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SUCCESS: SUbsurface CO2 storage – Critical Elements and Superior Strategy

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Abstract

SUCCESS is a Center for Environmental Energy Research in Norway and performs research related to geological storage of CO_2 in the subsurface. The SUCCESS centre is established by the Research Council of Norway together with several Norwegian research institutes and universities. The centre is hosted by Christian Michelsen Research. Through international cooperation and open research the SUCCESS centre will fill gaps in strategic knowledge and provide a system for learning and development of new competency to ensure safe and effective CO_2 injection, storage and monitoring. In this paper we briefly present the main focus areas of the centre and some recent results obtained by the research partners. The results relate to geochemical effects, reservoir modeling, monitoring the geomechanical respond and the marine environment. A brief status on the field trial, Longyearbyen CO_2 Lab, at Svalbard is also provided.

Keywords: National research centre, SUCCESS, CO_2 storage, injection, monitoring

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1. Introduction

SUCCESS is a Center for Environmental Energy Research in Norway and performs research related to geological storage of CO_2 in the subsurface. The SUCCESS centre is established by the Research Council of Norway and the following research partners: Christian Michelsen Research (CMR, host), University of Bergen (UiB), University of Oslo (UiO), Institute for Energy Technolgy (IFE), Norwegian Geotechnical Institute (NGI), Norwegian Institute for Water Research (NIVA), Uni Research and University Centre in Svalbard (UNIS). The industry partners of the centre are CGGVeritas, ConocoPhillips, Dong E&P, RWE Dea and Statoil.

The project addresses five important areas for CO_2 storage in the subsurface: (1) storage performance, (2) sealing properties, (3) monitoring techniques, (4) operational aspects and (5) the marine environment.

In addition to these five areas, a major educational program "CO_2-school" is facilitated by the project and the three universities that are involved (UiB, UiO, UNIS). The selected activities, which are considered to fill important knowledge gaps or be critical elements, will involve fundamental experimental and theoretical work, analysis of samples from outcrops and case studies, development of mathematical models, modelling activities and testing in case study environments. The competence of the SUCCESS consortium includes sedimentology, structural geology, fluid flow, reservoir characterization and modelling, geophysical modeling and interpretation, mathematical modelling, mineral reactions, geochemistry, geomechanics, petrophysics and marine ecology. On issues related to CO_2 storage, the centre will collaborate and co-ordinate its activity with BIGCCS, another Norwegian Center for Environmental Energy Research and hosted by SINTEF.

2. Objectives

The vision of SUCCESS is to provide a sound scientific base for CO_2 injection, storage and monitoring, to fill gaps in strategic knowledge, and provide a system for learning and development of new competancy. The center will focus on the following topics:

- quantification and modelling of reactions and flow in storages
- relation between flow, reactions and geomechanical response
- flow and reaction in faults and fractures
- integrity and retention capacity of sealing materials
- test, calibrate and develop new monitoring techniques
- ecological impact of CO2 exposure -marine monitoring methods
- extensive high quality education for CO2 storage

In the following sections we present specific results from recent work among the partners and focus areas that the center will work on in the future.

3. Storage: geo-characterization and geochemical modeling

The focus of this activity is the development of criteria for storage site selection and methods for storage performance prediction. To assess and predict reservoir behaviour with respect to its overall capasity and avoiding critical pressure build-up, it is required to have reliable forecasts of fluid flow accompanied by geomechanical and geochemical effects for the selected injection strategies. Special attention will be sought on issues related to geological heterogeneities, faults and fractures and imperfect geological description on the development of potential storage prospects and to develop a methodology in building geological reservoir models.

Geochemical modeling requires thermodynamic and kinetic data to predict responses to reactions between injected CO_2 solutions, formation water and reservoir minerals. SUCCESS will here build upon experimental and theoretical studies on mineral dissolution carried out in the research project "Subsurface storage of CO_2 - Risk Assessment, MOnitoring and REmediation (RAMORE)". The extent of CO2 - mineral reaction during long-term storage in the Utsira case has been revisited by using the geochemical code PHREEQC [1]. During CO_2 storage, mineral trapping is the safest storage mechanism in the long-term, and it is important to estimate the correct CO_2 portion trapped in mineral phases.

