Underground CO_2 storage: Can it be monitored?

By

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Abstract
World projections of energy use show that fossil fuel dependency will continue to 2030 and beyond; but sustainability will need CO_2 emissions reducing by 60% by 2050. The world is already experiencing rising sea level, ocean acidification and warming. Achieving such reductions is a major challenge and will require various strategies including a global alignment of national emission reduction targets within the next 20 years to avoid inappropriate infrastructure "lock-in". Important elements are to improve energy efficiency of energy conversion processes, reduce energy demand, fuel switch from coal and oil to natural gas, nuclear power including fission and fusion, increase the use of renewable energies and CO_2 capture and storage. Not all of these options are practical or acceptable to each nation and no single option will deliver the deep cuts in emissions that will be required this century. Capture and geological storage of CO_2 from fossil fuels however is an important and available method which could have widespread application worldwide and achieve large reductions (> 30%) in a transition period within the next 50 years towards a more sustainable energy society. A fast implementation is possible since no large-scale modifications to existing energy infrastructure and primary energy supply are necessary. For this reason it can be embraced by developing economies such as China, Russia and India, which are not likely to change their fossil fuel dependency over the coming decades. This chapter gives an overview of the research carried out in the Department of Geotechnology of the Faculty of Civil Engineering and Geosciences to support the large scale implementation of underground CO_2 storage.

Introduction

The feasibility of underground CO_2 storage has been demonstrated in various projects during the last decade. The most well-known example is the Sleipner storage offshore Norway, where about 1 million tons of CO_2 per year is injected in a saline aquifer at a depth of 800 meters. However there are still barriers to be overcome for large scale CO_2 capture and storage. For capture the main issues are the costs, for storage important hurdles to take are legal and regulatory frameworks and public confidence that storage will be effective and safe. Technically four important options are available for underground CO_2 storage.

Option 1: Deep saline aquifers

The first option consists of deep saline aquifers. Several demonstration projects have been initiated already worldwide, of which the Sleipner project offshore Norway is the first and largest so far (Zweigel et al., 2004, Arts et al., 2004). At Sleipner CO_2 has been successfully injected since 1996 at an average annual rate of 1 million tons of CO_2. Main issues that are not completely resolved in past and ongoing international projects with respect to aquifers are on storage capacity, monitoring and verification with respect to integrity of the caprock, long term behaviour of the injected CO_2, performance assessment and risk assessment.

Option 2: Depleted (or nearly depleted) gasfields

The second option consists of (almost) depleted gasfields. Especially for the Netherlands with most of its gasfields reaching the end of their lifecycle within the coming decades, this is considered as the most important option. It is no surprise, that the first and so far only demonstration project takes place in the Netherlands, where in the offshore K12-B gasfield since 2004 in the order of 20.000 tons per year are injected (van der Meer, 2005). An upscaling of this relatively small project to 400.000 tons of CO_2 is considered feasible. The main issues to be resolved for storage in depleted gasfields are somewhat different from storage in aquifers. Since these reservoirs have kept natural gas under high pressures for ages already, the containment integrity is less of an issue. However, due to gas extraction the cap rock in gas fields has been drilled and contains both abandoned and injection wells. The integrity of these wells with respect to (acid) CO_2 are important issues including potential corrosion of steel casings and dissolution of cement plugs. Furthermore the anelastic behaviour of caprock due to first depressurisation (gas production) followed by pressurisation (CO_2 injection) needs to be understood better. Finally in order to use nearly depleted gasfields instead of completely depleted gasfields we have to gain understanding of mixing properties of CO_2 and CH_4 and to optimise injection strategies. Potentially the CO_2 could contribute to Enhanced Gas Recovery (EGR).

