Final report, 1 July, 2014

ENVIRONMENTAL TECHNOLOGY FOR GEOLOGICAL STORAGE OF CARBON DIOXIDE **(DSF Project nr.** 0603-00303B**)**

http://co2gs.geus.net/

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Partners: Vattenfall AB, Institut for Geovidenskab og Naturforvaltning, Københavns Universitet, Institut for Geologi, Århus Universitet, DTU Vand og Miljø, RISØ DTU Danmarks Tekniske Universitet, Rambøll, GEO, Lawrence Berkeley National Laboratory, (Berkeley, California), Heriot-Watt University (Edinburgh).

Objective

The latest IPCC report indicates an imminent need to develop technologies that may remove CO_2 from the atmosphere. One of the few technologies that is able to do so is burning of biomass in combination with Carbon Capture and Storage (CCS). However the CCS technology is not yet mature and among the public there are serious concerns with respect to safety and possible environmental impacts. This project explores some environmental aspects concerning CCS. The main question to be answered is whether we can monitor and manage CCS systems in a save way. A secondary objective was to investigate the potential of technology for optimizing CO_2 storage in the underground with infiltrating groundwater by reactions with minerals in the soil zone.

WP 1: Dynamic and geomechanical behavior of CO_2 storage formations: *Team Leader Peter Frykman (GEUS). Participants; Ernest N. Mbia PhD student (DTU), Ida Fabricius (DTU), Christian Bernstone (Vattenfall R&D), Finn Dalhoff (Vattenfall R&D), Ann Troelsgaard (Vattenfall R&D), Gillian Pickup (Heriot-Watt Univ.), Frederik Peter Ditlevsen (GEO).*

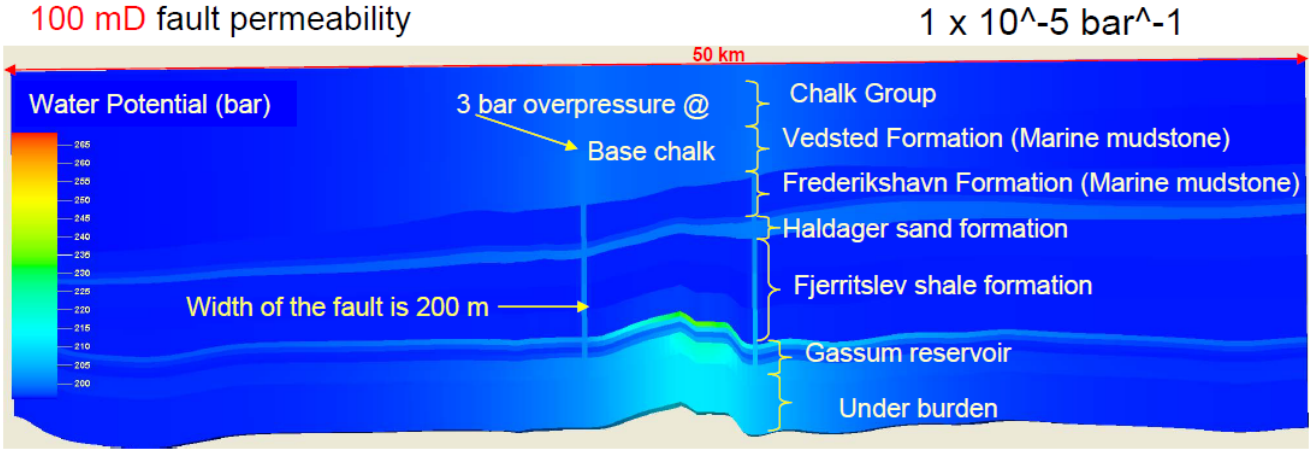


Figure 1. Model results for the Vedsted site for pressure propagation from the hypothetical CCS storage in the Gassum formation at 3 km depth. At the bottom of the chalk at 500 m depth an overpressure of 3 bar is calculated.

