Preface

Scientific environment

The work presented in this PhD thesis was undertaken at the Centre for Integrated Petroleum Research (Uni CIPR, division of Uni Research) and the Department of Earth Science at the University of Bergen, Norway. Substantial research stays, fieldwork and reservoir modelling was conducted at the Department of Arctic Geology at the University Centre in Svalbard (UNIS) in Longyearbyen, Svalbard. A research stay was also undertaken from January to April 2012 at the Department of Geosciences, University of Cape Town, South Africa.

Main supervisor:

Dr Jan Tveranger (Uni CIPR)

Co-supervisors:

Professor Alvar Braathen (UNIS and Uni CIPR)

Professor Sverre Planke (VBPR AS and University of Oslo)

Associate Professor Atle Rotevatn (University of Bergen and Uni CIPR)

Funding, software and data access

This three-year PhD project was financed by the Norwegian Research Council's CLIMIT program (project "Geological input to Carbon Storage: from outcrop to simulator", project #200006, Alvar Braathen as principal investigator). Funding for fieldwork was secured competitively through Arctic Field Grants from the Svalbard Science Forum (for fieldwork on Svalbard; 2011-2013) and the Meltzerfondet from the University of Bergen (for fieldwork in South Africa; 2012). A World Universities Network researcher mobility grant funded the research stay at the University of Cape Town. Some conference travel (AAPG conference in Milan, EAGE conference in Valencia and LASI V workshop in Port Elizabeth) was financed by Statoil through the Akademia scheme. A 'Centre of Excellence' grant awarded to Uni CIPR by the Norwegian Research Council financed part of the PhD, including additional conference travel. The work was undertaken in close collaboration with the Longyearbyen CO_2 lab project, managed by the UNIS CO_2 Lab AS and supported by numerous partners in academia and industry (http://co2-ccs.unis.no/). Lundin Norway AS is in particular appreciated for financing the seismic data lab at UNIS where the modelling and simulation work was undertaken.

Academic software licenses were kindly provided by Schlumberger (Petrel, ECLIPSE and FrontSIM), Geoknowledge AS (GeoX), Simon Buckley/Uni CIPR (Lime), Erik Lindeberg/SINTEF (CO_2Therm) and Google (Google Earth Pro). The open-source tool OpenStereo (Grohmann & Campanha, 2010) was used throughout for plotting stereoplots. Apart from the data sets provided by the Longyearbyen CO_2 lab project, I sincerely appreciate access to the digital shape-files of geological horizons provided by Winfried Dallmann and the NPI-Geonet project (http://geonet.npolar.no/), high-resolution aerial photos supplied by Harald Faste Aas at the Norwegian Polar Institute and topographic data available through 'Norge digitalt'. The Statoil-sponsored annual Svalex expeditions, collecting 2D seismic and magnetic data in Isfjorden since 2001 to the present day, have also generously contributed their data set. Luc Chevallier from the Council of Geosciences in Bellville kindly provided digital shape-files of the Eastern Cape study area within the Karoo Basin in South Africa.

Structure of the thesis

For readers accustomed to monographic dissertations a short introduction of the thesis structure is provided. This article-based dissertation is divided into two main parts and four appendices:

Part I Background and Synthesis: The first part introduces the scientific objectives of this work and synthesizes the main results addressed in depth in the various papers.

Part II Papers: The middle section presents a collection of eight research articles, and constitutes the bulk of the work conducted as part of the PhD study.

Appendices: In Appendix A, I list the details of two manuscripts in preparation to which I have contributed. Appendix B contains a collection of selected conference abstracts that I have presented during the PhD study, as well as five relevant extended abstracts to which I have contributed. Appendix C documents the Petrel project associated with this thesis. Appendix D illustrates an outreach project (‘Arctic Adventures of Dioxy’) that we have developed to introduce the Longyearbyen CO_2 lab project to the general public.

List of scientific manuscripts of the thesis

The following manuscripts are included in this PhD dissertation, and are reproduced in Part II of the dissertation.

Paper I

OGATA, K., **SENGER, K.**, BRAATHEN, A., TVERANGER, J., & OLAUSSEN, S. (2012). The importance of natural fractures in a tight reservoir for potential CO_2 storage: case study of the upper Triassic to middle Jurassic Kapp Toscana Group (Spitsbergen, Arctic Norway). In G. H. Spence, J. Redfern, R. Aguilera, T. G. Bevan, J. W. Cosgrove, G. D. Couples & J.-M. Daniel (Eds.), *Advances in the Study of Fractured Reservoirs, Geological Society of London Special Publication #374* (Vol. 374, pp. 22). London: Geological Society of London. doi:http://dx.doi.org/10.1144/SP374.9

Paper II

SENGER, K., OGATA, K., TVERANGER, J., BRAATHEN, A., & PLANKE, S. (submitted). Late Mesozoic magmatism in Svalbard: a review. *Submitted to Earth Science Reviews*.

Paper III

SENGER, K., ROY, S., OGATA, K., TVERANGER, J., PLANKE, S., BRAATHEN, A., MJELDE, R., NOORMETS, R., BÆLUM, K., RUUD, B. O., & BUCKLEY, S. (submitted). Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications on CO_2 sequestration. *Submitted to Norwegian Journal of Geology (accepted with minor revisions)*.

Paper IV

SENGER, K., PLANKE, S., POLTEAU, S., OGATA, K. & SVENSEN, H. (to be submitted). Sill emplacement and contact metamorphism of a siliciclastic reservoir on Svalbard, Arctic Norway. *To be submitted to Norwegian Journal of Geology Special Volume on CO_2 storage on Svalbard*.

Paper V

SENGER, K., TVERANGER, J., OGATA, K., BRAATHEN, A., OLAUSSEN, S., & LARSEN, L. (submitted). First order storage capacity assessment and risking of an unconventional pilot-sized CO_2 sequestration site in Svalbard, Arctic Norway. *Submitted to International Journal of Greenhouse Gas Control*.

Paper VI

SENGER, K., TVERANGER, J., OGATA, K., BRAATHEN, A., & OLAUSSEN, S., 2013. Reservoir characterization and modelling of a naturally fractured siliciclastic CO_2 sequestration site, Svalbard, Arctic Norway. UNIS CO_2 lab AS report 2013-2, Longyearbyen, Norway, 68p.

Paper VII

OGATA, K., **SENGER, K.,** BRAATHEN, A., & TVERANGER, J. (submitted). Fracture corridors as seal-bypass systems in siliciclastic reservoir-caprock successions: insights from the Jurassic Entrada Formation (SE Utah, USA). *Submitted to Journal of Structural Geology.*

Paper VIII

SENGER, K., BUCKLEY, S., CHEVALLIER, L., FAGERENG, Å., GALLAND, O., KURZ, T., OGATA, K., PLANKE, S., & TVERANGER, J. (in preparation). Fracturing in and around doleritic intrusions: insights from the Eastern Cape, South Africa. *Manuscript draft in preparation for submission in autumn 2013*.

Authorship and workload of thesis

Kim Senger is the sole author of Part I of this PhD thesis, and the principal author of six of eight manuscripts reproduced in Part II of this dissertation. The approximate contribution of Kim Senger and the co-authors to each manuscript is tabulated below.

Paper I: Natural fractures and CO_2 storage on Svalbard	
Principal author	Kei Ogata
Co-authors	Kim Senger, Alvar Braathen, Jan Tveranger, Snorre Olaussen
Text	Senger, Ogata
Figures	Senger (Figs. 5, 11, part of Figs. 3, 4) Ogata (all other figures)
Fieldwork and sampling	Ogata (stratigraphic logging, structural measurements on Dh4 and in field) Senger (structural measurements in field) Tveranger (reconnaisance, discussion in field)
Data processing	Ogata, Senger
Discussion and revision of earlier manuscript versions	Ogata, Senger, Tveranger, Braathen, Olaussen
Approximate total contribution	Ogata: 50% Senger: 40% Tveranger, Braathen, Olaussen (10% in total)
Status of manuscript	published in Geological Society of London Special Publication #374

Paper II: Review of late Mesozoic magmatism on Svalbard	
Principal author	Kim Senger
Co-authors	Jan Tveranger, Kei Ogata, Alvar Braathen, Sverre Planke
Text	Senger
Figures	Senger
Literature review	Senger
Discussion and revision of earlier manuscript versions	Senger, Ogata, Tveranger, Braathen
Approximate total contribution	Senger: 80% Tveranger: 10% remaining co-authors: 10% in total
Status of manuscript	submitted 3.8.2012 to Earth-Science Reviews

Paper III: Regional geometry of igneous complex on Svalbard	
Principal author	Kim Senger
Co-authors	Srikumar Roy, Alvar Braathen, Simon Buckley, Karoline Bælum, Laurent Gernigon, Rolf Mjelde, Riko Noormets, Kei Ogata, Snorre Olaussen, Sverre Planke, Bent Ole Ruud, Jan Tveranger
Text	Senger Gernigon (section on magnetic processing)
Figures	Senger (all figures except Figs. 4, 11 and 14) Ogata (Figs. 4 and 14) Roy (Fig. 11)
Fieldwork and data acquisition	Senger, Ogata (geological mapping, structural measurements) Braathen, Tveranger, Olaussen (shorter field reconnaisance) Ruud, Mjelde (seismic acquisition) Buckley (lidar acquisition)
Data processing and interpretation	Senger (seismic, magnetic and large-scale bathymetric interpretation, magnetic data preparation, topographic processing and calculations, aerial image processing, integrated overall interpretation) Roy (high-resolution bathymetry interpretation, pockmark mapping) Bælum (initial seismic interpretation) Ruud (seismic processing) Buckley (lidar processing) Tveranger (lidar interpretation) Gerningon (magnetic processing)
Revision of earlier manuscript versions	all co-authors
Approximate total contribution	Senger: 75% Roy, Gernigon, Ogata: 15% in total other co-authors: 10% in total
Status of manuscript	submitted 23.2.2013 to Norwegian Journal of Geology, accepted with minor revisions August 2013

Paper IV: Contact metamorphism around a thin intrusion	
Principal author	Kim Senger
Co-authors	Sverre Planke, Stephane Polteau, Kei Ogata, Henrik Svensen
Text	Senger Svensen (geochemical analyses, aureole processes)
Figures	Senger Ogata (Figs. 1 and 3)
Fieldwork and sampling	Polteau, Svensen (initial Dh4 sampling and logging) Senger, Ogata (additional Dh4 sampling, field mapping) Ogata (high-resolution Dh4 structural logging)
Laboratory analyses	IFE (handled by Svensen), Royal Holloway University (handled by Polteau)
Discussion and revision of earlier manuscript versions	all authors
Approximate total contribution	Senger: 30% Svensen: 30% other co-authors: 40% in total
Status of manuscript	ready for submission to Norwegian Journal of Geology

Paper V: UNIS CO_2 lab volumetric calculation	
Principal author	Kim Senger
Co-authors	Jan Tveranger, Alvar Braathen, Kei Ogata, Snorre Olaussen, Leif Larsen
Text	Senger
Figures	Senger (all figures except Fig. 12) Larsen (Fig. 12)
Method development and software implementation	Senger
Volumetric calculation input parameters	all authors
Discussion and revision of earlier manuscript versions	all authors
Approximate total contribution	Senger: 50% co-authors: 50% in total
Status of manuscript	submitted 8.5.2013 to International Journal of Greenhouse Gas Control

Paper VI: Reservoir modelling of UNIS CO_2 lab aquifer	
Principal author	Kim Senger
Co-authors	Jan Tveranger, Kei Ogata, Alvar Braathen, Snorre Olaussen
Text	Senger
Figures	Senger Ogata (Figs. 18, 19, 21 and 22) Larsen (Fig. 42)
Fieldwork	Senger (structural measurements in the field, mapping of igneous bodies) Ogata (stratigraphic logging, structural logging in field and in boreholes) Olaussen, Tveranger, Braathen (shorter field reconnaisance)
Reservoir characterization	All authors and associated researchers
Reservoir modelling	Senger, Tveranger
Approximate total contribution (Reservoir characterization)	Equal contribution by all authors and referenced researchers
Approximate total contribution (Reservoir modeling)	Senger: 75% Tveranger: 25%
Status of manuscript	published 15.8.2013 as internal UNIS CO_2 lab AS report

Paper VII: Fracture corridors as seal-bypass systems	
Principal author	Kei Ogata
Co-authors	Kim Senger, Alvar Braathen, Jan Tveranger
Text	Ogata
Figures	Ogata
Fieldwork	Ogata, Senger, Braathen, Tveranger and field assistants
Data processing	Ogata, Senger
Discussion and revision of earlier manuscript versions	all co-authors
Approximate total contribution	Ogata 80% other co-authors: 20% in total
Status of manuscript	submitted to Journal of Structural Geology

Paper VIII: Fracturing in and around igneous rocks	
Principal author	Kim Senger
Co-authors	Simon Buckley, Luc Chevallier, Åke Fagereng, Olivier Galland, Tobias Kurz, Kei Ogata, Sverre Planke, Jan Tveranger
Text	Senger
Figures	Senger Ogata (Fig. 14)
Fieldwork	Senger (scanline measurements, photo-collection, LiDAR acquisition) Kurz (LiDAR acquisition) Tveranger, Planke, Galland (shorter field reconnaissance)
Data processing	Senger (photo-mosaics) Buckley, Kurz (LiDAR processing)
Data analysis and interpretation	Senger
Discussion and revision of earlier manuscript versions	all authors
Approximate total contribution	Senger: 75% co-authors: 25%
Status of manuscript	manuscript draft (*c*. 90% complete), to be submitted in autumn 2013

Abstract

Increased anthropogenic emission of carbon dioxide (CO_2) into the Earth's atmosphere since the industrial revolution has enhanced the greenhouse effect and contributed to global climate change. Controlling atmospheric CO_2 emissions is thus essential to mitigate the environmental and socio-economic consequences related to these changes. Carbon capture and storage (CCS) was proposed as one possible option to control anthropogenic CO_2 emissions, and is particularly viable at CO_2 point sources such as coal-fuelled power plants. CCS was tested and applied globally in a variety of geological and top-side settings within the past decade, with varying success. In Longyearbyen, the main settlement on the Norwegian high-Arctic Svalbard archipelago, CO_2 may be captured at the local coal-fuelled power plant and injected into an unconventional siliciclastic target aquifer. The target aquifer, within the Late Triassic to Middle Jurassic Kapp Toscana Group, comprises an up to 300 m thick sequence of tight, naturally fractured sandstones inter-bedded with siltstones and shales. During the Early Cretaceous, igneous intrusions, collectively classified as the Diabasodden Suite, were emplaced in the target aquifer. The pilot-scale Longyearbyen CCS project envisions only modest storage volumes of CO_2, with the top-side CO_2 storage requirements determined by the annual CO_2 emissions from the local coal-fuelled power plant (*c.* 60 000 tons). As part of this PhD study, the geologically complex target aquifer was characterized and represented in a static geologic reservoir model. Fieldwork (e.g. structural and stratigraphic logs, geological mapping), borehole (e.g. drill core logs and plugs, wireline logs, water injection tests, vertical-seismic-profiling survey) and regional geophysical (e.g. 2D seismic, digital elevation model, magnetic data) data sets were used as input. Two main themes relating directly to the geological heterogeneity of the target aquifer were addressed in detail: (1) the natural fracture network, and, (2) the presence of igneous intrusions. Water injection tests, wireline logging and fracture mapping, in drill cores and at outcrops, all indicate that the tight heterolithic siliciclastic target aquifer is highly fractured, and that the pre-existing natural fracture network is critical for the injectivity of fluids. We integrated borehole (872 fractures measured along 302 m of drill core) and fieldwork data (7 672 fractures measured along > 1400 m of scanlines)

to develop a conceptual model grouping reservoir intervals with similar mechanical and lithological properties into five litho-structural units (LSUs; classified as LSU A-E). Fractures within the shale-dominated LSU A are predominantly low-angled and likely contribute to lateral fluid migration within the reservoir interval. In contrast, the predominantly high-angled fractures within the sand-dominated LSU C represent probable vertical intra-reservoir permeability pathways. Water injection tests indicate a linear flow pattern, particularly in the lower part of the aquifer (870-970 m depth). The orientation and configuration of the natural fracture network will thus ultimately control the migration direction and speed, and thus also the shape of the fluid plume. The highest overall fracture frequency is evident in LSU D (dolerite), but field observations suggest the majority of these fractures to be sealed by various types of cement (e.g. calcite), precipitated from percolating fluid in the transition zone between host rock and igneous intrusions. On a small scale, igneous intrusions form a contact metamorphic aureole in the surrounding host rock. This may significantly affect reservoir properties, even around relatively thin intrusions. We have studied such a thin (2.28 m thick) intrusion penetrated by the Dh4 borehole, and conclude that the total contact aureole is 160-195% the width of the sill itself. On a larger scale, igneous intrusions set up local-to-regional heterogeneities within the target aquifer, either as impermeable lateral to sub-vertical (sills and dykes, respectively) fluid flow barriers or as high-permeability pathways along fractured intrusion-host rock contact zones. We integrated numerous data sets to constrain the overall geometry of the igneous intrusions in Central Spitsbergen, and concluded that dykes and sills are the dominant geometries. Saucer-shaped intrusions were also mapped, but are located stratigraphically below the target aquifer. In general, igneous intrusions are most common in the lower one-third of the target aquifer, but in some cases dykes extend into the upper part of the aquifer, and even into the overlying cap rock. On a regional scale, igneous intrusions and sub-seismic faults are thus also likely to control the shape of the CO_2 plume, along with the matrix properties and natural fracture network within the country rock. The current geological understanding of the unconventional target aquifer was incorporated into a scenario-based calculation of potential CO_2 storage capacity. The wide range of low to high case (P90-P10) results, even for a given scenario with a deterministic areal extent, reflects the uncertainty attached to poorly constrained key parameters. These include the accessible segment size of the compartmentalized reservoir, the dominant CO_2 phase at reservoir conditions and the storage efficiency factor. Reservoir simulations are required to constrain these parameters further. At this stage, the calculated storage capacity appears to be adequate to fulfil the stipulated requirement for the first phase injection of up to 200 000 tons of CO_2. In summary, I present a collection of papers addressing the geological heterogeneity of an unconventional CO_2 target aquifer on Svalbard. In addition, I use outcrop analogues of fracture corridors (from south-eastern Utah) and intrusion-host rock interfaces (from South Africa) to better understand processes acting on the target aquifer. This broad geological understanding is used to characterize the target aquifer, and is subsequently incorporated into a static geological model of the Longyearbyen storage site. The model may then be used as a base for extensive fluid flow simulations to optimize future well placement, injection rates and monitoring techniques. The learnings from this work can be applied directly to the Longyearbyen CO_2 lab project, but may also be transposed as an analogue for storing CO_2 in unconventional, naturally fractured reservoirs or even for producing hydrocarbons from similar geologic settings.