The precipitation of carbonate minerals and the potential for mineral carbonate storage were solved using mineral rate equations defined to take account of differences in rate parameters between dissolution and growth and that included mineral nucleation preceding growth [2]. The data of the Utsira sand was applied together with updated kinetic rate data of some minerals [3]. After CO_2 injected into the reservoir, CO_2 dissolves in formation water and reacts with minerals in the rock. The most reactive clay minerals dissolves first together with minor amounts of calcite, while specially iron and magnesium containing carbonates, as ankerite ($Ca(Fe,Mg)(CO_3)_2$) were subsequent formed. Another carbonate mineral that formed was dawsonite ($NaAl(OH)_2CO_3$).

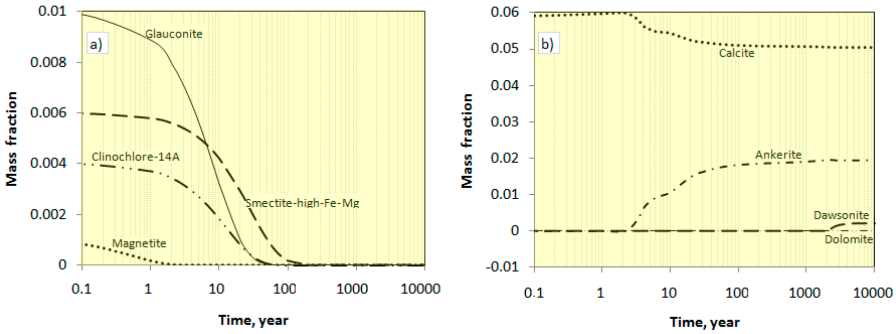

Figure 1: a) In the shorter time span (years - tens of years) common clay minerals dissolves and leads to corresponding carbonate precipitation, b) The carbonate precipitation is however delayed as the precipitation rate of the carbonate minerals depend on the supersaturation.

4. Reservoir modeling of CO_2 injection

The focus of this activity will be on improving simulation models to more accurately predict CO_2 dissolution, fingering mechanisms and effects of geological heterogeneities. The activity builds in part upon the established research of the project "Geological storage of CO2: Mathematical Modeling and Risk Assessment (MatMoRA)". Among recent advances we find results concerning development of new upscaling approaches based on vertically integrated formulations.

Development of vertically integrated models are motivated in parts by computational challenges associated with the huge length and time scales which are typical for geological storage. This computational challenge is manifested in intercomparison studies, where it has been observed that convergent results are seldom obtained, even for relatively simple model problems. A particularly striking result was obtained in a study spearheaded in collaboration with the University of Stuttgart, where even identical numerical codes yielded significantly different results as a consequence of different user implementations of the problem description [4]. Vertically integrated models try to alleviate this computational challenge by exploiting the relatively large aspect ratio of geological formations.

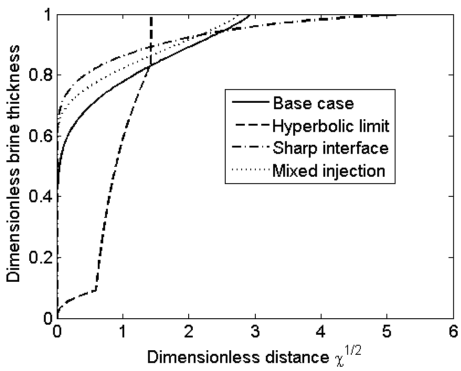

Figure 2: The solid line shows the vertically averaged brine content as a function of normalized distance during injection of CO_2 into a homogeneous formation for typical parameters for injection rate, relative permeability and capillary pressure. The area above the curves can therefore be interpreted as the CO_2 plume. The remaining lines explore the sensitivity to increasing the injection rate (dashed line), decreasing the capillary pressure (dash-dot line), or co-injecting 25% brine wih the CO_2 (dotted limit).

