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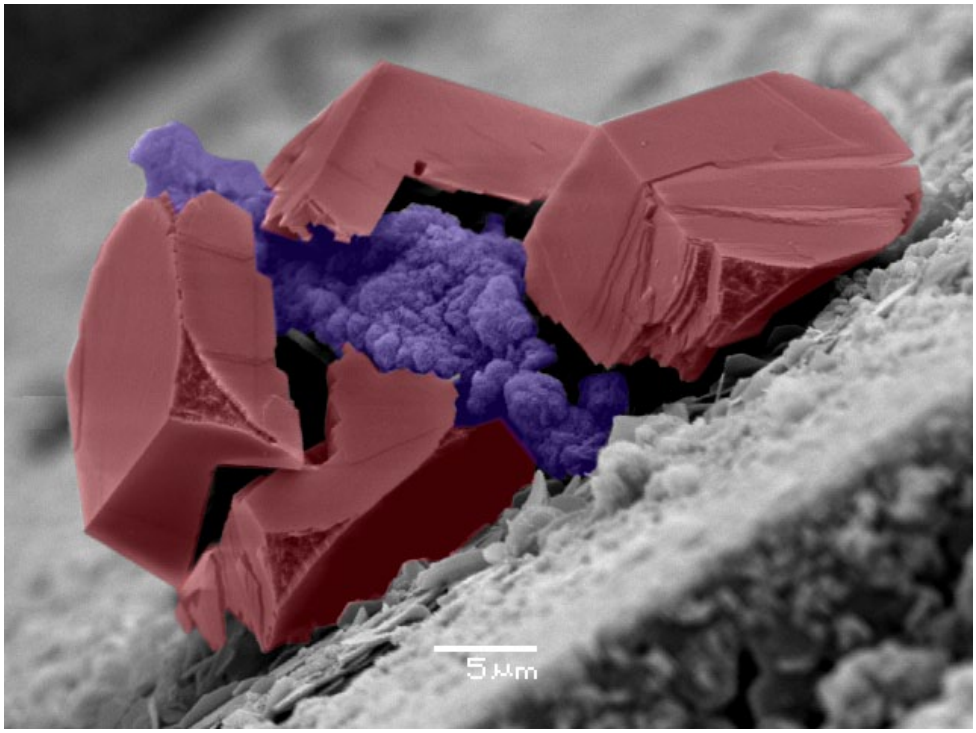
Summarizing the SSC-RAMORE project - Final report

Subsurface Storage of CO_2 - Risk Assessment, MOnitoring and REmediation (SSC-RAMORE)

2013



Project

Title: Subsurface Storage of CO_2 - Risk Assessment, MOnitoring and REmediation (SSC-Ramore)

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Leader: Professor Per Aagaard

Lead Institution: University of Oslo, Department of Geosciences

Scientific group: Per Aagaard and Helge Hellevang (University of Oslo), Bjørn Kvamme (University of Bergen), Harald Johansen, Inger Anne Munz and Øyvind Brandvoll (Institute for Energy Technology), Elin Skurtveit and Eyvind Aker (Norwegian Geotechnical Institute)

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Prepared by: Thor A. Thorsen, Per Aagaard and Gudmund A. Dalsbø

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Contact information about the report and the project

E-mail: geosciences@geo.uio.no

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Introduction

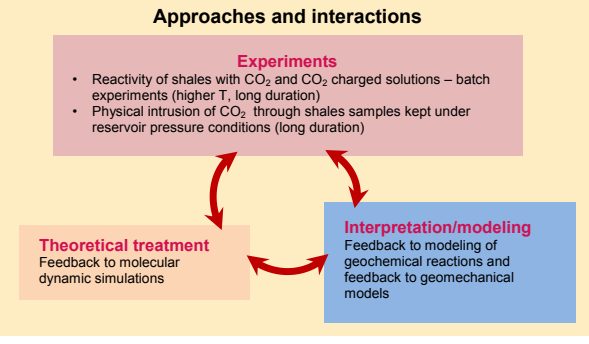
One of the promising strategies for reducing CO_2 emissions to the atmosphere is carbon capture and storage (CCS). Such storage in the subsurface could either be in saline aquifers or in depleted oil and gas reservoirs. Injection and storage of CO_2 started in 1996 in the Sleipner Field in the Norwegian sector of the North Sea. This industrial CCS-project is internationally pioneering and has stimulated to further development of such internationally leading expertise in Norway. Furthermore, in 2008 CO_2 injection and storage started at the Snøhvit Field in the Barents Sea, and further plans have been made for a heat-plant at Mongstad on the Norwegian west coast with a full CCS-chain including CO_2 storage offshore in the Troll Field. In addition, two Norwegian test sites for CO_2-injection have recently been established. One at Spitsbergen and one at Hurum. Thus, there is a need to develop new knowledge and expertise that can make a sound fundament for large scale CO_2 storage in the subsurface either on- or off-shore. Our research project, Subsurface Storage of CO_2 - Risk Assessment, Monitoring and Remediation (SSC-RAMORE), was aimed at establishing technology for risk assessment, monitoring and remediation of carbon dioxide subsurface storage based on a research effort to fill critical gaps of knowledge highlighted by the IPCC in "Carbon dioxide Capture and Storage", 2005.

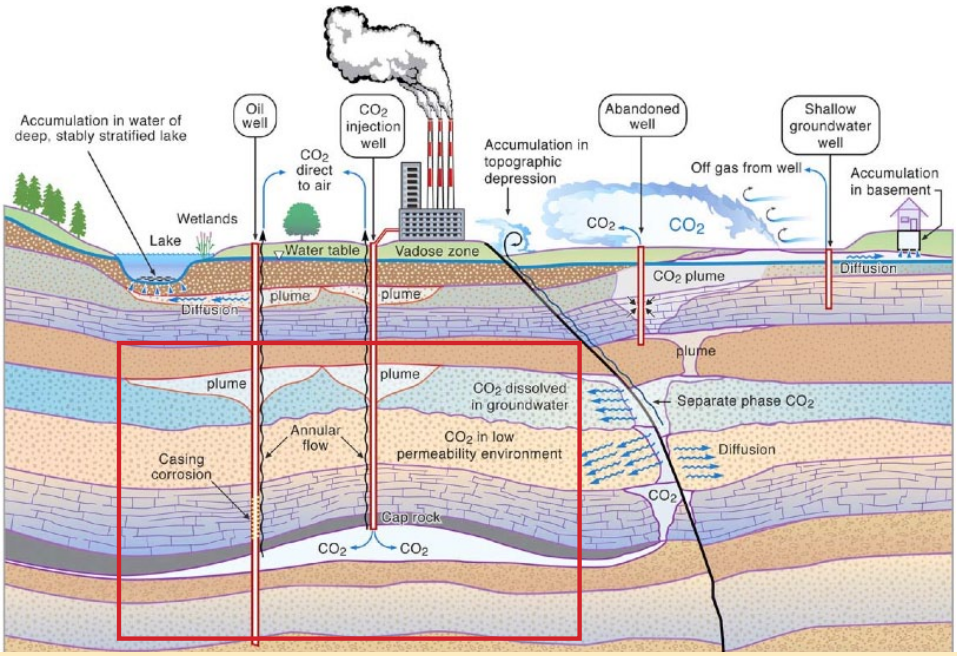
To evaluate potential CO_2 leakage from subsurface storage, SSC-RAMORE focused on the geochemical interaction of CO_2 with caprocks and with engineered materials in wells, as well as with the corresponding changes in geo-mechanical properties. Furthermore, the project carried out simulations of injected CO_2 in reservoir models to improve monitoring of CO_2 reservoirs, and developed a methodology for risk assessments of CO_2 storage in the subsurface.