Option 3: Enhanced Oil Recovery (EOR)

The third option consists of CO_2 injection into producing oil reservoirs. Besides storage this option has the potential to enhance the oil production (Enhanced Oil Recovery or EOR) by “pushing the oil” out of the reservoir. For the Netherlands this option is considered of less interest because of our small oil reserves and therefore the small storage potential. The option of exporting CO_2 to Norwegian oilfields for EOR however can be of great interest to the Netherlands. The largest demonstration project for CO_2 -EOR takes currently place in Weyburn (Canada) (IEA report Weyburn, 2004), where at a yearly basis since 2000 about 1500 ktons of CO_2 are injected.

Option 4: Enhanced Coal Bed Methane (ECBM)

The final option consists of injecting CO_2 in coal seems. During this process CO_2 molecules are absorbed by the coal while methane molecules are freed, which can be produced. This process is generally referred to as Enhanced Coal Bed Methane (ECBM) production. Only one demonstration project coordinated by TNO is available so far in Poland (van Bergen et al., 2006), where during 2004/2005 about 800 tons of CO_2 have been injected into a coal layer. This site has been studied in the European RECOPOL project and in the Dutch CATO-project by a number of research partners a.o. the TU Delft. Of the four options ECBM requires probably the largest research effort, but with an enormous potential. The physical processes (such as swelling, adsorption and cracking) and their implications on fluid flow are complicated and difficult to monitor. With a considerable potential storage capacity in coals in the Netherlands, this option needs more research both based on lab work and on field experiments.

Most of the research carried out at the TU Delft with respect to ECBM has been described in another chapter in this book (Bruining et al., this issue). This paper will focus on the research carried out from the viewpoint of monitoring underground CO_2 storage.

Time-lapse monitoring

Currently the most suitable technique to monitor underground CO_2 storage is considered to be time-lapse seismic monitoring. At the Sleipner site seismic monitoring has been applied successfully. An example is shown in Figure 1 (taken from Arts et al., 2005), where the distribution of the CO_2 in the reservoir can be clearly followed through the years.

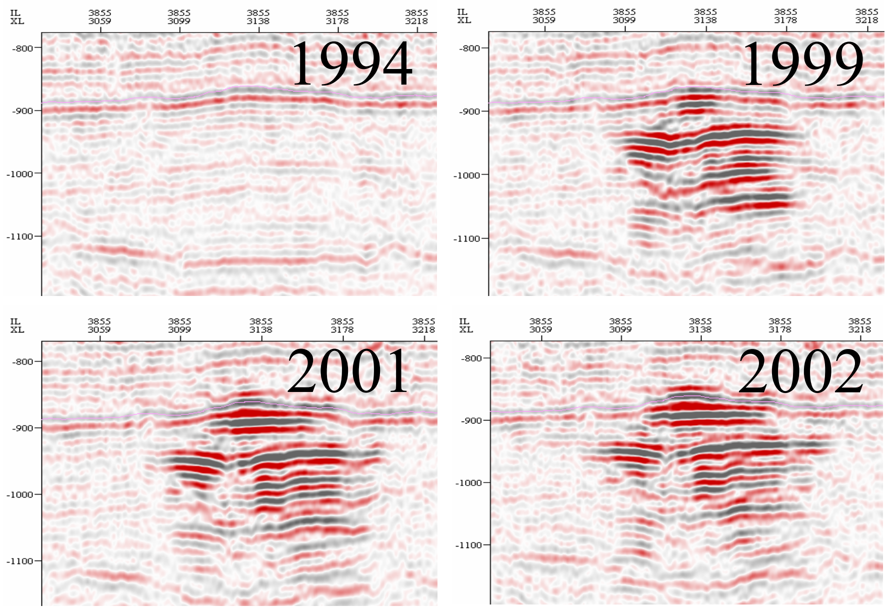

Fig1: Example of the time-lapse seismic data acquired at Sleipner showing the reservoir before CO_2 injection (2004) and after injection (1999, 2001 and 2002). (taken from Arts et al., 2005).