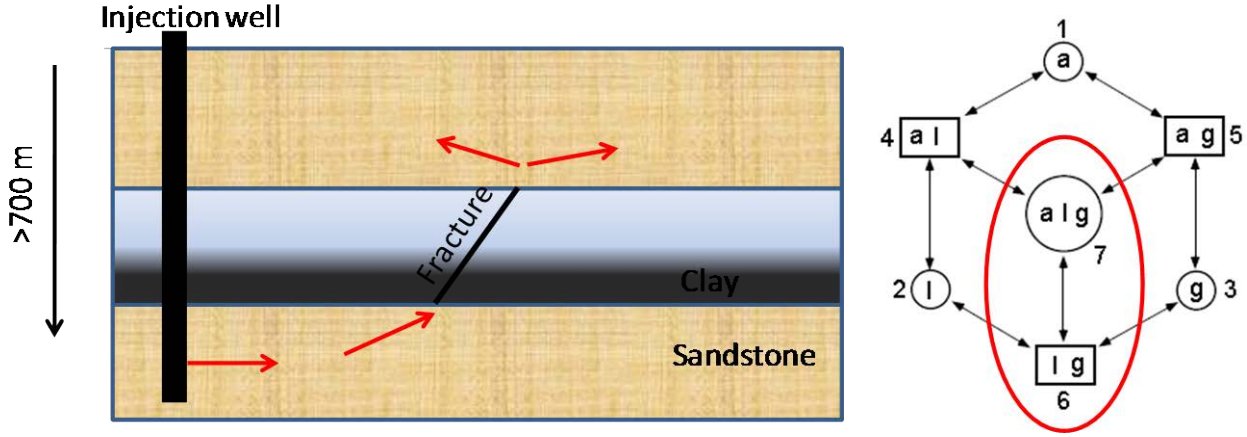
The Vedsted structure in N. Jutland has been evaluated as a potential CCS site. Using the specific geological conditions at the site the potential pressure propagation that may result from CO_2 injection in the storage layer at 3 km depth has been evaluated by using numerical simulations. The model includes the main formations all the way from the reservoir layer in the Gassum Formation to the ground surface. The study has focussed on the lateral and vertical pressure propagation, including the effect of permeable faults connecting the reservoir layer with shallower levels.

Caprock permeability and compressibility are important parameters in the model and laboratory investigations have been carried out to determine caprock properties, to be used as input to numerical flow simulations. The caprock permeability is a parameter that is difficult to obtain because caprocks have an extremely low permeability. Various scenarios and sensitivity testing of the parameters have been carried out. The model results indicate a moderate propagation of water pressure from the storage layer upward along fault zones to the base of the chalk formation at 500 m depth. The worst case scenario results in up to 3 bar overpressure at 500 m depth, with a limited impact on the shallow freshwater zone.

Results and Implications for Society and Industry
The developed model provides a tool for management and risk evaluation for the Vedsted site in the case that geological storage should be implemented her. However, it may also serve as a template for the development of similar models for other sites considered for CCS.

WP 2: Modelling multi-phase reactive transport of CO_2 in aquifers: *Team Leader Karsten H. Jensen (IGN, KU), Participants; Karsten Pruess (Lawrence Berkeley National Laboratory), Jacob Gudbjerg, Torben Sonnenborg (GEUS) Flemming Damgaard Christensen (Rambøll).*

Models can help us to investigate scenarios which cannot be investigated experimentally.
Scenario a): During CCS, CO_2 is injected in a supercritical (liquid like) state. Should liquid CO_2 escape from a storage, could this impose a risk for a blow-out where liquid CO_2 expands to gaseous CO_2? We have developed a model to calculate the migration of CO_2 in the subsurface describing all possible phase combinations. Applying the model to various hypothetical situations indicates that the actual risk for a blow-out is very small.
Scenario b): Fresh groundwater reservoirs used for drinking water are often separated from deeper salt water by a difference in density at about 150 m below the surface. The question to be answered was whether pressure changes generated by the models of *WP1* could be sufficient to disturb this layering and deteriorate the drinking water quality by mixing fresh and salt water. The question was explored using a groundwater model that considers density driven groundwater flow. The results for the Vedsted site indicate that the risk for a disturbance of the fresh-saltwater interface is small.



Figur 2 Left: A schematic of an underground storage of CO2 with a fracture in the sealing. Right: the possible phase combinations when CO2 moves through the fracture. The red circle marks the phase combinations that are new in the code. a = aqueous, l = liquid, g=gas.

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Results and Implications for Society and Industry
The two models, developed and implemented here, will prove to be strong tools for analyzing any locality where CCS in the underground is being considered, with respect to the potential pathways for CO_2 transport in the underground as well disturbances of the fresh-salt water interface.

