CO2CARE

CO_2 SITE
CLOSURE
ASSESSMENT
RESEARCH

Final Conference

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All illustrations by CO_2CARE consortium

Conference website: www.co2care.org

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Summary No. 1

CO_2CARE – Achievements after almost 3 years – an overview

Liebscher, A.

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The project *CO_2CARE – CO_2 Site Closure Assessment Research* aims at developing the necessary methodologies and strategies needed to meet the requirements by the EU Directive for site abandonment, post-closure safety and transfer of responsibility. Funded under the Seventh Framework Programme of the EU, 23 partners from academia, industry and regulators perform integrated laboratory and field experimental research supported by advanced numerical modelling to achieve the project´s aims. The focus of the work is on the high level criteria set out in the EU Directive to guarantee the safe and long-term storage of CO_2: i) Observed behaviour of the injected CO_2 conforms to the modelled behaviour, ii) No detectable leakage, and iii) Storage site is evolving towards a situation of long-term stability. The project´s site portfolio comprises 9 European and overseas CO_2 storage sites with a focus on the Sleipner, K12-B and Ketzin sites.

Within seven, strongly cross-linked work packages major results and progress have been achieved after almost three years of project research. For post closure reservoir management reservoir simulations at various spatio-temporal scales were performed and provide quantitative data on long-term safety as well as on the potential performance of remediation measures after leakage detection. Leakage detection itself leads directly to monitoring technologies which were investigated using existing field data as well as by looking at innovative technologies which provide alternatives to conventional 3D seismic surveying. For site risk management, procedures and criteria for site closure and transfer have been developed as well as tools and methods for supporting decision making. These procedures and tools were evaluated on the three key sites Sleipner, K12-B and Ketzin and the resulting risk management plans were implemented into dry-runs of the sites. These dry-runs were discussed and reviewed by Stakeholders on the Regulatory Panel including industry and EU/national regulators and form one of the central outcomes of CO_2CARE and the centrepiece of the final best practice guidelines.

Fig. 1: *Project meeting at TNO in Utrecht in March 2013.*

Summary No. 2

CO_2 Storage in Continental Flood Basalts of Eastern Washington State, USA

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Continental flood basalts globally form an important, but under-characterized target for geological storage of carbon dioxide (CO_2). In the northwestern U.S.A., basalt lava flows of the Columbia River plateau are up to 5 km thick and cover over 168,000 km^2. The tops of individual basalt lava flows are highly porous and permeable and thus constitute potential reservoirs for sequestration of millions tons of CO_2 in areas where they contain non potable water and are at depths greater than 800 m. After thorough screening, a pilot site was identified on the Boise Inc. mill property at Wallula, Washington (Fig. 1). A full geological characterization was performed and in 2009, the first sequestration pilot borehole well within continental flood basalts was completed to a total depth of 1344 m. Based on the results obtained during the active borehole characterization program, an injection reservoir was identified between the depth interval of 828 and 896 m that contained three individual breccia interflow zones. Thick and impermeable layers of rock above these porous layers will act as barriers or seals to prevent the CO_2 from travelling vertically upward. In July 2013, 1000 tons of CO_2 compressed into a liquid-like state were safely injected (Fig. 2). Fluid samples will be periodically extracted from the injection well until September 2014 and changes in chemical composition in comparison to baseline data compiled prior to injection will be tracked. These results will then be compared to predictions made using supercomputers. At the end of the monitoring period, rock samples will be taken from the well. They are expected to exhibit the formation of limestone crystals as a result of CO_2 reacting with minerals in the basalt.

This joint research is conducted under the Big Sky Carbon Sequestration Partnership led by Montana State University and funded by the U.S. Department of Energy and a consortium of industrial partners. Please visit http://geologic-storage.pnnl.gov/wallula/wallula_pilot.asp for more information.

***Fig. 1**: Location of the pilot well in northwestern USA*

***Fig. 2**: Preparation of the injection phase. The black injection well-head is on the left (Courtesy: Boise Inc.).*

Summary No. 3

Current closure research against the Frio timeframe

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Research to model and monitor migration of the CO_2 plume during the injection period is abundant and the field demonstrations needed to validate models are well underway. Many models also have been created to predict the long-term migration of CO_2 in the post-injection period, however, field demonstrations to validate these models are sparse. The Frio test, conducted in 2004 and 2006 and monitored until 2009, provides some experience and observational data confirming the general correctness of post-closure fluid flow models. The site was valuable to post-closure research because 1) injection was brief (10 days), permeability is high (2 Darcy), and dip is steep (15 degrees) so that the plume moved rapidly. The plume was observed using multiple technologies, and approached stabilization in a few months after the injection ended. CO_2 apparently was trapped by capillary forces over the multiyear period (observations of T. Daley, LBNL). However, monitoring to provide assurance that stabilization could be depended on over the long time frame needed for geologic storage was not undertaken during this project. Further, concepts and techniques needed to provide this assurance in field projects are immature.

Our current research is focused on developing techniques to assess plume stabilization in commercial settings. We are experimenting with using the single best known point in the plume, the injection well, with a program of saturation logging, emplaced tracers, and pulsed hydrologic testing to assess progress toward stabilization. Numerical models, small-scale physical models, and a field test are used to assess the value of these approaches.

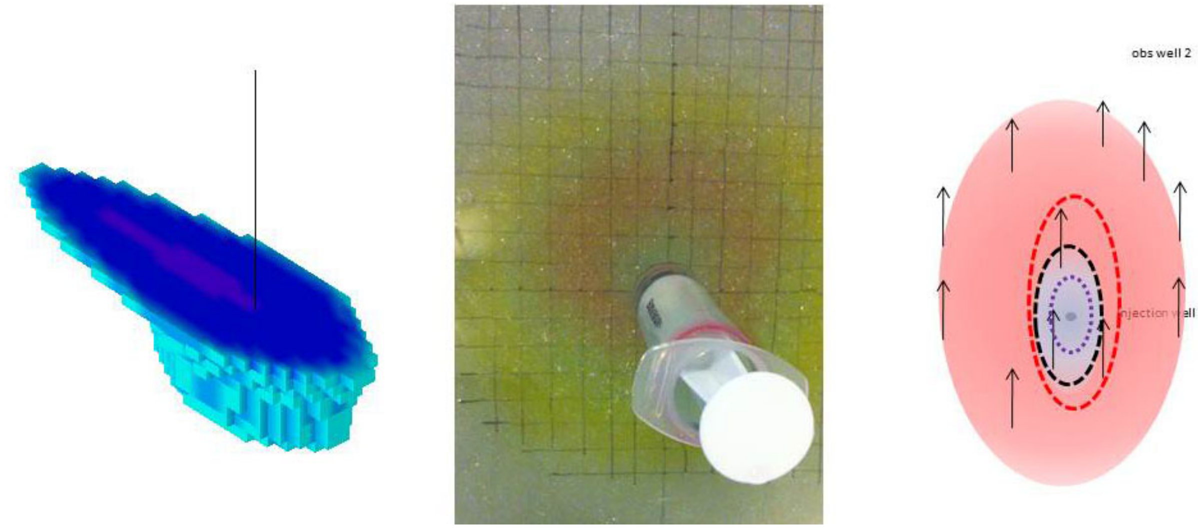

Fig. 1: *Numerical, physical, and conceptual models of tracer test designed to document stabilization during the post injection period.*

Summary No. 4

Otway - Overlapping regulatory jurisdictions in a CO_2 storage demonstration

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[1]*CO2CRC - Cooperative Research Centre for Greenhouse Gas Technologies*

At the CO2CRC Otway Project, the observational well is the legacy Naylor-1 well, which was previously used for production of natural gas. Naylor-1 penetrates the crest of the reservoir structure, where there is a residual methane gas cap. For monitoring the CO_2 injection, Naylor was recompleted with three U-tube sampling ports, pressure gauges, and hydrophones and geophones. Cabling and pipework passed through a special packer assembly which was intended to isolate most of the wellbore from the reservoir.

The CO_2 injection pre-dated CO_2 storage legislation in the state of Victoria, and the project was permitted with hybrid regulations involving the separate pieces of legislation governing water quality and security, hydrocarbon exploration and production, and general research and development exemptions. Several government departments and agencies were eventually involved.

Quite early in the project (March 2009), it was discovered that methane was leaking up the seismic cable; this was discovered when gas alarms were triggered in the monitoring cabin (which would be closed for two weeks at a time between sampling trips). The situation was openly discussed with regulators. At the same time, leaks were discovered at three of the Swagelok connectors on the well head. The seismic cable leakage point was moved out of the container. As both seismic cable leak and the leaks at the Swagelok connectors were very small (could only be seen by performing a snoop test), it was decided to monitor the equipment every week and report any change. Pressures in the wellhead annulus and wellhead cavity had also risen, indicating a breach at packer and tubing hanger levels.

In January 2013, a change was noticed during the monitoring trip. The wellhead cavity pressure had dropped and the leak at the seismic cable end had increased. All leaks at swageloks on the wellhead could no longer be detected caused by the drop in cavity pressure. The regulators were informed in writing of the change in situation but by then there had been government reorganizations and institutional memory of the previous conversations had been lost. The regulation of wellbores lies with petroleum production regulators. Before this, interactions had been mainly with environmental regulators who have a general responsibility for pollution and thus CO_2 leakages generally. Measurements of the gases in the wellhead cavity showed it to be about 70% methane, but the key aspect was not that a hydrocarbon had been found, but rather that there appeared to potentially be a well integrity issue. However methane cannot be detected at the wellhead using standard meters.

There are no specific guidelines governing fugitive methane emissions from wells in Victoria there is a state ban on shale gas exploration. The current position of the regulators is “zero tolerance” but this reflects concerns with well integrity rather than leakage per se. This discussion is continuing, with high stakes: it would be a serious matter for the CO2CRC to have to plug and abandon just one well at the site, given mobilization costs.

While this matter is unresolved, it does illustrate the potentially serious consequences of using a concept like “leakage” when the issue is actually about risk. The issue arises, not because of leakage, but because of wellbore integrity, and the assessment of whether a very small leak is actually an indicator of a risk to the wellbore.

SiteChar – Workflows for the characterisation of European CO_2 storage sites

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SiteChar is facilitating the implementation of CO_2 storage in Europe by improving, extending and testing standard site characterisation workflows, and by establishing the feasibility of CO_2 storage on representative potential CO_2 complexes suitable for development in the near term.

SiteChar has examined the entire site characterization chain, from the initial feasibility studies through to the final stage of application for a storage permit, on the basis of criteria defined by the relevant European legislation: storage capacities, modelling of aquifers at basin or reservoir scale, injection scenarios, risk assessment, development of the site monitoring plan, technical and economic analysis and public awareness.

The research focussed on five potential European storage sites, representative of a range of geological contexts, as test sites for the site characterisation workflow: a North Sea offshore multi-storage site in Scotland, an onshore aquifer in Denmark, an onshore gas field in Poland, an offshore aquifer in Norway and an aquifer in the Southern Adriatic Sea. At the Danish and Scottish sites the studies have developed dry-run storage permit applications (see Pearce *et al*., this conference) which have been evaluated by a group of independent experts. The studies conducted at the other sites focussed on specific barriers related to the site characterization methodology.

A key innovation was the development of internal dry-run storage permit applications, tested by relevant regulatory authorities. This iterative process helped to refine the storage site characterisation workflow and identifying gaps in site-specific characterisation needed to secure storage permits under the EC Directive, as implemented in host member states.

In addition to technical issues, SiteChar has considered the important aspect of the public awareness and public opinions of these new technologies. Site-specific public engagement activities were conducted on the Polish and Scottish sites.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 256705.

The feasibility of CO_2 storage in the depleted P18-4 gas field offshore the Netherlands (the ROAD project)

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Near the coast of Rotterdam CO_2 storage in the depleted P18-4 gas field is planned to start after 2015 as one of the six selected European demonstration projects under the European Energy Programme for Recovery (EEPR). This project is referred to as the ROAD project. ROAD (a Dutch acronym for Rotterdam Capture and Storage Demonstration project) is a joint project by E.ON Benelux and Electrabel Nederland/GDF SUEZ Group and is financially supported by the European Commission and the Dutch state.
The ROAD project is the first European CCS project that obtained a storage permit under the storage directive. Currently the project is awaiting the financial investment decision.

A post-combustion carbon capture unit will be retrofitted to EONs' Maasvlakte Power Plant 3 (MPP3), a new 1100 MWe coal-fired power plant in the port of Rotterdam. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 million tonnes of CO_2 per year. A 20 km long insulated pipeline will be constructed to the existing offshore platform operated by TAQA and an existing well will be worked over and re-used for injection. Natural gas production in the P18-4 field is projected to end just before the start of the CO_2 injection.