Contents

Part I

Part I – Background and Synthesis

This part introduces the scientific problem addressed in this PhD study and outlines the motivation behind the reservoir modelling of the unconventional CO_2 target aquifer on Svalbard. In addition, I attempt to provide an overview of the main results discussed at length within the individual manuscripts presented in Part II, and synthesize these within the broad framework defined by the title of the thesis, *'Impact of Geological Heterogeneity on CO_2 Sequestration: from Outcrop to Simulator'*.

1. Introduction and motivation

This dissertation is linked to a political vision of a CO_2-neutral Svalbard proposed by Gunnar Sand (then director of UNIS) and Alvar Braathen (Professor of Geology at UNIS) in December 2006 (e.g. NRK, 2006; Dagens Næringsliv, 2007). This vision assumes capturing CO_2 at the coal-fuelled power plant in Longyearbyen and storing it in the nearby subsurface. A drilling and data acquisition campaign, conducted from 2007-2013, provides a solid base for understanding the subsurface (e.g. Braathen *et al.*, 2012), and emphasizes the unconventionality of the succession; a naturally fractured, underpressured, heterogeneous unit affected by igneous intrusions. In this applied PhD thesis, I address some of these geological heterogeneities that may have an effect on CO_2 storage on Svalbard. In this section, I outline the aims and objectives of this dissertation, introduce how the papers in Part II fit together, and define important terms.

1.1 Hypothesis, aims and objectives

This integrated and applied PhD thesis has a clear general hypothesis that can be tested:

'It is possible to store CO_2 emissions from the Longyearbyen coal-fuelled power plant locally in the subsurface of Svalbard'.

In order to test the hypothesis, the geological heterogeneity of the target aquifer was investigated, with particular emphasis on features likely to affect reservoir performance such as natural fractures and the presence of igneous intrusions. This study focusses on these two structural geological heterogeneities, since they are considered to primarily control fluid flow (e.g. Braathen *et al.*, 2012). Sedimentological heterogeneity is considered reasonably well constrained at the near-well scale, with a conceptual layer-cake geological model constrained by facies characterization (Tveranger, 2011; section 2.3.1. in Paper VI) and associated drill core measurements (Farokhpoor *et al.*, 2010), and is not addressed in detail in this dissertation. The more specific aspects of this work address the following questions:

- What structural geological heterogeneities affect the target aquifer?
  - What are the main characteristics of the natural fracture network on Svalbard (e.g. orientation, spacing)?
    - How can we represent fractures seen at outcrop-scale in a reservoir model?
    - What impact do fracture properties (e.g. aperture, length, direction) have on overall fluid flow?
  - How can we use field analogues to constrain fluid flow through fractures?
    - How do fracture corridors affect subsurface fluid flow?
  - To what extent do igneous intrusions affect fluid flow?
    - What impact do igneous intrusions have on the reservoir properties at the local scale?
    - What is the overall geometry of the intrusions and can they cause compartmentalization of the aquifer?
    - Can we use outcrop analogues to better constrain fluid flow along intrusion-host rock interfaces?
  - How can we represent the various scales of heterogeneities in a reservoir model?
- Can we store CO_2 on Svalbard?
  - How much CO_2 can we store in the subsurface of Svalbard?

The overall aims of this PhD study are linked to the above questions, which are addressed in the individual papers. In essence, my main aim was to build a static geological model of the unconventional CO_2 target aquifer on Svalbard. This model should be suitable for fluid flow simulations and follow the *'from outcrop to simulation'* workflow by including critical outcrop data acquired specifically for this purpose during this PhD study.

1.2 Correlation of included papers

The papers included in this thesis fit into a pyramid building towards the improved understanding of the target aquifer on Svalbard (Figure 1). The base of the pyramid corresponds to the geological heterogeneity which must be mapped, analysed, understood and represented in reservoir models before concluding at the top of the pyramid. In this PhD study, two main themes were chosen for focussed study, namely igneous intrusions and natural fractures. Both of these are critical elements in the target aquifer on Svalbard, and have not been addressed previously with respect to CO_2 storage, in contrast to heterogeneities associated with facies variation (Lengler, 2012), petrophysical variation (Lengler *et al.*, 2010) or structural and stratigraphic aquifer configuration (Hovorka *et al.*, 2004).

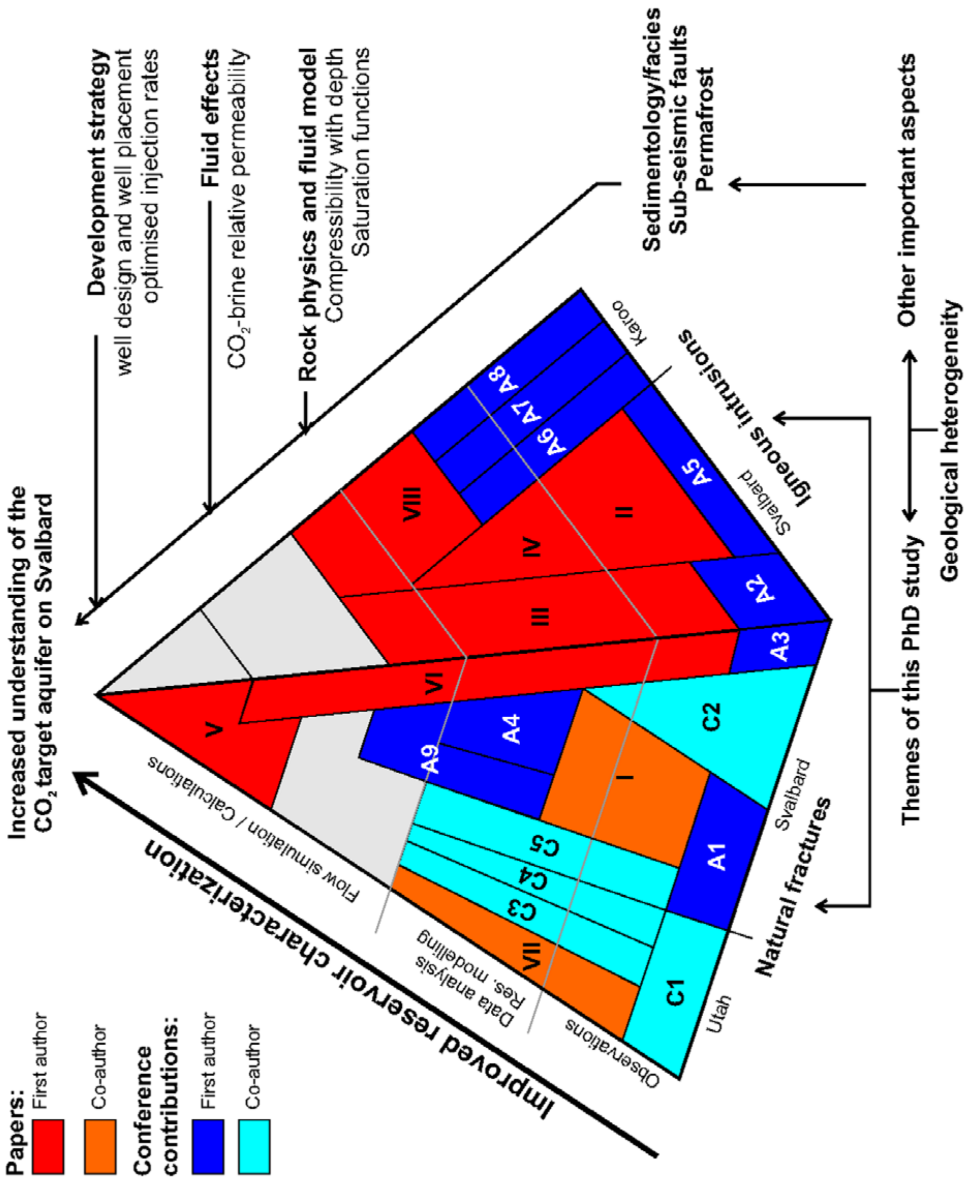

Figure 1: Schematic synthesis of the various papers and conference papers included in this PhD thesis, all within the framework of addressing the impact of geological heterogeneity on CO_2 storage on Svalbard. The top of the pyramid corresponds to the thesis hypothesis, 'It is possible to store CO_2 emissions from the Longyearbyen coal-fuelled power plant locally in the subsurface of Svalbard'. Work on data sets from field analogues on natural fractures (Utah) and igneous intrusions (Karoo) is shown along the pyramid edges. The other sides of the pyramid (e.g. sedimentological heterogeneity) are not addressed in detail in this PhD study. The conference contributions are reproduced in the appendix.

1.3 Terms and definitions

Geological heterogeneity = Non-uniformity within a body of rock.

Aquifer = A volumetrically defined body of rock through which fluids can move. The fluids are typically groundwater or saline brines.

Reservoir = In subsurface geology, a reservoir is a volumetrically defined body of rock through which fluids can move. The fluids are natural hydrocarbons, gases (e.g. CO_2) or injected fluids.

Reservoir model = The mathematical representation of the subsurface, typically constructed in order to predict subsurface fluid migration.

Geological grid = Grid typically aimed at static property modelling. The purpose of a geological grid is to facilitate the discretization of continuous rock properties into a manageable number of building blocks for property and flow modelling.

Simulation grid = Coarser grid typically aimed at flow simulations.

Unconventional reservoir = A reservoir which is challenging and often more expensive to produce (or inject into), often requiring novel technologies for development (McGlade, 2012). The boundary to conventional reservoirs is rather subjective and diffuse, but naturally fractured reservoirs are typically considered unconventional.

Fracture = A sharp structural discontinuity with no displacement defined by a local reduction in strength. Following Schultz & Fossen (2008).

Fault = A sharp structural discontinuity with displacement defined by slip planes. Following Schultz & Fossen (2008).

Dyke = Layer-discordant intrusion, transgressing across layers.

Sill = tabular igneous intrusion, dominantly layer-parallel, as defined by Planke *et al.* (2005).

Saucer-shaped intrusion = Igneous intrusion displaying a saucer-shaped overall geometry, as defined by Polteau *et al.* (2008).

Hydrothermal vent complex = Pipe-like complex formed by fracturing, transport and eruption of hydrothermal fluids and sediments, as defined by Planke *et al.* (2005).

2 Background and current state-of-the-art

In this section I define the concept of geological heterogeneity, which represents the 'red thread' in this PhD thesis. I then introduce the main study areas, before examining the importance of carbon capture and storage (CCS) in light of the dynamic and expanding global energy market. I wrap up with an introduction of the Longyearbyen CO_2 lab project to which this thesis is intimately linked, and examine the critical parameters behind the geological heterogeneity addressed in this work.

2.1 Geological heterogeneity

Given the title of this thesis, *'Impact of Geological Heterogeneity on CO_2 Sequestration: from Outcrop to Simulator'*, it is important to define the term geological heterogeneity. In its broadest sense, heterogeneity relates to the non-uniformity of materials (e.g. rocks) in terms of the composition and character. All rocks are thus by definition heterogeneous to some extent, though the level of heterogeneity varies at different scales (Guéguen & Palciauskas, 1994). In this study, I use the term 'heterogeneity' primarily to refer to structural heterogeneities, with a clear visual expression within the target aquifer (e.g. natural fractures at a small scale, and igneous intrusions at a larger scale).

However, reservoir engineering usually simplifies the heterogeneity of nature through the use of assumptions and simplifications in order to establish computable entities. In other words, heterogeneity is often mimicked as a quasi-homogeneous medium (e.g. Nordbotten *et al.*, 2005; Class *et al.*, 2009). There are valid reasons for simplifying nature in models, including computational capacity, the necessity of representing reality in coarse grid cells and the ability to focus on specific factors to be quantified. However, recent work has shown that geological heterogeneity has a profound effect on reservoir behaviour (e.g. Eaton, 2006; Howell *et al.*, 2008; Ashraf *et al.*, 2010). This has, amongst others, implications for CO_2 storage potential (e.g. Hovorka *et al.*, 2004; Lengler, 2012), reservoir performance (e.g. White *et al.*, 2001; Ambrose *et al.*, 2008) and groundwater movement (e.g. Runkel *et al.*, 2006). Geological heterogeneity is often quantified on the basis of field data, such as in naturally fractured carbonate reservoirs (Cooke *et al.*, 2006). These may then be used to characterize the hydrogeological properties of an aquifer (Tipping *et al.*, 2006). Finally, geological heterogeneity may be incorporated in numerical models to predict fluid migration, such as groundwater flow (Swanson *et al.*, 2006).

Nonetheless, understanding geological heterogeneity at a particular site, quantifying it using reliable data sets and implementing it in a flow simulation model are all challenging and time-consuming activities, fraud with uncertainty. This is particularly the case for the unconventional and geologically complex CO_2 target aquifer on Svalbard. This aquifer displays heterogeneity at all scales. This is further complicated by the fact that some key issues related to its formation are still debated. On the regional-scale, the Late Triassic to Middle Jurassic depositional environment controlled the dominant sedimentary facies present today, with no clear agreement on the regional depositional environments between numerous paleogeographic reconstructions (Mørk *et al.*, 1982; Steel & Worsley, 1984; Riis *et al.*, 2008; Worsley, 2008; Nagy *et al.*, 2011). This has partly controlled the development of core-scale geological heterogeneity reflected in the varied dissolution porosity within the target aquifer, reflecting both initial composition at the time of deposition as well as burial history (Mørk, 2013). The regional tectonic setting and complex geological history also exerted a fundamental control on the development of heterogeneous facies distributions and permeability pathways, such as fracture corridors or sub-seismic faults (Ogata *et al.*, 2013; Paper I). Also on the regional-scale, the emplacement of igneous intrusions within the Early Cretaceous (Nejbert *et al.*, 2011; Corfu *et al.*, 2013; Paper II) likely led to the development of semi-regional baffles as well as high-permeability fracture conduits along intrusion margins. The complex geological history of the aquifer, including a major Paleogene contractional event developing the West Spitsbergen fold-and-thrust belt (e.g. Bergh & Andresen, 1990; Braathen *et al.*, 1999), has also led to the development of a natural fracture system, a critical component for injectivity and flow (Braathen *et al.*, 2012; Ogata *et al.*, 2012b; Ogata *et al.*, 2013; Paper I).

In this thesis, I aim to represent the structural geological heterogeneity in a reservoir model addressing the Svalbard case study. The favourable geological exposure of the aquifer 15 km from the planned injection site allows for the detailed characterization of both the natural fracture network and igneous intrusions, serving to construct an outcrop-based reservoir model in a workflow going '*from outcrop to simulator*'.

2.2 Study areas

In this thesis the overall topic was studying the impact of geological heterogeneity on CO_2 sequestration. This was mainly conducted on the applied case of the Longyearbyen CO_2 lab project on Svalbard located in the high Arctic (Figure 2). However, two other field areas were investigated to provide additional analogue information and thus assist in understanding, modelling and de-risking the unconventional Svalbard aquifer.

The world-class geological laboratory of south-eastern Utah contains numerous natural CO_2 fields, some of which have leaked CO_2 along faults and fracture corridors during recent times (Shipton *et al.*, 2004; Dockrill & Shipton, 2010; Figure 2). Present-day eruptions of CO_2-charged fluids, past leaks with travertine build-ups as well as host rock bleaching in regions of paleo-fluid flow all attest to active CO_2 migration (Parry *et al.*, 2004; Wigley *et al.*, 2013). We conducted an extensive fracture mapping field campaign near Green River, Utah, in order to understand the migration of fluids from paleo-reservoirs through seals along faults, fractures and fracture corridors (Ogata *et al.*, 2012a; Paper VII). This knowledge was subsequently applied in de-risking and modelling of the naturally fractured reservoir on Svalbard.

The Karoo Basin of South Africa is known both for its spectacular and largely undeformed sedimentary record and for the exposures of the Karoo dolerite. This large igneous province was emplaced at *c.* 183 Ma (Svensen *et al.*, 2012) and provides countless exposures of dykes, sills and saucer-shaped intrusions across the basin. The good accessibility and outcrop exposure of the intrusions, in conjunction with their impact on groundwater flow in the water-deprived Karoo Basin (Chevallier *et al.*, 2001; Woodford & Chevallier, 2002), makes the basin a perfect site for studying the geometry and fracturing of igneous bodies, and particularly the fracture-driven contact zone permeability (Paper VIII). The Karoo dolerite provides an analogue to the intrusive Diabasodden Suite rocks on Svalbard (Nejbert *et al.*, 2011; Paper II), which are in places intruded into the CO_2 storage aquifer on Svalbard.