WP 3: Environmental assessment of CO_2 contamination in shallow aquifers: *Team Leader Rasmus Jakobsen (DTU). Participants; Aaron Cahill PhD student (DTU), Flemming Larsen (GEUS) Dieke Postma (GEUS).*

Consider the scenario where stored CO_2 gas enters a groundwater reservoir used for drinking water purposes. What would be the risk for the drinking water quality? Could the presence of CO_2 release harmful substances from the aquifer sediment? Laboratory tests of a range of Danish aquifer related materials indicated that sediment composition was very important. Carbonate free aquifers were most vulnerable to acidification, while aquitard materials had the highest potential for releasing elements critical to water quality. To study the effects in the field we carried out a CO_2 gas injection experiment in a shallow carbonate free aquifer, shared with *WP4*. 1600 kg of CO_2 was injected over 72 days into a sandy aquifer by inclined injection wells, 2 at 5 and 2 at 10 m below surface, targeting the upper aeolian and lower glacial sand. A distinct plume of high P_{CO_2} water was formed following the groundwater flow with a lowered pH (5.6-4.7) and elevated EC (166-304 µS/cm) and a concurrent increase in major and trace metal concentrations (Fig. 3) due to surface reactions induced by the increased H^+ and the Al^{3+} released from dissolving Al-hydroxides. The small increases seen in this system do not imply a serious water quality risk. Further modelling indicated increasing water quality effects with leak duration and depth, but modeled effects were still limited. Introduction of small amounts of carbonate minerals leads to higher concentrations of major ions but a very slow migration of the acidification.

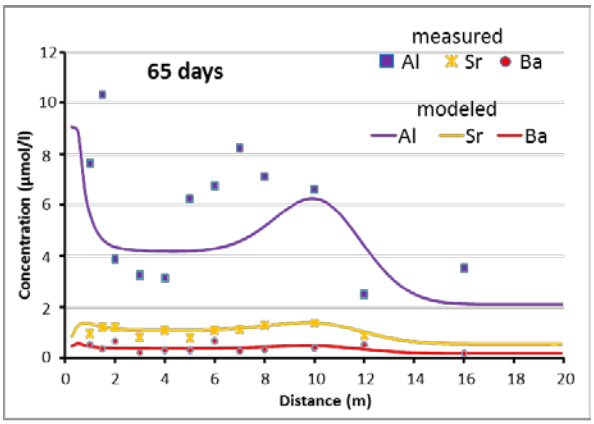

Figure 3: Trace metal concentrations measured down flow of the CO2 gas injection in the saturated zone of the glacial sand at 8 mbs.

Results and Implications for Society and Industry

This work provides both experimental, modelling and monitoring approaches for assessing the potential and actual changes in groundwater composition caused by the release of harmful substances from the aquifer rock, into the groundwater, as the result of the introduction of CO_2 gas into aquifer systems.

WP 4: Methods for detection of gaseous CO_2 in shallow aquifers*: Team Leader Esben Auken (GI, AU). Participants; Joseph Doetsch post doc (GI, AU), Anders Vest Christiansen (GI, AU), Rune Lassen PhD student (IGN KU), Karsten Høgh Jensen (IGN, KU), Torben O. Sonnenborg (GEUS),*

Tools are needed to detect the presence of CO_2 in the underground as measured from the earth surface. In this workpackage a number of geophysical methods were evaluated upon their ability to do so. The CO_2 injection experiment shared with *WP3* was used to carry out the field measurements.

Surface Resistivity and Induced Polarization (DC/IP) for 3D time-lapse monitoring data were gathered using a new 3D acquisition system before and during the CO_2 injection experiment. A 2D inversion code has been developed to invert time domain DCIP datasets. Figure 4 shows the ratios obtained from the 2D time-lapse inversion using a pre-injection reference and time steps at 39 days and 114 days after injection. The orange and red signatures indicate the presence of dissolved CO_2 being strong and surface-near in the early stage and more diffuse at the later stage when injection has stopped. The plume of dissolved CO_2 migrates in the direction of the groundwater flow.