In the first phase a total storage of around 5 Mt CO_2 is envisaged with an injection timeframe of 5 years. This presentation gives a description of the field and of the studies underlying the storage permit application, carried out to investigate the suitability of the field for CO_2 storage.

Summary No. 7

Design and planning of highly controlled CO_2 injection experiments in the frame of the EU-FP7 MUSTANG, PANACEA, CO2QUEST and TRUST projects

[1]Jacob Bensabat, representing the project's teams.

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The Heletz reservoir (Israel) is a depleted oil field. This is a sandstone reservoir (the Heletz sands) at a depth of 1640 m below ground surface and is sealed from above by a 40m-thick layer of shale and marl. The cumulative reservoir thickness is of 10 m. In the frame of four EU funded projects we shall conduct a number of CO_2 injection experiments aimed investigated key processes involved during the injection and containment of the CO_2.

In the frame of the MUSTANG project we shall conduct: 1) a push-pull experiment of water CO_2 and tracers in the water, aimed at the evaluation of field values of key trapping mechanisms (residual trapping and dissolution); 2) a two-well dipole experiment, consisting in the injection of CO_2 and tracers in the injection well and abstraction in the monitoring well for the investigation of the impact of heterogeneity on the these two trapping mechanisms.

In the frame of the PANACEA project we develop and test a prototype of an integrated monitoring module (Resistivity, Seismicity, Temperature, Geochemistry) to be deployed in the field, first in a shallow well then in a deep well.

In the frame of the CO2Quest project we shall investigate in the field the impact of key impurities in the CO_2 stream on the trapping mechanisms and of the integrity of the formation and the caprock, by means of a two-step push-pull experiment (step one without impurities and step two with one soluble impurity and one non-condensable impurity).

In the frame of the TRUST project we shall deploy in Heletz the integrated monitoring system adopting a "behind the casing" approach (all the monitoring devices will be installed in the cemented part of the well), thus reducing leakage risks from wells.

Additionally, we shall investigate the impact and efficiency of CO_2 injection strategies aimed optimizing the trapping of the CO_2 in the reservoir (including thermally and chemically). So far two deep wells have been drilled, the design of the completion of the injection and monitoring wells is completed and actual instrumentation should start in January 2014. The drilling and instrumentation of the third monitoring well will be carried out in Q2 or Q3 of 2014. A versatile and mobile CO_2 injection kit has been designed and is being manufactured. Together, these four projects will allow a better understanding of the processes involved during the injection and storage of the CO_2 under super-critical conditions in correlation with various CO_2 conditioning strategies above the ground. Online reporting is available from the project sites (www.co2mustang.eu, www.panacea-co2.org, www.co2quest.eu and www.trust-co2.org).

Summary No. 8

Well integrity at Nagaoka site using time-lapse logging data

Takahiro Nakajima[1] and Ziqiu Xue[1]

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In order to secure the safety of geological CO_2 storage, it is essential to assess the integrity of wells. Time-lapse loggings for the well integrity assessment have been conducted at Nagaoka CO_2 injection site, where 10,400 tons of CO_2 was injected into saline aquifer from July 2003 to January 2005. It is important to employ multiple tools for the assessment to make sure the well integrity from multiple aspects, therefore sonic (CBL) and ultrasonic tools have been used for four times each over 10 years to assess the integrity of observation wells at Nagaoka site. The results indicate that there was no sever damage or deformation in the casing at the reservoir depth. No clear change in cement between the casing and the formation can be seen even at the depth where the cement was exposed to CO_2. These results show no clear evidence of CO_2 leakage at Nagaoka site, and support the safety of underground CO_2 storage.

Summary No. 9

Full-scale modelling of well loading history using finite element method: applications to a CO_2 injector and an injection-distant well

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Considering CO_2 storage risk management issues, wellbores -such as faults- have been identified as main potential/possible leakage pathways. The risk concerns first CO_2 injector wells but any other well that may be intersected by the CO_2 plume or the CO_2-saturated brine during injection, closure and post-closure for abandonment. Then, assessing the well mechanical history to state on its integrity and to prepare its abandonment is crucial. Our study aims at identifying mandatory steps and developing a methodology to optimize/improve well abandonment. It is based on a full-scale well approach using finite elements modelling in order to assess in particular the cement sheath behaviour. We first limited our work to the mechanical aspects consecutive to the pressure variations but this should be completed by taking into account thermal and geochemical effect in combination with the mechanical ones. In practice we investigated two scenarios where CO_2 is injected in a saline aquifer (Figure 1): an appraisal well distant from the CO_2 injector at Sleipner and the Ketzin injection well. The different stages of the well construction are introduced in the simulation such as the drilling and completion steps in order to assess the initial stresses in the wellbore and the cement sheath prior to the abandonment phase. In these two cases, the storage pressure is above the initial reservoir pressure.

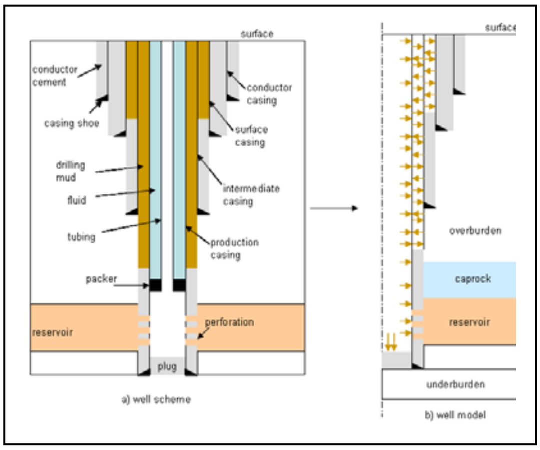

Figure 1: *Scheme of the full-scale well model.*

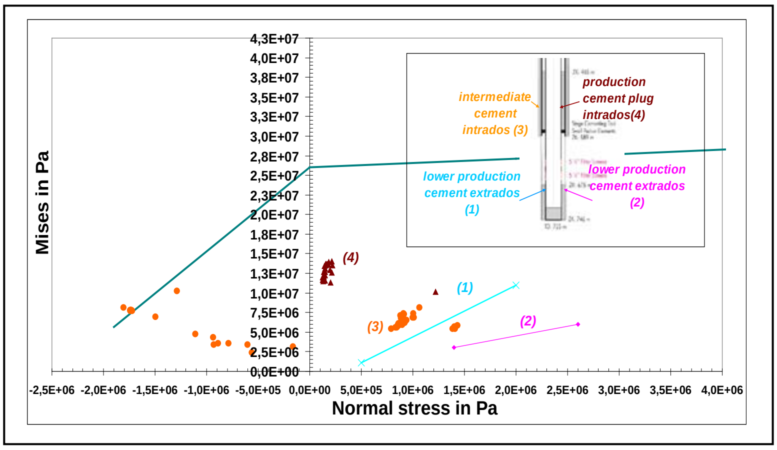

Figure 2: *Von Mises stress vs. normal stress at different locations of the cement sheath.*

CO_2 leakage paths could occur through the cement sheath and its interfaces with the rock formation and the casings. The Drucker-Prager yield criterion is introduced as a failure criterion for the cement – for the reservoir formation the Mohr-Coulomb criterion is applied- to evaluate the risk of rock failure. Figure 2 shows the results of the Ketzin injector where the Von Mises stresses of different cement locations are plotted versus the normal stresses. Considering the complete loading history from drilling until end of injection is a key issue to establish the effective stresses in the wellbore prior the abandonment phase. Wellbore model boundary conditions are computed using 3D reservoir modelling.

Summary No. 10

Creating an additional well barrier by the creep of rock salt caprocks

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We address abandonment of wells in CO_2 storage formations overlain by viscoelastic rock salt caprocks. Experiences with drilling through rock salt show that the salt material around a wellbore is capable of plastic flow causing a reduction of borehole diameter, sticking of the bottom hole assembly and collapse of casing.

The viscous character of rock salt, which causes potential problems during drilling and well construction operations, can be favorably utilized during well abandonment. The natural process of salt creep can be used to reinstate the integrity of rock salt caprocks and create an additional well barrier. The method requires removing of a part of the casing set through a salt caprock formation. Differential stresses at the wellbore wall, resulting from a difference between the wellbore fluid pressure and the stresses in salt, would initiate the process of salt creep leading to a reduction of wellbore diameter and closure of the uncased section of the wellbore (Fig. 1).

Geomechanical numerical simulations were conducted to evaluate creep induced wellbore convergence leading to wellbore closure in salt formations. Finite element simulations were performed assuming that the rock salt obeys a two-component creep constitutive material model. The material model takes into account the contribution of the non-linear creep component, which is dominant under high differential stresses, and the linear creep component, which is dominant under low differential stresses (i.e. less than a few MPa). Model input parameter values are in accordance with the values determined by history matching of surface subsidence caused by deep solution salt mining in the Netherlands.

The calculation results show an increase in the creep strain rate with depth due to increasing temperature and differential stresses. The creep strain rate decreases exponentially with decreasing wellbore radius. The shortest borehole closure time for a depth of 3.5 km, which is applicable for well abandonment in the K12-B CO_2 Injection Project, amounts to about 500 days. Backfilling of the wellbore with crushed salt and reducing the fluid pressure in the wellbore will speed up the process of wellbore closure.

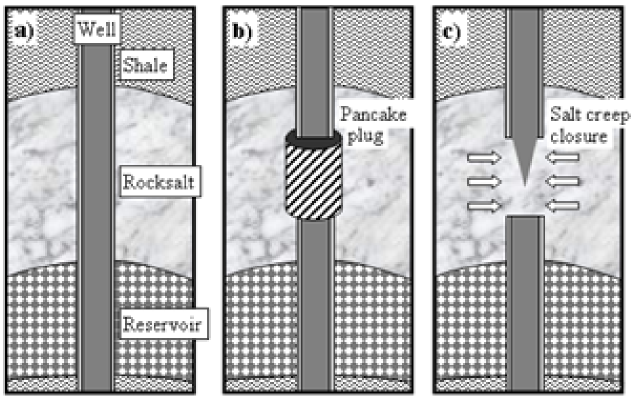

***Fig. 1**: a) A well penetrating the salt deposits abandoned by b) a pancake plug set across the caprock and c) using an alternative way of well abandonment based on the closure of an open wellbore by the creep of rock salt.*

Summary No. 11

Results of pilot monitoring surveys at Ketzin

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At the Ketzin Pilot Site for the geological storage of CO_2, a variety of geophysical monitoring technologies are applied for detecting and imaging a relatively small amount of stored gas in the reservoir formation. The main tasks of geophysical reservoir monitoring are, on the one hand, to indicate the lateral and vertical propagation of stored CO_2 in the reservoir, and, on the other hand, to detect potential anomalous and unexpected behaviour of the gas plume. For saline aquifers, repeated 3D surface seismic surveys have proven to be an indispensable tool for imaging the lateral propagation of the stored CO_2 in the reservoir formation, in particular during the operational phase of the storage site. In the long-term phase after closure of the site, an efficient monitoring design is needed, avoiding cost-intensive and environmentally invasive large scale surface operations.

The Ketzin Pilot Site is equipped with the infrastructure for applying different monitoring technologies in the context of imaging small quantities of CO_2. Injection and monitoring wells provide access to the reservoir and enable high-resolution seismic and geoelectrical borehole and surface-downhole measurements. Additionally, a permanent passive seismic array deployed in shallow boreholes (TNO, see also Arts, this volume) delivers continuous passive seismic data and is available for repeated active seismic surveys focussing on the reservoir level close to the injection point without deploying seismic receivers.

For long-term monitoring using active seismic measurements, alternative seismic source are required, either as permanently installed sources, or being highly mobile, flexible and producing signals at a high degree of repeatability. A simulation study has shown that a permanent seismic source, combined with a linear array of seismic receivers close to the surface, is able to detect small quantities of CO_2, provided that these are located in the area covered by the acquisition setup.