CCS sites in Norway.

The overall approach was to group the research tasks into three main work packages: 1) theoretical treatment, 2) experiments and 3) modeling with interpretations. Between these main work packages there were feedback as an iterative process through the whole project period ensuring integration of the project results.

Along with a theoretical treatment of the interaction at the mineral surface





The sketch demonstrates the major processes involved in subsurface storage of CO_2. The red square highlights the processes studied here.

Normally, CO_2-injection is in the lower part of the reservoir, and not in the top as shown here. Thus, this gives the injected CO_2 time and space to rise and flow to fill most of the pore space in the whole reservoir body. Furthermore, the pressure rise will be evenly distributed over a wide area. These differences in the types of wells might not be clearly demonstrated in this sketch. In addition, it should be pointed out that both types of wells may be more horizontal at depth, and not vertical in all its length as indicated here.

with aqueous solutions of CO_2 and with molecular simulations, an experimental test program was conducted to study long-term seal integrity and the effect of fluid transport in fractures. A wide range of standard geotechnical tests as well as new constructions and procedures for the CO_2 interaction or penetration was applied. The corresponding geochemical reactions were traced in the same experiments and for other experiments, specifically designed. Complementary theoretical treatment on interfaces is crucial to estimate solid and fluid properties, especially interfacial properties and corresponding entrance pressure for water and CO_2 fluid interfaces. Stability and possible extra sealing effects of hydrates in contact with clays in caprocks were also evaluated. Coupled geochemical - geomechanical models were implemented into existing reservoir modelling software. This new knowledge gave basis for recommendations for material testing procedures, monitoring and remediation techniques.

The 5-year research project was funded by the CLIMIT program of the Research Council of Norway. In addition, the five industrial partners Statoil, Norske Shell, ConocoPhillips, Schlumberger and RWE Dea Norge have supported the project. The project was led by Professor Per Aagaard at the Department of Geosciences, University of Oslo (UiO), and was in cooperation with the Department of Physics and Technology, University of Bergen (UiB), Norwegian Geotechnical Institute (NGI) and Institute for Energy Technology (IFE). Along with filling crucial gaps of knowledge based on research, an important part of SSC-RAMORE has been to train and prepare experts and researchers, thus creating solid competence in subsurface storage of CO_2. The training of a number of PhD and Postdoctoral Research Fellows has been an integrated part of the project.

Background documents

Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

IPCC, 2005, Carbon dioxide Capture and Storage. Special report IPCC. Cambridge University Press, UK, 1-431. http://www.ipcc.ch/publications_and_data/_reports_carbon_dioxide.htm

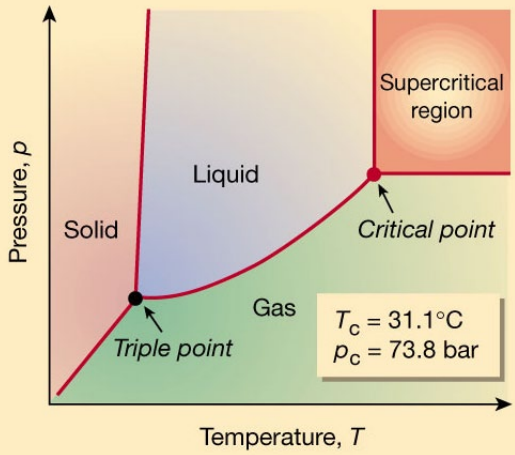
CO_2 interactions with the caprock and well cement

The risks of leakage by subsurface storage of CO_2, both through the caprock and through engineered materials in wells, were evaluated in the project. The caprock seals off the reservoir. It prohibits the CO_2 from escaping the storage space of the geological formations. Engineered materials, such as cement, are being used in wells both to stabilize the walls during injection and when plugged and abandoned.

One of the key elements was the geochemical and geomechanical reactions between CO_2 in the formation water and the caprocks. PhD-student Binyam Lema Alemu, University of Oslo, performed the experiments that concluded that the risks involved with CO_2 storage in water saturated formations at sufficient depth below the sea floor were small. Based on laboratory geochemical experiments (both grinded shale samples and standard clay mineral samples), he found that the reactivity of silicious caprocks to CO_2 is not large enough to deteriorate the sealing efficiency. In addition, as carbonate minerals normally also are present in reservoirs and caprocks, increase and buffering of pH take place. Dissolving clays (and other silicates) also produce bicarbonate and divalent cations into the pore water, which in turn further increases the pH and forms new carbonates.

For long-term storage, diffusion of CO_2 into the caprock will take place. However, simulation studies find large reduction of the effective diffusion due to geochemical reactions. Changes in geomechanical behavior due to diffused CO_2 into shale are thought to be limited, although this has not been the subject to further study.

Capillary entrance of supercritical CO_2 into shale does not appear to be the main process. Instead CO_2 may be forced into shales by microfractures. In this context capillary forces will contribute. Experimental studies of CO_2 breakthrough processes in shale were done in order to define the stress conditions for opening/reopening of microfractures in the caprock and to see how this influences CO_2 flow processes in shale. Experiments conducted on samples from the Draupne Formation from the Troll Field in the North Sea, showed that this is a suitable caprock for CO_2 storage in North Sea, and possibly also the Johansen Formation. This is a significant finding since Johansen Formation is a candidate for



Supercritical CO_2

CO_2 occurs in three phases as shown in the figure; gas, liquid and solid. At depth in the subsurface or conditions similar to CO_2-injection with relative high pressures and temperatures, supercritical CO_2 occurs with properties between liquid and gas. Thus, supercritical CO_2 has density as liquid, but viscosity as gas.

Binyam Lema Alemu studied the reactivity of shales with CO_2 and rock physics effects due to CO_2 flooding in sandstone during his PhD study at University of Oslo from September 2008 to August 2011. In close cooperation with the staff at NGI and IFE, he carried out laboratory work in the respective institutes.

His thesis is entitled: *Subsurface storage of CO_2 Two-phase flow, rock physics and geochemical interactions - An experimental study.* Department of Geosciences, University of Oslo, 2012.

He later joined Statoil in Stavanger as a petrophysicist.