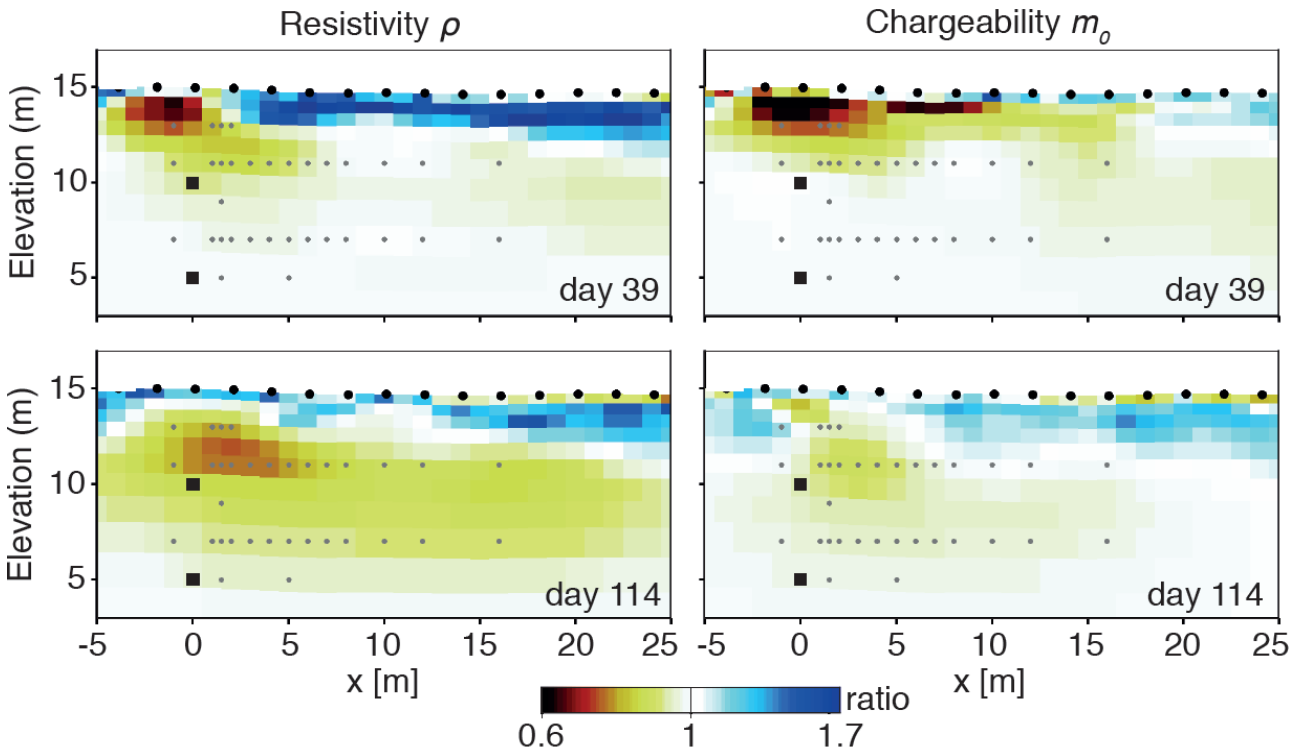

Figure 4. Left; the resistivity model difference between the reference model before injection and the resistivity model at day 39 and 114. Right: the same for chargeability. Injection points are marked with black squares. The data have been inverted with a 2D DC-IP code

Measurements of CO_2 gas migration in the underground were also carried out by georadar. This method has proved effective in tracing gas in the underground and the results show that geological heterogeneity exerts a dominating control on the migration of CO_2 gas. The migration of gaseous and dissolved CO_2 in the underground has been modelled using the reactive transport computer code completed under *WP2*.

Results and Implications for Society and Industry

Measurement of CO_2 migration in the underground, carried out from the earth surface will be an important early warning tool at any CCS site. Our results indicate that geophysical methods may be well suited to fulfil this task.

WP5: Enhanced storage of CO_2 in aquifers: *Team Leader Dieke Postma (GEUS). Participants: Søren Jessen Postdoc (IGN, KU), Eike Marie Thaysen PhD student (DTU), Iver Jakobsen (DTU), Majken Caroline Looms Zibar (IGN, KU), Per Ambus (DTU), Rasmus Jakobsen (GEUS)*

Below agricultural fields, the CO_2 soil gas content is highest during late summer and early fall Fig. 6a) when groundwater recharge commences. By applying different amounts of lime to the soil we intended to convert CO_2 soil gas to dissolved inorganic carbon (DIC). With the infiltrating water the DIC enters the groundwater zone (Fig. 6b) and is in this way be removed from the earth surface. The mechanisms of these processes were studied in the field and in laboratory mesocosmos experiments with lime and concrete waste and found to be effectively increasing the DIC. However, at our field site we found a buried acidification front, dating back to the epoch of acid rain, which obstructs downward DIC transport by converting DIC back to gaseous CO_2 which will escape into the atmosphere. Unfortunately the end result at our field site is therefore that adding lime to the soils increases the release of CO_2 to the atmosphere rather than decreasing it as intended.