The seismic research at the Department of Geotechnology of the Faculty of Civil Engineering and Geosciences is focused around the following themes (topic 1-4):

1. Improved interpretation of time-lapse seismic surface data including geomechanical effects
2. Improved interpretation of time-lapse seismic crosswell data (tomography)
3. Physical modeling on a laboratory scale of time-lapse seismic data to mimic the ECBM process
4. Continuous monitoring using a (semi-)permanent monitoring system (like LOFAR)

A short description of the four different topics is given hereafter. Besides seismic monitoring alternative geophysical monitoring methods are considered. In the last section, topic 5, a description is given of laboratory experiments carried out to measure the electric response of rocks when water is replaced by CO_2. The aim is to investigate whether electric methods can track the fluid distribution of CO_2 in rocks.

Topic 1: Geomechanical effects of CO_2 injection on time-lapse seismic data.

The quantification of injection induced changes in reservoir properties (i.e. pressure and saturation) can be determined using seismic attributes derived from 4D seismics such as traveltime shifts and amplitude changes. In this type of studies frequently the assumption is made, that changes only occur in the reservoir and not in the overburden. Especially in the case of gas or CO_2 injection (storage) associated with large pressure changes in the reservoir, this assumption may be violated due to compaction and stress build-up in the overburden (Hatchell and Bourne., 2005, Angelov et al., 2005). Angelov et al. (2004) demonstrate the error one makes in the inversion by negelecting these overburden effects using synthetic models. Geomechanical models are used to quantify the effects in the overburden. An example of such a model is given in Figure 2. For the inversion a modification of Landro's (2001) method is used based on AVO (Amplitude versus offset) analysis. Results show, that in case of production the changes in the overburden are more severe than for injection, but can still lead to completely erroneous estimations of pore pressure in the reservoir. In such cases the incorporation of geomechanical modelling in the inversion process is recommended.

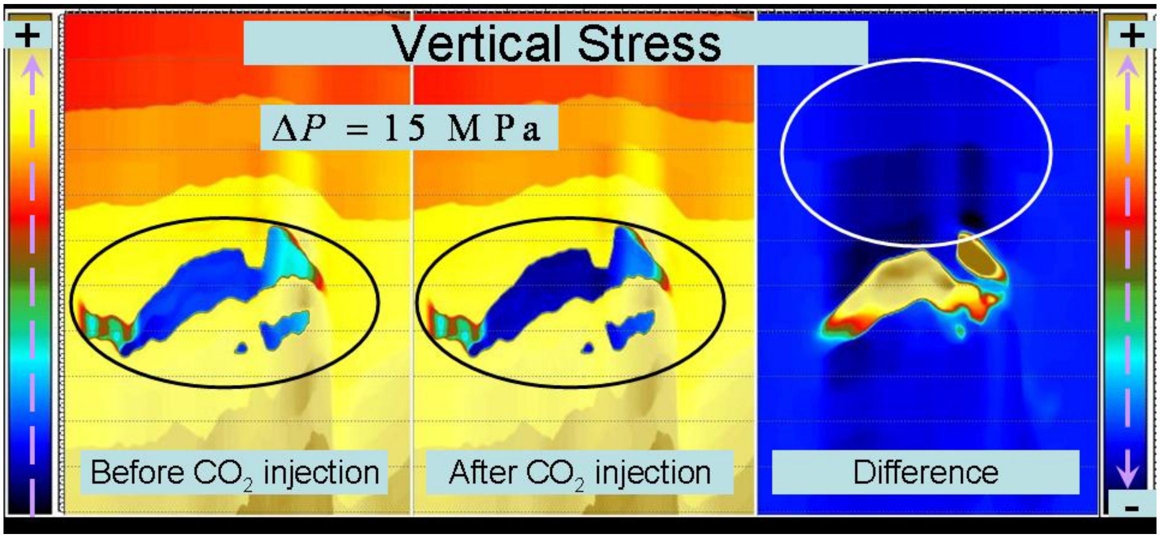

Fig 2: Geomechanical model showing the vertical stress in a reservoir model before injection of CO_2 (left), after injection of CO_2 (middle) and the difference between the two (right). On the two left images the reservoir is delineated by the black circle. A stress increase can be observed in the reservoir due to the injected CO_2. In the rightmost image it can clearly be seen (white circle), that stress changes also occur in the overburden, not only in the reservoir.