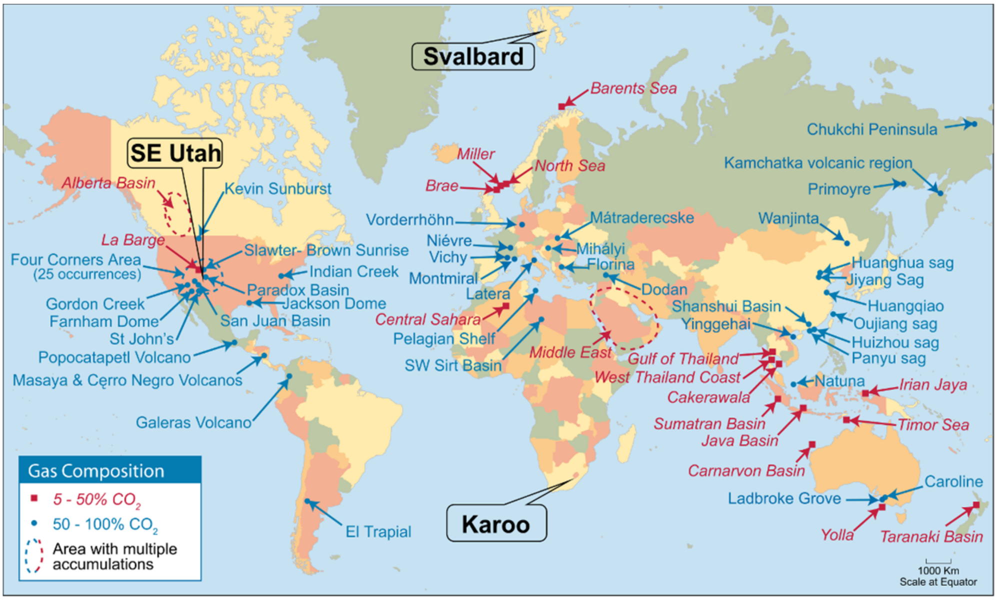

Figure 2: Location map illustrating the three main study areas discussed in this thesis. The base map, from IPCC (2005), illustrates the location of natural CO_2 fields throughout the world.

2.3 Carbon sequestration and the global energy market

As the world population is growing, and standards of living are increasing globally, the demand for energy has almost doubled from 1973 to 2006 (IEA, 2008). While renewable energies are expected to provide a greener energy mix in the future, fossil fuels currently dominate the global energy demand and will continue to do so in the near-term future (BP, 2012). Energy production from non-renewable fossil fuels generates atmospheric CO_2 emissions and it is therefore of little surprise that there is a strong correlation between global energy consumption and global energy-related atmospheric CO_2 emissions (Figure 3). The majority of energy-related CO_2 emissions are presently focussed in OECD countries (Organisation for Economic Cooperation and Development; Kirby, 2008) but forecasts by the International Energy Agency

(IEA) clearly illustrate the future contribution of developing countries, notably China and partly India (Figure 4; IEA, 2010). Most scenarios predict a steady increase in CO_2 emissions until 2020 (Figure 4b), with uncertainty related to global politics and energy market development establishing a 'CO_2-emission wedge' bounded by a maximum and minimum scenario defined by the IEA. Under the maximum 'Current Policies Scenario' CO_2 emissions steadily increase in the future. The '450 Scenario', which assumes stabilization of global atmospheric CO_2 at 450 ppm as defined by the Copenhagen Accord, requires active measures to be reached. It is notable that up to 19% of these measures equate to the use of carbon capture and storage (CCS, Figure 4d). In absolute volumes this would equate to approximately 4 Gigatons ($4*10^9$ or 4000 000 000 tons) of CO_2 sequestered underground on an annual basis by 2035. This equates to *c.* 4 000 million tons of CO_2 sequestered each year from today to 2035 (Nøttvedt, A., pers. comm.), roughly corresponding to 4 000 Sleipner-scale CO_2 projects (Eiken *et al.*, 2011). The obvious question is whether we are in a scientific and technical position to undertake such a major task.

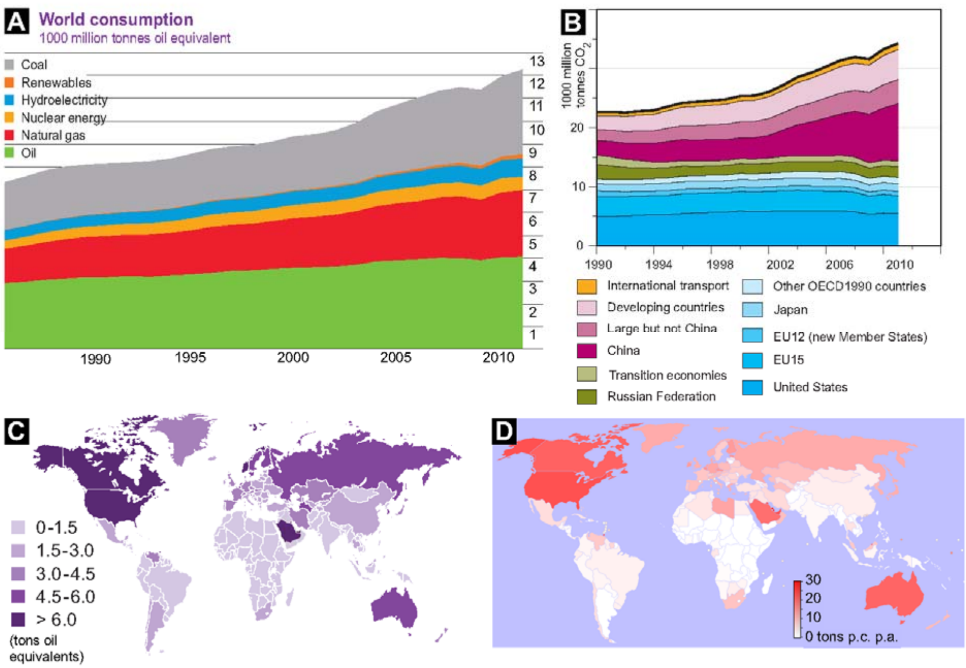

Figure 3: Historical global energy consumption and CO_2 emissions. A) Global energy consumption from 1986 to 2011, subdivided into energy

source (BP, 2012). B) Global CO_2 emissions per region from fossil fuel use and cement production. Figure from Olivier et al. (2012). C) Global per capita energy consumption in 2011 (BP, 2012). D) Global per capita CO_2 emissions in 2000 (Boden et al., 2012).

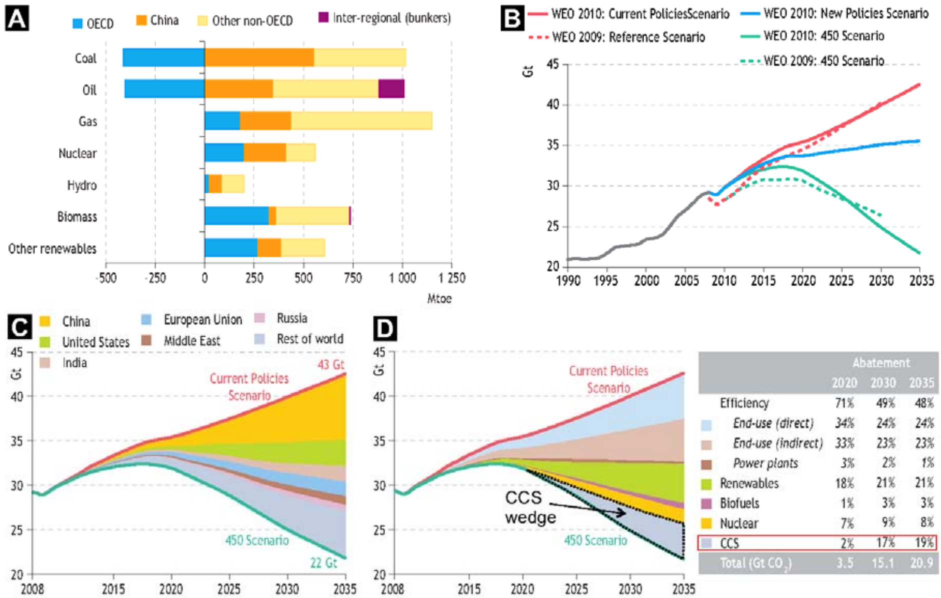

Figure 4: Predicted usage and associated CO_2 emissions in the period 2008-2035. All figures from the International Energy Agency's World Energy Outlook 2010 (IEA, 2010). A) Incremental primary energy demand by fuel and region in the New Policies Scenario. B) Scenario-based approach illustrating the probable global energy-related CO_2 emissions. C) Global energy-related CO_2-emission "wedge" and regions which have the potential to contribute most to obtain a more sustainable emission level. D) Technologies which may help to reduce the global energy-related CO_2-emission wedge. Note particularly the listing of carbon capture and storage (CCS; highlighted by the red box).

2.4 CO_2 sequestration on Svalbard and elsewhere

In order to prevent these 4 Gigatons of CO_2 from being emitted to the atmosphere, a viable strategy is to capture the CO_2 at point sources (e.g. coal-fuelled power plants or other major CO_2-emitting industrial plants), transport it to suitable injection sites (e.g. by pipelines, ships or trucks) and inject it into suitable subsurface target aquifers (e.g. saline aquifers, depleted hydrocarbon fields; IPCC, 2005; Bachu, 2008; Benson & Cole, 2008). This geological carbon storage differs from both deep ocean storage of CO_2 and mineral CO_2 sequestration in that the injected CO_2 will be trapped in the subsurface in a system shielded from dynamic changes in oceanic currents and associated temperature variation (Voormeij & Simandl, 2004; IPCC, 2005). The technology for injecting CO_2 into the subsurface is reasonably well understood and has been employed by the hydrocarbon industry since the 1980s for increasing oil recovery (Beliveau *et al.*, 1993). Although the global CCS picture is several orders of magnitude more ambitious and complex, in this thesis I investigate the feasibility of storing modest amounts of CO_2 in an unconventional heterogeneous storage site beneath Longyearbyen, Arctic Norway. This pilot-scale project, where the maximum capture potential equates to the annual *c.* 60 000 tons of CO_2 emitted by the local coal-fuelled power plant (Lokalstyre, 2011), would obviously not have a significant impact on global CO_2 emissions but rather provide a case study of a small community with a nearly closed energy system. Locally mined coal is burnt to provide the *c.* 2000 inhabitants (Bore *et al.*, 2012) with heat and power, and the planned injection site lies only 5 km from the settlement. The complex geology, introduced by Braathen *et al.* (2012) and expanded by Ogata *et al.* (2012b; Paper I), makes this the perfect case study for studying the '*Impact of Geological Heterogeneity on* CO_2 *Sequestration*'. The results from the studies on the Longyearbyen CO_2 lab project thus have a global value for the emerging CCS industry.

The practical aspect of CCS is currently best illustrated by a handful of industrial-scale projects that operated in the past decade (Figure 5, Table 1). Their combined stored CO_2 (*c.* 40 Mt within the past decade) amounts to only 1% of the annual 4 Gt target outlined above. Furthermore, the majority of projects are only profitable due to increased production (enhanced oil recovery projects in the USA) or lower CO_2 tax bills (gas separation projects offshore Norway). A major global application of CCS would thus likely require a change in legislation together with a globally co-ordinated CO_2 market system. The projects nonetheless illustrate that technology and know-how exist for storing CO_2 underground, and that well-known technologies used in the hydrocarbon industry can be successfully used to predict and monitor the migration of the CO_2 plume. This is best exemplified by time-lapse seismic data acquired by the Sleipner CO_2 sequestration project (Eiken *et al.*, 2011), inSAR satellite data from In-Salah (Vasco *et al.*, 2008) and a strong monitoring focus of the Weyburn field (White *et al.*, 2004; Whittaker *et al.*, 2004). Pilot-scale projects in Japan (Xue *et al.*, 2006), Ketzin in Germany (Förster *et al.*, 2006), the Frio project in Texas (Daley *et al.*, 2008; Doughty *et al.*, 2008) or CarbFix in Iceland (Aradóttir *et al.*, 2011) all confirm the feasibility of the storage part of CCS under various subsurface and top-side conditions. Furthermore, small-scale projects with modest CO_2 volumes, like the Longyearbyen CO_2 lab project, can establish high-resolution datasets and test, through history-matched reservoir modelling, the feasibility of monitoring networks to detect even minor CO_2 migration and assess leak risks. These may subsequently be applied in industrial-scale projects as benchmarks for CO_2 plume behaviour in conventional and unconventional aquifers. In a broader sense, unconventional naturally fractured reservoirs, including tight gas sands and shale gas, are becoming increasingly important plays in hydrocarbon production and knowledge of their behaviour is in strong demand.

Accurate CO_2 storage capacity estimates are essential in order to allow governments to assess the feasibility of storing CO_2 in a given country, region or site. Various methods for estimating CO_2 storage capacity have been proposed (e.g. Bachu *et al.*, 2007a; Bradshaw *et al.*, 2007; Zhou *et al.*, 2008; Allen *et al.*, 2010). These methods, with some modifications, have been applied in a plethora of storage-potential atlases, amongst others for the United Kingdom (Gammer *et al.*, 2011), the Norwegian North Sea (Halland *et al.*, 2011), the Netherlands (Ramírez *et al.*, 2010), Europe (GeoCapacity, 2008), South Africa (Cloete, 2010), North America (NETL, 2010; NACSA, 2012), the Gulf Coast (Núñez-López *et al.*, 2008) and Australia (Gibson-Poole *et al.*, 2008; Bradshaw *et al.*, 2010). Needless to say, such regional-scale atlases require many simplifications. Focussed studies characterizing specific sites were provided, amongst others, for an unnamed North Sea aquifer (Obi & Blunt, 2006), the Teapot Dome in the USA (Chiaramonte *et al.*, 2008), a pilot-site in Japan (Ogawa *et al.*, 2011), the Utsira Formation offshore mid-Norway (Lindeberg *et al.*, 2009; Pham *et al.*, in press), the Schweinrich structure in Germany (Meyer *et al.*, 2008), and the Longyearbyen CO_2 lab project (Paper V in this thesis).

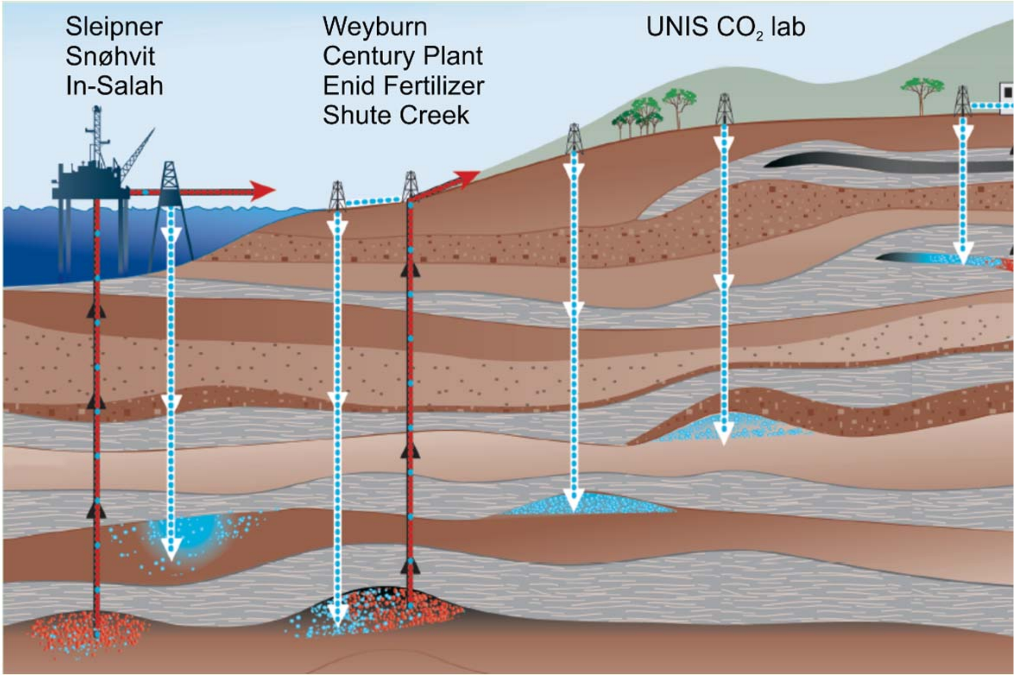

Figure 5: Summary cartoon illustrating the concept of geological storage and usage of CO_2 in different scenarios. Figure adapted from IPCC (2005).

Table 1: Summary of the eight industrial-scale operating projects using CO_2 for enhanced oil recovery (EOR) or storing it in geological deep saline aquifers (G-DSA). Data from Global CCS Institute (2012).