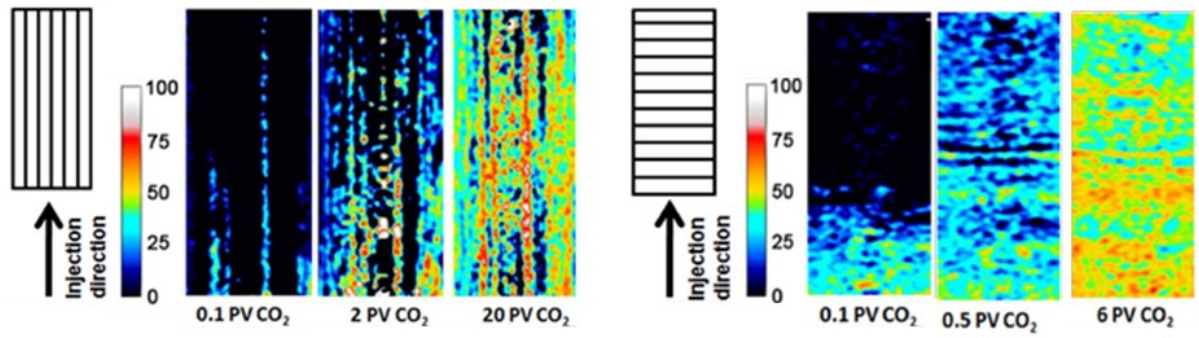
storing CO_2 from the planned full-scale CCS project at Mongstad.

In the overall context of CO_2 storage, the experimental results demonstrated how a reduction in effective pressure lowers the seal integrity of the shale, but also how the flow can be stopped by increasing the effective pressure again. This also illustrates the importance of pressure control during CO_2 injection.

Cement is used as a seal between the well casing and the surrounding bedrock in offshore oil wells. Similarly, oil wells are filled with cement when abandoned. The same procedure will also be used when the injection of CO_2 comes to an end, and the potential leakage route through the well needs to be sealed off. Based on laboratory geochemical experiments carried out at IFE (both with batch and flow reactors) well cement clearly showed reactivity towards CO_2, producing alteration; especially decalcification and carbonation. Although such alterations of well cement have been observed, the self-limiting effects cement decalcification have on mass transfer rates, in combination with the carbonation of Portlandite, probably mean that the risk of induced leakage pathways along the wellbore is marginal. This is confirmed by operational experience from CO_2 injection sites for EOR in the US, where no or very limited leakage has been detected from 30 years of operation. These lessons learned in the US showed that CO_2 leakages through the cement primarily were due to the quality of craftsmanship when sealing off the well. Bearing the importance of this in mind while performing the operation will therefore reduce this risk.

Some limited mechanical testing of well cement exposed to CO_2 has also been carried out.

Studies at IFE comparing CO_2 reacted cement plugs with non-reacted ones revealed that the CO_2 reacted plugs became stronger due to carbonation. However, care is needed using these results as the number of tests were limited. Furthermore, mechanisms like drying of the plug and the curing conditions for the cement could also influence its strength.



Distribution of injected CO_2 in a core parallel with (left) and perpendicular to bedding plane (from Alemu et al. 2012).

Magnus Soldal achieved his Master of Science in 2008 for his work at Department of Geosciences, University of Oslo, as part of this project carrying out the laboratory work at and in close collaboration with NGI. A new experimental design allowed a caprock sample from The Draupne Formation, the North Sea, to be prepared for flooding of CO_2 and tested.

His thesis is entitled: *Caprock interaction with CO_2. Geomechanical and geochemical effects.* Department of Geosciences, University of Oslo, 2008. http://www.duo.uio.no/publ/geofag/2008/79555/masteroppgave.pdf

He later joined NGI on a permanent basis.

CO_2 flow in the reservoir

Another important task has been to better understand how the CO_2 flows within the reservoir and how this can be simulated in a reservoir model. Most of the CO_2 injected into the subsurface or a reservoir will flow at a supercritical phase. Thus appropriate tools for multiphase flow should be applied. Only a small fraction of CO_2 will dissolve into the reservoir water. Nevertheless, it is this fraction which promotes interactions with the minerals both in reservoirs and caprocks. During reactions between dissolved $CO_2$and minerals, CO_2 is consumed. Therefore, more CO_2 from the supercritical phase is dissolved and enters into the pore water. In previous similar simulations, geochemical reactions involving dissolved CO_2 in the water have not been included.

A correct understanding and simulation of how CO_2 penetrates into the reservoir and drains it, is crucial to monitor the behavior of the reservoir rock during CO_2 injection. To do such a study for the first time, a CT-scanner was acquired and used at NGI. Core samples from the North Sea were tested for changes in sound velocities and electrical resistivity, knowledge of importance for geophysical monitoring of CO_2 flow.

Geochemical simulations by PhD-student Van Thi Hai Pham, University of Oslo, has re-examined the geochemical trapping capacity of the Utsira sand. Furthermore, she demonstrated that the potential for mineral trapping is considerably larger than pure solubility trapping. However, this depends mostly on the amount of initial reactive minerals. Mineral trapping will ensure long term safe and stable storage, as these reactions consume and transfer CO_2 from the supercritical fluid phase, thereby reducing the fluid pressure.

Pham also simulated the CO_2 injection in the Snøhvit Field in the Barents Sea, as well as potential future storage scenarios in the Sleipner Field with the Utsira Formation and the Skade Formation below. The two cases demonstrate two

Matthieu Angeli was a Postdoctoral Research Fellow at NGI from March 2008 to March 2010. Prior to this he had been working on the relationship between deformation and fluid flow in rocks since 2005, and he achieved his PhD in Earth Sciences from Université Cergy-Pontoise in 2007. His primary research interests were deformation of sandstones and limestones under stress. He has also been studying porous network description and the relationship between rock microstructures and its hydromechanical properties. Another important part of his work was to understand how a modification of these microstructures (e.g. salt precipitation) would modify these large scale hydromechanical properties.

When joining the project at NGI in 2008, he focused at tighter material such as shales. His experimental work gave insight to the relationship between in-situ stresses and shale flow properties, particularly in the presence of microcracks networks. In 2010 he joined University of Oslo and started studying these shale properties at a larger scale, and setting up a method to evaluate fluid flow processes in shale formations at the basin scale from geophysical data (seismic lines and well log data).

Van Thi Hai Pham carried out her PhD study at the University of Oslo from November 2008 to August 2011. Her work focused on simulation of CO_2 injection in the Snøhvit Field in the Barents Sea and the potential future storage scenarios at Sleipner in the North Sea both in the Utsira Formation and the formation below, Skade, as well as the geochemical trapping capacity of the Utsira sand.

Her thesis is entitled: *CO_2 storage – Simulations for forecasting the behaviour of CO_2 injection in geological formations.* Department of Geosciences, University of Oslo, 2013.

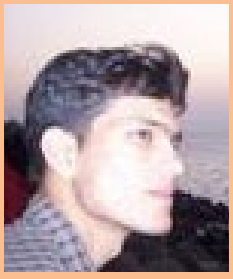
She joined the Norwegian Petroleum Directorate in August 2011 on a permanent basis.

extreme reservoir conditions with different injectivity and pressure boundaries. The Utsira Formation consists of sandstone with high porosity and permeability and large lateral communication, ideal for receiving large quantities of CO_2. The Snøhvit Field on the other hand, the initial storage unit, consists of a less permeable silica cemented sandstone, with pressure compartments bounded by faults, and is not able to receive the rate and amount of CO_2 expected. Therefore, the pressure increased in the reservoir, and Statoil needed to change their injection strategy shortly after the injection started. The lesson here highlight the importance of sufficient knowledge of the properties of the reservoir rock, and especially fracture pressure and fault properties.