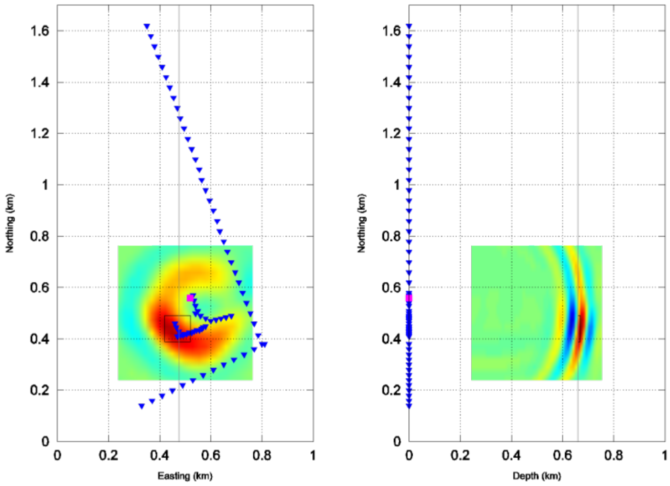

Fig. 1: *Simulated time-lapse image of CO_2 plume at Ketzin, using a seismic monitoring setup with one permanent seismic source (pink square) and an extended seismic array.*

CO_2 mass estimation at Ketzin visible in time-lapse 3D seismic data

Ivanova, A.[1], Baumann, G.[1], Henninges, J.[1], Ivandic, M.[2], Daniel Sopher[2], Kashubin, A.[3], Bergmann, P.[1], Gil, M.[1], Lüth, S.[1], Juhlin, C.[2]

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At Ketzin (Germany), a town close to Berlin, the first European onshore pilot scale project for geological storage of carbon dioxide (CO_2) was initiated in 2004. The focus of the Ketzin project is on testing and further developing monitoring technologies. 3D seismic time-lapse surveys are an essential tool for large scale reservoir characterization and for providing information on injection related processes including geological storage of CO_2. At Ketzin, a 3D baseline seismic survey was acquired in autumn of 2005. CO_2 injection into a sandstone saline aquifer started in June 2008 at a depth of about 650 m. A smaller 3D seismic repeat survey was acquired in the autumn of 2009 in the area around the injection site after approximately 22,000 tons of CO_2 were injected. This first repeat survey showed that the CO_2 plume was concentrated around the injection well with a lateral extent of approximately 300-400m. A second 3D repeat seismic survey was acquired in the summer/autumn of 2012, when approximately 61,000 tons of CO_2 had been injected. Results show further growth of the time-lapse anomaly induced by the CO_2 injection (further 100-200m) and its migration mostly to the west.

Time-lapse seismic processing, petrophysical measurements on core samples and geophysical logging of CO_2 saturation levels allowed for an estimate of the total amount of CO_2 visible in the seismic data to be made. This estimate is dependent upon a choice of a number of parameters and contains a number of uncertainties.

These main uncertainties are following. Firstly, the constant reservoir porosity and CO_2 density used for the estimation are probably an over-simplification since the reservoir is quite heterogeneous. Secondly, CO_2 saturation values from the geophysical logging are significantly dependent on the way of interpretation. Thirdly, although velocity dispersion is probably present in the Ketzin reservoir rocks, we do not consider it to be large enough that it could affect the mass of CO_2 in our estimation using the laboratory experiments. In addition, there are only a small number of direct petrophysical observations, providing a weak statistical basis for the determination of seismic velocities based on CO_2 saturation. Furthermore, we have assumed that the petrophysical experiments were carried out on samples that are representative for the average properties of the whole reservoir. Finally, the most of the time delay values in the both 3D seismic repeat surveys within the amplitude anomaly are near the noise level of 1–2 ms, however a change of 1 ms in the time delay affects significantly the mass estimate, thus the choice of a cutoff for the mass calculation based on the amplitude change map is crucial.
In spite of these uncertainties, the close agreement (over 90%) between the injected and observed amount is encouraging for quantitative monitoring of a CO_2 storage site using seismic methods.

Summary No. 13

Time-lapse seismic and electrical resistivity tomography combined for monitoring of the Ketzin CO_2 storage site, Germany

Bergmann, P.[1], Ivandic, M.[2], Norden, B.[3], Rücker, C.[4], Kiessling, D.[5], Lüth, S.[1], Schmidt-Hattenberger, C.[1], and Juhlin, C.[2]

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A case study for the combination of geoelectric and seismic processing by means of a structurally constrained inversion approach is presented. Structural constraints are interpreted from the seismic data and integrated into the geoelectric inversion through a local regularization which allows inverted resistivities to behave discontinuous across defined boundaries (Figure 1). This arranges seismic processing and constrained resistivity inversion in a sequential workflow, making the generic assumption that the petrophysical parameters, relevant to each method, change across common lithostructural boundaries.

The approach is evaluated using both a numerical example and a real data example from the Ketzin CO_2 pilot storage site, Germany. The latter demonstrates the efficiency of this approach for combining 4D seismic and surface-downhole geoelectric data. In consistence with the synthetic example, the constrained resistivity inversions of the real data produce clearer delineated images along the reservoir-caprock boundary. Near the CO_2 flooded reservoir, the seismic and geoelectric time lapse anomalies correlate well. At some distance to the downhole electrodes, however, the geoelectric images convey a notably lower resolution in comparison to the corresponding seismic images. Although a northerly direction for the CO_2 migration was initially expected, both methods image a rather northwesterly migration trend. The results confirm the relevance of the presented approach for the combination of both methods for geophysical CO_2 storage site monitoring.

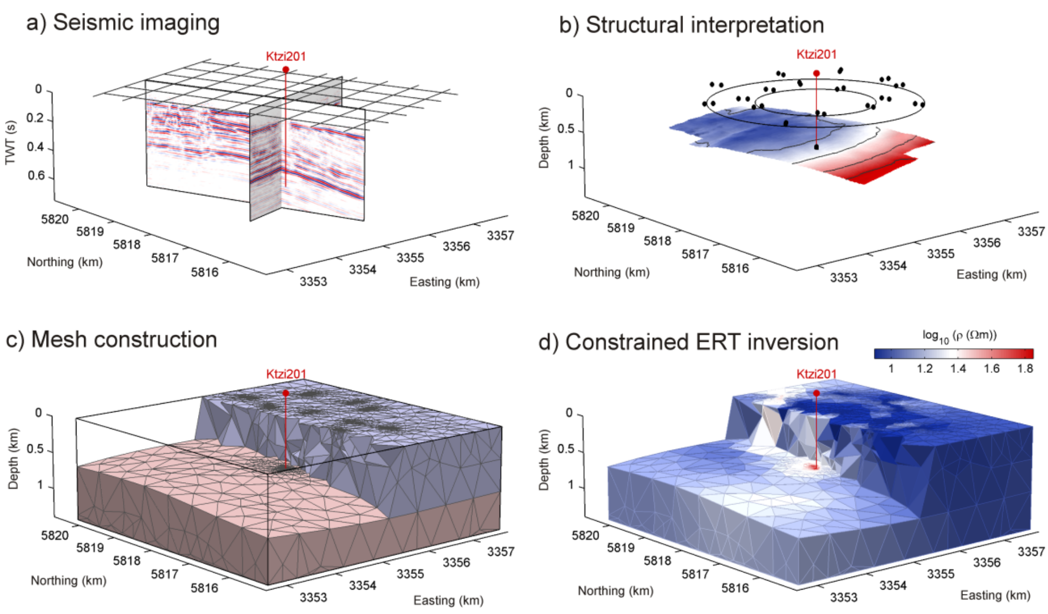

Fig.1: *Realisation of the constrained inversion workflow for the Ketzin data.*

Summary No. 14

Electrical resistivity tomography, seismic and electromagnetic tomography for CO_2 monitoring in the subsoil

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Geological storage is one of the solutions to avoid the emission of CO_2 to the atmosphere. This process requires a careful monitoring of the injected CO_2, which can be performed by means of electrical resistivity tomography (ERT), seismic and electromagnetic (EM) methods, from the comparison of seismic and electric properties obtained in repeated surveys.

The ERT technique has been proven to be efficient in CO_2 geological storage to monitor the injected plumes in cross-well and surface-downhole experiments. In this work, we tested the ERT technique to monitor possible early-stage CO_2 migrations along a wellbore at the caprock level, where seismic methods are less sensitive to the presence of the CO_2. To this aim, we built a representative model of a possible CO_2 migration close to a well, on the basis of petrophysical data from sandstone saline aquifer reservoirs, and carried out single-well electrical simulations to perform a sensitivity study. In our scenario, we assumed that the CO_2 migration may occur within 1 m around the well, because of the presence of fractures and cracks induced by drilling operations. We used different electrode spacings and three electrode configurations, i.e., Wenner-alpha, pole-pole, and pole-dipole. The simulations (Figure 1) suggest that the pole–dipole array is the most effective when the electrode spacing is lower than 2.5 m and the dipole spacing factor is 7. The inversions also suggest that possible CO_2 migrations in the well annulus can be imaged using the Wenner-alpha or the pole-dipole configurations with electrodes spaced 0.5 m at the most.

We also applied a combined rock-physics methodology of electromagnetic (EM) and seismic wave propagation to the detection and monitoring of CO_2 in cross-well experiments. To test the feasibility of detecting the gas, we performed cross-well EM tomographic and seismic inversions on a synthetic data set generated from a realistic sandstone aquifer partially saturated with CO_2. Besides the electrical conductivity and seismic velocity, we also obtain the seismic quality factor by performing attenuation (frequency shift) tomography. In both cases, it is essential to correctly pick the first arrivals, particularly in the EM case where the diffusion wavelength is large compared to the source-receiver distance.

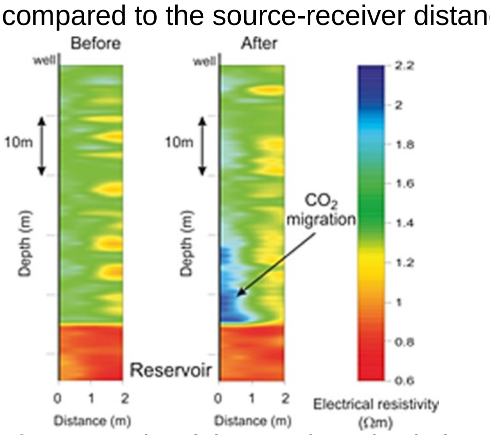

Fig. 1: *Results of the ERT inversion before and after the CO_2 migration using the pole-dipole configuration.*

We built a realistic CO_2 plume, and assumed to acquire the data before the injection and after some years from the injection, when CO_2 had spread upwards in the reservoir. The EM traveltimes are smaller after the injection due to the higher resistivity caused by the presence of carbon dioxide, while the effect is opposite in the seismic case, where water replaced by gas decreases the seismic velocity. Finally, we obtained the conductivity, seismic velocity and quality factor models by performing traveltime and attenuation (frequency shift) tomography. The RMS differences between the inverted and true initial models show that the results are reliable.

Leakage Detection in 3D volumes

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In order to close a CO_2 storage site and transfer liability back to the national authority, the site operator needs to demonstrate ‘zero detectable leakage’, where leakage is defined as the subsurface migration of CO_2 from the defined Storage Complex. Time-lapse 3D seismic surveys offer a very powerful monitoring tool to achieve this, because of their capability to detect small changes in fluid content of the overburden rock volume above the reservoir. Changes in the time-lapse seismic signature due to small accumulations of CO_2 are manifest as either reflectivity changes or time-shifts in the seismic arrivals. Both are visible on seismic ‘difference’ datasets, with the detectability of small amounts of CO_2 depending both on the physical properties of the CO_2 and the seismic response of the trapping geology.

At the Sleipner CO_2 storage operation, which currently stores around 15 million tonnes of CO_2, a comprehensive time-lapse 3D seismic monitoring programme has been acquired with a baseline (pre-injection) dataset and a number of repeat surveys. These show no evidence of either reflectivity changes or time-shifts in the overburden to the storage reservoir.

CO_2CARE has assessed the capability of the time-lapse seismics at Sleipner to detect small amounts of CO_2 in the overburden. A statistical assessment of time-lapse reflectivity changes shows that, at the base of the overburden, accumulations of CO_2 as small as 2800 tonnes should be possible to detect reliably. At shallower depths within the overburden, the CO_2 becomes progressively less dense, more reflective, and correspondingly even more detectable. Let us assume a hypothetical CCS project operating under Sleipner conditions, storing five million tonnes per year over a period of twenty years (100 million tonnes in total). An absence of ‘detected leakage’ at the end of injection, with a detectability limit of 2800 tonnes, would guarantee a leakage rate of less than 0.0023% per year. This is comfortably below the leakage threshold range of 0.1 – 0.01% per year which has been proposed as a satisfactory greenhouse gas mitigation performance criterion.

Summary No. 16

Seismic acquisition with the TNO permanent seismic array installed at Ketzin

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This presentation will show the results of the activities carried out at TNO on the use of the data of the TNO Array:

- Microseismic monitoring
- Ambient Noise Correlation
- Permanent source experiment August 2013

Formally only the third topic is part of the CO2CARE project, but for completeness a brief overview on the other two topics will also be provided.

The main purpose of the experiments carried out at Ketzin by TNO in the CO2CARE project is to investigate whether minor changes, particularly pressure relaxation, can be monitored with permanent seismic systems. The idea behind is that the increase in resolution, repeatability and SNR related to permanent systems are sufficient to pick up these subtle changes. To test the validity, experiments have been carried out over periods, where injection was stopped temporarily, mimicking the abandonment conditions. The first experiment carried out in May 2012 has been reported at the previous CO2CARE workshop and has resulted in improvements of the prototype source. This year results of a second experiment carried out in August 2013 are reported.