Project	Country	Operator	Storage type	Transport	Industry	CO_2 annual capture rates (Mt)	Total CO_2 injected (Mt)
Century Plant	USA	Occidental Petroleum	EOR	256 km onshore	Natural gas processing	5	10
Enid Fertilizer	USA	Koch Nitrogen Company	EOR	225 km onshore	Fertiliser production	0.68	1.5
Shute Creek	USA	ExxonMobil, Chevron-Texaco and Anadarko	EOR	190 km onshore	Natural gas processing	7	various
Great Plains-Weyburn	USA/ Canada	Cenovus Energy	EOR	315 km onshore	Synthetic natural gas	2	20
Val Verde	USA	Various	EOR	132 km onshore	Natural gas processing	1.3	various
In Salah	Algeria	BP	G-DSA	14 km onshore	Natural gas processing	1	4
Sleipner	Norway	Statoil	G-DSA	0 km offshore	Natural gas processing	1	14
Snøhvit	Norway	Statoil	G-DSA	152 km offshore	Natural gas processing	0.7	1.4

2.5 Longyearbyen CO_2 lab project

The Longyearbyen CO_2 lab project was described in the literature (e.g. Braathen *et al.*, 2012; Bælum *et al.*, 2012; Ogata *et al.*, 2012b; Mørk, 2013) as well as in numerous contributions in this thesis. To avoid repetition, only the major factors affecting geological heterogeneity in the target aquifer are presented in this section. Phase I of the project, as described by Braathen *et al.* (2012), identified a target aquifer within the Late Triassic to Middle Jurassic heterolithic siliciclastic Kapp Toscana Group. The stratigraphy is well constrained both by drilling and extensive fieldwork on exposed outcrops around Spitsbergen. Two main heterogeneities thought to be critical to subsurface fluid flow were identified at different scales:

1) A **natural fracture network**: The presence of natural fractures is evident from both borehole and outcrop studies and water injection tests indicate that fluid flow in the lower part of the target aquifer is almost exclusively through the fracture network. Matrix contribution to fluid flow was suggested to be more important in the upper part of the aquifer (Larsen, 2012), in line with matrix permeability measurements on drill cores (Farokhpoor *et al.*, 2010). The accurate and representative reservoir modelling of the natural fracture network is critical for the accurate prediction of CO_2 flow in the subsurface. In order to better predict fracture flow, well-exposed fracture corridors with evidence of paleo-fluid flow in south-eastern Utah serve as an analogue to fluid flow through naturally fractured siliciclastic rocks.

2) Presence of **igneous intrusions**: Igneous intrusions were identified in the CO_2 target aquifer based on borehole, seismic, magnetic and field data. Analogue studies in the Karoo Basin indicate that intrusions can act both as baffles and barriers to fluid flow with a potential to compartmentalize a reservoir. They may also offer high-permeability pathways leading to enhanced fluid flow along the intrusion-host rock contacts, where fracture corridors are common. Understanding intrusion geometry, density and impact, and subsequently implementing these in a regional geological model is thus important for predicting CO_2 flow in the subsurface.

2.5.1 Natural fracture systems

As conventional, easily producible hydrocarbon resources are being depleted, alternative, more challenging resources and plays are being targeted. Naturally fractured carbonate reservoirs are a prime example with a large reward, hosting the largest proportion of the remaining conventional resources (Burchette, 2012). Nonetheless, recovery factors and producibility are intimately linked to understanding and correctly implementing the natural fracture system, with the need of characterizing both the matrix and fracture properties as well as their interaction (Baker & Kuppe, 2000). The Svalbard aquifer is siliciclastic, but its tight nature and low matrix permeability, with a natural fracture system driving injectivity, requires the use of a dual porosity-dual permeability reservoir model, similar to what is used in many carbonate and unconventional fields.

The presence of natural fractures within the target aquifer is evident from drilled cores, outcrops and well test data. The first water injection test during August-September 2010, conducted in the 870-970 m interval close to the bottom of the target aquifer, identified an underpressured, naturally fractured reservoir (Larsen, 2010). In short, the aquifer exhibited an order of magnitude higher injectivity than would be expected given the low laboratory-measured porosity-permeability data (matrix permeability < 2 mD; Farokhpoor *et al.*, 2010; Braathen *et al.*, 2012). The presence of natural fractures both in drill core and outcrop was subsequently documented in Paper I, with their accurate and representative modelling described in Abstract A4 and Paper VI.

2.5.2 Igneous intrusions and fluid flow

Igneous intrusions were identified in the study area previously, and were partly reviewed by Nejbert *et al.* (2011) as well as in Paper II. The Early Cretaceous, predominantly doleritic, intrusions occur as both sills and dykes and were identified through drilling (Braathen *et al.*, 2012), seismic investigations (Bælum *et al.*, 2012) and by fieldwork (Paper III). As discussed above, underpressure was detected within the CO_2 target aquifer during water injection tests in August-September 2010. Due to the open-type aquifer configuration, in which the target aquifer is exposed at the surface *c.* 15 km from the planned injection site, lateral flow barriers restricting communication to the surface are a pre-requisite for the underpressure. Igneous intrusions, along with stratigraphic pinch-outs, sub-seismic faults, gentle detachment folds and the presence of impermeable permafrost, were hypothesized as possible factors contributing to the development of such barriers (Ogata *et al.*, 2012b; Paper I).

Previous work in other volcanic basins has shown that, in their unweathered state, dykes may act as baffles and barriers preventing cross-dyke fluid flow (Morel & Wikramaratna, 1982; Perrin *et al.*, 2011) while highly fractured dykes clearly leak (Sankaran *et al.*, 2005) and may even act as preferential fluid pathways (Mège & Rango, 2010). Igneous intrusions were shown to significantly affect groundwater movement in the South African Karoo Basin (Chevallier *et al.*, 2001; Woodford & Chevallier, 2002). This paradox of intrusions acting both as barriers and carriers to fluid flow was recently discussed by Rateau *et al.* (2013) in the context of hydrocarbon migration in the Faroe-Shetland basin, concluding that the natural fracture network is one of the most important parameters driving fluid flow in- and around intrusions. In order to judge the impact of igneous intrusions on the regional-scale fluid flow, their overall geometry must nonetheless first be mapped. In Paper III, an integrated study addressed the geometry of the igneous intrusions within Central Spitsbergen, and suggested that the CO_2 target aquifer is affected by intrusions, particularly in its lower third (*c*. 850-970 m in the Dh4 borehole).

At the local scale, emplacement of igneous intrusions initiates geochemical aureole processes which, together with the intrusion, cause perturbations within the surrounding host rock. This process is significant even with thin sills, as illustrated in Paper IV where a 2.28 m thick intrusion penetrated by the Dh4 borehole was studied in detail. On-going work, partly presented in the draft of Paper VIII, focusses on quantifying the fracturing patterns, and associated fluid flow pathways, at igneous-host rock interfaces at selected exposures in the Karoo Basin. This work will ultimately improve the understanding of how even minor igneous intrusions, such as the sills and dykes in the CO_2 target aquifer, affect subsurface fluid flow and reservoir compartmentalization.

2.5.3 Database

This integrated thesis builds on a wealth of pre-existing and newly acquired data sets, including outcrop, borehole, geophysical and published data (Figure 6). The various data sets were described in more detail within the relevant manuscripts. The majority of the data was integrated using the Petrel software (Schlumberger, 2011) as a work platform.

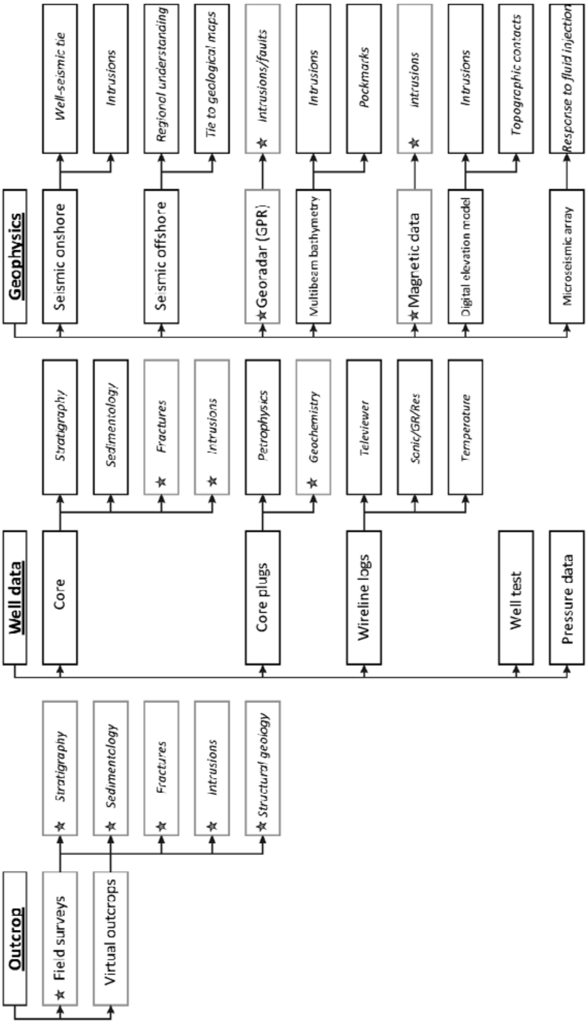

Figure 6: Integrated database utilized for understanding the CO_2 target aquifer on Svalbard. The red boxes and stars highlight data sets to which this PhD study has significantly contributed with data acquisition or processing. For more details on the data sets see Figure 5 and Table 1 in Paper VI. Additional outcrop-based data sets from outcrop analogues in Utah and South Africa are not included here.

3 Methods

The increased use of outcrop data in building reservoir models is related to two main factors. Firstly, the petroleum industry is shifting towards unconventional reservoirs as the ‘easy oil’ is being depleted, and more challenging reservoirs need to be found and developed (Larsen, 2008). Secondly, the use of techniques such as lidar scanning allow for the rapid acquisition of immense data sets directly usable to characterize various aspects of reservoir analogues at field-scale (e.g. Pringle *et al.*, 2006; Enge *et al.*, 2007; Rotevatn *et al.*, 2009).

The broad nature of this PhD study integrated a wide spectrum of methods (Figure 7), which are outlined in detail in the relevant manuscripts. A large pre-existing database associated with the UNIS CO_2 lab was used in this study, but critical data sets (e.g. fracture mapping, stratigraphic logging, intrusion mapping, analogue studies) needed to be acquired as part of this PhD project. The broad range of geological, geophysical and reservoir engineering methods applied clearly need to be integrated to be utilized to their full potential. In this work, I have used the Petrel reservoir modelling software (Schlumberger, 2011) as a tool for model building, visualizing and jointly interpreting the various data sets. Finally, Petrel was also used as an interface to control fluid flow simulations conducted using FrontSIM and ECLIPSE, as well as for displaying the simulation results.

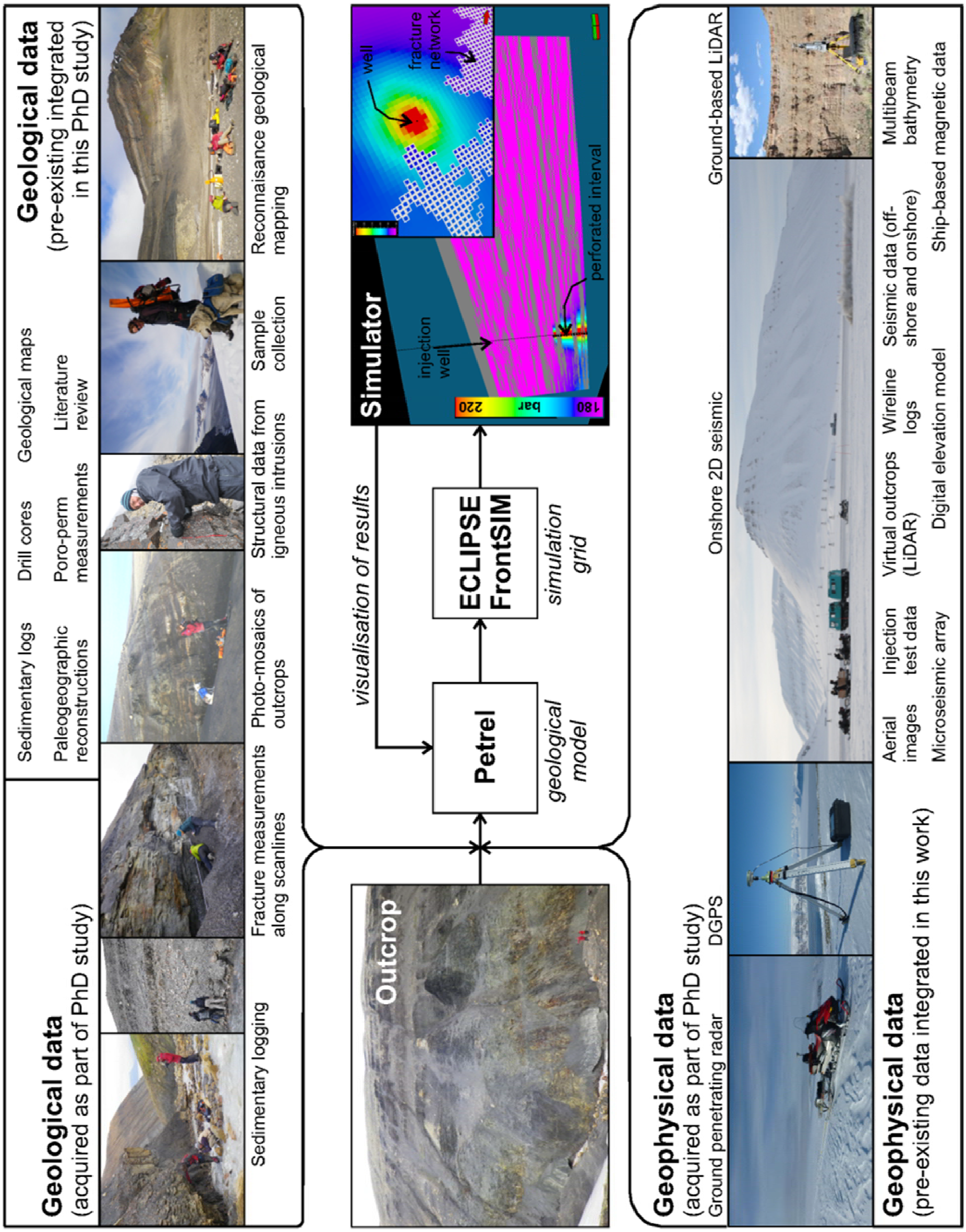

Figure 7: Synthesis of the wide range of geological and geophysical methods applied in this study.

4 Main results

In this section I outline the main results of each paper, before synthesizing the broader results of this PhD thesis in the next chapter.

4.1 Paper I – Natural fractures and CO_2 storage in Svalbard

This initial contribution, written following the manual fracture logging of the Dh4 borehole and one field season, focusses on integrating borehole and outcrop data to illustrate the importance of natural fractures for CO_2 storage on Svalbard. The inclusion of field data was critical at this stage, since it provided the first accurate data on the orientation of various fracture sets, given that the drill cores were not oriented. The publication also formed a vital building block for subsequent work by providing a clear link between the injection site and the outcrops through stratigraphic correlation (Figure 7 in Paper I). The data set was, with additional fieldwork, expanded to a large database of over 7 700 individual fractures measured along more than 1 400 m of scanlines. Results related to this database were subsequently presented at numerous conferences (see Appendix B, particularly abstracts A1, A4, C2 and C5), with abstract A4 introducing the workflow used for incorporating the field data in the reservoir model.

In Paper I, focus was given to the upper part of the reservoir, the Knorringfjellet Formation, which, at the time of publication, was not yet tested by water injection tests. Furthermore, an initial working hypothesis was presented, linking the various fracture sets to specific events in the geologic history, with the development of the Paleogene West Spitsbergen fold-and-thrust belt dominating the development of fractures (Figure 10 in Paper I). This understanding was used to develop an initial conceptual fluid flow model (Figure 12 in Paper I), which introduces the concept of variable fluid flow through different lithologies. The concept of these 'litho-structural units' was critical since it was directly used in subsequent volumetric calculations (Paper V) and reservoir modelling (Paper VI).

4.2 Paper II – Review of late Mesozoic magmatism on Svalbard

Paper II reviews the broad theme of Late Mesozoic igneous intrusions on Svalbard. The last comprehensive review of the intrusions was published by Tyrrell & Sandford (1933), with more recent contributions providing additional information on the geochemistry (Nejbert *et al.*, 2011) and the links to the High Arctic Large Igneous Province (HALIP; Maher, 2001). Intrusions are known to affect a given reservoir both locally, through contact metamorphism (e.g. Aarnes *et al.*, 2010), and regionally, through reservoir compartmentalization and channelling of fluid flow (e.g. Rateau *et al.*, 2013). The presence of igneous intrusions within the CO_2 target aquifer was documented in the Dh4 borehole (Braathen *et al.*, 2012), seismic data (Bælum *et al.*, 2012) and outcrop studies (e.g. Nejbert *et al.*, 2011; Paper III) and a review contribution was deemed necessary to set the scene and define the research gaps, some of which (e.g. overall geometry, impact of intrusions on host rock properties) were addressed in subsequent papers (Paper III and Paper IV respectively) in this PhD thesis.

The Early Cretaceous Diabasodden Suite igneous rocks were known since at least the early 19th century (Keilhau, 1831). These predominantly doleritic intrusive rocks are present throughout the Svalbard archipelago, and represent a well exposed part of the circum-Arctic High Arctic Large Igneous Province (HALIP; Dallmann *et al.*, 1999; Maher, 2001). Nonetheless, this igneous suite was often overlooked by on-going research, with questions on timing of magmatism and overall geometry particularly poorly constrained. Nejbert *et al.* (2011) presented a comprehensive geochemical database illustrating the affinity of igneous rocks scattered throughout the Svalbard archipelago, and provided a range of new Ar-Ar dates. Recent work using the more robust U-Pb dating technique conducted by Corfu *et al.* (2013) constrained the magmatism geochronology significantly to *c.* 124.5 Ma.