During injection of CO_2 into a reservoir, pressure build-up might increase the stress within the reservoir and the seal, as well as in the formations above, ultimately leading to fracturing of reservoir rock and caprock. Therefore it is significant to foresee the conditions when this might occur. COMSOL Multiphysics package solves all necessary equations simultaneously within the software. Based on the software, NGI developed the link between CO_2 injection and geomechanical deformation. The deformations are based on poro-elastic response, and different fracture criteria may be applied. The properties used in the model are based on data from a large range of sandstones (reservoir rocks) and shales (caprocks) representing a wide range of burial histories. The model has been used to simulate the observed local uplift in In Salah, Algeria, as well as to simulate leakage scenarios combined with risk evaluation of CO_2 storage.

Similarly, in the geochemical modeling tool of CO_2 storage, poro-elastic response has been included in the adoption of the software RetrasoCodeBright at the University of Bergen. This research group also has performed theoretical studies on how CO_2 reacts with carbonates and clay minerals, and included a link to the geochemical reactions in the modeling tool. Furthermore, by molecular dynamic simulations the amounts of CO_2 attached to clay minerals have been estimated.

In addition, the dynamic formation and dissolution of gas hydrates from CH_4 and CO_2 are included in the modifications of RetrasoCodeBright. Formation of hydrates may also be critical in pipeline transport of CO_2. This has been taken into account when simulating reservoirs of hydrates during injection of CO_2 and N_2. Development of software for design and monitoring of subsurface storage of CO_2 has therefore been crucial within the project.



Ashok Kumar Chejara carried out his PhD study at the University of Bergen from May 2009 to May 2012.

His thesis is entitled: *Gas Hydrates in Porous Saline Aquifers: CO_2 Storage and CH_4 Production*. Department of Physics and Technology, University of Bergen, 2013.

Martin Haynes achieved his Master of Science in 2009 for his studies at Department of Physics and Technology, University of Bergen.

His thesis is entitled: *Vannutfelling på rustoverflater i gassrør.* Department of Physics and Technology, University of Bergen, 2009.

Leakage simulations and risk assessment

A methodology for risk assessment applicable for CO_2 storage was developed by NGI based on a literature review aimed at generic methods and concepts of risk assessment. The steps are in accordance with the regulations in the EU directive for CO_2 storage (2009). Included in the methodology is an evaluation of critical scenarios with events, features and processes that could lead to CO_2 leakage. Furthermore, included in the methodology are also defining steps for an event tree analysis and present this with potential outcomes by the sequence of events assigned as different leakage rates. And finally, a probability of the events is assigned and the overall probability for the leakage rates estimated. To quantify the probabilities in each step, the potential leakage pathway and construction of the event tree, a modeling software was designed and utilized at NGI. Such risk assessment methodology should be used when evaluating a reservoir for CO_2 storage.

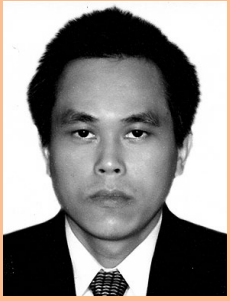
One important aspect in the risk assessment for CO_2 storage is the characterization of potential hazards. Identification of leakage pathways, magnitude of leakage and how critical parameters like reservoir pressure, injection rate and temperature affect the potential leakage scenarios are important. Secondary effects of CO_2, such as interactions between fluids and rock, should also be considered. Within the framework of risk assessment focus is on identifying the most critical parameters of a leakage scenario. Laboratory scale experiments can help evaluating the controlling parameters e.g. for flow in shale. Numerical models are efficient tools for evaluating the effect of variation and uncertainty in the controlling parameters and for giving estimates for leakage rates.

The test site for CO_2-injection at Spitsbergen

The CO2LYB test site for CO_2 injection close to Longyearbyen at Spitsbergen offers continuous rock samples from the caprock and the planned reservoir rocks. A key question for this site is the extent of communication in the rock formations above the seal off the reservoir with the atmosphere. To test this, a number of gas samples from different shale units in the overburden was analysed by IFE. The gas compositions demonstrated different origin of the gases and minor communication between the rock formations. This suggests that the sediment package is a good seal for a CO_2 reservoir here unless major fracturing or reactivation of faults should occur.

Other project outcomes

SSC-RAMORE has been successful in many respects. First of all, it has established technology for risk assessment, monitoring, and remediation of CO_2 leakages including the potential for hydrate sealing and well leakages. Thus, crucial gaps of knowledge previously pointed out by the IPCC (2005) have been narrowed. Furthermore, new geochemical datasets from representative caprocks from Norwegian CCS sites have been established and included in the new



Phan Van Cuong carried out his PhD study at the University of Bergen from May 2009 to May 2012.

His thesis is entitled: *Transport and adsorption of CO_2 and H_2O on calcite and clathrate hydrate.* Department of Physics and Technology, University of Bergen, 2012.

Olivier Regnault was a Postdoctoral Research Fellow at IFE, working in the project from May 2008 to May 2010.

modelling tools developed for different scales and levels.

The results have been disseminated and summarized in meetings and in the closing seminar in May 2012 with the project partners as well as in numerous scientific conventions and conferences, in articles, technical reports and more popular notes, both in English and Norwegian (see the appendix).

The project staff involved in the cooperating research institutes has increased its knowledge and expertise in subsurface storage of CO_2 and contributed to increased competence in CO_2 storage in Norwegian research institutes. Two students completed their Master of Science thesis, and a number of PhD-students and postdoctoral fellows have carried out their research within the framework of the project. Several of these candidates are now seeking a career utilizing their competence in CO_2 storage in other organisations or have moved to a partner institution, whereas others still carry out research within the field in the original organization.

SSC-RAMORE has also strengthened the cooperation among the research partners, especially within CO_2 storage. This fruitful cooperation has been acknowledged outside the partner institutions and by stakeholders in CCS research such as the Research Council of Norway/CLIMIT, and has contributed to establishing the national centre of environmental friendly energy on Carbon Storage (FME SUCCESS) and other cooperative projects among SSC-Ramore's research partners. There are still unknown geomechanical and geochemical factors in subsurface storage of CO_2. The competence and knowledge gained in the spirit of this collaboration will be maintained and further developed within new constructions and research projects.

Julien Declercq focused on improving the understanding of water-rock interactions in his PhD study at University of Oslo in this project, but also in a joint project with Laboratoire des Matériaux et Transfert en Géologie, Toulouse, France.

His thesis is entitled: *Dissolution rates and mechanisms – experiments on alteration and reactivity of glasses and carbonates*. Department of Geosciences, University of Oslo, 2010. http://www.duo.uio.no/publ/geofag/2010/108092/dravhandling-declercq.pdf

Concluding points of the project

- Experiences and cooperation network established in SSC-Ramore led to FME SUCCESS and its spin-offs.
- The geomechanical behavior of shales is still not fully understood and there is still more to be done. How do the geomechanical properties change with diagenetic processes (cementation), structural deformation processes, and uplift etc?
- The effects of faults as leakage routes for CO_2 are vital knowledge gaps. Conditions for opening/closing of faults are studied in an associated project, IMPACT.
- The importance of the whole overburden above the primary reservoir-seal pair if there should be a leakage from the primary CO_2 reservoir. How effectively is CO_2 sorbed or trapped by chemical/physical processes in the overburden?