Practical constraints on the availability of the source, the possible locations of the source and uncertainty on the date of the injection stop made an exact repeat of the previous experiment impossible. A mobile more conventional seismic source was used instead (hammer source). The advantage over the first experiment was, that more than a single location can be used for shooting daily.

Repetitive measurements on several points were carried out. Measurements along a line were also repeated four times. The offset, which was a problem during the previous permanent source measurement campaign, leading to high amplitude source related noise, was not a problem this time.

The analysis of the data is shown. Unfortunately it can be concluded that the application of this conventional seismic source applied on “standard” locations did not provide data quality that is sufficient for monitoring purposes. This result highlights the added value of permanent sources. The main issue is the repeatability, which is much higher for the permanent sources.

Summary No. 17

Coupled reservoir simulation across all time scales of the Ketzin pilot site

Kempka, T. [1], Kühn, M. [1]

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To assess the long-term reservoir stabilisation at the Ketzin pilot site (Germany), the contribution of the four CO_2 trapping mechanisms (structural, residual, dissolution and mineralisation trapping) was determined by numerical modelling. In the first step, dynamic flow simulations were undertaken using a reservoir simulator. The second step comprised batch simulations applying a geochemical simulator. Coupling between both simulators was achieved by time-step dependent integration of water saturation calculated in the reservoir simulations. After a simulation time of 16,000 years, about 98.3 % of the injected CO_2 is dissolved in the formation fluid and 1.5 % mineralised, while residual trapping contributes with 0.2 % and structural trapping is negligible. Furthermore, coupled hydro-mechanical simulation results emphasize that reservoir, caprock and fault integrity are not compromised during the CO_2 storage operation.

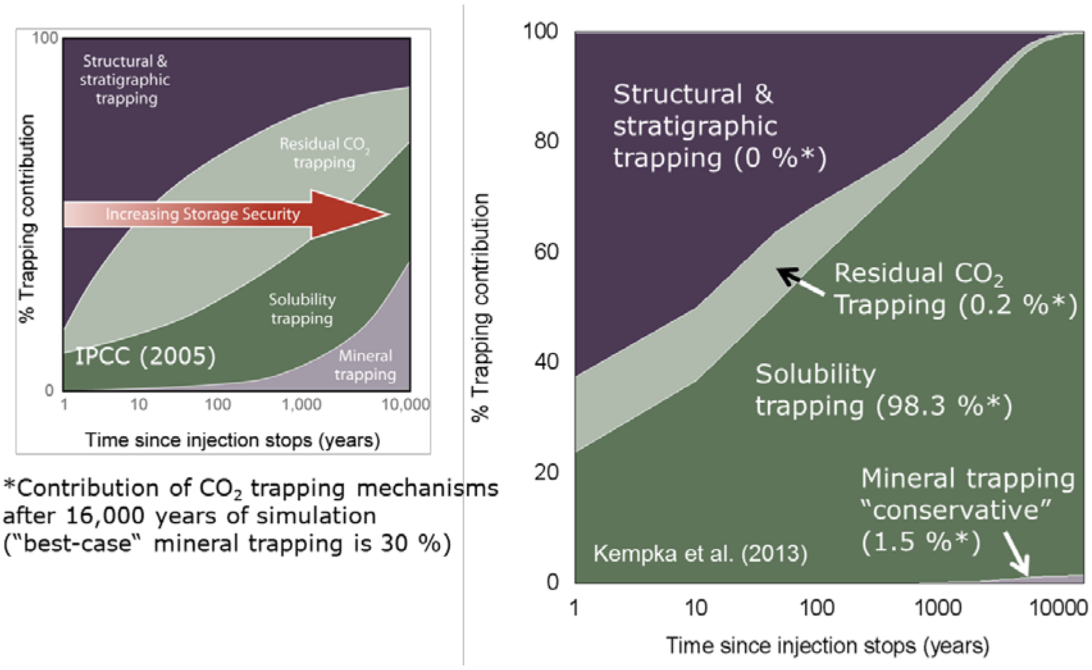

Fig. 1: *IPPC diagram on CO_2 trapping mechanisms (left) adapted for the Ketzin pilot site based on coupled numerical simulations (right).*

Summary No. 18

Long-term geochemical processes at the Ketzin pilot site

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Geochemical reactions induced in the reservoir and caprock by the injected CO_2 could possibly lead to alteration of the host rocks and thus of the integrity of the storage system, but also to the immobilization of the injected carbon dioxide into newly formed carbonate minerals. The relevance of these geochemical processes over a time scale of several thousand years was assessed through coupled and uncoupled numerical models based on the available results from laboratory experiments on Ketzin sandstones from the Stuttgart formation and analysis of pristine formation fluids. For the reservoir, thermodynamic models predict almost negligible alterations of the mineralogy and of the hydrodynamic properties of the sandstone, while a considerable amount of the injected CO_2 is trapped in reservoir. The simplified coupling strategy developed to overcome the computational burden of reservoir-scale reactive transport simulations was successfully validated (Fig. 1), resulting in a systematic error of about 15 % w.r.t fully-coupled simulations. This discrepancy is more than acceptable given the uncertainty associated with the geochemical models. Finally, the integrity of the sealing anhydritic mudstone (Weser formation) is not compromised by the diffusive propagation of CO_2 rich fluids. This result was achieved by long term 1D reactive transport models.

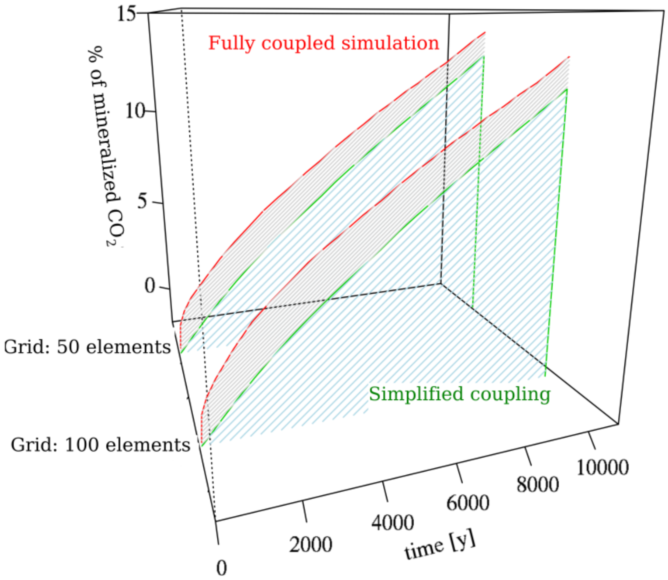

Fig. 1: Validation of the simplified coupling approach with respect to fully-coupled reactive transport simulations, based on a 1D benchmark discretized in 50 and 100 elements respectively. The systematic error (highlighted in red) is acceptable given the uncertainties associated with the geochemical

Summary No. 19

Determination of thermodynamics in a CO_2 injection well using pressure and distributed temperature sensing

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At the pilot site in Ketzin CO_2 is injected into the subsurface. In a depth of 640 m there is a 12 m thick sandstone layer, which has small pores into which the CO_2 is injected. A hole is drilled from the ground surface down to the sandstone layer. The outer wall of the hole consists of concrete, at the elevation of the sandstone there is a window in the concrete and the hole is connected with the sandstone. This hole is called injection well.

The injection well is used to conduct CO_2 from the ground surface to the sandstone layer. The CO_2 is compressed to about 60 bars at the ground surface (that is 60 times higher than atmospheric pressure) because it should replace the water in the pores. The water in the pores has a natural pressure of about 62 bars, which is higher than the CO_2 pressure at the ground surface, so how can the CO_2 replace the water?

The injection well is filled with gaseous CO_2 that has a density of about 180 kg/m³, which is about 180 times denser than air and about one sixth of the density of water. The vertical column of CO_2 in the well has a weight, and this weight increases the pressure from the ground surface continuously to the reservoir, where is has a pressure of 72 bars, so a pressure difference of 10 bars causes the CO_2 to flow from the well into the sandstone.
The CO_2 has a temperature of about 35 °C at the ground surface, but cools down because the ground is colder. At the same time, the CO_2 is heated up because it is compressed in the injection well, similar to the warming of the pump when inflating the tire of a bicycle. A model is developed to simulate these processes. The model calculates the exact pressure and density of the CO_2.

It is important to ensure the CO_2 is above a defined temperature and below a defined pressure. Otherwise the CO_2 gas condensates to liquid CO_2, which would disturb the technical routines of injection and monitoring. The model also calculates how much heat flows from the well to the ground. This is important to know to calculate the heating of the ground, which gives a thermodynamic feedback to the temperature inside the well.

Summary No. 20

Inversion Applications to Modeling Pumping Tests and Early Leakage Detection at the Ketzin Site

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This paper reports LBNL activities within CO_2CARE: (1) modeling and inversion of the pumping tests conducted prior to injecting CO_2 at the Ketzin pilot site, and (2) evaluating the potential for early leakage detection using pressure signals during the injection phase in hypothetical well-leakage scenarios. The first activity involved the analysis of several pumping tests that were conducted in the injection well (Ktzi 201) and two monitoring wells (Ktzi 200 and 202). The pumping test data were used to characterize the multi-scale spatial variability of hydrogeological properties and help interpret the behavior of injected CO_2. To numerically simulate these tests, we developed two different groundwater flow models, which honor the vertical layering of the *Stuttgart Formation* with a sandstone layer of 6-18 m thickness embedded in a thick low-permeability mudstone (about 70-80 m). The first model was calibrated using iTOUGH2 with 13 zones of different permeabilities in the near-well region for the sandstone layer, while the second model was calibrated using 3D hydraulic tomography with ~8,000 unknown permeabilities covering both the near-well and far-field regions. Calibration results from the first model show intermediate-scale variability of permeability in the near-well region: distinct permeable zones connecting Ktzi 202 with Ktzi 200/Ktzi 201, a low-permeability zone between Ktzi 201 and Ktzi 200, and a semi-closed hydrogeologic system for the near-well region. The second model calibration arrives at similar large-scale permeability patterns. In addition, this model demonstrates smaller-scale variability of permeability and the geological features in the far field.

In the second activity, the early leakage detection problem was formulated by introducing a hypothetical leaky well ~600 m away from the injection well. A TOUGH2/ECO2N model was developed to simulate the CO_2 behavior in the *Stuttgart Formation* and to model the migration of brine/CO_2 up the leaky well into the shallower *Exter Formation*. The model was then used to obtain the “observed” pressure signals at the three wells in the *Stuttgart Formation* and at the shallow well (P300) in the *Exter Formation*, for alternative leakage scenarios with different leaky-well permeability. Using these synthetic observation data, the leaky-well permeability was inversely estimated with iTOUGH2. Our inversion results show that as long as the leakage rate is sufficiently large, the inversion methodology can accurately estimate the leaky-well permeability using the fast propagating pressure signals. The detection time is earlier than the time of CO_2 leakage at the well, demonstrating the benefits of early leakage detection in risk management.

Summary No. 21

Direct CSEM modeling of CO_2 plume propagation through Ketzin reservoir

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This work integrates the framework of CSEM modeling and data analysis started by Girard J-F et al., 2011. Strong effort has been made for the enhancement of 3D modeling of CO_2 plume propagation through the Ketzin saline aquifer. Developments were conducted using COMSOL in order to model the influence of geo-electrical units, such as an anhydrite layer over the reservoir and the metallic casings in the boreholes, on the surface electromagnetic field.
Significant progress was also made in modeling the "exact" geometry of the injection electrode array in the double-MAM configuration. Modeling tools have been developed using both Matlab and COMSOL and can be used for other projects involving CSEM modeling. The final step of our work was to provide a sensitivity estimation of such array to resistivity changes (induced by CO_2 saturation changes) at reservoir depth. In this aim, we simulated the CO_2 plume migration in the reservoir over different preferential directions. We finally compared the field data of the 4 years monitoring with the synthetic EM fields using different criterions.