A family of vertically integrated models is defined through different physical balances utilized in the upscaling from three-dimensional equations to two-dimensional equations. The applicability of vertically integrated models therefore depends fundamentally on dimensionless groups. These issues have recently been investigated by members of the MatMoRA project [5-7]. One of the results of those investigations highlights the role of capillary forces during the injection phase of a storage operation, as shown in Figure 2. Counter to the results which would have been obtained by a radial analysis of the 3D equations, we see that capillary forces do not smooth the solution, but rather leads to a sharper injection front entering the system. This result is due to the smearing of the front on the local scale which leads to a zone of strongly coupled two-phase flow. In this zone, the total mobility of the fluids will be lower, and form what amounts to a flow barrier, and subsequent build-up of CO_2 saturation.

5. Monitoring the reservoir and the geomechanical response

The purpose of this activity is to develop methods and concepts providing early warnings about potential leakage of CO_2 from the reservoir and monitor the injection performance. The calibration and tuning of geophysical methods (e.g. seismic, electromagnetic) against more direct observations is an important element in this activity. To illustrate this we present a coupled poro-elastic and two-phase flow finite element model applicable to model surface heave due to CO_2 injection. The model has been tested and calibrated on data from In Salah, Algeria, where the surface deformation around three different injection wells (KB501, KB502 and KB503) has been detected by InSAR [8]. Three case studies has been simulated to investigate various impacts on the surface heave: Base case; best-guess estimate of the available parameters [9], Fracture case; inserting a high permeable lower caprock layer above the reservoir (in effect increasing the thickness of the reservoir) and Fault case; adding a high permeable vertical fault plane through the caprock. The FEM model describing full coupled equations of two-phase fluid flow in porous rock and poro-elasticity is implemented in the commercially available software COMSOL Multiphysics [10,11].

The surface heave at the three injection wells from two different references [8,9] is shown in Figure 3, left plot. The Base case model (Figure 3, middle plot) matches the observed heave after 3 years and shows a smooth and steadily declining heave rate, while the Fracture case (Figure 3, right plot) gives a distinct shape of the surface heave profile; an abrupt change in heave rate followed by an almost linear increase in heave with time. The change in rate occurs when the plume reaches the caprock, or top of the fractured layer, indicating that the temporal evolution of the heave can say something about the thickness of the injection layer and the time that the plume reaches the caprock.

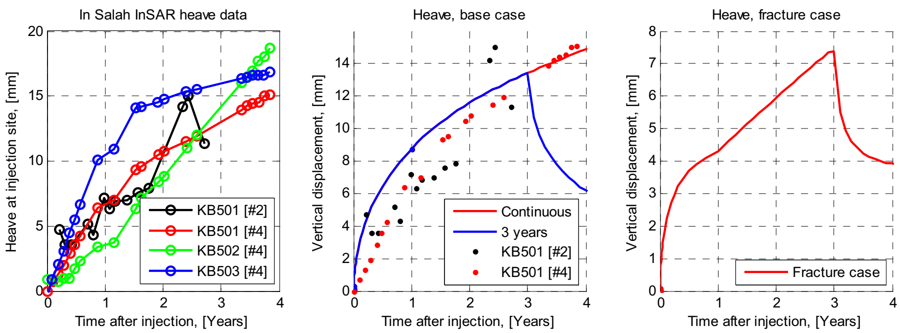

Figure 3: Left: Measured heave data at the injection wells from two different references: [8,9]. Centre: Close-up (0-4 years after injection) of surface heave (modelled Base case; line) compared with measured data for injection well KB501 (dots). Red curve is from continuous injection and blue curve when injection is stopped after 3 years. Right: Close-up (0-4 years after injection) of surface heave (Fracture case).

By introducing a vertical fault plane through the caprock (the Fault case), a distinct and noticeable uplift of the surface directly above the fracture is observed (Figure 4). The heave is not due to leakage, but to increased fluid pressure in the fault because of more favourable flow conditions (higher permeability). This indicates that a high permeable fault plane, even outside the reach of the injected CO_2 plume, can be visually determined by measurements like InSAR.