Topic 2: CO_2 Monitoring of an Onshore Sandstone Reservoir by Seismic Tomography

Japan's first onshore pilot-scale CO_2 sequestration experiment is located at the Minami-Nagaoka gas and oil field that is close to Nagaoka, Niigata prefecture (200 km north-west of Tokyo). Between July 2003 and January 2006, a total of 10400 tons of CO_2 was injected into a sandstone reservoir. The reservoir is a porous sandstone bed at 1100 m depth. The overlying 160 m thick formation (i.e. the caprock) is mudstone that seals off the reservoir completely. The thickness of the reservoir is about 60 m and the average permeability is about 12 milidarcy.

The CO_2 injection was monitored over time in a seismic crosswell experiment. A baseline seismic data set was recorded before the injection was initiated. Several monitor seismic data sets were as well acquired for the injection states of 3200 tons (MS1), 6200 tons (MS2) and 10400 tons (MS4) injected CO_2. The monitor state MS3 corresponding to 8900 tons of injected CO_2 is omitted here, because the MS3 and MS4 crosswell data are almost identical. Oyo corporation, Japan, was responsible for the crosswell data acquisition.

3D seismic tomography was used to image the reservoir zone at the injection state MS1, MS2 and MS4. Figure 3 presents the estimated tomographic time-lapse velocity models. The abbrevation for the source-receiver plane and the plane perpendicular to the source-receiver plane at 1100 m depth are the SR-plane and P-plane, respectively. An inspection of the estimated time-lapse velocity models in the SR-plane reveals a large negative velocity anomaly below the CO_2 release point with an extension upwardly in the sandstone aquifer. In the P-plane, the negative velocity anomaly is roughly 5 m wide on average. This negative velocity anomaly is caused by the injection of CO_2. The maximum strength of the negative velocity anomaly is about -500 m/s, or in percentage -18 %. Xue et al. (2006) measured using time-lapse well logging in a nearby observational well that the sonic P-wave velocity decreases by -21 % after the CO_2 breakthrough. Notice that there is a minor anomaly extending into the caprock. We believe this is a result of uncertainties in the observed time-lapse traveltime delays and not of migrating CO_2 into the caprock. In general CO_2 leakage is considered highly unlikely in the Nagaoka experiment based on the properties of the caprock. This is supported by laboratory CO_2 injection experiments using samples from drilled cores in the caprock formation, demonstrating that the caprock is impermeable (RITE, 2005).