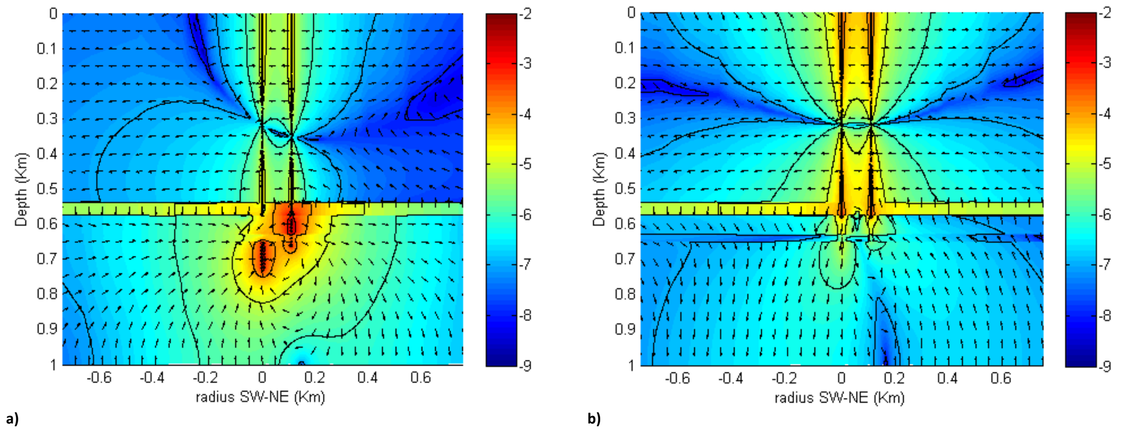

Figure 1: *Pre-injection CSEM model for Ketzin in the YZ plane. Modeled amplitude maps of in phase (a) and quadrature (b) electric field in log10 scale in the vertical plane passing through boreholes K201 and K202 and centered on K201. Normalized field vectors are projected on the vertical plane and plotted as black arrows.*

Long term fate of CO_2 in a saline aquifer: modelling issues

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Post-closure reservoir modelling aims at describing the long term fate of the CO_2 under the different trapping mechanisms within the storage reservoir or eventually within the storage complex. It deals with 3D fluid flow modelling, geochemistry and also geomechanical modelling in the early stage, *i.e.* until pressure stabilisation is observed or predictable. Prediction of combined effects should be done using explicitly-coupled simulations, which is not easy to achieve or not possible to perform nowadays with available software and knowledge.

In the case of Sleipner, where geomechanical effects due to injection pressure are not an issue, we tackled part of the problem by considering reactive transport phenomena only, within the reservoir or the caprock. The following cases were investigated:

- A 2D reactive transport study within a vertical grid where a lot of attention was paid to take into account thin intra-reservoir shale layers (Figure 1) and to evaluate their impact on CO_2 trapping mechanisms efficiency. Because of a lack of information on parameter values, we run a sensitivity study on a few of them to be able to state on CO_2 mineralisation ranges.

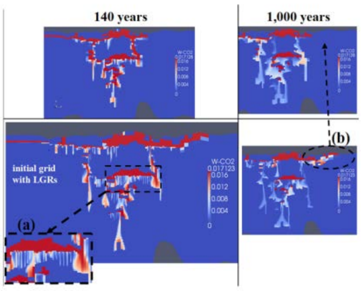

Figure 1: *2D reactive transport simulations – grid and dissolved CO_2 molar fraction W-CO_2 at 140 and 1,000 years: with or without Local Grid Refinements (LGRs).*

- A simulation study of the CO_2 migration by diffusion through the reservoir cap rock (Figure 2) looking at quantifying the CO_2-penetrated thickness and the amount of CO_2 trapped in the long term. Main conclusion is that most of the CO_2 that has diffused within the caprock is mineralized after only 100 years.

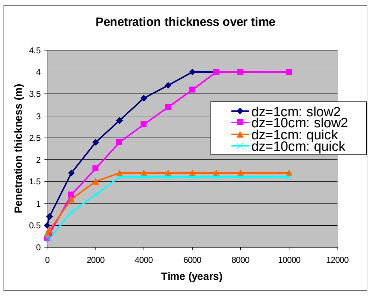

Figure 2: *Penetration thickness against time for two cell sizes (dz=1cm and dz=10cm) – "slow2" and "quick" cases.*

- A specific 3D study to quantify the properties of the CO_2 plume intersecting an injection-distant well. The aim is to assess the associated risk of leakage it may represent while stating on well integrity issues prior and during abandonment.

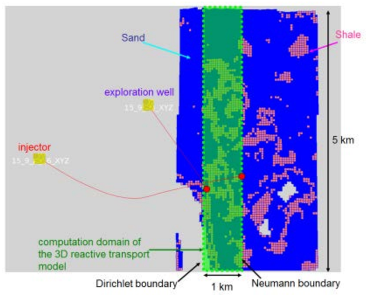

Figure 3: *Computation domain of the 3D reactive transport model in a specific layer.*

In these different studies, we took special care at considering the impacts on our results of the modelling assumptions we did -including model geometry. Sensitivity analyses have been led by taking into account the parameters uncertainty and the consequences on the CO_2 trapping mechanisms results have been studied.

Summary No. 23

A methodology for CO_2 storage system risk and uncertainty assessment

Shi, J-Q.[1], Chen, D. [1], Govindan, R. [1], Korre, A. [1] and Durucan, S. [1]

[1]Imperial College London, United Kingdom

A methodology for assessing CO_2 leakage risk, with special reference to the post closure period, has been developed. It is recognised that mobile CO_2 phase in the storage reservoir (source for potential leakage) has a tendency to follow the general topography and migrate up dip with time, further beyond the area the plume is located at the time of site closure. Therefore, as a first step, CO_2 plume evolution and migration over time as a dynamic source for potential leakage out of the primary storage reservoir is evaluated by taking into account reservoir heterogeneity. To facilitate leakage risk assessment, it is useful to divide the simulated CO_2 plume footprint broadly into a transient (free CO_2 largely passing through) and a non-transient source region. A third region - near wellbore region - may also be defined to evaluate the source for potential leakage through the injection well. The amount of free CO_2 in different regions over time are then tracked to evaluate when and for how long the leakage risk might be present in any given region, as well as the size of the source available for leakage. To assess uncertainty in the plume migration, whilst honouring the available 4D seismic data, multiple realisations of petrophysical properties are generated and the results analysed. This part of the methodology has been applied to the Ketzin storage site.

In the second step, potential CO_2 leakage through a leaky patch of the caprock is simulated for different scenarios regarding the leakage path permeability and detection threshold. The outcome of this step is the mapping of leakage profiles (magnitude and duration) at different caprock locations (within the plume footprint) after the simulated leaked amount has exceeded a pre-set detection threshold and injection is terminated. This knowledge is useful for informing both the monitoring strategy and appropriate remediation methods for the site.

The final step considers an individual risk component, namely natural or induced pathways (due to CO_2 injection) in the caprock (e.g. fractures, faults), injection well failure risk due to the sealing behaviour of rock-cement-casing interface, and leakage risk due to the geological structure of the storage system (sealing behaviour of faults). Relevant research from the literature as well as the work carried out in CO2CARE (wellbore cement–casing behaviour and caprock fracture characterisation) on the properties of leakage pathways (leakage probability, likely rates etc.) are used to evaluate leakage risk and associated uncertainty in conjunction with the source behaviour.

To demonstrate this methodology, a generic reservoir model (characteristics informed by a suite of CO2CARE test sites) has been used to simulate CO_2 injection at a rate of 1 Mt/year for a scheduled 30 years (or until the detection of leakage). The same model has been used to simulate and evaluate the two remediation methods, namely pressure gradient reversal (Subtask 3.4.1) and polymer injection (Subtask 3.4.2), considered in this research.

Summary No. 24

CO_2 storage uncertainty and risk evaluation for the post-closure period at the Ketzin Site

Govindan, R.[1], Shi, J-Q.[1], Korre, A.[1] and Durucan, S.[1]
[1]Imperial College London, London, UK.

CO_2 storage at the Ketzin pilot site was safely carried out from June 2008 to August 2013. During this period, approximately 70,000 tonnes of CO_2 was injected into the sandstone units of the upper Triassic Stuttgart formation at a depth interval of 630m to 650m. Comprehensive knowledge of the site has been gained by researchers within the framework of CO_2SINK, CO_2ReMoVe and CO_2MAN projects, through detailed data aquisition and analysis, modelling, and verification. Research wasalso undertaken under the current CO_2CARE project, focusing on reservoir and risk management for the post-closure period. GFZ and GEUS have jointly developed a static geological 3D model of the Ketzin reservoir which has been successfully history matched with field monitoring data. This model was implemented in the long term post-closure simulation studies by GFZ in order to understand the trapping mechanisms in the reservoir. The general forecast is that the free CO_2 will essentially become structurally trapped at the top of the Ketzin anticline along the fault network.

In this presentation, the authors describe a methodology to evaluate the uncertainty in the plume migration behaviour during the post-closure period, especially in the far-field region of the reservoir, owing to the uncertainty in reservoir heterogeneity. Using the history matched static model provided by GFZ, an Eclipse 300 model was setup for CO_2 injection and post-closure simulations. Since this model had a fine scale gridding, it was found necessary to perform appropriate grid upscaling in the lateral direction. The uncertainty and risk evaluation carried out using the upscaled grid broadly consists of two parts: (1) modelling the far-field uncertainties of the fluvial channels distribution in the floodplain, which involves the generation of multiple realisations of facies distributions and their corresponding petrophysical properties, namely porosity and permeability; and (2) simulating the plume migration using the realisations in order to assess the risks based on the transient and non-transient locations of the plume.

In the first part, 25 realisations of channel distributions were created. In order to ensure compliance with the known channel positions in the near field region, the realisations were conditioned using control points of the facies distribution and petrophysical properties in the near-field region. The near-field region is defined by the extent of the plume at the time when the most recent seismic survey was acquired in 2012. In this region, the facies and property attribution are known with high confidence, according to the history matching results. Ranges of values for channel layout parameters, namely orientation, amplitude, wavelength, width and thickness, were also honoured in the model to generate the realisations.

In the second part, the realisations were then implemented in the Eclipse models to simulate the uncertainty in far-field plume migration for 500 years during the post-closure period. Four regions were defined in the model for the purpose of keeping track of: (a) the time the plume takes to arrive at a particular region; (b) the duration of time the plume resides in a particular region; and (c) the mass of free CO_2 available in a particular region. Additionally, the results obtained from the flow simulations for all the realisations were summarised by estimating the free CO_2 distribution probability maps that describe the likely location of the plume in the reservoir at different times of the post-closure period. Overall, these results are considered to be very useful for monitoring and risk management during the post-closure period at the Ketzin site.

Pressure gradient reversal for site remediation

Chen, D.[1], Shi, J-Q. [1], Syed, A. [1], Durucan, S. [1], Korre, A. [1]

[1]Imperial College London, United Kingdom

Pressure gradient reversal (PGR) method - injecting brine in a permeable caprock layer to raise its pressure so as to hinder the buoyancy-driven flow of CO_2 from the storage reservoir, has been proposed as a potential means to reducing or even eliminating CO_2 leakage through the caprock. Recognising that a CO_2 plume (the source for leakage) tends to migrate in the up dip direction along the top surface of the storage formation, the early research effort focused on establishing an understanding of CO_2 leakage profile (in the absence of remediation) in two distinctive regions (within the CO_2 plume footprint) characterised by the migration behaviour of CO_2, namely a transient (where the mobile CO_2 is of transient nature) and non-transient source zone. During leakage scenario simulations, the amount of CO_2 leaked out of the target storage reservoir at a selected location is continuously monitored, and the injection is terminated once a pre-set detection threshold is exceeded. The leakage, however, is allowed to continue until its source (the free CO_2 in the storage reservoir available for leakage) is exhausted to yield the total leakage volume - a benchmark for evaluating the effectiveness of any remediation measure, including PGR.

Building upon the previous work, a generic 3D reservoir/overburden model has been used to simulate brine injection into a permeable layer (about 180 m above the storage reservoir) and evaluate the effectiveness of the PGR method for leakage remediation. In the model CO_2 leakage is through a column of leaky gridblocks (each measuring 200m by 200m and assigned an absolute permeability of between 1 and 10 mD) which provide a flow path between the storage reservoir and the overlying aquifer in otherwise impermeable caprock. During simulations, the CO_2 injection well would be converted to a brine injection well when leakage is deemed to be detected at selected locations, either during the scheduled injection period (1 Mt/year for 30 years), in which case the injection is terminated, or during the post closure period. The simulation results in terms of the effectiveness of PRG under different leakage conditions (leakage point distance to the injection well, unmitigated leakage profile, leakage path permeability, CO_2 leakage detection threshold etc) are presented and discussed.

Summary No. 26

The use of polymer-gel solutions for site remediation

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Geological storage of CO_2 is being considered as a viable option for reduction in anthropogenic CO_2 emissions. Although significant research has been carried out on the behaviour of CO_2 in the subsurface geological formations, the mitigation of potential leakages from the storage reservoir through a fractured caprock, abandoned and unaccounted wells or any other form of abnormal CO_2 flow behaviour has not been fully investigated.

WP3.4.2 in CO2CARE attempts to fill this gap and proposes a methodology for the mitigation of non-conformal flow of CO_2 in subsurface reservoirs. This work presents a detailed laboratory investigation into the use of a polymer gel system to control the abnormal flow behaviour in the host and cap rock. A polymer-gel based on Polyacrylamide triggered by the addition of a Chromium Acetate cross-linker was used. Prior to core flood experiments, behaviour of the polymer gel was studied in order to ascertain its rheological characteristics at different concentrations of polymer over a range of temperatures and salinities. The gelation time was measured for different combination of polymer (2.1%, 4% and 6%) and cross linker concentrations (30,000 and 50,000ppm). Laboratory measurements carried out at a temperature of 20^{o}C, indicated that the gelation time decreases with increase in the concentration of polymer in the system. Both temperature and salinity were found to have significant impact on performance of the polymer gel system.