Appendix

Master of Science students

Magnus Soldal (2008). *Caprock interaction with CO_2. Geomechanical and geochemical effects.* Department of Geosciences, University of Oslo. http://www.duo.uio.no/publ/geofag/2008/79555/masteroppgave.pdf

Martin Haynes (2009). *Vannutfelling på rustoverflater i gassrør.* Department of Physics and Technology, University of Bergen.

PhD students

Julien Declercq (UiO)

Thesis 2010: *Dissolution rates and mechanisms – experiments on alteration and reactivity of glasses and carbonates*. Department of Geosciences, University of Oslo. http://www.duo.uio.no/publ/geofag/2010/108092/dravhandling-declercq.pdf

Binyam Lema Alemu (UiO, September 2008 – August 2011)

Thesis 2012: *Subsurface storage of CO_2 Two-phase flow, rock physics and geochemical interactions - An experimental study.* Department of Geosciences, University of Oslo.

Phan Van Cuong (UiB, May 2009 – May 2012)

Thesis 2012: *Transport and adsorption of CO_2 and H_2O on calcite and clathrate hydrate.* Department of Physics and Technology, University of Bergen.

Van Thi Hai Pham (UiO, November 2008 – August 2011)

Thesis 2013: *CO_2 storage – Simulations for forecasting the behavior of CO_2 injection in geological formations.* Department of Geosciences, University of Oslo.

Ashok Kumar Chejara (UiB, May 2009 – May 2012)

Thesis 2013: *Gas Hydrates in Porous Saline Aquifers: CO_2 Storage and CH_4 Production.* Department of Physics and Technology, University of Bergen.

Postdoctoral Research Fellows

Matthieu Angeli (NGI, Mar 2008 – Februray 2010)

Olivier Regnault (IFE, May 2008 – April 2010)

Scientific articles from the project

Alemu, B.L., Aagaard, P., Munz, I.A. & Skurtveit, E., 2011: Caprock interaction with CO_2: A laboratory study of reactivity of shale with supercritical CO_2 and brine. *Applied Geochemistry*, 26 (12), 1975–1989. doi:10.1016/j.apgeochem.2011.06.028

Alemu, B.L., Aker E., Soldal, M., Johnsen, Ø. & Aagaard, P., 2011: Influence of CO_2 on rock physics properties in typical reservoir rock: A CO_2 flooding experiment of brine saturated sandstone in a CT-scanner. *Energy Procedia,* 4, GHGT-10, 4379–4386. doi: 10.1016/j.egypro.2011.02.390

Alemu, B.L., Aker, E., Soldal, M., Johnsen, Ø. & Aagaard, P., 2013: Effect of sub-core scale heterogeneities on acoustic and electrical properties of a reservoir rock: A CO_2 flooding experiment of brine saturated sandstone in a CT-scanner, *Geophysical Prospecting*, 61 (1), 235-250.

Angeli, M., Soldal, M., Skurtveit, E. & Aker, E., 2009: Experimental percolation of supercritical CO_2 through a caprock. *Energy Procedia*, 1, GHGT-9, 3351–3358.

Brandvoll, Ø., Regnault, O., Munz, I.A., Iden, I.K. & Johansen, H., 2009: Fluid-solid interactions related to subsurface storage of CO_2: Experimental tests of well cement. *Energy Procedia*, 1, GHGT-9, 3367–3374.

Buanes, T., Kvamme, B. & Svandal, A., 2009: Two Approaches for Modelling Hydrate Growth. *Journal of Mathematical Chemistry*, 46 (3), 811–819. doi: 10.1007/s10910-009-9551-3

Chejara, A., Kvamme, B., Vafaei, M.T. & Jemai, K., 2013: Simulations of long term methane hydrate dissociation by pressure reduction using an extended RetrasoCodeBright simulator. *Energy Conversion and management,* 68, 313-323.

Cuong, P.V., Kvamme, B., Kuznetsova, T. & Jensen, B., 2012: Molecular dynamics study of calcite and temperature effect on CO_2 transport and adsorption stability in geological formations. *Molecular Physics*, 110 (11-12), 1097-1106. doi: 10.1080/00268976.2012.679629

Ersland, G., Husebø, J., Graue, A. & Kvamme, B., 2009: Transport and storage of CO_2 in natural gas hydrate reservoirs. *Energy Procedia,* 1, GHGT-9, 3477–3484.

Farmahini, A.H., Kvamme, B. & Kuznetsova, T., 2011: Molecular Dynamics Simulation Studies of Absorption in Piperazine Activated MDEA Solution. *Physical Chemistry Chemical Physics*, 13, 13070–13081. doi: 10.1039/C0CP02238A

Hellevang, H., Pham, V.T.H. & Aagaard, P., 2013: Kinetic modelling of CO_2-water-rock interactions. *International Journal of Greenhouse Gas Control, 15, 3-15.*

Hellevang, H., Declercq, J. & Aagaard, P., 2011: Why is Dawsonite Absent in CO_2 Charged Reservoirs? *Oil Gas Sci. Technol. – Rev. IFP Energies nouvelles,* 66 (1), 119–135. doi: 10.2516/ogst/2011002

Husebø, J., Ersland, G., Graue, A. & Kvamme, B., 2009: The impact of brine salinity on fill fraction of methane hydrates formed in sandstone. *Energy Procedia*, 1, GHGT-9, 3731–3738.

Jensen, B., Kvamme, B., Kuznetsova, T. & Oterhals, Å., 2011: Molecular dynamics study of selective adsorption of PCB on activated carbon. *Fluid Phase Equilibria*, 307 (1), 58–65. doi: 10.1016/j.fluid.2011.05.001

Khattri, S.K., Hellevang, H., Fladmark, G.E. & Kvamme, B., 2011: Simulation of Long-Term Fate of CO_2 in the Sand of Utsira. *Journal of Porous Media,* 14 (2), 149–166. doi: 10.1615/JPorMedia.v14.i2.40

Kvamme, B. & Kuznetsova, T., 2010: Investigation into stability and interfacial properties of CO_2 hydrate – aqeuous fluid system. *Mathematical and Computer Modelling,* 51 (3–4), 156–159. doi: 10.1016/j.mcm.2009.08.007

Kvamme, B., Kuznetsova, T. & Uppstad, D., 2009: Modeling excess surface energy in dry and wetted calcite systems. *Journal of Mathematical Chemistry*, 46 (3), 756–762.

Kvamme, B. & Liu, S., 2009: Reactive Transport of CO_2 in Saline Aquifers with implicit geomechanical analysis. *Energy Procedia*, 1, GHGHT-9, 3267–3274.

Kvamme, B. Graue, A., Buanes, T., Kuznetsova, T. & Ersland, G., 2009: Effects of solid surfaces on hydrate kinetics and stability. *In* Long, D., Lovell, M.A., Rees, J.G. & Rochelle, C.A. (eds.) *Sediment-Hosted Gas Hydrates. New Insights on Natural and Synthetic systems*. *Geological Society Special Publication,* 319, 131–144.