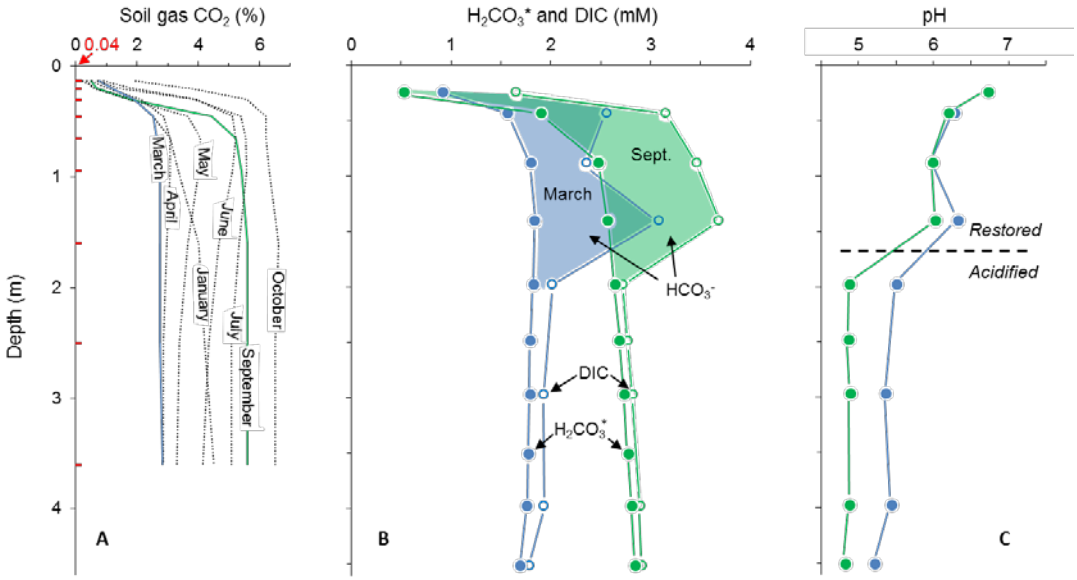

Figure. 5 The distribution of the CO_2 partial pressure, dissolved inorganic carbon and pH in the unsaturated zone of a sandy aquifer below limed agricultural fields.

Results and Implications for Society and Industry

The CO_2 flux from the soil to the atmosphere is one largest in the global carbon cycle and it is important to understand the upward and downward carbon fluxes particularly on agricultural fields in order to optimize their carbon cycling. As illustrated by our research, the downward carbon fluxes are still poorly understood. However, because downward CO_2 fluxes enable removal of CO_2 from the atmosphere, the controlling processes deserve further study.

Research Education

PhD studies were completed by Ernest Mbia, Rune Lassen, Eike Marie Thaysen and Aaron Cahill as part of the project. In addition Søren Jessen, Joseph Doetsch and Jacob Gudbjerg worked as post docs on the project. Also two M.Sc. studies were performed within the project.

Cooperation

Cooperation between partners: WP1 has been an integrated effort between Vattenfall, DTU, GEO and GEUS with Ernest Mbia staying for some time at each institution. In WP 2, Jacob Gudbjerg, Flemming D. Christensen, Rambøll, and Ernest Mbia have cooperated on the interface between the model describing processes at depths > 500 m models for aquifers at <500 m depth. The CO_2 injection experiment was a concerted effort of WP 3 and WP4 and used for investigations of groundwater geochemistry (DTU), modeling (IGG, KU) and geophysics (GI AU). In WP5, soil ecologists (DTU) collaborated with geochemists at GEUS and hydrologists from IGG KU. *International Cooperation*: Ernest Mbia (WP1) had a study stay with project partner Heriot-Watt Univ., Edinburgh. Jacob Gudbjerg (WP2) did spend three months at Lawrence Berkeley National Lab. with Karsten Preuss working on the TOUGH modeling code. Rune Lassen (WP 4) spend six months at the Colorado School of Mines working on laboratory experiments. Esben Auken collaborated with Andrew Binley (Univ. Lancaster) and Gianluca Fiandaca (Univ. Palermo) on code development. Aaron Cahill had a study stay at the Univ. of Montana learning from their earlier CO_2 injection experiment. Eike Marie Thaysen (DTU) collaborated with Diederik Jacques (Belgian Nuclear Research Centre) and Jirka Šimunek (UCR, California) on the code HP1. The project is linked up to EU FP7 CCS initiatives; SiteChar, MUSTANG, CGS Europe, RISCS, CCSNETWORK and CO2GeoNet.