4.3 Paper III – Regional geometry of igneous complex on Svalbard

As discussed in Paper II, the regional geometry of the Diabasodden Suite was particularly poorly constrained. Furthermore, the structural framework of an igneous complex plays a central role in channelling fluid flow along the contact zones of igneous intrusions, with local processes (e.g. fracturing at host rock interfaces, contact metamorphism) merely superimposed on the regional geometry. In Paper III, we document the various igneous bodies within central Spitsbergen, with particular focus on the CO_2 storage target aquifer in the Kapp Toscana Group. The integrated study of this onshore-offshore igneous province, utilizing a broad range of geological and geophysical data sets, resulted in a conceptual model illustrating the typical igneous features in the study area (Figure 14 in Paper III). The study area exhibits a wide range of igneous features, with sills of varying thickness most common, presumably linked together by a series of dykes. These relatively thin (< 5 m) dykes extend through the entire target aquifer, and even penetrate an unknown distance into the overlying cap rock. On the basis of outcrop analogues, particularly from the Karoo Basin (Paper VIII), we argue that such dykes have the potential to locally channel fluid flow along their fractured margins and should thus be represented in regional-scale reservoir models. Saucer-shaped sills were also identified and thoroughly documented for the first time on Svalbard, but are most common in the stratigraphic levels below the Kapp Toscana Group. The structural complexity of the igneous features appears to decrease with depth in the stratigraphy (from complex dyke-sill interactions to thick, extensive sills), but the absolute amount of igneous material appears to increase with depth. We thereby conclude that while igneous intrusions alone are unlikely to generate laterally sealing pressure compartments within the target aquifer, dykes will, through their local modification on regional fluid flow, likely exert control on the areal extent of an injected CO_2 plume. Apart from the direct applicability to the CO_2 target aquifer on Svalbard, this onshore-offshore volcanic province also serves as a useful analogue for other volcanic basins worldwide (e.g. Møre and Vøring Basins offshore mid-Norway).

4.4 Paper IV – Contact metamorphism around a thin intrusion

In Paper IV, we study the contact metamorphism around a 2.28 m thick igneous intrusion drilled and cored in the Dh4 borehole. The emplacement of the intrusion, located at 949.71-951.99 m depth in the lower part of the Kapp Toscana Group CO_2 target aquifer, led to the development of a symmetric contact aureole, particularly well defined by the reduction of total organic carbon towards the intrusion. The full coring, along with the presence of massive black shale as the host rock, allowed us to log and sample both the intrusion and the surrounding host rock. The visibly bleached zone extends 0.5-1 m away from the intrusion, but organic geochemistry delineates an up to 2 m wide metamorphic aureole, symmetric on both sides of the intrusion (Figure 6 in Paper IV). The total aureole thickness equates to 160-195% of the sill intrusion thickness. Together with the sill, this results in a six meter thick zone where rheological and geochemical perturbation affects the CO_2 target aquifer. Furthermore, the intrusion displays increased fracturing both within and around the intrusion, also evidenced at outcrops of similarly-sized sills. Aureole studies conducted in the Karoo Basin (e.g. Haave, 2005; Aarnes *et al.*, 2010) quantified the thermally and chemically affected area, and described the various processes acting on the host rock that ultimately lead to a reduction in porosity and the loss of organic carbon. Based on this local case study, we suggest that the reservoir properties of the CO_2 target aquifer will be locally degraded by the igneous intrusions, but their limited spatial extent and deeper stratigraphic setting will restrict significant loss of reservoir quality in the main target section in the upper part of the aquifer.

4.5 Paper V – UNIS CO_2 lab volumetric calculation

Paper V addresses one of the main aims of this PhD study, namely defining the CO_2 storage capacity of the Kapp Toscana Group. Determining the CO_2 storage capacity of a particular site is clearly one of the most critical steps towards storing CO_2 in the subsurface. We apply a stochastic, volumetric-based workflow to calculate the probable range of storage capacity volumes. This transparent method, taking probability distributions of specific parameters as input, generated a P90-P10 range for six different scenarios. The chosen method did not directly incorporate results from the water injection tests but, due to its transparency and simplicity, allows for the discussion of the input parameters and a qualitative risking of the storage capacity. In addition, the variance of each input parameter was calculated to allow the identification of the parameters exhibiting the largest influence on the volumetric estimates. These factors, including CO_2 density, CO_2 saturation and the storage efficiency factor, can then be addressed and constrained in future studies. The absolute results are thus arguably less important than the technical process of assigning the input parameter ranges based on well-documented subsurface evidence. The clear top-side storage requirements constrained by the annual CO_2 emissions from the existing power plant (*c.* 60 000 tons/year) were compared to the available subsurface volumes to give a matched CO_2 storage capacity following Bachu *et al.* (2007b). Due partly to the modest storage requirements, sufficient storage capacity seems to be present in most scenarios, with the CO_2 phase (supercritical versus gas-phase end members) being the most critical parameter for total volumes. In absolute volumes, the mean practical storage potential ranges from 12 to 12 000 million tons of CO_2 (assuming supercritical CO_2) and from 0.05 to 50.7 million tons of CO_2 (assuming gas-phase CO_2). We have also risked the storage capacity estimates with respect to several cases of top-side CO_2 storage requirements, concluding that the success rate is high (>90%) in R&D-scaled pilot projects with planned injection volumes of up to 200 000 tons of CO_2.

4.6 Paper VI – Reservoir modelling of UNIS CO_2 lab aquifer

In Paper VI, we document the development of the current version of the static geological reservoir model and run initial flow simulations, thus spanning the full *'from outcrop to simulator'* workflow. The report is structured in two sections, with the first documenting the integrated characterization of the unconventional aquifer and the second documenting how this information was applied to build the reservoir model and test its viability for simulating water injection through conducting deterministic fluid simulation cases on selected model realizations. A reservoir model is critical for addressing a range of questions relating to site-specific CO_2 storage, as illustrated by Figure 2 in Paper VI. The reservoir model can, however, only be as good as the input data used. On Svalbard, the large database accumulated by the Longyearbyen CO_2 lab project since its initiation in 2007 provides a strong foundation for reservoir modelling. Nonetheless, critical input data was not available at the beginning of this PhD study, notably the fracture network characterization and the extent and characteristics of the igneous intrusions. Therefore, much focus was devoted to acquiring, processing and interpreting these data sets (see Papers I, II, III and IV) in order to provide a robust reservoir model presented in Paper VI. This report documents both the reservoir characterization of the unconventional target aquifer, as well as the workflow used for building a series of reservoir models. In the final part, the utility of using these models for conducting fluid flow simulations was presented, together with history matching of the water injection tests. At this stage, these simulation cases did not give a robust match to the observed pressure data during injection, but nonetheless provide a framework for running a matrix of numerous water simulation cases on a range of realizations of the geological model. While the report truly spans the *'from outcrop to simulator'* workflow, it must be stressed that much work (e.g. simulating CO_2 injection rather than water injection), and the development of advanced simulation tools, remains before full-field CO_2 injection into this unconventional aquifer can be accurately simulated with confidence.

4.7 Paper VII – Fracture corridors as seal-bypass systems

In Paper VII, we present a detailed field-study of fracture corridors in south-eastern Utah, focussed on fracture corridors displaying evidence of paleo-fluid flow (i.e. bleaching; Dockrill & Shipton, 2010). Similar fracture corridors are thought to be present in the subsurface of Svalbard, where water injection tests into the CO_2 target aquifer, as reported by Larsen (2010), suggest linear flow with partially sealing boundaries parallel to a hypothetical fracture. This pattern of flow could be related to the presence of fracture corridors, identified in outcrop studies primarily due to the enhanced fracturing within the fracture corridors compared to the background (e.g. Questiaux *et al.*, 2010). Even though fracture corridors strongly influence subsurface fluid flow, there are only few high-resolution outcrop studies which address their geometry and generation. In Paper VII, we presented a detailed (6 379 individual fractures measured) outcrop-based study of fracture corridors in an exhumed reservoir-cap rock succession around Green River, south-eastern Utah. The analysed interval within the paleo-reservoir of the Jurassic Entrada Formation, an eolian unit with a characteristic red colour, testifies to ancient circulation of reducing fluids through an exhumed paleo-reservoir-cap rock succession. The resultant bleaching haloes, particularly prominent at fracture corridors, were caused by oxide removal from grain coatings due to circulation of CO_2 or hydrocarbon-charged brines (e.g. Dockrill & Shipton, 2010). Based on the field observations, we identify three distinct types of fracture corridors, associated with (1) fault damage zones, (2) fault tip process zones and (3) fold-related crestal zones. These can be seen as end-member examples within a continuum of structural elements (Figure 15 in Paper VII). Ultimately, this framework can serve as a base for subsequent testing and calibration of reservoir models, with fault damage zone and fold-crestal zone fracture corridors particularly relevant to the CO_2 target aquifer on Svalbard.

4.8 Paper VIII – Fracturing in and around igneous rocks

In Paper VIII, we focus on mapping the fracture network at intrusion-host rock interfaces, using the well-exposed Karoo dolerite as an analogue to the Diabasodden Suite dolerites on Svalbard. Igneous intrusions were shown to act both as barriers/baffles and high-permeability carriers to fluid flow (e.g. Rateau *et al.*, 2013). The low matrix permeability of igneous rocks requires an open natural fracture to be present for significant fluid flow to occur. The characteristics of this fracture network (e.g. fracture spacing, fracture aperture, fracture connectivity) will subsequently determine whether a particular intrusion will act as a barrier, potentially compartmentalizing a given reservoir, or as a carrier leading fluids to by-pass reservoir segments. The importance of natural fractures for fluid flow was well constrained by hydraulic testing in the Palisades sill (Matter *et al.*, 2006), as well as by comprehensive groundwater exploration in the Karoo Basin (Chevallier *et al.*, 2001; Woodford & Chevallier, 2002). Nonetheless, few high-resolution outcrop-based studies address the fracturing patterns at intrusion-host rock interfaces, considered by many to be the primary fluid conduits. In Paper VIII, we present and analyse five virtual outcrop models (acquired using lidar; Buckley *et al.*, 2008) collected in the Eastern Cape Province of South Africa. At all sites, the Karoo dolerite, in various intrusion geometries, intruded a heterogeneous siliciclastic host rock. Fracture orientations were shown to be complex in the dolerite intrusions, but typically aligned along two main expected sets: (1) parallel to the main intrusion contact, and, (2) perpendicular to the main intrusion contact. Fracture spacing was more variable in the dolerite compared to the surrounding rocks. In some cases, fracture frequency increased in sedimentary rocks towards the intrusion. We concluded by presenting a conceptual model for fluid flow at intrusion-host rock interfaces. Ultimately, this could provide control for both small-scale site-specific fluid flow simulations and regional-scale fluid flow simulations in volcanic basins.

5 Synthesis

This integrated PhD thesis addresses the reservoir characterization and static reservoir modelling of an unconventional aquifer targeted for CO_2 storage on Svalbard, in a workflow *'from outcrop to simulator'*. The broad collection of scientific papers is illustrated schematically in Figure 1 and conceptually, within the framework of the CO_2 target aquifer on Svalbard, in Figure 8 below.

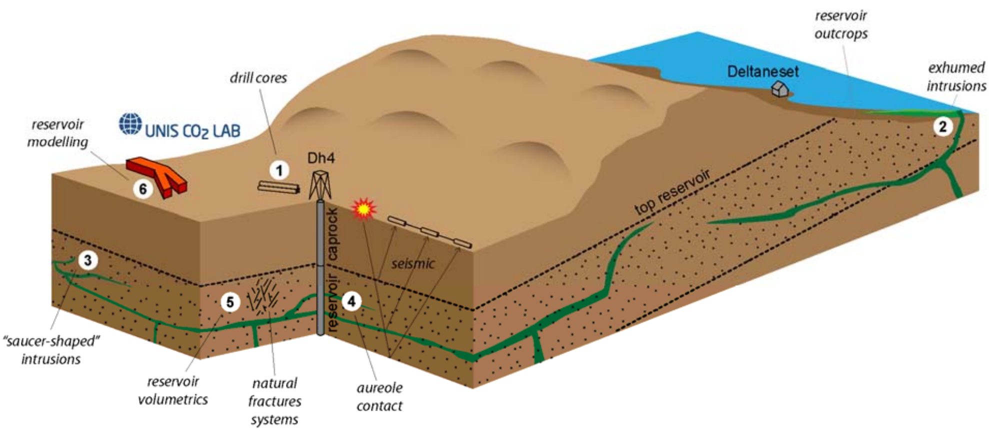

Figure 8: Conceptual synthesis of the various aspects of the Svalbard unconventional CO_2 target aquifer addressed by the broad spectrum of papers included in this PhD thesis (marked by circled numbers, the outcrop analogue Papers VII and VIII are not marked). Figure drafted by Kei Ogata, following a conceptual sketch by Kim Senger.

But what makes the target aquifer so unconventional? Phase I of the Longyearbyen CO_2 laboratory project largely demonstrated the unconventionality of the Kapp Toscana Group target aquifer (Braathen *et al.*, 2012). The heterolithic aquifer consists of tight cemented sandstones, which display moderate injectivity during water injection tests, but have matrix permeability well below 2 mD (Farokhpoor *et al.*, 2010). Most of the matrix porosity is related to secondary dissolution (Mørk, 2013). Dynamically, the target aquifer is also abnormal, with a sub-hydrostatic initial pressure regime and natural gas presence within the cap rock shales immediately above the target aquifer (Braathen *et al.*, 2012; Olaussen *et al.*, 2013). Furthermore, the whole aquifer section, and particularly its lower part, is affected by the presence of Early Cretaceous igneous intrusions belonging to the Diabasodden Suite.

Clearly, such an unconventional aquifer offers numerous aspects all meriting further research. In this broad PhD study, two themes related to the geological heterogeneity at different scales were addressed in detail: (1) fine-scaled heterogeneity associated with the natural fracture network, and, (2) regional-scale heterogeneity associated with the igneous intrusions. The two themes are introduced in two manuscripts, Paper I and Paper II respectively.

With the strong focus on igneous intrusions in this PhD study, it quickly became apparent how little is known about the Diabasodden Suite dolerites on Svalbard, even as on-going research is being conducted (e.g. Minakov *et al.*, 2012; Corfu *et al.*, 2013). Furthermore, igneous intrusions undoubtedly have both a local and regional effect on reservoir properties and fluid flow (e.g. Aarnes *et al.*, 2010; Rateau *et al.*, 2013), as well as hydrocarbon generation (e.g. Hubred, 2006). Nonetheless, limited work on real-life case studies involving igneous intrusions and their immediate effect on hydrocarbon production or CO_2 injection was conducted. In light of this, the Longyearbyen CO_2 lab target aquifer is truly outstanding, offering a comprehensive integrated database and a segmented target aquifer with igneous intrusions. To set the scene for specific papers addressing various aspects of the intrusions, such as the regional geometry (Paper III) and contact metamorphism (Paper IV), a review article (Paper II) was clearly warranted. A thorough understanding of the Svalbard dolerites is also important in order to tie the Diabasodden Suite to analogous magmatic provinces, such as the Karoo dolerite. Paper III addresses one of the research gaps identified in the review article (Paper II), namely the regional geometry of the Diabasodden Suite intrusives, and links it directly to the CO_2 target aquifer. The study provides critical input to both reservoir characterization (Paper VI) and the volumetric calculation (Paper V), since the intrusions may affect the size and shape of an injected CO_2 plume. In Paper III, this is evidenced by the inter-relation of doleritic ridges on the seafloor and pockmarks, causally suggesting fluid flow channelling along the impermeable base of the sills. The overall geometry of the intrusions nonetheless only provides a qualitative image of how regional-scale fluid flow may be channelled by the igneous intrusions through the Kapp Toscana Group.

Previous work indicates that permeability within igneous intrusions is associated with the fracture network, particularly along intrusion boundaries (e.g. Woodford & Chevallier, 2002; Matter *et al.*, 2006). Detailed studies of intrusion-host rock interfaces were, however, lacking, providing the motivation for Paper VIII. By using the well-exposed and easily accessible Karoo dolerite as an analogue to the Svalbard dolerites, we can now transpose the conceptual model (Figure 14 in Paper VIII) onto the regional geometry of igneous bodies illustrated in Paper III to build a next-generation reservoir model. This model should also incorporate geochemical rock-fluid interactions, since the enhanced reactivity of CO_2 with igneous rocks may block the natural fracture system through carbonate formation (e.g. Aradóttir *et al.*, 2011).

However, igneous intrusions not only affect the fluid flow but also have a direct effect on the reservoir properties (e.g. matrix porosity and permeability) through contact metamorphism of the host rock. As shown in Paper IV, borehole observations and organic geochemistry indicate that the country rock is affected in a zone 160-195% the thickness of the sill. This result may then be extrapolated across the whole target aquifer, using the overall geometry of the igneous complex provided by Paper III, to suggest the fraction of the target aquifer likely to be affected by intrusions (*c.* 1% in the Dh4 borehole).