Kvamme, B. & Liu, S., 2009: A new reactive transport reservoir simulator for aquifer storage of CO_2 – with implicit geomechanical analysis. *In* Eide, L.I. (ed.) *Carbon Dioxide Capture for Storage in Deep Geologic Formations*, Volume 3, Chap 24, CPL Press and BP.

Liu, S., Lågeide, L.A. & Kvamme, B., 2011: Sensitivity study on storage of CO_2 in saline aquifer formation with fracture using reactive transport reservoir simulator RCB. *Journal of Porous Media*, 14 (11), 989-1004. doi: 10.1615/JPorMedia.v14.i11.40

Skurtveit, E., Aker, E., Soldal, M., Angeli, M. & Wang, Z., 2012: Experimental investigation of CO_2 breakthrough and flow mechanisms in shale. *Petroleum Geoscience*, 18, 3-15.

Pham, V.T.H., Lu, P., Aagaard, P., Zhu, C. & Hellevang, H., 2011: On the potential of CO_2–water–rock interactions for CO_2 storage using a modified kinetic model. *International Journal of Greenhouse Gas Control*, 5 (4), 1002–1015. doi: 10.1016/j.ijggc.2010.12.002

Pham, V.T.H., Maast, T.E., Hellevang, H. & Aagaard, P., 2011: Numerical modeling including hysteresis properties for CO2 storage in Tubåen formation, Snøhvit field, Barents Sea. *Energy Procedia,* 4, GHGT-10, 3746–3753. doi: 10.1016/j.egypro.2011.02.308

Pham, V.T.H., Hellevang, H. & Aagaard, P., 2012: On the potential for CO_2 storage in continental flood basalts. *Geochemical Transactions*, 13 (5), 1-12. doi: 10.1186/1467-4866-13-5

Pham, V.T.H., Hellevang, H. & Aagaard, P.: Modeling of CO_2 injection and the geomechanical response in the Tubåen Formation, Snøhvit Field, Norway. (Unpublished manuscript).

Qasim, M., Kvamme, B. & Baig, K., 2011: Phase field theory modeling of CH_4/CO_2 gas hydrates in gravity fields. *International Journal of Geology*, 5 (2), 48-52.

Svandal, A. & Kvamme, B., 2009: Modeling the dissociation of carbon dioxide and methane hydrate using the Phase Field Theory. *Journal of Mathematical Chemistry*, 46 (3), 763-769. doi: 10.1007/s10910-009-9545-1

Vafaei, M.T., Kvamme, B., Chejara, A. & Jemai, K., 2011: Nonequilibrium modeling of hydrate dynamics in reservoir. *Energy Fuels*, 26 (6), 3564-3576. doi: 10.1021/ef300348r

Vafaei, M.T., Kvamme, B., Chejara, A. & Jemai, K., 2011: Simulation of Hydrate Dynamics in Reservoirs. Society of Petroleum Engineers, 2, IPTC 2012, 1351-1363.

Participation on International Conferences

2012

Cuong, P.V., Kvamme, B., Kuznetsova, T. & Jensen, B.: The Impact of Short-Range Force Field Parameters and Temperature Effect On Selective Adsorption of Water and CO_2 On Calcite. 9th WSEAS International Conference on HEAT and MASS TRANSFER (HMT'12) http://www.wseas.us/conferences/2012/harvard/hmt/, Harvard, Cambridge, USA, January 25-27, 2012.

Cuong, P.V., Kvamme, B., Kuznetsova, T. & Jensen, B.: The impact of short-range force field parameters and temperature effect on CO_2 transport in geological formations. *18th Symposium on Thermophysical Properties*. Boulder, USA, June 24-29, 2012.

Kuznetsova, T., Van Cuong, P., Kvamme, B.: Effect of temperature and calcite on carbon dioxide transport and hydrate stability in geological formations. *Third EAGE CO_2 Geological Storage Workshop*, Edinburgh, UK, March 26–27, 2012.

Vafaei, M. T., Kvamme, B., Chejara, A. & Jemai, K.: Simulation of Hydrate Dynamics in Reservoirs. *International Petroleum Technology Conference*, Bangkok, Thailand, February 7-9, 2012.

2011

Aker, E., Wang, Z., Skurtveit, E. & Soldal, M.: On the sealing capacity of cap-rock: The effect of micro-fractures and fluid on acoustic properties of shale. *Poster presentation, The Trondheim CCS-6 Conference*, Trondheim, Norway, June 14–16, 2011.

Alemu, B.L., Aker, E., Soldal, M., Johnsen, Ø. & Aagaard, P.: Experimental study on the influence of CO_2 on rock physics properties of a typical reservoir rock with the use of ultrasonic velocity, resistivity and X-ray CT-scanner. *The Trondheim CCS-6 Conference*, Trondheim, Noway, June 14–16, 2011.

Alemu, B.L., Aagaard, P. & Hellevang, H.: Effect of temperature and mineralogical composition on the reactivity of shale: a comparison study of potential caprock from two potential CO_2 storage sites. *Poster presentation, Goldschmidt 2011 conference,* Prague, Czech Republic, August 14–19, 2011.

Chejara, A., Kvamme, B., Vafaei, M.T. & Jemai, K.: Theoretical studies of Methane Hydrate Dissociation in porous media using RetrasoCodeBright simulator, *2nd International Conference on Advances in Energy Engineering (ICAEE 2011),* Bangkok , Thailand, December 27-28, 2011, 19 pages.

Kvamme, B., Vafaei, M.T., Chejara, A. & Jemai, K.: Reservoir scale simulation of hydrate dynamics. *European Geosciences Union – General Assembly*, Vienna, Austria, April 3–8, 2011.

Kvamme, B., Jemai, K., Chejara, A. & Vafaei, M.T.: Simulation of geomechanical effects of CO_2 injection in fractured reservoir. *European Geosciences Union – General Assembly*, Vienna, Austria, April 3–8, 2011.

Kvamme, B., Vafaei, M.T., Chejara, A., Jemai, K.: Simulation of Hydrate dynamics in reservoirs. *7th International Conference on Gas Hydrates (ICGH 2011),* Edinburgh, Scotland, July 17–21, 2011.

Kvamme, B., Jemai, K., Chejara, A. & Vafaei, M.T.: Simulation of geomechanical effects of CO_2 injection in cold aquifers with possibility of hydrate formation. *7th International Conference on Gas Hydrates (ICGH 2011),* Edinburgh, Scotland, July 17–21, 2011.

Kvamme, B., Kuznetsova, T, Quasim, M., Vafaei, M.T., Chejara, A., Jemai, K., Baig, K., Jensen, B., Cuong, P., Kivela, P.-K. & Bauman, J.: Multiscale modelling of CO2 storage in cold reservoirs. Invited presentation, *CECAM workshop Microscopic-Scale View of CO_2 sequestration*, CECAM-HQ-EPFL, Lausanne, Switzerland, June 22-24, 2011.

2010

Alemu, B.L., Aagaard, P., Munz, I.A. & Skurtveit, E.: Contribution of mineralogical variability of shale in regard to reactivity with supercritical CO_2: implication to subsurface storage of CO_2. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Bjørnarå, T.I., Aker, E., Cuisiat, F. & Skurtveit, E.: Modeling CO_2 storage Using Coupled Reservoir-Geomechanical Analysis, *COMSOL User Conference*, Paris, France, 2010.