Core flood experiments were carried out on high permeable sandstone cores and a fractured marble core to investigate the flow characteristics of polymer gel in porous media. Laboratory core floods revealed significant reduction in permeability [greater than 99%] with different concentrations of polymer gel in the injected water. Similar results were obtained for the fractured core wherein a permeability reduction of 90% was noted, demonstrating its suitability for the possible remediation of leakage through caprock. The results obtained from the experimental work were used as an input to reservoir simulations to assess the suitability of polymer gel in realistic field scenarios.

Reservoir simulations supported the feasibility of polymer-gel remediation at reservoir scale and identified the spatial extent of the leakage that can be remediated for various concentrations of polymer-gel solutions. The data obtained from the laboratory experiments have indicated that mitigation of leakage at a distance of 20m from the polymer injection well would be possible, but an appropriate selection of a polymer is likely to mitigate leaks further away into the storage formation.

Risk management in the context of closure and responsibility transfer of CO_2 storage sites

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Risk Management in the context of closing and abandoning a CO_2 storage site encompasses all the measures required to demonstrate the long-term safety of a CO_2 storage site. This is a pre-condition for transferring the responsibility for the abandoned site from the operator to the Competent Authority (CA). The timeline to be considered encompasses the final injection period within the operational phase as well as the post-closure/pre-transfer and post-transfer period of a storage project.

Before the transfer of responsibility can be approved by the CA, the operator has to demonstrate (EC Directive):

a) the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour,

b) the absence of any detectable leakage,

c) the storage site is evolving towards a situation of long-term stability.

A milestone chart in accordance to given EC regulations has been developed to facilitate an industrially applicable procedure for risk management measures in the context of responsibility transfer and abandonment of a CO_2 storage site. Risk management criteria, termed "R-type" criteria have been defined for individual milestones. Some of these R-type criteria refer to comparison of model output and monitoring measurements and observed deviations or irregularities in both types of information. For the treatment of observed irregularities, a traffic light system with an associated workflow has been set up. This workflow is connected with an additional set of criteria (technical or "T-type" criteria). The major goal of the traffic light system is to provide a framework for dealing with offsets of model predictions and monitoring data.

The risk management workflow with traffic light system and accompanying criteria was successfully tested on the operations at the K12-B CO_2 injection pilot.

Summary No. 28a

Project dissemination (A)

CCS deployment and public awareness: with a little help from students

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Carbon Capture and Storage (CCS) deployment fails at the moment in European countries mainly because of economics issues but also because of the local public opposition. Two major reasons for the lack of public acceptance are the NIMBY (Not In My Back Yard) syndrome in association with ignorance of what CCS is and the feeling that the CCS option might delay the transition to renewable energy. To rapidly reduce anthropic CO_2 emission to the atmosphere, more pragmatism and a better awareness on each one's individual responsibility are expected. This calls first to increase public awareness on CCS so as to allow a constructive debate within stakeholders.

Working on dissemination at IFPEN gives the opportunity to involve students from IFP School and some other universities and engineering schools to investigate how to develop public awareness on CCS on such a specific part of the public and in partnership with it. Most of the students had already a master degree in engineering sciences or geosciences or are involved at the master level. This might explain that, as observed from polls, all students are aware of global warming and climate changes even if only few of them have heard about CCS and much more less really know about it.

IFP School students worked in the frame of a "personal skills module" in teams of six students from different countries and background on how to enhance communication on CCS for a population bracket of their choice. After polling on the web or in their entourage, they have proposed very **attractive tools such as cartoons, video, comics, website to inform and debate objectively on CCS** addressing quite a large public audience. Their work gives unusual and interesting information on the way stakeholders could communicate on CCS and later on R&D results, real projects and industrial issues.

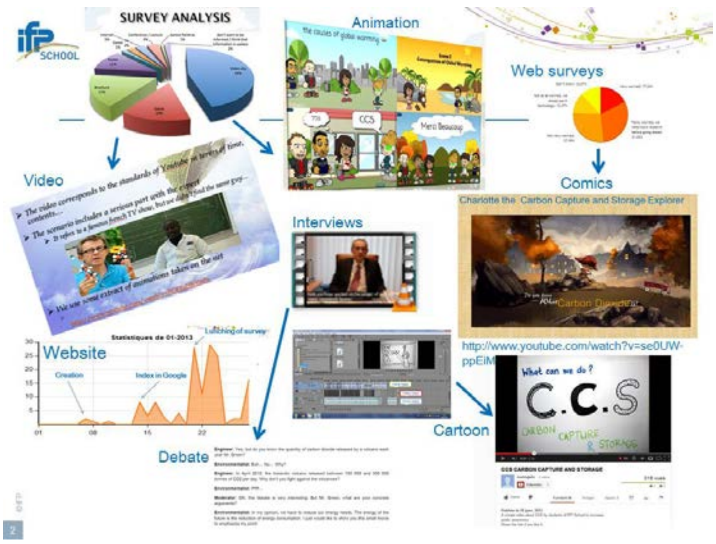

Figure 1: *Illustration of IFP School students communication tools on CCS.*

Summary No. 28b

Project dissemination (B)

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The main objective of the CO_2CARE project is to demonstrate the validity of CCS (Carbon Capture and Storage) technology concerning the procedures for well abandonment and post-closure safety. In this contest, dissemination of research results constitutes an important factor to successfully propagate correct and understandable information about the project to stakeholders and the public.

A first step in the task “dissemination” was the creation of a project website, enabling the users to access and exchange all information regarding scientific results and general news. The website, a content management system (CMS), is divided into a "public" and a "reserved" part. In particular, presentations and (open access) publications were uploaded into the website. Also news about important events related to the project was inserted into the "event section” of the website, e.g. conferences, workshops and meeting of the project, and some international scientific conferences which were attended by CO_2CARE members.

Furthermore, newsletters and FAQs were integrated into the website as well as information films of CO_2 storage sites which are studied within the project. Two brochures were issued showing the CO_2CARE main objectives and key findings. The latest version will be translated into several languages. Best Practice Guidelines in English language are in preparation and will be available at the end of the project. It will include full documentation and evaluation of the tested methodologies and research findings, to make a comprehensive set of recommendations for site abandonment best practice in a European context.

Specific workshops were organised in order to discuss CCS technology with students and to work out appropriate methods for dissemination and exploitation of results. During the whole project, a communication strategy was developed, including special media training for staff members who are in contact with the press. Moreover, press releases for the final CO_2CARE conference in English, German, Italian and French were created and distributed to journalists.

***Fig. 1**: Frontpage of the CO_2CARE website.*

Summary No. 29

“Dry runs” – hypothetical closure for Ketzin, K12-B and Sleipner

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Dry run site transfer documents were prepared assuming, hypothetically, that the Sleipner, Ketzin and K12-B CO2 storage sites were about to be closed. These documents show how the requirements for site closure and site transfer described in the EU CO_2 Storage Directive could be met at each of the three individual sites. They were presented to a workshop of CO_2 storage site regulators to tease out gaps and issues around site closure and transfer from both the regulators and site operators perspectives.

Thanks to the participation of the regulators and some site operators, the workshop produced several important recommendations, which will be discussed during the presentation and will be included in the Best Practice Recommendations for site closure and transfer, which is one of the major deliverables of the CO_2CARE project.

Summary No. 30

Can we demonstrate conformance? Sleipner case study

Chadwick , A. [1], Noy, D. [1]

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In order to close a CO_2 storage site and transfer liability back to the national authority, the site operator needs to demonstrate that the observed behaviour of the injected CO_2 conforms to modelled behaviour. It is also necessary to show a robust ability to predict future plume development into the medium and long-term. In practice it is impossible to achieve perfect matching between modelled or predicted results and observations due to imperfect understanding and characterisation of subsurface complexity, and limitations in both modelling tools and monitoring datasets.

In order to investigate some of the issues, CO_2CARE has carried out a detailed conformance study of the Sleipner injection operation, based on the progressive growth and spread of the injected CO_2 plume as imaged by time-lapse 3D seismic reflection data. The basis of the study is a series of three predictive modelling sequences of plume growth based on datasets available at three points in time: in 1996 prior to injection; in 2001 after two repeat surveys and in 2006 after five repeat surveys. The accuracy of the predictive models is assessed by comparing selected performance measures (e.g. plume area, migrated distance from the injection point etc.) with the actual monitoring data up to 2008.

The models were all run with ranges of parameter uncertainty appropriate to the datasets available. Key parameters were the permeabilities of the reservoir sands and mudstones, and CO_2 properties, the latter dependant on reservoir temperature. The 1996 (pre-injection) models showed high predictive uncertainty with a very wide range of possible outcomes. This was largely because, based on the data available, it was not clear whether the plume would spread in the reservoir as a single large CO_2 layer or as several smaller ones. Observed results generally fell within the (very wide) predicted ranges. By 2001 the seismic data showed that the plume was spreading as multiple layers, enabling the single layer scenarios to be disregarded, with a corresponding large reduction in uncertainty. By 2006 reservoir temperatures were much better constrained and layer spread well calibrated, with a further reduction in uncertainty. It remained difficult to match the modelled and observed plumes exactly, but it is clear that, overall, plume growth processes were well understood. The steady reduction in uncertainty with time as more monitoring data has become available suggests that plume development processes are stable and that current levels of uncertainty are unlikely to lead to unexpected plume behaviour in the future.

In terms of best practice, it is clear that full consideration should be given to parameter uncertainty, particularly early in the injection operation when development of the injection footprint (principally CO_2 and pressure distribution) is most uncertain. It is particularly important to focus on the parameter range end-members. It is these, rather than the median parts of the parameter ranges, that can lead to unexpected and divergent outcomes which might impact on the viability of the storage scheme.

Summary No. 31

CO_2CARE – Site Closure Assessment Research - Recent Results

Wipki, M.[1], Liebscher, A.[1], Kühn, M.[1], Lüth, S.[1], Durucan, S.[2], Deflandre, J.-P. [3], Wollenweber, J. [4], Chadwick, A. [5], and Böhm, G. [6]

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The EU project CO_2CARE, which started in January 2011, supports the large scale demonstration of CCS technology by addressing requirements of operators and regulators in terms of CO_2 storage site abandonment.
The CO_2CARE consortium, consisting of 24 project partners from universities, research institutes, and industrial partners, investigate technologies and procedures for abandonment and post-closure safety, satisfying the regulatory requirements for the transfer of responsibility.
Nine key injections sites in Europe, USA, Japan, and Australia, each with a specific (hydro) geological and environmental character, were selected for investigations (Fig. 1). These sites can be divided into the CO_2 storage types on-shore, off-shore, natural CO_2 reservoir, depleted gas reservoirs, and saline aquifers.
The project mainly focuses on three key areas:

- well abandonment and long-term integrity;
- reservoir management and prediction from closure to the long-term;
- risk management methodologies for long-term safety.

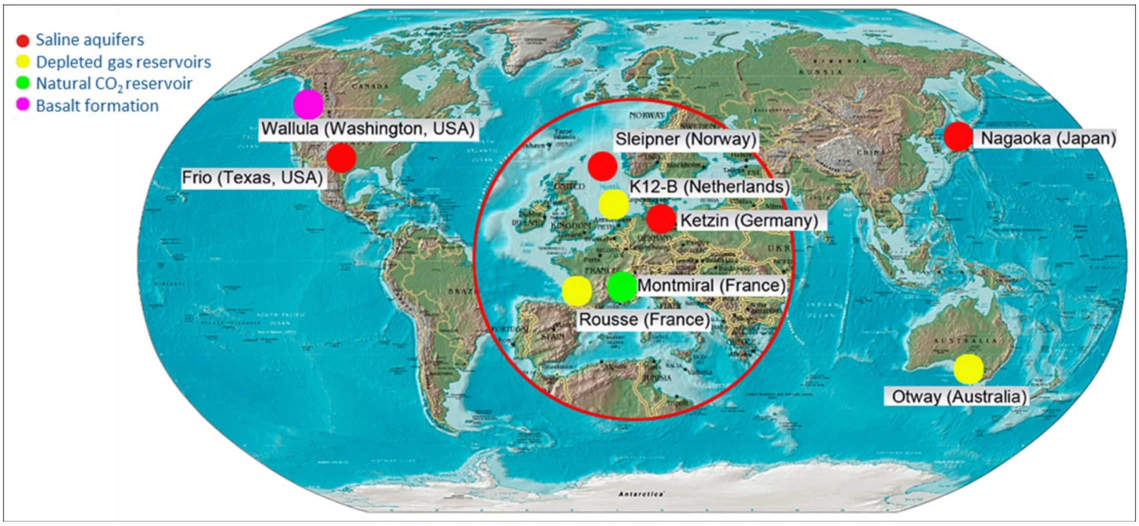

***Fig. 1:** Nine CO_2 storage sites in Europe and overseas studied in CO_2CARE.*

These key areas are in turn closely linked to the three high-level requirements of the EU Directive 2009/31/EC, Article 18 for CO_2 storage which are: (i) absence of any detectable leakage, (ii) conformity of actual behaviour of the injected CO_2 with the modelled behaviour, and (iii) the storage site is evolving towards a situation of long-term stability.
At the end of the project`s lifetime, an overview of the project`s goals and the most relevant research findings are presented. The essential results of the different working groups in CO_2CARE will feed into overall guidelines for regulatory compliance and “Best Practice” for site abandonment.