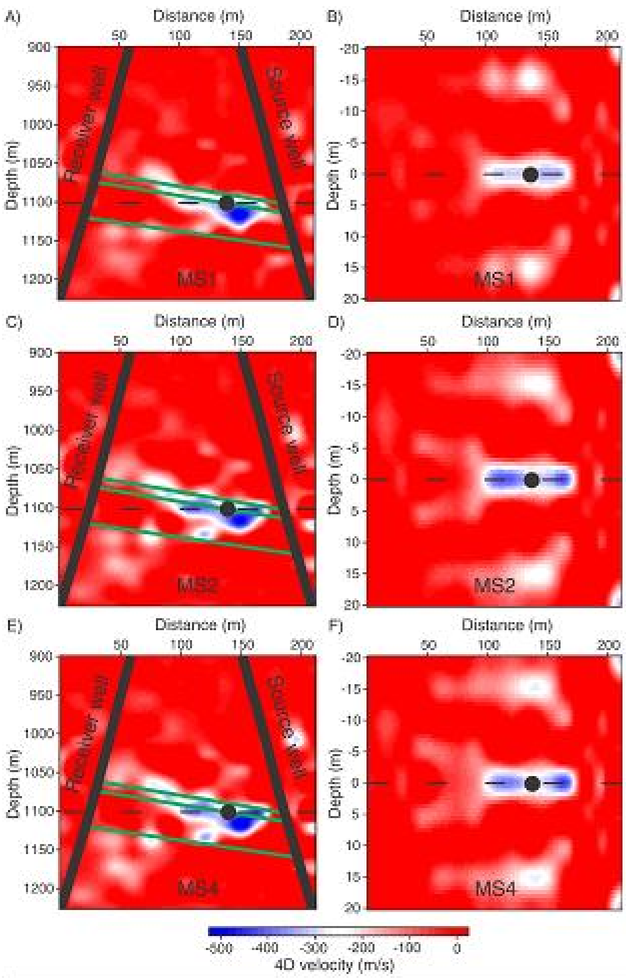

Fig 3: The black circle indicates the location of the CO_2 release point. (A) SR-plane (MS1), (B) P-plane (MS1), (C) SR-plane (MS2), (D) P-plane (MS2), (E) SR-plane (MS4) and (F) P-plane (MS4).

Topic 3: Physical modeling on a laboratory scale of time-lapse seismic data to mimic and monitor the ECBM process

The RECOPOL[1] project (van Bergen et al., 2006) is an EU co-funded combined research and demonstration project to investigate the possibility of permanent subsurface storage of CO_2 in Carboniferous coal. The CO_2 is injected into coal seams at a depth of 1050-1090 m where it adsorbs to the coal and replaces its methane gas simultaneously. Consequently, methane and water are produced. Daily

[1] RECOPOL stands for: 'Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland'.

12-15 tons of CO_2 were injected with a total of circa 760 tons into coal seams with thicknesses varying from 1 to 3 m.
As part of the RECOPOL project seismic monitoring was envisaged by using crosswell seismic data, similar as described above in topic 2 for the Japanes aquifer storage project. The aim of the TU Delft in this project is to investigate if such time-lapse data can be used for monitoring purposes and to test innovative inversion methods.

Physical modeling on a laboratory scale seemed to be an appropriate way to obtain better insight into the real field situation and to test the applicability of our seismic inversion methods.
To this end a coal-overburden model, as realistic as possible, has been fabricated from natural and artificial materials similar in velocities to the real field situation (coal, sand, and coal saturated with CO_2). In the field the wells are located at a distance of 150 m from each other. The target zone of the survey covers a vertical range of about 350 m. A scaling factor of 1000, based on the frequency range of our experimental data (experimental data of 500 kHz with respect to field data of 500 Hz), has been used to define the dimensions of our model: i.e. 350 mm long and 150 mm wide. A scaling factor of 1000 implies that a spatial sampling interval of 2 m in a seismic scale corresponds to 2 mm on a model scale; similarly, a temporal interval of 2 ms corresponds to 2 μs and 500 Hz to 500 kHz. Note that seismic velocities remain unchanged using this scaling.

The experimental setup of our laboratory is presented in Fig. 4a. The main components are the signal generation system, the source and detector, the data acquisition system and the physical model itself. The experimental measurements are recorded in the following way: The source signal is defined and generated in the waveform generator, where it is converted from a digital signal to an analog signal. The analog signal is sent to a power amplifier via an oscilloscope, which serves for the visualization mainly, and fed into the source transducer, which on its turn transforms electrical signals into acoustic pulses. The propagating sound waves are received by the detector, amplified and digitized. Again via the oscilloscope, all data are stored. The signal-to-noise ratio is increased by stacking, i.e., each trace is an average of a number of individual measurements (in total 1024 traces). The averaging is also carried out via the oscilloscope. Each averaged trace is stored in a separate file.

The physical model consists of a thin epoxy layer (v~2300m/s) representing the coal seam sandwiched between carboniferous rocks (v~4200m/s) represented in Fig. 4b. The crosswell data acquisition area of 3 cm is scanned and seismic common shot-gather have been recorded.
To simulate injection of CO_2 into the coal, we replaced the epoxy layer with an alternative material of lower velocity and we repeated the measurements. Time-lapse tomography reveals small velocity change induced by CO_2 injection, the result is shown in Fig. 4c.