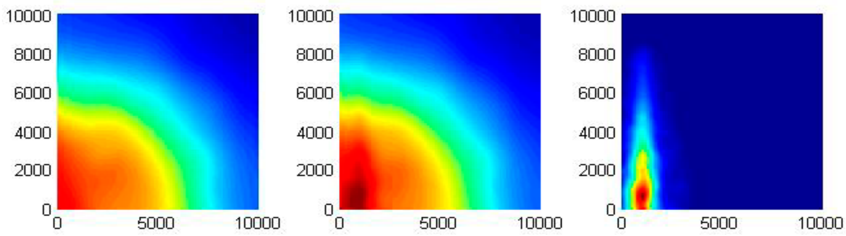

Figure 4: Vertical heave of the top surface after 3 years injection for Base case (left) and Fault case (middle) when a fault is intersecting the caprock. The difference in heave between Base case and Fault case is plotted to the right for comparison. Color scale is 0-15 mm (0-3 mm in difference plot). Note that only half of the model is shown.

6. Geochemical effect on sealing interfaces

The geochemical effect of CO_2 on well cement and caprock, has been subjected to considerable attention in the RAMORE project. Future research in SUCCESS will build on gained methods and results. Well cement (class G) forms into characteristic layering (Figure 5, left) when exposed to brine saturated by a CO2 headspace under subsurface conditions (10 MPa, 50°C, 35 g/l NaCl). When excess water is available, layering occurs due to the rapid (<10 days) decalcification/carbonation at the cement surface to form a carbonate/silica gel mix of reddish brown color. Outer layer depth is typically 200-300 µm, and apparently time-independent, suggesting that further reaction is limited by mass transfer across the formed outer layer, i.e. the diffusion of aqueous species to and from the reactive surface. Intermediate layers are found to be enriched in carbonate from the conversion of Portlandite ($Ca(OH)_2$, resulting in reduced porosity and apparent retention of structural strength, as cations have not been leached from these layers. The interior of the cement is unaffected by the exposure under conditions of free water (i.e. submerged), but fully carbonated when exposed to dry conditions (Figure 5, right).

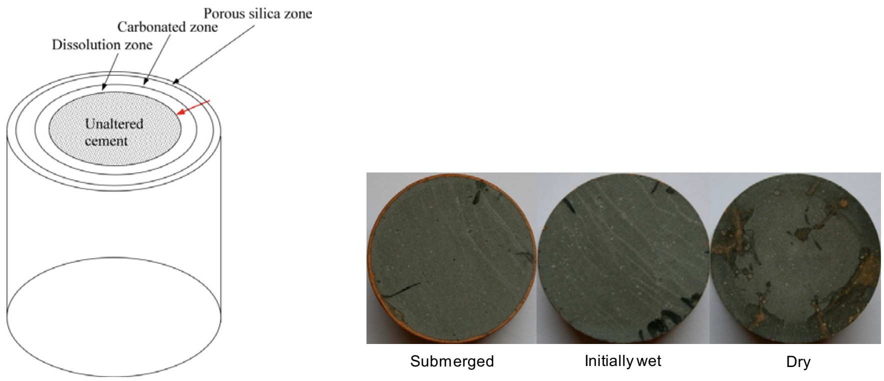

Figure 5: Left: Schematic of typical layers resulting from the exposure of well cement class G to CO_2/brine mixtures under subsurface conditions (10 MPa, 50°C , 35 g/L NaCl); Calcium Silicate Hydrate (CSH) decalcification (Porous silica zone); carbonation of Portlandite, $Ca(OH)_2$ (Carbonated zone); partially decalcified/carbonated zone (Dissolution) and unaltered cement (red arrow). Right: Cross-sectional cuts through cement plugs that have been exposed to a mixture of brine and supercritical CO_2 at 10 MPa, 50°C and 35 g/L NaCl. The samples were put in titanium autoclaves and exposed for 30 days with an excess of supercritical CO_2.