Summary No. 32

Results from a source test at the Ketzin CO_2 injection site

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Seismic methods provide one of a range of geophysical methods which can be used to image a given CO_2 storage reservoir, and monitor movement of the injected CO_2 within it. At Ketzin, seismic methods have proven effective at imaging the overall structure and geometry of the reservoir unit. Time lapse surface seismic methods have been applied successfully to monitor and assess the volume of injected CO_2 between 2005 and 2012. Other examples of the use of seismic methods at Ketzin include cross hole seismic traveltime and waveform tomography, 3D seismic traveltime tomography in order to image the shallow subsurface at Ketzin and passive seismic interferometry. Seismic methods have also been applied successfully to monitor other CO_2 storage sites such as Sleipner in the North Sea and Weyburn in Canada.

Active seismic imaging requires a source that provides the input signal. Ideally, a seismic source should provide a high amplitude, broad bandwidth (spike-like) signal. Sources can be impulsive (e.g. dynamite, weight drop or sledgehammer), providing a spike-like signal directly, or they can emit a long controlled signal over many seconds which can be through processing converted to a more ideal spike-like signal (e.g. Vibroseis). Two types of seismic sources that were tested at Ketzin within the CO_2CARE project were a small SIST (Swept Impact Seismic Technique) source, referred to as VIBSIST, and a small weight drop. As a baseline for comparison, a survey with a larger VIBSIST source was used. In the SIST method a series of impacts are produced over 10s of seconds (referred to as a sweep) by a hydraulic hammer with time intervals between the hits gradually decreasing or increasing. The data are decoded using a shift and stack process to give a coherent spike-like response.

Choice of source for a seismic survey is important as its characteristics define to a large extent the quality of the image obtained from the data of a given geological target. However, when planning and executing a seismic survey other considerations must be taken into account beyond the purely technical goal of imaging the reservoir. Practical aspects such as cost, productivity, environmental impact and manoeuvrability of a source are also highly important. During the acquisitions at Ketzin, issues have arisen with local landowners concerning tracks left across agricultural land, leading to delays in acquisition and payment of compensation to the landowners. Therefore, small low cost sources are worthy of testing.

In addition to generating standard stacked sections to compare the efficiency of the tested sources, the frequency content and amplitude of the tested seismic sources are compared by analysing the pre-stack data. The smaller VIBSIST source is lighter, cheaper and less invasive than the larger VIBSIST source and in a low noise environment it is capable of producing a good image of the target reservoir at Ketzin (approximately 650m depth). The same is true for the small weight drop source. In higher noise environments a larger, more expensive and invasive source is required.

Summary No. 33

The AUGE Project: Compilation of scientific results to underpin the implementation of the German transposition of the European CCS Directive

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In August 2012 the German Parliament passed the transposition of the EC Directive 2009/31/EC the "Carbon Dioxide Storage Law" (KSpG). The law focuses on the demonstration of the CO_2 storage technology. Two appendices have been added to the law which are in accordance with the appendices of the EC directive.

As the law has a conceptual character, appendix 1 provides a description of criteria for the characterisation and assessment of a potential CO_2 storage site starting with field data ending with requirements for dynamic modelling of the storage complex. Appendix 2 describes the expected monitoring system during all relevant phases of a life cycle of a CO_2 storage site. The law and appendices are using the term "state of the art". Moreover, the criteria given in the appendices are of general nature, which reflects on one hand that the CO_2 storage technologies are still being developed and on the other hand the site specific aspects, which need to be considered. In order for the mining authorities of the German states to grant permission and secure long-term security of a storage site a more detailed set of criteria is needed.

In 2004 the Federal Ministry of Education and Research of Germany launched the programme GEOTECHNOLOGIEN with one key aspect being the development of technologies for a sustainable storage of carbon dioxide in geological formations. Within this research field more than 30 projects in three phases have been funded.

During the first funding phase, 2005-2008, several different technologies for the reduction of CO_2 have been tested including the reaction of CO_2 with acidic mining water, adsorption of CO_2 onto coal, enhanced gas recovery and CO_2 sequestration in saline aquifers. A wide range of techniques have been tested in numerical simulations, laboratory studies and field experiments. The research carried out was independent of a certain storage location.

In the second phase, 2008-2011, research focused on methods with the capacity to significantly reduce the German CO_2 production, which leaves carbon dioxide sequestration in saline Aquifers and exploited natural gas fields. At the same time research started at two specific locations: the Ketzin site, which stores CO_2 in a saline aquifer and is up and running and at a gas field in the Altmark as a measure of EOR.

The third period started in 2011 and is looking at an in-depth understanding of processes of the CO_2 storage with a focus of monitoring and long-term safety.

In order to benefit from the gathered knowledge and use the experiences for the policy/law making process the umbrella project AUGE has been launched. AUGE is a 3 year project, which started in October 2012 and is the last project within this research field under the GEOTECHNOLOGIEN programme. The aim of the project is to review and compile all results of projects funded during the three phases. The scientific results will underpin the appendices of the KSpG. Currently funded projects will help to define the state of the art in their respective field and will propose guidelines and weighing up criteria which need to be considered for the permission of a storage site.

Inverse modelling of cross hole pumping tests in Ketzin

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At the pilot site in Ketzin CO_2 is injected into the subsurface. In a depth of 640 m there is a 12 m thick sandstone layer, which consists of sand grains and the small pores between the grains. The pores are filled with very salty water. The injected CO_2 replaces the water between the pores. The pores are very small and the sand grains represent a resistance to the flowing water and the flowing CO_2. The resistance is a property of the sandstone and affects both CO_2 and the salty water in a similar way. In order to determine the magnitude and a map of the resistances spatial distribution, a series of pumping tests have been carried out prior to the injection of CO_2.

Three wells were drilled at the pilot site Ketzin. These wells are connected to the sandstone. The water can flow from the sandstone to the well and also the other direction from the well to the sandstone. During pumping test water is extracted with a submerged pump from one well and as consequence the pore water flows from the sandstone in the well. The pore water in the sandstone also starts to flow. This flow is hindered by the resistance of the sandstone and the pressure in the sandstone decreases. This pump test is carried out in succession in each of the three wells

There are pressure gauges in each well and record how much the pressure changes over time. These data are used to recalculate how much resistance the sandstone provides to the flowing water.

In general two methods exist to recalculate the resistance of the sandstone. The first method is an analytical solution. This solution can evaluate one observation time series at a time. To evaluate all nine observation time series (Three experiments with three time series each), a sequence of nine analyses was carried out. For each time series one value for the resistance is calculated and it is very difficult to derive the spatial distribution of the resistance and draw a map. Therefore a second method is carried out. The nine time series of all experiments are introduced into a numerical model. This based on the commercial simulation program Eclipse 100 and represents the water, the sandstone layer and a map of the resistance. The model calculates the pressure, but at the beginning the calculated pressure and the observed pressure are very different. The resistance map is changed systematically. If the resistance is changed in one part of the map, all nine calculated pressures are affected. The aim is to change the resistance map in such a way, that the model reproduces all nine observed pressure time series. This is carried out with a computer program called PEST, that varies the resistance map in a systematic way such that the calculated pressure time series are in good agreement with the observed pressure time series. And more important, a map with the resistance of the sandstone is obtained. This map is used to analyse and predict how the CO_2 flows in the sandstone.

Summary No. 35

SiteChar – Defining appropriate geological site characterisation to meet European regulatory requirements

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EU regulations on CO_2 define a range of performance standards that recognise specific high-level uncertainties and long-term issues which storage project developers will have to address. A limited number of projects, notably ROAD and the Goldeneye field, have undertaken detailed site characterisation while others are progressing. However, the appropriate level of site characterisation required to successfully apply for a storage permit has not been systematically-evaluated or clearly-defined for all storage types.

The FP7 EU SiteChar project has developed exemplar permit applications for two credible CO_2 storage sites to test a site characterisation workflow and determine the level of site knowledge required to successfully obtain a permit to store under EU regulations.

The selected sites are representative of two realistic storage options, though neither is currently being considered as a near-term candidate. The first case study is a depleted hydrocarbon field and contiguous saline aquifer in the outer Moray Firth, UK northern North Sea, which investigates a multi-store concept that anticipates storage in both the depleted field and the aquifer of the Captain Sandstone Formation. The second case study extends existing investigations of site characterisation at the Danish Vedsted site, a deep onshore aquifer, and requires exploitation of estimated large-scale capacity in saline aquifers where pre-existing data may be sparse. These 'dry-runs' allow evaluation of some of the more challenging aspects of storage permitting requirements, without the constraints of a commercial project.

Site-specific dry-run storage permit applications, though necessarily reduced in scope from those anticipated for full storage projects have been produced and evaluated by a separate team, acting as an independent regulator.

Both case studies have addressed key issues of the permit process, such as:

- Defining the storage complex boundaries. This may be challenging, especially where expected pressure responses may extend laterally for some distance or where lateral structural boundaries may be less clearly defined;
- Determining the level of appropriate, robust site characterisation necessary to secure storage permits in areas of limited data availability;
- Defining a range of metrics against which site performance can be measured.

Acknowledgements

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Capillary properties of sandstones at simulated reservoir conditions

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The trapping of CO_2 by capillary forces is discussed to contribute to the immobilisation of CO_2 in saline aquifers. The so-called residual trapping occurs at the tail of a migrating CO_2 plume, when the formation water flows back into a zone saturated with CO_2. Due to capillary forces the refluent water enters the smaller pore constrictions first. Thus, with increasing water saturation patches of CO_2 become disconnected from the plume. On the one hand, the understanding of the capillary pressure behaviour is crucial to assess the long-term behaviour of saline CO_2 reservoirs. On the other hand, a proper interpretation of geophysical reservoir monitoring data requires the knowledge about the physical rock properties as function of the reservoir saturation. However, experimental data at relevant pressures and temperatures are still scarce.

In the framework of the EU funded projects CO2CARE and SiteChar a set-up was developed, which allows for the combined measurements of the capillary pressure, ultrasonic wave velocities, and electrical resistivity at different brine-CO_2 saturations under simulated reservoir conditions. Drainage (displacement of brine by CO_2) and imbibition (displacement of CO_2 by brine) cycles were performed on Triassic sandstone samples. The experiments were conducted in a temperature controlled oil pressure autoclave to apply a maximum confining pressure of 400 bar and a maximum working temperature of 150°C. Two high-precision syringe pumps were used to displace a quantified volume of brine by CO_2 (and vice versa) and determine the corresponding sample saturation. At each saturation level the capillary pressure was measured using the micropore membrane technique. Additionally, P and S wave velocities as well as the electrical resistivity of the sample were determined. The measurements provide information about the efficiency of capillary trapping and are a calibration of petrophysical properties on saturation.