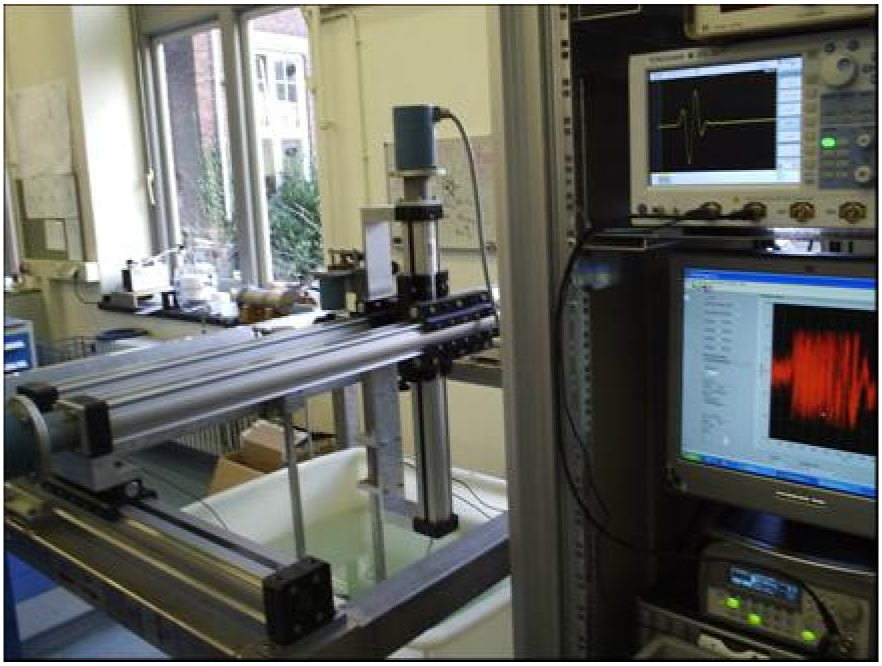

Fig 4a: Photo of the experimental set-up.

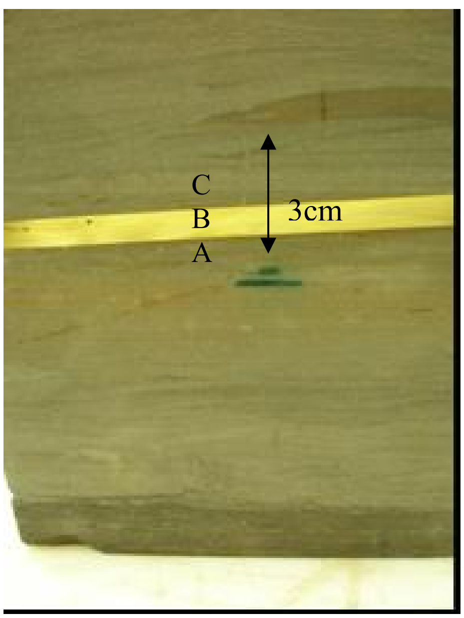

Fig. 4b: Photo of the model.

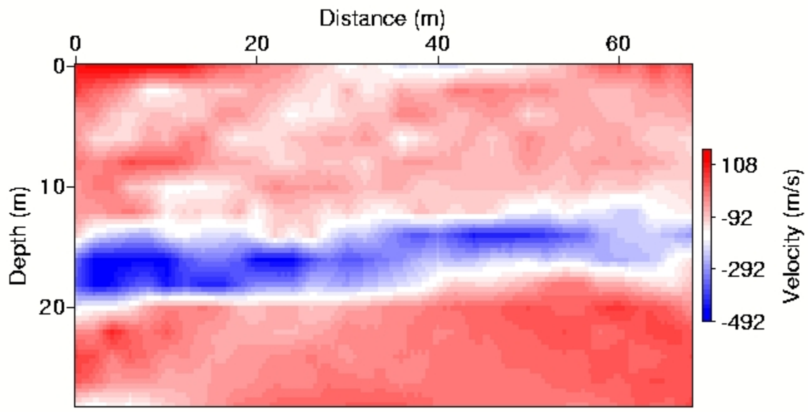

Fig. 4c: Velocity change observed after time-lapse data inversion scaled back to the field dimensions.