Under partially desiccated, static conditions, i.e. resembling the conditions in close proximity to the wellbore, we have no indication that CO_2 injection will adversely affect the cement sealing properties. As no aqueous phase is present in which cation leaching can occur, only carbonation reactions have been observed, penetrating along veins and cracks into the centre of the sample. Cracks are also typically found to be cemented as a result of carbonation.

Under conditions of laminar reactive flow over the cement surface (e.g. brine/CO_2 leakage), however, rapid and full degradation of the exposed cement surface has been observed. Bulk movement of the brine facilitates the rapid transport of aqueous products out of the system, while at the same time supplying fresh reactive brine for reaction.

The combined effects results in penetration depths reaching several millimeters after 1-2 weeks of exposure. Based on these findings, it is believed that degradation reactions will probably have self-enhancing effects resulting in increased leakage rates. It should also be noted that in case of large leakage rates, flow will probably be turbulent, leading to additional adverse effects, due to shear forces occurring at solid interfaces. Examples after 30 days batch exposure is provided in Figure 5 (right). For further details about the experimental setup and related work see [12] and [13], respectively

7. Status of the Longyearbyen CO_2 Lab

Collaboration with the Longyearbyen CO2 Lab by UNIS will give an opportunity to test methodology developed in the SUCCESS centre. The CO2 Lab (see e.g. [14,15]) is located on Svalbard which has a unique location for studying energy and climate-related issues with its closed energy system, using coal as the main energy carrier, and also representing a key location for analyzing possible climate changes. By the end of 2009 the CO2 Lab summarized results of the pilot study (Phase 1) by concluding on the following aims: 1) to explore for a sandstone reservoir that is capable of receiving a large amount of CO_2, 2) to document an efficient top-seal (shale) and 3) to investigate if permafrost can act as an extra top-seal. The next phase(s) will further qualify injectivity and storage capacity of the reservoir as the project moves towards CO_2 injection.

The targeted reservoir/aquifer, filled with brine, is at 670-1000 m depth. The fourth well, DH4, encountered the c. 22 m thick Willhelmøya Formation and then the much thicker De Geerdalen Formation [16,17] down to the well was terminated at a depth of 970m (TD) (all depths are TVD; True Vertical Depth). The well was continuously cored from surface to TD. Sedimentological studies of the potential “storage units” suggest that the succession offers shallow marine shoreline and coastal plain hetereolithic facies, with some thicker massive sandstone beds, probably of tidal channel fill and spit origin. The net-to-gross of the reservoir succession is estimated to 0,3. As expected, both the porosity and permeability of the Willhelmøya and De Geerdalen formations show low values, in the order of 5 to 18% and 0.1 to 2 mD, respectively.

A feasibility water injection test in well DH4 shows that the lowest 100 m open hole part of the well has a stable water flow at a max pump pressure of 10 bar of 48 cum/d comparable to 10000 ton/yr. As the un-tested 670-870 m (TD) reservoir section offers better properties in drill cores, and the 870-970 m TD section shows injectivity, it can be concluded that it is feasible to inject water into the encountered sandstones of the Wilhelmøya and De Geerdalen formations. The aquifer shows clear signs of good fracture permeability. A new injection program are undertaken in August 2010 with a stronger pump to characterize the fracture permeability.