The natural fracture network not associated with the doleritic intrusions was introduced using borehole and outcrop data in Paper I. The importance of the fracture network for fluid flow in the tight, unconventional, aquifer was known early on in the study (e.g. Larsen, 2010; Braathen *et al.*, 2012; Ogata *et al.*, 2012b). However, only limited outcrop-based studies have focussed on studying fracture flow in siliciclastic rocks, in stark contrast to the numerous studies on carbonates (e.g. Cooke *et al.*, 2006; Guerriero *et al.*, in press). This provided the main motivation for Paper VII, the outcrop-based study of paleo-fluid flow in siliciclastic rocks in Utah. By addressing fluid flow along fracture corridors, which were also identified in the CO_2 target aquifer on Svalbard, we can use the conceptual model (Figure 15 in Paper VII) to predict and incorporate fracture corridors in the next-generation reservoir model. At the present time, natural fracture sets are incorporated in a 3*3 km reservoir model, documented in Paper VI. Fracture permeability is crucial for history-matching water injection test data (Larsen, 2010), but the contribution of the fracture network to overall storage capacity was poorly constrained. This is partly addressed in the volumetric calculation (Paper V), which uses the state-of-the-art understanding of the unconventional reservoir, building on Papers I, III, IV, VI, abstracts A1-A5 and other UNIS CO_2 lab studies (e.g. Braathen *et al.*, 2012; Larsen, 2012). The fracture network provides less than 1% of the initial porosity, but may open up following an increase in pressure during injection. Furthermore, the fracture network is likely to control the CO_2 access to the largely secondary porosity and thus indirectly contribute to the overall storage capacity. Due to the low volume requirement given the pilot-scale of the project and the low CO_2 emissions in Longyearbyen, the calculated volumes appear able to accommodate the estimated 'top-side' CO_2 requirement, particularly if it is at least partly stored in supercritical phase. This static calculation, however, does not incorporate full-field CO_2 injection simulation, considered to be beyond the scope of this PhD study, and arguably also beyond the capabilities of present-day reservoir simulators.

To summarize, the natural fracture network represents the fine-scaled geological heterogeneity addressed in this PhD study. The extensive borehole and outcrop-based fracture database (Paper I) was simplified by grouping individual scanlines into litho-structural units (LSUs), which were subsequently incorporated in both reservoir modelling (Paper VI) and volumetric calculation (Paper V). On the broad scale, igneous intrusions are present in the CO_2 target aquifer and set up regional heterogeneity with a compartmentalization potential. Their impact on the reservoir properties is shown to be restricted to the host rock immediately surrounding individual intrusions. Since the intrusions are mostly present in the lower one-third of the target aquifer, this direct impact is considered minimal on the upper part of the aquifer (Knorringfjellet Formation, Zone A in Paper V). Nonetheless, the regional-scale heterogeneity established by the magmatic plumbing system of dykes, sills and saucer-shaped intrusions will most likely affect fluid flow and thereby partly control the shape of future CO_2 plume. The exact prediction of the plume shape would require additional regional-scale reservoir simulations, incorporating the regional geometry of igneous bodies (Paper III) as well as the finer-scaled effects associated with fracturing at intrusion boundaries (Paper VIII) and contact metamorphism (Paper IV).

To synthesize, all these papers build on each other, and the related conference contributions, in order to better characterize and model the unconventional target aquifer on Svalbard. The geological heterogeneity on both the small scale (natural fracture network) and the larger scale (igneous intrusions) was considered throughout. Two papers focussing on outcrop analogues (Papers VII and VIII) both provide additional field-based conceptual models to incorporate in the next-generation reservoir model. The learnings from this PhD study are thus applicable both locally on Svalbard, but also globally where unconventional reservoirs in complex geological settings are increasingly targeted in the production of hydrocarbons.

6 Conclusions

To conclude, let us first examine the overall hypothesis introduced above:

'It is possible to store CO_2 emissions from the Longyearbyen coal-fuelled power plant locally in the subsurface of Svalbard'.

The short answer to this hypothesis is 'probably yes', as presented in the volumetric calculation in Paper V. However, the highly complex geology of this unconventional target aquifer requires further work to definitely answer this question. The problem-specific conclusions were listed in the individual manuscripts but, in the broadest sense, I infer the following from this integrated PhD study:

- The unconventional target aquifer on Svalbard relies on the presence of a natural fracture network for fluid injectivity.
  - On Svalbard, natural fractures were mapped and analysed in both drill cores and outcrops, and found to be predominantly controlled by the lithology and regional tectonic events. This has led to the development of a conceptual model of fractures based on a sub-division into litho-structural units (LSUs).
  - Natural fractures were represented in a 3*3 km large reservoir model on the basis of the LSU zonation extrapolated away from the wells/outcrop logs. Initial water simulations indicated fluid flow along the fracture system in two directions corresponding to the mean fracture set orientations – generally E-W and NNW-SSE.
  - Synthetic modelling suggested that the natural fracture network is likely to contribute less than 2% of the total porosity available for storage, but is critical for providing high-permeability pathways accessing secondary porosity.
  - Natural fractures display evidence for past fluid (including CO_2) migration, particularly along fracture corridors, in south-eastern Utah. Three end-member fracture corridor types were proposed, occurring

along faults, fault process zones and along crestal zones of anticlinal structures.

- The target aquifer on Svalbard is affected by the presence of Early Cretaceous igneous intrusions, particularly in the lower part of the De Geerdalen Formation. Intrusions occur predominantly as sills and dykes, with some evidence for saucer-shaped sills. These sills are frequently seen in volcanic basins worldwide but have previously not been mapped in detail on Svalbard.
  - On the local scale, even relatively thin (2.28 m thick) intrusions generate a contact aureole up to twice the thickness of the intrusion. Within this contact aureole, reservoir properties (e.g. porosity, permeability) and total organic carbon were significantly reduced.
  - Fracturing at intrusion-host rock interfaces appears to favour enhanced fluid flow along intrusions than across them. As such, intrusions within the CO_2 target aquifer may provide preferential fluid flow pathways between different reservoir compartments. The intrusions may, on the other hand, also contribute to the lateral reservoir segmentation, particularly in the lower half of the target aquifer where the intrusions are most common.
- A reservoir model of the target aquifer was constructed on the basis of a highly integrated dataset.
  - Outcrop-data was collected, analysed and integrated in the reservoir model to construct an implicit fracture network.
  - Initial flow simulations based on the water injection tests conducted confirm the feasibility of using the reservoir model for extensive fluid flow simulations.
  - We apply a stochastic volumetric calculation to indicate that sufficient subsurface space appears to be present, particularly if the modest CO_2 top-side requirement is considered.

6.1 Outlook

As with any PhD project, additional work could be conducted to address the many questions that arise during the data acquisition and interpretation. This is best illustrated by the phrase *'You learn as long as you drill'* used by Olaussen *et al.* (2013) in the context of presenting the Longyearbyen CO_2 lab project's many surprising findings.

The current data sets are listed in Table 2, together with their completeness and future potential. The importance of natural fractures was discussed at length already, but important parameters of the fracture network are still poorly understood. The dynamic behaviour of the different fracture sets at different pressures, for example, may have a large effect on fracture aperture size and the permeability field. Laboratory techniques designed to measure the fracture aperture using CT scanning (Wennberg *et al.*, 2007) under different pressures could improve the current reservoir model. Software already exists to coupling geomechanics directly to reservoir models (Bush, 2010), and with constraining lab-based measurements this may lead to the development of a next-generation Longyearbyen CO_2 lab reservoir model. As described by Smith *et al.* (2011), such updated models with constraining, site-specific, laboratory data on the geology, rock physics and the fluid model provide much more accurate and reliable predictions. Additional data sets, including new seismic, borehole, injection tests and laboratory analyses of drill cores would undoubtedly add further details, but must be weighed up with a cost-benefit analysis. Similarly, the geological model needs to be updated continuously as new data become available, incorporating state-of-the-art techniques for modelling crucial geological features, such as the fault facies concept (Fachri *et al.*, 2013) as well as constraining the underlying sedimentological framework (Husteli *et al.*, 2012).

Table 2: Summary of data sets discussed in this thesis, and proposed possible future research directions linked to the data sets and studies. Sources: 1 = Paper I, 2 = Ogata et al. (2013), 3 = Bælum et al. (2012), 4 = Paper III, 5 = Larsen (2010), 6 = Larsen (2012), 7 = Pettersen (2012), 8 = Paper VI, 9 = Farokhpoor et al. (2010), 10 = Paper V, 11 = Elvebakk (2010), 12 = Paper VII, 13 = Paper VIII.

Data set/Analysis	Description	Application	Source	Completeness/Future potential
Natural fracture database - from fieldwork	Structural data for fracture orientation and density	Basis for reservoir modelling	1,2	Database complete for present purpose, limited value of additional scanlines. Fieldwork focus to shift on sub-seismic faults in the reservoir section and surrounding strata.
Natural fracture database - from boreholes	Manual structural logging (dip only) and televiewer data (dip angle and azimuth)	Basis for reservoir modelling	1	Additional structural logging within the complete overburden section could be undertaken, but perhaps of limited value since the seal integrity is confirmed by leak-off tests and differential pressure above and below the seal unit.
Stratigraphic logging	High-resolution sedimentologic logging of boreholes and outcrop exposures	Reservoir modelling, well correlation	1,2	Tie to regional Triassic-Jurassic stratigraphic framework, constrain overall depositional model, address local stratigraphic heterogeneity using high-resolution logging and update model.
Wireline logging	Wireline logging suite (Gamma Ray, Seismic velocity, Resistivity, Caliper, Temperature, Televiewer)	High-resolution borehole characterization	11	Limited spatial coverage in wells due to risk of borehole collapse prior to casing, wireline data should be prioritized in future wells.
Seismic data	Onshore and offshore 2D seismic data	Regional mapping of top reservoir and igneous intrusions	3, 4	Onshore 2D seismic line along Adventdalen-Helvetiadalen-De Geerdalen would link boreholes to outcrop, otherwise terrain is unsuitable for seismic acquisition. A 3D offshore seismic cube would further constrain igneous geometries.
LiDAR data	Heli-based LiDAR scan of Botneheia mountain	Mapping of intrusions and lateral continuity of sand bodies	4	Additional heli-LiDAR acquisition on the north shore of Isfjorden could better constrain the geometries of igneous bodies, but the added value is limited (already well-covered through fieldwork) compared to the high cost. Ground-based LiDAR for high-resolution fracture mapping could be useful but access to and quality of outcrops may make this unsuitable.
Ground-penetrating radar	Onshore GPR study directly on top of the outcropping reservoir at Botneheia	Mapping of discontinuities (faults) and intrusion in the shallow (< 10 m) subsurface		Processing and interpretation of a feasibility study ongoing, can be expanded into a 3D GPR cube if found to be effective.
Analogue studies	Outcrop-based studies of similar features (e.g. natural fractures in Utah, intrusions in Karoo basin)	Define conceptual models, acquire statistical data sets (e.g. fracture network around intrusions) and implement them in the reservoir model	12,13	Relevant analogue studies can be conducted to address features poorly exposed on Svalbard, such as fluid flow through fracture networks (bleached fracture corridors in Utah) or the fracturing patterns at intrusion-host rock interfaces (Karoo basin). Nonetheless, the added value to the CO_2 storage aquifer on Svalbard must be weighed up against cost and duration of such projects.
Analysis of well test data	Downhole and well-head pressure and temperature data during water injection tests	History-matching and forward modelling water injection tests	5,6,7	Shut-in curves for water-injection tests from Dh4 and Dh7 were matched, as was (partly) the Dh4 injection-period pressure curve. Other tests (e.g. minifrac) could still be matched using the same model set-up. No model can match the complete Dh4 test sequence.
Reservoir modelling	Construction of static, stochastic geological reservoir models	Data compilation, basis for outcrop-based fluid flow simulations	8	Reservoir model needs to be continually updated as new data become available. There is ample room for improving the current reservoir model, but this requires additional data sets (e.g. high-resolution stratigraphic information, stratigraphic framework, distribution of pressure cells).
Full-field CO_2 simulations	Fluid simulation models (e.g. ECLIPSE/ FrontSIM)	Predict subsurface behaviour of CO_2, confirm storage capacity, optimize injection, determine CO_2 storage efficiency	9	Initial full-field CO_2 simulations grossly misrepresent the reservoir due to lack of critical data (e.g. natural fracture network). With more data, more robust simulations can be conducted but the unconventional nature of the reservoir with expected dynamic CO_2 phase changes makes simulations difficult with present-day tools. Nonetheless, much focus should be devoted to conducting extensive fluid flow simulations using the outcrop-based geological model as input.
Storage capacity assessment	Volumetric-based	Determine the theoretical and effective CO_2 storage potential	10	As with reservoir modelling, storage capacity assessments need to be updated as new data become available, leading to a more robust probability spread.

However, at this stage the actual injection of CO_2 into the target aquifer is arguably more important than additional data acquisition, since the question of how the injected CO_2 will behave in this unconventional aquifer needs to be addressed prior to full-scale CCS. The injection of CO_2 must be conducted in conjunction with the instalment of a surface and downhole high-resolution monitoring system, which would also provide important pre-injection baseline data as well as monitoring the development of the CO_2 plume (Chadwick *et al.*, 2009). During and following injection, a plethora of monitoring tools, as reviewed by Chadwick *et al.* (2009), are available to understand the subsurface behaviour of the CO_2. The presence of permafrost and the limited amounts of CO_2 envisioned to be sequestered on Svalbard require high-resolution monitoring, with the feasibility of each method carefully screened with the aid of the constantly updated reservoir model.

This would provide important injection and plume development data to history match and fine-tune the model. At present, the focus remains on history matching to water injection tests but the increased chemical reactivity of CO_2 may lead to unexpected results, including the blocking of some fractures through the precipitation of carbonate minerals (Baines & Worden, 2004). Simulating these effects, as well as the effects of dynamic CO_2 phase changes during full-field injection, will ultimately be required to predict the subsurface behaviour of CO_2. This was best summed up by Doughty *et al.* (2008) who, summarizing the achievements of the pilot-scale Frio CO_2 injection project, maintain that *"...only through the injection and monitoring of CO_2 could the impact of the coupling between buoyancy flow, geologic heterogeneity, and history-dependent multi-phase flow effects truly be appreciated."*

References

AARNES, I., SVENSEN, H., CONNOLLY, J. A. D., & PODLADCHIKOV, Y. Y. (2010). How contact metamorphism can trigger global climate changes: Modeling gas generation around igneous sills in sedimentary basins. *Geochimica et Cosmochimica Acta, 74*, 7179-7195. doi:http://dx.doi.org/10.1016/j.gca.2010.09.011

ALLEN, D., FAZIO, J., GORECKI, C., HUERTA, N., MCINTYRE, D., KUTCHKO, B., ROMANOV, V., & SMALL, M., 2010. US DOE: Summary of the Methodology for Development of Geologic Storage Estimates for Carbon Dioxide. US Department of Energy, Pittsburgh, USA, p. 17.

AMBROSE, W., LAKSHMINARASIMHAN, S., HOLTZ, M., NÚÑEZ-LÓPEZ, V., HOVORKA, S., & DUNCAN, I. (2008). Geologic factors controlling CO_2 storage capacity and permanence: case studies based on experience with heterogeneity in oil and gas reservoirs applied to CO_2 storage. *Environmental Geology, 54*(8), 1619-1633. doi:http://dx.doi.org/10.1007/s00254-007-0940-2

ARADÓTTIR, E. S. P., SIGURÐARDÓTTIR, H., SIGFÚSSON, B., & GUNNLAUGSSON, E. (2011). CarbFix: a CCS pilot project imitating and accelerating natural CO_2 sequestratioon. *Greenhouse Gas Science Technology, 1*, 105-118. doi:http://dx.doi.org/10.1002/ghg.18

ASHRAF, M., LIE, K. A., NILSEN, H. M., & SKORSTAD, A. (2010). *Impact of Geological Heterogeneity on Early-stage CO_2 Plume Migration: Sensitivity Study.* Paper presented at the ECMOR XII - 12th European Conference on the Mathematics of Oil Recovery, 6-9 September 2010, Oxford, UK.

BACHU, S. (2008). CO_2 storage in geological media: Role, means, status and barriers to deployment. *Progress in Energy and Combustion Science, 34*, 254-273. doi:http://dx.doi.org/10.1016/j.pecs.2007.10.001

BACHU, S., BONIJOLY, D., BRADSHAW, J., BURRUSS, R., CHRISTENSEN, N. P., HOLLOWAY, S., & MATHIASSEN, O. M., 2007a. Phase II Final Report from the Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation. Carbon sequestration leadership forum, Washington, United States, p. 43.

BACHU, S., BONIJOLY, D., BRADSHAW, J., BURRUSS, R., HOLLOWAY, S., CHRISTENSEN, N. P., & MATHIASSEN, O. M. (2007b). CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control, 1*(4), 430-443. doi:http://dx.doi.org/10.1016/s1750-5836(07)00086-2

BAINES, S. J., & WORDEN, R. H. (2004). The long-term fate of CO_2 in the subsurface: natural analogues for CO_2 storage. In S. J. Baines & R. H. Worden (Eds.), *Geological Storage of Carbon Dioxide* (Vol. 233, pp. 59-85). London: Geological Society, London. doi:http://dx.doi.org/10.1144/gsl.sp.2004.233.01.06

BAKER, R. O., & KUPPE, F. (2000). Reservoir Characterization for Naturally Fractured Reservoirs. *SPE International, 63286*, 11. doi:http://dx.doi.org/10.2118/63286-MS

BELIVEAU, D., PAYNE, D. A., & MUNDRY, M. (1993). Waterflood and CO_2 Flood of the Fractured Midale Field (includes associated paper 22947). *Journal of Petroleum Technology, 45*(9), 1-7. doi:http://dx.doi.org/10.2118/22946-PA

BENSON, S. M., & COLE, D. R. (2008). CO_2 Sequestration in Deep Sedimentary Formations. *Elements, 4*(5), 325-331. doi:http://dx.doi.org/10.2113/gselements.4.5.325

BERGH, S. G., & ANDRESEN, A. (1990). Structural development of the Tertiary fold-and-thrust belt in east Oscar II Land, Spitsbergen. *Polar Research, 8*(2), 217-236. doi:http://dx.doi.org/10.1111/j.1751-8369.1990.tb00385.x

BODEN, T. A., MARLAND, G., & ANDRES., R. J., 2012. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov/trends/emis/overview_2009.html, accessed 18/11/2012. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., p.