Topic 4: Continuous monitoring using a (semi-)permanent monitoring system (LOFAR/Persimmon)

In 2004 astronomers, agriculturists, and earth scientists have joined forces in setting up the LOFAR network (Lofar stands for Low Frequency Array), a broad band monitoring ICT infrastructure in the Northeastern part of the Netherlands (figure 5).

Figure 5: Artists impression of the LOFAR Network (source ASTRON).

This project started as an innovative effort to force a breakthrough in sensitivity for astronomical observations at radio frequencies below 250 MHz. It was soon realized though that LOFAR could be

turned into a more generic Wide Area Sensor Network. Sensors for geophysical research and studies in precision agriculture have been incorporated in LOFAR already. Several more applications are being considered, based on the increasing interest in sensor networks that "bring the environment on-line."
Geophysical interest in the LOFAR project predominantly concerns seismic monitoring, that could be used a.o. to ensure the integrity of future CO_2 storage sites. In this respect three distinct monitoring approaches are recognized:

- monitoring seismic events related to small earthquakes;
- monitoring background noise and synthesis of subsurface models using seismic interferometry;
- monitoring subsurface properties by performing active time-lapse experiments.

The geophysical application of the Lofar project is called Persimmon (Permanent Seismic Monitoring Network).
Small earthquakes (< 3.5 on Richter scale) that occur in this area are expected to stem from gas extraction from nearby reservoirs. Analysis of these events helps to identify source positions and focal mechanisms and will yield an insight into the corresponding reservoir processes.
Recording the 'diffuse' background noise wavefield and subsequent correlation of the response measured at different locations results in the reflection response (Green's function) of the medium (Wapenaar 2004). Repetition of this process at regular time intervals may reveal changes in the extracted reflection response as related to changes in the subsurface.
Combining the abovementioned passive monitoring techniques with active seismic tests at regular time intervals - sharing the installed sensor infrastructure - is expected to furthermore increase our understanding of reservoir properties and processes and to enable us to install permanent monitoring systems over storage sites in the future.

Topic 5: Monitoring CO_2 migration in porous media by electric impedance spectroscopy

Capillary pressure versus water saturation relations are used in subsurface flow engineering applications such as hydrocarbon production, soil remediation techniques, carbon dioxide (CO_2) sequestration, and groundwater flow in the vadose zone. Hysteretic behavior between the drainage (decreasing water saturation) and imbibition (increasing water saturation) of capillary pressure is widely observed and extensively investigated. This saturation history dependence of capillary pressure can be attributed to contact angle hysteresis, irreversible pore-scale fluid redistributions, and the interfacial area. Because capillary pressure is an interfacial property, it can be used as an indicator of the thermodynamic energy state. This results in a uniquely defined relationship for capillary pressure as a function of water saturation and interfacial area. Because all these phenomena also contribute to the complex permittivity of porous fluid-bearing rocks, simultaneous measurements of capillary pressure and permittivity may reveal the fundamentals and physical behavior of capillary pressure hysteresis.

We conclude that different mechanisms are responsible for both the capillary pressure and the complex permittivity behavior. In this work we investigate the capillary pressure and electric behavior for the sand - distilled water - gas system during main drainage and main imbibition. We have done several laboratory scale experiments for simultaneous measurement of capillary pressure and electric permittivity while controlling the water saturation under quasi-static flow conditions. Hysteresis in capillary pressure and electric permittivity is observed between drainage and imbibition in a wide frequency range up to the MHz range. It becomes more pronounced at higher water saturations, as shown in Figure 6 for the extreme values of 100 kHz, where hysteretic behavior is strong and for 3 MHz where hysteretic behavior is almost absent. Finally, we suggest that a better description of the capillary pressure hysteresis can be obtained from accurate permittivity data than from water saturation. This allows the monitoring of CO_2 for long times after it has been injected and the difference in drainage and imbition also allows for the detection of the flow direction at very small flow rates.