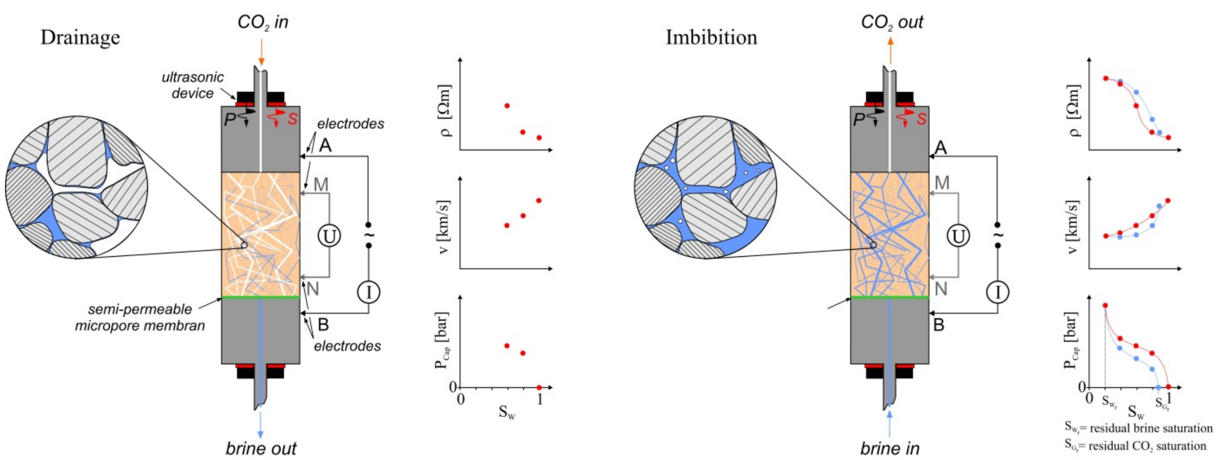

***Figure 1**: Schematic overview of the measuring arrangements for the determination of the capillary pressure, ultrasonic velocities, and electrical resisitivity during drainage (right) and imbibition (left).*

Summary No. 37

The long-term Time-Trapping-Safety

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The long-term safety of storage sites over time-spans of 1,000-10,000 years has been the focus of various types of modelling studies involving predictions and extrapolations. One of the very first published illustrations was a fully conceptual diagram of time evolution of trapping proportions by various mechanisms, included in the special volume treating Geological storage, published by the IPCC. This diagram has since been re-used to comfort the audience about the favourable development of the safety due to trapping of the injected CO_2 in immobile phases such as minerals, dissolved in water, or trapped as residual phase.

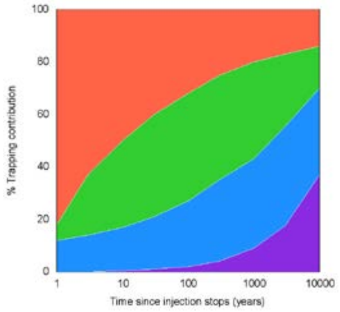

Fig. 1: *Re-coloured version of the conceptual diagram from Benson & Cook (2005). The concept is that the safety of the site is linked to the significant reduction in the mobile phase for CO_2 (red), whereas the proportion trapped in residual phase by capillary forces (green), the dissolved CO_2 in the water (blue), and the precipitation of minerals incorporating the CO_2 (purple) steadily increases over time.*

A meta-study of published results from simulations of long-term trapping in a variety of potential storage sites shows that there might be significant deviations from the conceptual description. The only consistent agreement seems to be the very limited amount of mineral trapping.
Despite the uneven background data for the meta-study, and sometimes lack of information about input for the simulations, it seems clear that the trapping diagram must be highly site specific. The distribution of trapping of the different mechanisms depends on reservoir architecture, depth, brine salinity, and injection strategy. This diversity among different injection sites is exemplified with a few examples.

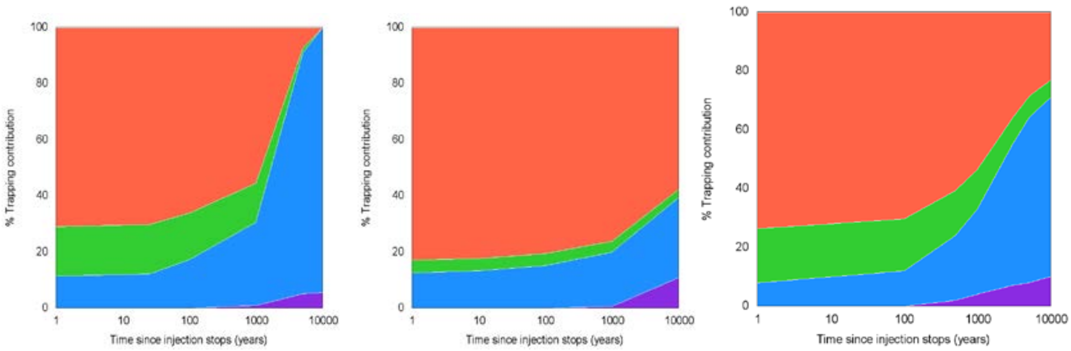

Fig. 2: *Trapping diagrams constructed from results in Audigane (2007). Zhang (2009), and Ranganathan (2011)*

Summary No. 38

Contribution to well mechanical history modelling prior abandonment

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Well abandonment is one of the key issues at end of the CO_2 storage phase when considering the long term integrity of the site. It is both site and well dependent. Especially the mechanical loading path will completely be different when storing in a saline aquifer reservoir -above the initial pressure- than when storing in a previously depleted oil & gas reservoir. The case of a CO_2 injection well differs from the case of a distant well that can be over time intersected by the CO_2 plume. Variations of pressure/effective stresses, temperature and fluid composition at wellbore will be different in term of mechanical loading, corrosion and at least possible damaging of materials.

Main steps to consider are plotted in Figure 1, they are illustrated by a well case corresponding to a depleted gas reservoir (Figure 2). In addition to collecting material properties and state behaviour laws, the knowledge of initial in situ stresses remain a key point to state on effective location of each material in its damaging/failure envelop over time. To also consider thermal and corrosion effects due to the presence of an acid fluid, adapted state laws must be used, they can be determined using laboratory studies.

In this study we only focus on the mechanical aspects aiming at evaluating the state of stress at wellbore; a mandatory step to assess rock, cement and casing integrity. The solicitation leading to the stress change is considered to be only the fluid pressure variation (no thermal and chemical effects). 2D modelling of a horizontal reservoir section has been first performed to state on wellbore stresses just after drilling and completion. Then 3D modelling is achieved to consider the stress variations. The final state of stress is then compared to the material envelop to assess risks.

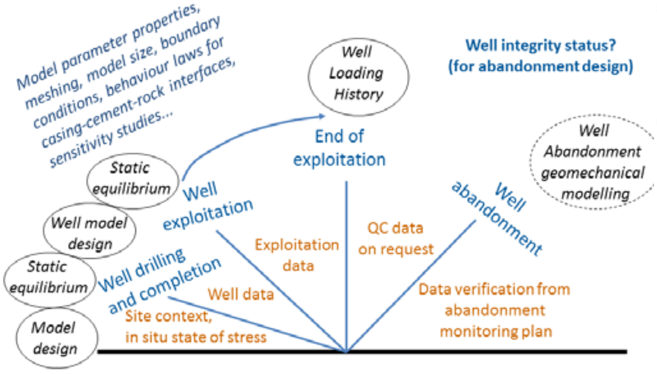

Fig. 1: *Well mechanical history modelling workflow (prior to abandonment).*

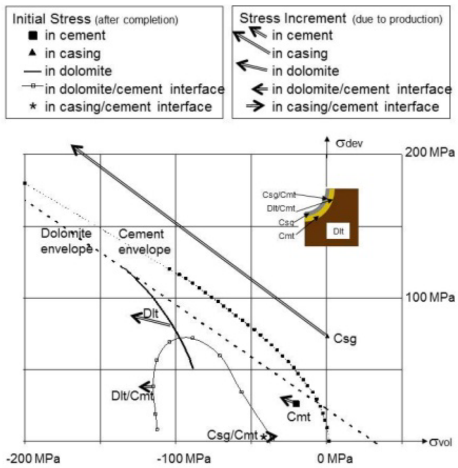

Fig. 2: *Materials behaviour due to pressure variation.*

Summary No. 39

Public Outreach for the Ketzin Pilot Site within the CO_2MAN Project

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The GFZ German Research Centre for Geosciences runs Europe´s longest-operating on-shore CO_2 storage site near the city of Ketzin/Havel since 2004. The Ketzin pilot project provides fundamental knowledge about CO_2 storage in a saline aquifer on the research scale [1].
As public outreach is an important aspect of the Ketzin project the research activities are accompanied by open and transparent information to the public [2]. This is reflected in a positive broad media coverage both domestically and internationally and numerous visitors on site. The dissemination of up-to date, transparent and factual information about the project activities is also important to generate and keep trust of the persons concerned. Therefore, an important objective of the on-going CO_2MAN project (2010-2013) is to respond to questions and concerns, e.g. regarding the monitoring and the behavior of the CO_2 in the subsurface and the abandonment of the wells.
In order to reach the various target groups, e.g. the general public, the science community, media and authorities, the concept of communication and dissemination of information on the Ketzin pilot site includes (Fig. 1):

1) a visitor centre on site with weekly guided tours
2) close cooperation with the local community (e.g. mayor, city council, fire brigade)
3) public events, e.g. annual “Open House Day” at the Ketzin site, “Long Night of Sciences” at GFZ, and visits at local schools
4) different information tools and materials like project website (www.co2ketzin.de), short films, brochures and exhibits [3].

Fig. 1: *About 2,000 visitors from all over the world visited the Ketzin pilot site within the CO_2MAN project (middle), children visited the GFZ (left) and GFZ personnel visited local schools (right).*

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Experimental and theoretical studies into the sealing behaviour of rock-cement-casing interfaces at the wellbore

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Wellbore integrity is an essential requirement to ensure the success of a CO_2 Storage project as leakage of CO_2 from the injection well or other abandoned wells in the storage complex could not only severely impede the efficiency of CO_2 injection and storage but also may result in adverse impacts on the surrounding environment. Early research has revealed that improper well completions and/or significant changes in the operating bottomhole pressure and temperature could lead to the creation of a microannulus at the cement-casing interface, which may constitute a preferential pathway for potential CO_2 leakage. Research in Work Packages 2.1 and 2.2 of CO2CARE investigated the sealing behaviour of such microannulus at the cement-casing interface under simulated subsurface reservoir pressure and temperature conditions and used the experimental findings to develop a methodology to assess the overall integrity of CO_2 storage.

A full scale wellbore experimental test set up was constructed for use under elevated pressure and temperature conditions encountered in typical CO_2 storage sites. The wellbore cell consists of an assembly of concentric elements of full scale casing (Diameter= 0.1524m), cement sheath and an outer casing. The stainless steel outer ring is intended to simulate the stiffness offered by the reservoir rock to the displacement applied at the wellbore. The Central Loading Mechanism (CLM) consists of four case hardened shoes that can impart radial load onto the well casing. The radial movement of the shoes is powered through synchronised movement of four precision jacks controlled hydraulically which could impart radial force up to 5 tonnes. The cell body is a gas tight enclosure that houses the wellbore and the central loading mechanism. The setup is enclosed in a laboratory oven which acts both as temperature and safety enclosure.

Prior to a test, freshly prepared cement mix is poured between the casing and the outer steel ring. A radial pressure is maintained on the wellbore casing during cement setting process (i.e., the casing is in a state of tension), so that a microannulus can be created by subsequent contraction of CLM when the radial pressure is relieved during the long-term curing period. Once the cement is cured, permeability of the microannulus is first measured using Nitrogen as the pore fluid. The cement is then saturated with brine (salinity of brine is of the field conditions tested) and, by controlling the aperture (permeability) of the microannulus by varying the CLM pressure on the casing, microannulus permeability is measured for varying CLM pressures to yield a stress- permeability relationship. The long-term CO_2 flow experiments during which the CLM pressure on the casing is maintained constant are carried out and the permeability behaviour under simulated downhole conditions is monitored over time.

Three test cases were experimentally analysed: a) Shallow depth, low salinity, low temperature and moderate pressure conditions (Sleipner type: T= 40^{o}C, P=10MPa, Salinity=3.5%) b) Shallow depth, high salinity, low temperature and moderate pressure conditions (Ketzin type, T= 34^{o}C, P= 8 MPa, Salinity = 25%) and c) Deep, moderate salinity, high pressure and high temperature North sea type reservoir settings (T= 92^{o}C, P=35 MPa, Salinity = 12.5%). Long term experiments with continuous flow of CO_2 through the microannulus have shown that the permeability of microannulus is progressively reduced with time for the two shallow reservoir settings (case scenarios: a and b above) indicating self-sealing behaviour of the microannulus. This self-sealing behaviour was attributed to the carbonation reactions between CO_2, brine and alkaline cement. Self-sealing behaviour was not observed for the high pressure and high temperature deep North Sea case (case scenario c above), indicating the dominant effect of subsurface environmental conditions.

Relationships for the reduction in permeability of the microannulus with time were derived from the experimental data for use in reservoir simulations. Numerical reservoir simulations were carried out using Schlumberger's ECLIPSE reservoir simulation software and a realistic geological reservoir model for all three case scenarios (a, b and c) to assess the impact of leakage at the wellbore casing and cement interface on integrity of CO_2 storage. As an initial step, a fixed amount of CO_2 was injected into the reservoir (injection rate = 1Mt/year for 20 years). Leakage from the wellbore block (2mX2mXdepth of the caprock) into a shallow aquifer was assumed to commence once the injection of CO_2 had stopped. Sealing behaviour was implemented through a series of restarts of the ECLIPSE simulation software, during which the permeability of the wellbore block was modified in accordance with the permeability-time relationship derived from the experimental data. Simulations were carried out to monitor the CO_2 saturations/plume evolution in the shallow aquifer for 90 years.

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