BORE, R. R., ANDREASSEN, I., KRISTIANSEN, J. E., & MODIG, I., 2012. [Dette er Svalbard - hva tallene forteller][This is Svalbard - what the numbers show](in Norwegian). Statistics Norway, Oslo, Norway, p. 28.

BP, 2012. BP Statistical Review of World Energy June 2012. BP, London, United Kingdom, p. 48.
BRAATHEN, A., BAELUM, K., CHRISTIANSEN, H. H., DAHL, T., EIKEN, O., ELVEBAKK, H., HANSEN, F., HANSSEN, T. H., JOCHMANN, M., JOHANSEN, T. A., JOHNSEN, H., LARSEN, L., LIE, T., MERTES, J., MØRK, A., MØRK, M. B., NEMEC, W. J., OLAUSSEN, S., OYE, V., RØD, K., TITLESTAD, G. O., TVERANGER, J., & VAGLE, K. (2012). Longyearbyen CO_2 lab of Svalbard, Norway – first assessment of the sedimentary succession for CO_2 storage. *Norwegian Journal of Geology, 92*, 353-376.
BRAATHEN, A., BERGH, S. G., & MAHER, H. D., JR. (1999). Application of a critical wedge taper model to the Tertiary transpressional fold-thrust belt on Spitsbergen, Svalbard. *Geological Society of America Bulletin, 111*(10), 1468-1485.
BRADSHAW, B. E., SPENCER, L. K., LAHTINEN, A.-L., KHIDER, K., RYAN, D. J., COLWELL, J. B., CHIRINOS, A., BRADSHAW, J., DRAPER, J. J., HODGKINSON, J., & MCKILLOP, M., 2010. An assessment of Queensland's CO_2 geological storage prospectivity - the Queensland CO_2 geological storage atlas. CO_2 Geological Storage Solutions Pty Ltd, Fyshwick, Australia, p. 10.
BRADSHAW, J., BACHU, S., BONIJOLY, D., BURRUSS, R., HOLLOWAY, S., CHRISTENSEN, N. P., & MATHIASSEN, O. M. (2007). CO_2 storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control, 1*(1), 62-68. doi:http://dx.doi.org/10.1016/s1750-5836(07)00027-8
BUCKLEY, S. J., HOWELL, J. A., ENGE, H. D., & KURZ, T. H. (2008). Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. *Journal of the Geological Society, 165*(3), 625-638. doi:http://dx.doi.org/10.1144/0016-76492007-100
BURCHETTE, T. P. (2012). Carbonate rocks and petroleum reservoirs: a geological perspective from the industry. In J. Garland, J. E. Neilson, S. E. Laubach & K. J. Whidden (Eds.), *Advances in Carbonate Exploration and Reservoir Analysis, Geological Society of London Special Publications #370* (Vol. 370, pp. 17-37). London: Geological Society of London. doi:http://dx.doi.org/10.1144/sp370.14
BUSH, I. (2010). An integrated approach to fracture characterization. *Oil Review Middle East*(2), 88-91.
BÆLUM, K., JOHANSEN, T. A., JOHNSEN, H., RØD, K., RUUD, B. O., & BRAATHEN, A. (2012). Subsurface geometries of the Longyearbyen CO_2 lab in Central Spitsbergen, as mapped by reflection seismic data. *Norwegian Journal of Geology, 92*, 377-389.
CHADWICK, R. A., ARTS, R., BENTHAM, M., EIKEN, O., HOLLOWAY, S., KIRBY, G. A., PEARCE, J. M., WILLIAMSON, J. P., & ZWEIGEL, P. (2009). Review of monitoring issues and technologies associated with the long-term underground storage of carbon dioxide. In D. J. Evans & R. A. Chadwick (Eds.), *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe* (Vol. 313, pp. 257-275). London: Geological Society. doi:http://dx.doi.org/10.1144/sp313.15
CHEVALLIER, L., GOEDHART, M., & WOODFORD, A. C. (2001). The influences of dolerite sill and ring complexes on the occurrence of groundwater in Karoo fractured aquifers: a morpho-tectonic approach. *Water Resource Commission Reports, WRC Report No. 937/1/01*, 165.
CHIARAMONTE, L., ZOBACK, M., FRIEDMANN, J., & STAMP, V. (2008). Seal integrity and feasibility of CO_2 sequestration in the Teapot Dome EOR pilot: geomechanical site characterization. *Environmental Geology, 54*(8), 1667-1675. doi:http://dx.doi.org/10.1007/s00254-007-0948-7
CLASS, H., EBIGBO, A., HELMIG, R., DAHLE, H., NORDBOTTEN, J., CELIA, M., AUDIGANE, P., DARCIS, M., ENNIS-KING, J., FAN, Y., FLEMISCH, B., GASDA, S., JIN, M., KRUG, S., LABREGERE, D., NADERI BENI, A., PAWAR, R., SBAI, A., THOMAS, S., TRENTY, L., & WEI, L. (2009). A benchmark study on problems related to CO_2 storage in geologic formations. *Computational Geosciences, 13*(4), 409-434. doi:http://dx.doi.org/10.1007/s10596-009-9146-x
CLOETE, M., 2010. Atlas on geological storage of carbon dioxide in South Africa. Council for Geoscience, Pretoria, South Africa, p. 62.
COOKE, M. L., SIMO, J. A., UNDERWOOD, C. A., & RIJKEN, P. (2006). Mechanical stratigraphic controls on fracture patterns within carbonates and implications for groundwater

flow. *Sedimentary Geology, 184*(3–4), 225-239. doi:http://dx.doi.org/10.1016/j.sedgeo.2005.11.004

CORFU, F., POLTEAU, S., PLANKE, S., FALEIDE, J. I., SVENSEN, H., ZAYONCHECK, A., & STOLBOV, N. (2013). U-Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. *Geological Magazine*, 1-9. doi:http://dx.doi.org/10.1017/S0016756813000162

DAGENS NÆRINGSLIV. (2007). [Vil grave ned klimagasser på Svalbard][Wants to bury greenhouse gases on Svalbard](in Norwegian), *Dagens Næringsliv (Reported by Jan-Morten Bjørnbakk, published 15.09.2007)*. Retrieved from http://e24.no/naeringsliv/vil-grave-ned-klimagasser-paa-svalbard/1995868

DALEY, T., MYER, L., PETERSON, J., MAJER, E., & HOVERSTEN, G. (2008). Time-lapse crosswell seismic and VSP monitoring of injected CO_2 in a brine aquifer. *Environmental Geology, 54*(8), 1657-1665. doi:http://dx.doi.org/10.1007/s00254-007-0943-z

DALLMANN, W. K., DYPVIK, H., GJELBERG, J. G., HARLAND, W. B., JOHANNESSEN, E. P., KEILEN, H. B., LARSSEN, G. B., LØNØY, A., MIDBØE, P. S., MØRK, A., NAGY, J., NILSSON, I., NØTTVEDT, A., OLAUSSEN, S., PCELINA, T. M., STEEL, R. J., & WORSLEY, D. (1999). *Lithostratigraphic Lexicon of Svalbard: Review and recommendations for nomenclature use*. Tromsø: Norsk Polarinstitutt

DOCKRILL, B., & SHIPTON, Z. K. (2010). Structural controls on leakage from a natural CO_2 geologic storage site: Central Utah, U.S.A. *Journal of Structural Geology, 32*(11), 1768-1782. doi:http://dx.doi.org/10.1016/j.jsg.2010.01.007

DOUGHTY, C., FREIFELD, B., & TRAUTZ, R. (2008). Site characterization for CO_2 geologic storage and vice versa: the Frio brine pilot, Texas, USA as a case study. *Environmental Geology, 54*(8), 1635-1656. doi:http://dx.doi.org/10.1007/s00254-007-0942-0

EATON, T. T. (2006). On the importance of geological heterogeneity for flow simulation. *Sedimentary Geology, 184*(3–4), 187-201. doi:http://dx.doi.org/10.1016/j.sedgeo.2005.11.002

EIKEN, O., RINGROSE, P., HERMANRUD, C., NAZARIAN, B., TORP, T. A., & HØIER, L. (2011). Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit. *Energy Procedia, 4*(0), 5541-5548. doi:http://dx.doi.org/10.1016/j.egypro.2011.02.541

ELVEBAKK, H., 2010. Results of borehole logging in well LYB CO2, Dh4 of 2009, Longyearbyen, Svalbard. NGU, Trondheim, Norway, p. 35.

ENGE, H. D., BUCKLEY, S. J., ROTEVATN, A., & HOWELL, J. A. (2007). From outcrop to reservoir simulation model: Workflow and procedures. *Geosphere, 3*(6), 469-490. doi:http://dx.doi.org/10.1130/ges00099.1

FACHRI, M., TVERANGER, J., BRAATHEN, A., & SCHUELLER, S. (2013). Sensitivity of fluid flow to deformation-band damage zone heterogeneities: A study using fault facies and truncated Gaussian simulation. *Journal of Structural Geology, 52*, 60-79. doi:http://dx.doi.org/10.1016/j.jsg.2013.04.005

FAROKHPOOR, R., TORSÆTER, O., BAGHBANBASHI, T., MØRK, A., & LINDEBERG, E. G. B. (2010). Experimental and Numerical Simulation of CO_2 Injection Into Upper-Triassic Sandstones in Svalbard, Norway. *SPE International, SPE 139524*, 11. doi:http://dx.doi.org/10.2118/139524-MS

FÖRSTER, A., NORDEN, B., ZINCK-JØRGENSEN, K., FRYKMAN, P., KULENKAMPFF, J., SPANGENBERG, E., ERZINGER, J., ZIMMER, M., KOPP, J., BORM, G., JUHLIN, C., COSMA, C.-G., & HURTER, S. (2006). Baseline characterization of the CO_2SINK geological storage site at Ketzin, Germany. *Environmental Geosciences, 13*(3), 145-161. doi:http://dx.doi.org/10.1306/eg.02080605016

GAMMER, D., GREEN, A., HOLLOWAY, S., SMITH, G., & THE UKSAP CONSORTIUM. (2011). The Energy Technologies Institute's UK CO_2 Storage Appraisal Project (UKSAP). *SPE International, 148426*, 14.

GEOCAPACITY, 2008. EU GeoCapacity: Assessing European Capacity for Geological Storage of Carbon Dioxide. GEUS Project no. SES6-518318, Copenhagen, Denmark, p. 37.

GIBSON-POOLE, C., SVENDSEN, L., UNDERSCHULTZ, J., WATSON, M., ENNIS-KING, J., VAN RUTH, P., NELSON, E., DANIEL, R., & CINAR, Y. (2008). Site characterisation of a basin-scale CO_2 geological storage system: Gippsland Basin, southeast Australia. *Environmental Geology, 54*(8), 1583-1606. doi:http://dx.doi.org/10.1007/s00254-007-0941-1

GLOBAL CCS INSTITUTE. (2012). http://www.globalccsinstitute.com/projects/browse. Retrieved 1/12, 2012,

GROHMANN, C. H., & CAMPANHA, G. A. (2010). *OpenStereo: Open Source, Cross-Platform Software for Structural Geology Analysis (http://www.igc.usp.br/index.php?id=openstereo)*. Paper presented at the AGU Fall Meeting, 13-17 December 2010, San Francisco, USA.

GUÉGUEN, Y., & PALCIAUSKAS, V. (1994). *Introduction to the physics of rocks*. Princeton, New Jersey: Princeton University Press.294p.

GUERRIERO, V., MAZZOLI, S., IANNACE, A., VITALE, S., CARRAVETTA, A., & STRAUSS, C. (in press). A permeability model for naturally fractured carbonate reservoirs. *Marine and Petroleum Geology*(0). doi:http://dx.doi.org/10.1016/j.marpetgeo.2012.11.002

HAAVE, C. (2005). Metamorphic and petrophysical effects of sill intrusions in sedimentary strata: the Karoo Basin, South Africa. unpublished MSc thesis, University of Oslo, Norway, p. 168.

HALLAND, E. K., GJELDVIK, I. T., JOHANSEN, W. T., MAGNUS, C., MELING, I. M., PEDERSEN, S., RIIS, F., SOLBAKK, T., & TAPPEL, I. (2011). *CO_2 Storage Atlas: Norwegian North Sea*. Stavanger, Norway: Norwegian Petroleum Directorate.72p.

HOVORKA, S. D., DOUGHTY, C., BENSON, S. M., PRUESS, K., & KNOX, P. R. (2004). The impact of geological heterogeneity on CO_2 storage in brine formations: a case study from the Texas Gulf Coast. In S. J. Baines & R. H. Worden (Eds.), *Geological Storage of Carbon Dioxide* (Vol. 233, pp. 147-163). London: Geological Society of London. doi:http://dx.doi.org/10.1144/gsl.sp.2004.233.01.10

HOWELL, J. A., SKORSTAD, A., MACDONALD, A., FORDHAM, A., FLINT, S., FJELLVOLL, B., & MANZOCCHI, T. (2008). Sedimentological parameterization of shallow-marine reservoirs. *Petroleum Geoscience, 14*(1), 17-34. doi:http://dx.doi.org/10.1144/1354-079307-787

HUBRED, J. H. (2006). Thermal Effects of Basaltic Sill Emplacement in Source Rocks on Maturation and Hydrocarbon Generation. unpublished MSc thesis, University of Oslo, Norway, p. 303.

HUSTELI, B., JENSEN, M., & OLAUSSEN, S. (2012). *Tidally related heterogeneities in sand bodies sought parameterized for refined reservoir modelling*. Paper presented at the Tidalites 2012 - 8th International Conference on Tidal Environments, Caen, France, 31/7-2/8 2012.

IEA, 2008. Key world energy statistics. International Energy Agency, Paris, France, p. 82.

IEA, 2010. World Energy Outlook 2010. International Energy Agency, Paris, France, p. 738.

IPCC. (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. In B. Metz, O. Davidson, H. C. de Coninck, M. Loos & L. A. Meyer (Eds.), *Carbon Dioxide Capture and Storage* (pp. 443). Cambridge, UK and New York, NY, USA: Cambridge University Press.

KEILHAU, B. M. (1831). *[Reise i Öst og Vest-Finnmarken samt til Beeren-Eiland og Spitsbergen i Aarene 1827 og 1828][Journey to East and West Finnmark as well as Bjørnøya and Spitsbergen in the years 1827 and 1828](in Danish)*. Christiania: Johan Krohn.269p.

KIRBY, A., 2008. CCCC Kick the habit: A UN guide to climate neutrality. United Nations Environment Programme/GRID Arendal, Arendal, Norway, p. 202.

LARSEN, L. (2008). Geoscientists in High Demand in the Oil Industry. *Science, 321*, 857-858.

LARSEN, L., 2010. Analyses of Injection and Falloff Data from Dh4, Aug. 12 - Sept. 4, 2010. unpublished UNIS CO_2 lab report, Longyearbyen, Norway, p. 30.

LARSEN, L., 2012. Summary of Well Test Results from DH4, DH5, DH6, DH5R and DH7a. unbpublished UNIS CO_2 lab report, Longyearbyen, Svalbard, p. 52.

LENGLER, U. (2012). [Einfluss von heterogenen Permeabilitätsfeldern auf die CO_2-Speicherung in salinen Aquiferen am Beispiel vom Pilotstandort Ketzin] [The effect of heterogeneous permeability fields on CO_2 storage in saline aquifers, as exemplified by the Ketzin project] (in German). PhD, Technische Universität Hamburg-Harburg, p. 222.

LENGLER, U., DE LUCIA, M., & KÜHN, M. (2010). The impact of heterogeneity on the distribution of CO_2: Numerical simulation of CO_2 storage at Ketzin. *International Journal of Greenhouse Gas Control, 4*(6), 1016-1025. doi:http://dx.doi.org/10.1016/j.ijggc.2010.07.004

LINDEBERG, E., VUILLAUME, J.-F., & GHADERI, A. (2009). Determination of the CO_2 storage capacity of the Utsira formation. *Energy Procedia, 1*(1), 2777-2784. doi:http://dx.doi.org/10.1016/j.egypro.2009.02.049

LOKALSTYRE, 2011. [Årsberetning 2011][Annual report 2011](in Norwegian). Longyearbyen Lokalstyre, Longyearbyen, Svalbard, p. 52.

MAHER, H. D., JR. (2001). Manifestations of the Cretaceous High Arctic Large Igneous Province in Svalbard. *The Journal of Geology, 109*(1), 91-104.