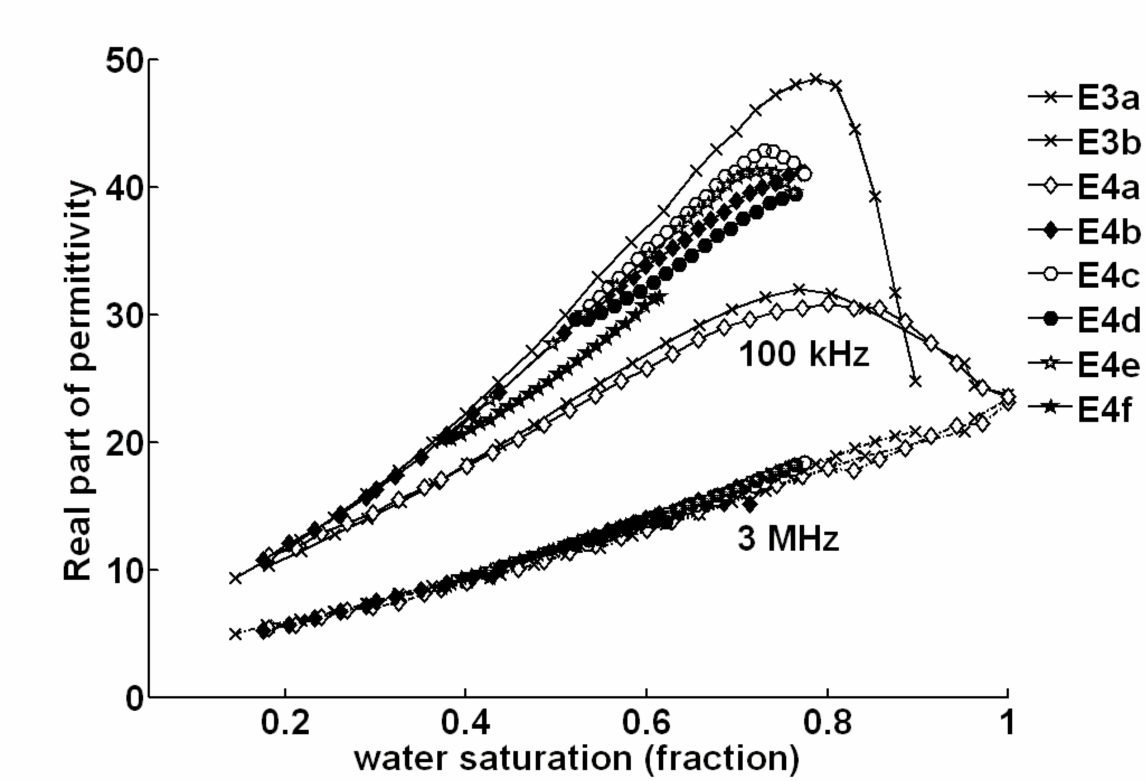

Figure 6: The permittivity as function of water saturation for the CO_2-sand-water system. E3a and E4a represent the primary drainage curves for the 8 bar and 13 bar pressure conditions, respectively and E3b and E4b are the corresponding secondary imbibition curves. The solid lines represent the real part of electric permittivity as a function of water saturation for the 100 kHz case and the dashed lines the 3 MHz case. The low frequency curves demonstrate clear hysteresis and non-monotonic behavior is observed where the secondary imbibition curves (E3b and E4b) are above the primary drainage curves (E3a and E4a). The 3 MHz, scanning curves (E4c-f), conducted for the 13 bar CO_2 case, coincide with the secondary imbibition curve. At 100 kHz, the drainage scanning curves (E4c,e) are above the imbibition curves (E4d,f) and approximate the secondary imbibition curve.

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