Brandvoll, Ø., Munz, I.A., Kihle, J., Haug, A. & Machenbach, I.: Development of novel reactors for aqueous mineral carbonation – feasibility perspectives and relevance for subsurface CO_2 storage. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Declercq, J., Hellevang, H. & Aagaard, P.: Dawsonite dissolution mechanism. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Hellevang, H., Declercq, J. & Aagaard, P.: Carbonation of forsterite at 10 bar PCO_2 and 80 to 120 °C – Comparisons of numerical simulations and laboratory experiments. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Hellevang, H. & Aagaard, P.: Can carbonate precipitation rates be derived from dissolution rate data? *20th Goldschmidt Conference*, Knoxville, Tennesee, USA, une 13-18, 2010.

Munz, I.A., Brandvoll, Ø., Iden, K., Smeets, R. & Haug, T.A.: Mechanisms and rates of plagioclase carbonation reactions. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Pham, V., Hellevang, H. & Aagaard, P.: On the potential of carbonate formation during CO_2 storage The Utsira case revised. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

Qasim, M., Kvamme, B. & Baig, K.: Phase field theory modeling of CH_4/CO_2 gas hydrates in gravity fields. *European Conference of Chemical Engineering (ECCE '10),* Puerto De La Cruz, Tenerife, November 30 – December 2, 2010, 164–167.

Skurtveit, E., Angeli, M., Aker, E. & Soldal, M.: Impact of microcracks on CO_2 migration trough cap rocks. *29th Nordic Geological Winter meeting*, Oslo, Norway, January 11–13, 2010.

2009

Aagaard, P., Hellevang, H. & Jahren, J.: Burial diagenesis of siliciclastic reservoirs and control on formation water chemistry. *19th V.M. Goldschmidt conference.* Davos, Switzerland, June 21–26, 2009.

Aagaard, P., Pham, V.T.H. & Hellevang, H.: A modeling study of the long-term mineral trapping in deep saline marine sands aquifers. *American Geophysical Union*, San Fransisco, December 14–18, 2009.

Aker, E.: Sealing properties of cap-rock – towards best practice for coupled flow and geomechanical testing in the laboratory. *5th Trondheim Conference on CO_2 Capture, Transport and Storage*, Trondheim, Norway, June 16–17, 2009.

Alemu, B.L., Aagaard, P., Skurtveit, E. & Munz, I.A.: Effect of CO_2 Interaction with Svalbard Shale: Implications to Caprock Integrity for Subsurface Sequestration of CO_2. *19th V.M.Goldschmidt conference.* Davos, Switzerland, June 21–26, 2009.

Alemu, B.L., Aagaard, P., Munz, I.A. & Skurtveit, E.: Caprock interaction with CO_2 laboratory study of reactivity of shale with supercritical CO_2 and brine mixtures at 250 °C and 110 bars. *American Geophysical Union*, San Fransisco, December 14–18, 2009.

Angeli, M., Soldal, M., Skurtveit E. & Aker E.: Influence of microcracks on fluid migration through caprocks. *8th Euro Conference of Rock Physics & Geomechanics,* Ascona, Switzerland, September 13–18, 2009.

Angeli, M., Soldal, M., Skurtveit, E., Aker, E. & Braathen, A.: Percolation of supercritical CO_2 through a shale from the Janusfjellet subgroup (Svalbard, Norway). *International Conference on Deep Saline Aquifers for geological storage of CO_2 and energy,* IFP, Rueil-Malmaison, May 27–29, 2009.

Baig, K., Qasim, M., Kivelä, P.-H. & Kvamme, B.: Phase Field Theory modeling of methane fluxes from exposed natural gas hydrate reservoirs. *ICCMSE 2009*, Rhodes, Greece, September 28 – October 4, 2009.

Bjørnarå, T.I.: Evaluation of safe storage parameters during CO_2 injection using coupled reservoir-geomechanical analysis. *International Conference on Deep Saline Aquifers for geological storage of CO_2 and energy,* IFP, Rueil-Malmaison, May 27-29, 2009.

Bjørnarå, T.I.: Evaluation of safe storage parameters during CO_2 injection using coupled reservoir-geomechanical analysis. *4th Biot Conference on Poromechanics,* New York, June 8–10, 2009.

Declercq, J., Hellevang, H. & Aagaard, P.: Dawsonite dissolution rate and mechanism at acidic and basic pH; implications for CO_2 sequestration. *International Conference on Deep Saline Aquifers for geological storage of CO_2 and energy,* IFP, Rueil-Malmaison, May 27–29, 2009.

Hellevang, H., Declercq, J. & Aagaard, P.: Why is dawsonite absent in CO_2 charged reservoirs? *International Conference on Deep Saline Aquifers for geological storage of CO_2 and energy,* IFP, Rueil-Malmaison, May 27–29, 2009.

Hellevang, H., Sokalska, E. & Aagaard, P.: Hydration of forsterite at 1 atm PCO2 and 80 to 120 °C – Comparisons of numerical simulations and laboratory experiments to understand the factors that govern the overall mineral transformation rate. *19th V.M. Goldschmidt conference.* Davos, Switzerland, June 21–26, 2009.

Kvamme, B., Kuznetsova, T. & Haynes, M.: Molecular dynamics studies of water deposition on hematite surfaces. *ICCMSE 2009*, Rhodes, Greece, September 28th – October 4, 2009.

Regnault, O., Brandvoll, Ø., Munz, I.A., Iden, I.K. & Johansen, H.: Study of well cement reactivity with CO_2-rich fluids: Combined flow-through and batch experiments. ? *International Conference on Deep Saline Aquifers for geological storage of CO_2 and energy,* IFP, Rueil-Malmaison, May 27–29, 2009.

Skurtveit, E., Aker, E., Angeli, M. & Soldal, M.: Coupled flow and geomechanical testing of low permeable material – application for CO_2 storage. *EAGE Fault and top seal 2009*, Montpellier, France, September 21–24, 2009.

Presentations at scientific meetings in Norwegian and English

End seminar - SSC RAMORE

Oslo, Norway, May 2012 - Program and Presentations:

Reactivity of caprocks and sealing materials

Induced reactions on various caprocks and clay minerals under subsurface storage conditions, Harald Johansen, Øyvind Brandvoll & Kjersti Iden, IFE

Caprock reactivity and integrity, Binyam Lema Alemu, UiO

Experimental methods to characterize sealing properties of cap rock, Elin Skurtveit, Eyvind Aker, Magnus Soldal, Matthieu Angeli & Z. Wang, NGI

Adsorption of H_2O and CO_2 on calcite and clathrate hydrate, Phan Van Cuong, Bjørn Kvamme & Tatiana Kuznetsova, UiB

Portland well cement versus CO_2 rich fluids – Wellbore Implications, Øyvind Brandvoll, IFE

Seal integrity and risk of leakage

A numerical tool for modeling leakage rates, Tore Bjørnarå & Eyvind Aker, NGI

Usage of event tree to characterize risk of leakage, Eyvind Aker & Elin Skurtveit, NGI

Reservoir response to CO_2 injection

Impact of hydate formation during aquifer storage of CO_2, Bjørn Kvamme, UiB

Modeling storage of CO_2 in reservoirs containing natural gas hydrate, Bjørn Kvamme, UiB

CO_2 storage simulations – Summary of work done by PhD student Van Pham, Helge Hellevang, UiO

The Ramore experience – lessons learned

Summing up the results and pointing forward, Project leader Per Aagaard, UiO

2011

Jemai, K., Kvamme, B., Chejara, A. & Vafaei, M.T.: Simulation of geomechanical effects of CO_2 injection in fractured reservoir, *European Geosciences Union, General Assembly 2011*, Vienna, Austria, April 3–8, 2011.