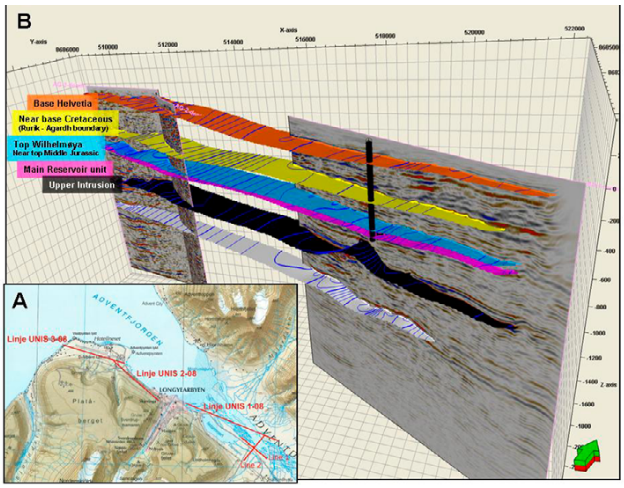

Figure 6: A) Seismic lines collected by the project (activity supervised by Department of Earth Science, University of Bergen, supported by Bergen Oilfield Services and UNIS), with acquisition activity in the early spring of 2008 and in February 2010. B) Bedding surfaces with colors (in depth) in the Adventdalen area, showing the main geological units identified in the well DH4 (located as black line) that are linked to the seismic reflectors. Note the undulating geometry of the intrusion, probably with a geometry of a sill but partly also cutting layering as a dyke. 0m is the ground surface. Illustration supplied by K. Bælum.

Results from outcrop data and analysis of existing and new seismic lines, offering a regional 2D coverage, constrain the geometry of the targeted aquifer, which climbs gently (1-3 degrees) towards the surface in the NE. Several good reflectors can be mapped through the area (Figure 6), but there are also challenging reflectors and noise related to intrusions with high accosting impedance in the reservoir level (two of which are cored in DH4). To further investigate the area around the injection site, seismic data was acquired along two orthogonal lines, each of 1.2 km and intersecting close to the DH4 well position. In parallel, a Vertical Seismic Profiling (VSP) in was performed in DH4, and later placed at in the neighboring well, DH3. The system also monitored a swarm of micro-earthquakes during water injection in DH4. The micro-seismic dataset is not yet fully investigated; however, the success of this survey motivated the use of microseismic for the injection test in August 2010.

8. The marine component

This activity will address the potential impact of CO_2 seepage from the sub-seafloor and into the marine environment, on the physical chemical and biological compartments of the marine environment. Under a CO_2 seepage scanerio, one expects disturbance of the chemical properties of the bottom boundary layer, and possibly of the water column above it, leading to modification in the properties, the biological composition and the basis functions of benthic and possibly pelagic ecosystems. If the effect of CO_2 on some marine organisms (ex: calcareous organisms) is well know, there is a significant lack of knowledge on the integrated response of marine ecosystems to long-term and/or massive exposure to CO_2 (and likely mobilized CH_4 and contaminants). SUCCESS will contribute in accumulating new knowledge regarding e.g. individual response of marine faunal and microbial communities in the upper sediment, the bottom layer and the water column; ecosystem response and major changes in ecosystem functioning; detailed description of the marine carbonate system under CO_2 seepage; and emission, spreading and dilution of various form of CO_2 in the marine environment. This new knowledge is the necessary and mandatory information to sustain (1) the development of sounded environmental characterization of offshore storage sites; (2) the development of cost-efficient monitoring programs for detection seeps, assessment and documentation of potential ecological effects of CO_2 seepage; and (3) the elaboration of remediation plans.

Most recent results show that the possibility to chemically detect CO_2 seepage requires a detailed knowledge on natural variability in the marine carbon system (also linked to climate change and ocean acidification). Bridging the two research topics is therefore sought in SUCCESS. Simulation of droplet migration shows that it is important to identify the nature of the seeps in order to assess what volume of water may be affected by the seeps. Recent research on in-situ CO_2 exposure of benthic ecosystem, with the help of an advanced benthic chamber system (Figure 7) has concluded that the change in benthic ecosystem composition and functioning may lead to the definition and development of robust biological and biochemical indicators of CO_2 seepage, which can be an efficient way of monitoring long-term small seepage over large areas. SUCCESS will address the later topic in detail and will contribute in developing connected new investigation and monitoring technologies.

Figure 7: Benthic Chamber System (NIVA/CO2GeoNet)

9. CO_2 school

Education and training are key components of the SUCCESS center. The educational institutions (UNIS, UiO and UiB) will offer research-based training as individual course that emphasis subsurface storage of CO_2. These courses make up parts of MSc and PhD degree programs in petroleum geology. The CO_2 courses will be an important arena for collaboration and exchange of knowledge between all of the involved partners, as well as being an important arena providing qualified candidates to the industry, research institutes, universities and university colleges.

10. Acknowledgement

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