MATTER, J., GOLDBERG, D., MORIN, R., & STUTE, M. (2006). Contact zone permeability at intrusion boundaries: new results from hydraulic testing and geophysical logging in the Newark Rift Basin, New York, USA. *Hydrogeology Journal, 14*(5), 689-699. doi:http://dx.doi.org/10.1007/s10040-005-0456-3

MCGLADE, C. E. (2012). A review of the uncertainties in estimates of global oil resources. *Energy, 47*(1), 262-270. doi:http://dx.doi.org/10.1016/j.energy.2012.07.048

MÈGE, D., & RANGO, T. (2010). Permanent groundwater storage in basaltic dyke fractures and termite mound viability. *Journal of African Earth Sciences, 57*(1–2), 127-142. doi:http://dx.doi.org/10.1016/j.jafrearsci.2009.07.014

MEYER, R., MAY, F., MÜLLER, C., GEEL, K., & BERNSTONE, C. (2008). Regional search, selection and geological characterization of a large anticlinal structure, as a candidate site for CO_2 storage in northern Germany. *Environmental Geology, 54*(8), 1607-1618. doi:http://dx.doi.org/10.1007/s00254-007-0939-8

MINAKOV, A., MJELDE, R., FALEIDE, J. I., FLUEH, E. R., DANNOWSKI, A., & KEERS, H. (2012). Mafic intrusions east of Svalbard imaged by active-source seismic tomography. *Tectonophysics, 518-521*, 106-118. doi:http://dx.doi.org/10.1016/j.tecto.2011.11.015

MOREL, E. H., & WIKRAMARATNA, R. S. (1982). Numerical modelling of groundwater flow in regional aquifers dissected by dykes. *Hydrological Sciences Journal, 27*(1), 63-77. doi:http://dx.doi.org/10.1080/02626668209491086

MØRK, A., KNARUD, R., & WORSLEY, D. (1982). Depositional and diagenetic environments of the Triassic and Lower Jurassic succession of Svalbard. In A. F. Embry & H. R. Balkwill (Eds.), *Arctic Geology and Geophysics* (Vol. 8, pp. 371-398): Canadian Society of Petroleum Geologists.

MØRK, M. B. E. (2013). Diagenesis and quartz cement distribution of low-permeability Upper Triassic –Middle Jurassic reservoir sandstones, Longyearbyen CO_2 lab well site in Svalbard, Norway. *AAPG Bulletin, 97*, 577-596. doi:http://dx.doi.org/10.1306/10031211193

NACSA, 2012. The North American Carbon Storage Atlas 2012. US Department of Energy, Pittsburgh, USA, p. 52.

NAGY, J., HESS, S., DYPVIK, H., & BJÆRKE, T. (2011). Marine shelf to paralic biofacies of Upper Triassic to Lower Jurassic deposits in Spitsbergen. *Palaeogeography, Palaeoclimatology, Palaeoecology, 300*(1-4), 138-151. doi:http://dx.doi.org/10.1016/j.palaeo.2010.12.018

NEJBERT, K., KRAJEWSKI, K. P., DUBIŃSKA, E., & PÉCSKAY, Z. (2011). Dolerites of Svalbard, north-west Barents Sea Shelf: age, tectonic setting and significance for geotectonic interpretation of the High-Arctic Large Igneous Province. *Polar Research, 30*(7306), 1-24. doi:http://dx.doi.org/10.3402/polar.v30i0.7306

NETL, 2010. Carbon sequestration atlas of the USA and Canada. US Department of Energy, Pittsburgh, USA, p. 162.

NORDBOTTEN, J. M., CELIA, M. A., & BACHU, S. (2005). Injection and Storage of CO_2 in Deep Saline Aquifers: Analytical Solution for CO_2 Plume Evolution During Injection. *Transport in Porous Media, 58*(3), 339-360. doi:http://dx.doi.org/10.1007/s11242-004-0670-9

NRK. (2006). [Pilotprosjekt for CO_2-reinsing: Kolkraftverket i Longyearbyen kan bli eit pilotprosjekt for forsking og testing av ny og effektiv reinseteknologi for CO_2][Pilot-project for CO_2-capture: Coal-fuelled power plant in Longyearbyen can become a pilot project for testing of new and effective CO_2 capture technology](in Norwegian), *NRK (Reported by Eivind Molde, published 10.12.2006)*. Retrieved from http://www.nrk.no/nyheter/1.1462017

NÚÑEZ-LÓPEZ, V., HOLTZ, M., WOOD, D., AMBROSE, W., & HOVORKA, S. (2008). Quick-look assessments to identify optimal CO_2 EOR storage sites. *Environmental Geology, 54*(8), 1695-1706. doi:http://dx.doi.org/10.1007/s00254-007-0944-y

OBI, E.-O. I., & BLUNT, M. J. (2006). Streamline-based simulation of carbon dioxide storage in a North Sea aquifer. *Water Resources Research, 42*(3), W03414. doi:http://dx.doi.org/10.1029/2004wr003347

OGATA, K., BRAATHEN, A., SENGER, K., TVERANGER, J., PETRIE, E., & EVANS, J. (2012a). *Fracture-related fluid flow in sandstone reservoirs: insights from outcrop analogues of south-eastern Utah.* Paper presented at the Third EAGE Geological Storage of CO_2 workshop, 26-27 March 2012, Edinburgh, United Kingdom.

OGATA, K., SENGER, K., BRAATHEN, A., OLAUSSEN, S., & TVERANGER, J. (2013). *High-resolution studies of natural fracture systems in a siliciclastic CO_2 target aquifer, Central Spitsbergen, Arctic Norway*. Paper presented at the EAGE 2nd Sustainable Earth Science Conference & Exhibition, Pau, France, 30/9-4/10 2013.

OGATA, K., SENGER, K., BRAATHEN, A., TVERANGER, J., & OLAUSSEN, S. (2012b). The importance of natural fractures in a tight reservoir for potential CO_2 storage: case study of the upper Triassic to middle Jurassic Kapp Toscana Group (Spitsbergen, Arctic Norway). In G. H. Spence, J. Redfern, R. Aguilera, T. G. Bevan, J. W. Cosgrove, G. D. Couples & J. M. Daniel (Eds.), *Advances in the Study of Fractured Reservoirs, Geological Society of London Special Publication #374* (Vol. 374, pp. 22). London: Geological Society of London. doi:http://dx.doi.org/10.1144/SP374.9

OGAWA, T., NAKANISHI, S., SHIDAHARA, T., OKUMURA, T., & HAYASHI, E. (2011). Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment. *International Journal of Greenhouse Gas Control, 5*(2), 318-326. doi:http://dx.doi.org/10.1016/j.ijggc.2010.09.009

OLAUSSEN, S., BRAATHEN, A., ANELL, I., JOHANSEN, H., JOHANSEN, I., LARSEN, L., MØRK, A., MØRK, M. B. E., NEMEC, W., PLANKE, S., OGATA, K., OYE, V., & SENGER, K. (2013). *"You learn as long as you drill" - Unexpected results from the UNIS CO2 LAB drilling and testing campaign in Adventdalen, Svalbard.* Paper presented at the NGF Geological Winter Meeting, 8-10/1/2013, Oslo, Norway.

OLIVIER, J. G. J., JANSSENS-MAENHOUT, G., & PETERS, J. A. H. W., 2012. Trends in global CO_2 emissions: 2012 Report. PBL Netherlands Environmental Assessment Agency, The Hague/Bilthoven, p. 40.

PARRY, W. T., CHAN, M. A., & BEITLER, B. (2004). Chemical bleaching indicates episodes of fluid flow in deformation bands in sandstone. *AAPG Bulletin, 88*(2), 175-191. doi:http://dx.doi.org/10.1306/09090303034

PERRIN, J., AHMED, S., & HUNKELER, D. (2011). The effects of geological heterogeneities and piezometric fluctuations on groundwater flow and chemistry in a hard-rock aquifer, southern India. *Hydrogeology Journal, 19*(6), 1189-1201. doi:http://dx.doi.org/10.1007/s10040-011-0745-y

PETTERSEN, Ø. (2012). *Simulation of LYBCO$_2$ DH4 5-Day Injection Test*. Paper presented at the International CO_2 workshop, 17-20 September 2012, Longyearbyen, Norway.

PHAM, V. T. H., RIIS, F., GJELDVIK, I. T., HALLAND, E. K., TAPPEL, I. M., & AAGAARD, P. (in press). Assessment of CO_2 injection into the south Utsira-Skade aquifer, the North Sea, Norway. *Energy*(0). doi:http://dx.doi.org/10.1016/j.energy.2013.03.026

PLANKE, S., RASMUSSEN, T., REY, S. S., & MYKLEBUST, R. (2005). Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. In A. G. Dore & B. A. Vinning (Eds.), *Proceedings of the 6th Petroleum Geology Conference* (pp. 833-844). London: Geological Society.

POLTEAU, S., MAZZINI, A., GALLAND, O., PLANKE, S., & MALTHE-SØRENSSEN, A. (2008). Saucer-shaped intrusions: Occurrences, emplacement and implications. *Earth and Planetary Science Letters, 266*, 195-204.

PRINGLE, J. K., HOWELL, J. A., HODGETTS, D., WESTERMAN, A. R., & HODGSON, D. M. (2006). Virtual outcrop models of petroleum reservoir analogues: a review of the current state-of-the-art. *First Break, 24*, 33-42.

QUESTIAUX, J.-M., COUPLES, G. D., & RUBY, N. (2010). Fractured reservoirs with fracture corridors. *Geophysical Prospecting, 58*, 279-295. doi:http://dx.doi.org/10.1111/j.1365-2478.2009.00810.x

RAMÍREZ, A., HAGEDOORN, S., KRAMERS, L., WILDENBORG, T., & HENDRIKS, C. (2010). Screening CO_2 storage options in The Netherlands. *International Journal of Greenhouse Gas Control, 4*(2), 367-380. doi:http://dx.doi.org/10.1016/j.ijggc.2009.10.015

RATEAU, R., SCHOFIELD, N., & SMITH, M. (2013). The potential role of igneous intrusions on hydrocarbon migration, West of Shetland. *Petroleum Geoscience, Online First. DOI: http://dx.doi.org/10.1144/petgeo2012-035*. doi:http://dx.doi.org/10.1144/petgeo2012-035

RIIS, F., LUNDSCHIEN, B. A., HØY, T., MØRK, A., & MØRK, M. B. E. (2008). Evolution of the Triassic shelf in the northern Barents Sea region. *Polar Research, 27*, 318-338. doi:http://dx.doi.org/10.1111/j.1751-8369.2008.00086.x

ROTEVATN, A., BUCKLEY, S. J., HOWELL, J. A., & FOSSEN, H. (2009). Overlapping faults and their effect on fluid flow in different reservoir types: A LIDAR-based outcrop modeling and flow simulation study. *AAPG Bulletin, 93*(3), 407-427. doi:http://dx.doi.org/10.1306/09300807092

RUNKEL, A. C., TIPPING, R. G., ALEXANDER JR, E. C., & ALEXANDER, S. C. (2006). Hydrostratigraphic characterization of intergranular and secondary porosity in part of the Cambrian sandstone aquifer system of the cratonic interior of North America: Improving predictability of hydrogeologic properties. *Sedimentary Geology, 184*(3–4), 281-304. doi:http://dx.doi.org/10.1016/j.sedgeo.2005.11.006

SANKARAN, S., RANGARAJAN, R., & DHAR, R. (2005). Delineation of hydraulic connectivity across a dolerite dyke through hydrogeological, geophysical and tracer studies—a case study. *Environmental Geology, 48*(4), 411-419. doi:http://dx.doi.org/10.1007/s00254-005-1230-5

SCHLUMBERGER. (2011). Petrel E&P Software Platform, v. 2011. *Software*.

SCHULTZ, R. A., & FOSSEN, H. (2008). Terminology for structural discontinuities. *AAPG Bulletin, 92*(7), 853-867. doi:http://dx.doi.org/10.1306/02200807065

SHIPTON, Z. K., EVANS, J. P., KIRSCHNER, D., KOLESAR, P. T., WILLIAMS, A. P., & HEATH, J. (2004). Analysis of CO_2 leakage through 'low-permeability' faults from natural reservoirs in the Colorado Plateau, east-central Utah. In S. J. Baines & R. H. Worden (Eds.), *Geological Storage of Carbon Dioxide* (Vol. 233, pp. 43-58). London: Geological Society of London. doi:http://dx.doi.org/10.1144/gsl.sp.2004.233.01.05

SMITH, M., CAMPBELL, D., MACKAY, E., & POLSON, D., 2011. CO_2 aquifer storage site evaluation and monitoring - Understanding the challenges of CO_2 storage: results of the CASSEM Project. Heriot-Watt University, Edinburgh, Scotland, p. 200.

STEEL, R. J., & WORSLEY, D. (1984). Svalbard's post-Caledonian strata - an atlas of sedimentational patterns and paleogeographic evolution. In A. M. Spencer (Ed.), *Petroleum Geology of the North European Margin* (pp. 109-135). London: Graham & Trotman.

SVENSEN, H., CORFU, F., POLTEAU, S., HAMMER, Ø., & PLANKE, S. (2012). Rapid magma emplacement in the Karoo Large Igneous Province. *Earth and Planetary Science Letters, 325–326*(0), 1-9. doi:http://dx.doi.org/10.1016/j.epsl.2012.01.015

SWANSON, S. K., BAHR, J. M., BRADBURY, K. R., & ANDERSON, K. M. (2006). Evidence for preferential flow through sandstone aquifers in Southern Wisconsin. *Sedimentary Geology, 184*(3–4), 331-342. doi:http://dx.doi.org/10.1016/j.sedgeo.2005.11.008

TIPPING, R. G., RUNKEL, A. C., ALEXANDER JR, E. C., ALEXANDER, S. C., & GREEN, J. A. (2006). Evidence for hydraulic heterogeneity and anisotropy in the mostly carbonate Prairie du Chien Group, southeastern Minnesota, USA. *Sedimentary Geology, 184*(3–4), 305-330. doi:http://dx.doi.org/10.1016/j.sedgeo.2005.11.007

TVERANGER, J., 2011. Preliminary report on reservoir characterization and geo-modeling of the Upper Triassic Kapp Toscana Group reservoir, Longyearbyen, Svalbard. unpublished CIPR report, Bergen, Norway, p. 26.

TYRRELL, G. W., & SANDFORD, K. S. (1933). Geology and petrology of dolerites of Spitsbergen. *Proceedings of the Royal Society of Edinburgh*, 284-341.

VASCO, D. W., FERRETTI, A., & NOVALI, F. (2008). Reservoir monitoring and characterization using satellite geodetic data: Interferometric synthetic aperture radar observations from the

Krechba field, Algeria. *Geophysics, 73*(6), WA113-122. doi:http://dx.doi.org/10.1190/1.2981184

VOORMEIJ, D. A., & SIMANDL, G. J. (2004). Geological, Ocean, and Mineral CO_2 Sequestration Options: A Technical Review. *Geoscience Canada, 31*(1), 11-22.

WENNBERG, O. P., RENNAN, L., & BASQUET, R. (2007). *CT-scan Images of 3D Natural Open Fracture Networks in a Porous Media; Geometry, Connectivity and Impact on Fluid Flow.* Paper presented at the EAGE/SEG Research Workshop 2007, Perugia, Italy, 3 - 6 September 2007.

WHITE, C. D., WILLIS, B. J., NARAYANAN, K., & DUTTON, S. P. (2001). Identifying and Estimating Significant Geologic Parameters With Experimental Design. *SPE Journal, 6*(3), 311-324. doi:http://dx.doi.org/10.2118/74140-PA

WHITE, D., BURROWES, G., DAVIS, T., HAJNAL, Z., HIRSCHE, K., HUTCHEON, I., MAJER, E., ROSTRON, B., & WHITTAKER, S. (2004). Greenhouse gas sequestration in abandoned oil reservoirs: The International Energy Agency Weyburn pilot project. *GSA today, 14*(7), 4-11.

WHITTAKER, S., WHITE, D., LAW, D., & CHALATURNYK, R., 2004. IEA GHG Weyburn CO_2 Monitoring & Storage Project Summary Report 2000-2004. From the proceedings of the 7th International Conference on Greenhouse Gas Control Technologies held September 5-9, 2004, Vancouver, Canada. Regina, Canada, p. 283.

WIGLEY, M., DUBACQ, B., KAMPMAN, N., & BICKLE, M. (2013). Controls of sluggish, CO_2-promoted, hematite and K-feldspar dissolution kinetics in sandstones. *Earth and Planetary Science Letters, 362*(0), 76-87. doi:http://dx.doi.org/10.1016/j.epsl.2012.11.045

WOODFORD, A., & CHEVALLIER, L., 2002. Hydrogeology of the Main Karoo Basin: Current knowledge and future research needs. Water Resource Commission, WRC Report No. TT 179/02, p. 506.

WORSLEY, D. (2008). The post-Caledonian development of Svalbard and the western Barents Sea. *Polar Research, 27*, 298-317. doi:http://dx.doi.org/10.1111/j.1751-8369.2008.00085.x

XUE, Z., TANASE, D., & WATANABE, J. (2006). Estimation of CO_2 saturation from time-lapse CO_2 well logging in an onshore aquifer, Nagaoka, Japan. *Exploration Geophysics, 37*(1), 19-29. doi:http://dx.doi.org/10.1071/EG06019

ZHOU, Q., BIRKHOLZER, J. T., TSANG, C.-F., & RUTQVIST, J. (2008). A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. *International Journal of Greenhouse Gas Control, 2*(4), 626-639. doi:http://dx.doi.org/10.1016/j.ijggc.2008.02.004