Pham, V., Hellevang, H. & Aagaard, P.: Modelling CO_2 injection in the Tubåen formation and Geomechanics respond, Snøhvit field, Norway. *SUCCESS workshop*, Finse, Norway, March 21-22, 2011.

Skurtveit, E.: Experimental investigation of CO_2 breakthrough and flow mechanisms in shale. *Challenges in CO_2 Sequestration Workshop*, Moab region, May 22–25, 2011.

Skurtveit, E., Aker, E., Soldal, M., Angeli, M. & Wang, Z.: Experimental investigation of CO_2 breakthrough and flow mechanisms in shale. *SUCCESS scientific days*. Gardermoen, Oslo, Norway, September 26–27, 2011.

2010

Aagaard, P.: Lagringspotensial på norsk sokkel. *Tekna konferanse CO_2-håndtering – post København,* Trondheim, January 7–8, 2010.

Kuznetsova, T., Kvamme, B., Donoven, C.R. & Ellingwood, B.: Impact of solid surfaces on hydrate stability and reformation potential. *Telluride Workshop on the Microscopic Description of Gas Clathrate, TSRC*, Telluride, USA, July 12–16, 2010.

Kvamme, B.: Report from 6th Fiery Ice, Bergen, Norway, 2008. *7th Fiery Ice From the Seas*, Wellington, New Zealand, May 10–12, 2010.

Kvamme, B.: CO_2 replacement phenomena in methane hydrates. Invited presentation on the *Gordon Research Conference: Natural Gas Hydrate Systems. Hydrate-Sediment-Fluid Interactions at Pore to Regional Scale*. Colby College Waterville, ME, USA, June 6–11, 2010.

Kvamme, B.: Production of natural gas hydrates using CO_2 injection. *Invited presentation 7th Fiery Ice From the Seas*, Wellington, New Zealand, May 10-12, 2010.

Kvamme, B.: GANS – an interdisciplinary Norwegian national project on hydrate resource mapping offshore Norway. *7th Fiery Ice From the Seas*, Wellington, New Zealand, May 10–12, 2010.

Kvamme, B.: CO_2 for EOR and production of natural gas hydrates. *Plenary lecture, ICIPEG 2010*, Kuala Lumpur, Malaysia, June 15–17, 2010.

Kvamme, B.: Hydrate as phase for separation, transport and storage – Challenges towards environmentally friendly solutions. *Plenary lecture at IPCEAM 2010*, Kuala Lumpur, Malaysia, June 15–17, 2010.

Kvamme, B.: Molecular simulations as a tool for multiscale modelling of phase transition kinetics. *Invited presentation, Telluride Workshop on the Microscopic Description of Gas Clathrate, TSRC*, Telluride, USA, July 12–16, 2010.

Kvamme, B.: CO_2 storage – challenges and opportunities, projects. *Korea – Norway seminar Carbon Capture Storage (CCS),* KAIST, Deajon, Korea, September 9, 2010.

Kvamme, B.: Status of CO_2 storage research and projects in Norway. Conference on Carbon value Chain (CVC) Technologies. *Experiences of and Opportunities between Norway and Korea*. Seoul, Korea, September 10, 2010.

Kvamme, B.: Hydrate phase transition dynamics in porous media. Invited presentation, *International Symposium on Methane Hydrate Resources*, Mallik to Nankai through, Tokyo, Japan, November 15–17, 2010.

2009

Aagaard, P., Austrheim, H. & Hellevang, H.: CO_2 sequestration in serpentinized peridotite – thermodynamic modelling of a natural occurrence. *The 23rd Kongsberg seminar "Physics of hydrocarbon-bearing systems",* Kongsberg, Norway, May 6–8, 2009.

Aagaard, P.: Fangst og lagring av CO_2. *Norges Tekniske Vitenskapsakademi,* Oslo, Norway, September 2, 2009.

Munz, I.A., Aagaard, P., Skurtveit, E., Regnault, O. & Brandvoll, Ø.: Risk assessment of CO_2 leakage through wells and cap rocks. *Tekna konferanse, CO_2-håndtering: er vi i rute?,* Trondheim, Norway, January 8–9, 2009.

Technical reports

Angeli, M., Skurtveit, E., Alemu, B. & Regnault, O., 2010: Laboratory Testing - Janusfjellet cap rock material. NGI 20061337-00-10-R

Angeli, M., Soldal, M. & Aker, E., 2011: CO_2 Laboratory Testing - Draupne I. NGI 20061337-00-8-R

Børresen, M. & Skurtveit, E., 2010: Literature review of CO_2 laboratory experiments. NGI 20061337-00-7-R

Munz, I. A. et al., 2010: Sampling and characterisation of the Nordmela Formation (Snøhvit storage site). IFE/KR/F – 2010/027

Regnault, O., 2009: CO_2 storage – a review on well cement experimental studies. IFE/KR/F – 2010/065

Regnault, O. & Brandvoll, Ø., 2010: RAMORE – Experimental results on Portland cement reactivity with CO2-rich fluids. IFE/KR/F – 2010/087

Skurtveit, E. & Eidsvig, U., 2010: CO_2 storage and risk assessment. NGI 20100201-00-2-R

Skurtveit, E., 2011: CO_2 Laboratory testing - Draupne II. NGI 20061337-00-13-R

Skurtveit, E., Angeli, M. & Regnault, O., 2011: Mechanical strength testing of CO_2-exposed cement plugs. NGI 20061337-00-9-R

Some of the popular notes and articles

Locate suitable storage sites, Elin Skurtveit, NGI: http://www.ngi.no/en/Selected-topics/CO2-storage-for-improved-global-climate/Find-deposit-sites/

Subsurface Storage of CO_2 - Risk Assessment, MOnitoring and REmediation (SSC RAMORE), UiO: http://www.mn.uio.no/geo/english/research/projects/ssc-ramore/index.html

CO_2 påvirker reservoarenes geofysiske egenskaper, Eyvind Aker, NGI, GEO, desember 2010, http://geo365.no/miljo/deponeringavco2/.

Oppmuntrende resultater fra lekkasjeprosjekt, Per Aagaard, UiO, geoforskning.no: http://www.geoforskning.no/nyheter/klima-og-co2/179-oppmuntrende-resultater-fra-lekkasjeprosjekt

Prosjekt: Taket holder tett i CO_2-lagrene (RaMoRe), Claude R. Olsen, CLIMIT, February 2012, http://www.climit.no/taket-holder-tett-i-co2-lagrene