DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/40**

# Capture, Storage and Use of $CO_2$ (CCUS)

## Geophysical Methods to monitor injection and storage of $CO_2$
## (Part of Work package 7 in the CCUS project)

Marie Keiding

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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# Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective $CO_2$ capture technologies, (2) the potentials for both temporary and permanent storage of $CO_2$ in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the $CO_2$ usage potentials, including business case for converting $CO_2$ to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plant in Denmark.

The present report forms part of Work package 7 and focuses on geophysical monitoring of ground motion and $CO_2$ plume migration.

# Contents

# Dansk sammendrag

Geofysiske metoder kan bruges til at monitere om lagringen af $CO_2$ i undergrunden forløber som forventet. Metoderne kan bruges til at monitere eventuelle bevægelser på jordoverfladen eller udbredelsen af $CO_2$ i undergrunden.

Injektion af $CO_2$ vil få trykket i reservoiret til at stige, hvilket kan medføre hævning af de overliggende geologiske lag. En sådan hævning vil kunne måles på jordoverfladen med geofysiske måleinstrumenter som GPS, radar fra satellit og tiltmetre. Metoderne er meget præcise og kan registrere landhævninger på helt ned til nogle få millimeter med stor nøjagtighed. Det skal understreges, at det kan, men typisk ikke vil, føre til skader på bygninger og infrastruktur, at jordoverfladen eventuelt løfter sig i forbindelse med $CO_2$ lagring, fordi hævningen vil ske over et stort område med meget små gradienter. Moniteringen af bevægelser på jordoverfladen i forbindelse med $CO_2$-lagring udføres derfor primært for at holde øje med, om reservoiret reagerer som forventet, eller om der sker uventede bevægelser og eventuelt lækage langs svaghedszoner i undergrunden.

Andre geofysiske metoder kan bruges til at monitere udbredelsen af $CO_2$ i undergrunden. Til det kan en række forskellige metoder bruges: seismiske, gravimetriske, tryk og elektromagnetiske målinger, som kan udføres med sensorer på overfladen eller i borehuller. Resultaterne af målingerne kan efterfølgende omdannes til billeder af udbredelsen af den lagrede $CO_2$ i undergrunden, og kan være med til at afdække eventuel lækage fra reservoiret. Disse metoder kan både bruges til havs og på land. Den seismiske metode er indtil videre den mest effektive i forbindelse med lagring af $CO_2$, men forskellige metoder kan med fordel kombineres for at få indbyrdes uafhængige målinger.

# Summary

This chapter describes various geophysical methods relevant for monitoring of $CO_2$ injection. The methods are divided into two: those for monitoring ground motion, and those for monitoring the subsurface migration of the $CO_2$ plume. Both surface and subsurface monitoring techniques can be useful for detecting leakage or other unexpected behavior of the injected $CO_2$.

The ground motion monitoring can be based on a combination of remote sensing and ground based techniques: InSAR, GNSS, levelling and tiltmeters, that are capable of documenting millimeter scale uplift of the ground near the injection site. Uplift due to $CO_2$ injection may occur in areas with buildings and infrastructure, however, the uplift dome will typically be so broad that no damages will occur. The methods are primarily applied to ensure that the reservoir responds to $CO_2$ injection as expected and that no leakage occurs. Ground motion monitoring is currently only applicable for land-based $CO_2$ storage. Prior to the start of injection baseline data must be acquired at least one year in advance to establish the natural deformation patterns, including seasonal variations. The vertical seasonal signal on the order of +/-1 cm in Denmark will in most cases exceed the expected signal due to $CO_2$ injection.

The monitoring of the subsurface $CO_2$ plume migration can be based on a number of complementary geophysical methods: 3-dimesional seismic, gravimetry, pressure, and electrical resistivity surveys, that can be applied both offshore and on land. To date, 3-dimesional seismic monitoring is the most powerful method for tracking of subsurface $CO_2$ plume migration and early detection of leakage, however it is also a costly technique compared to the other described methods. For each of the monitoring methods, surveys must be performed before the start of injection to establish baseline and repeated during injection to produce time-lapse data showing the temporal evolution of the $CO_2$ plume migration.

# Introduction

Geophysical methods are widely applied to monitor surface deformation and to detect and map near-surface features by exploiting contrasts in the subsurface in a number of physical properties. This chapter describes state-of-the-art methods for geophysical monitoring relevant to $CO_2$ storage projects. The methods are grouped into two: ground motion monitoring and tracking of the $CO_2$ plume migration. While available methods for ground motion monitoring are primarily used on land, some underwater geodetic methods are available as described below. The geophysical methods for tracking $CO_2$ plume migration can be applied both offshore and on land.

In any $CO_2$ project, monitoring using geophysical methods is an important tool to control that the injected $CO_2$ behaves as expected and to detect any abnormal behaviour, e.g., due to leakage.

# Ground motion monitoring

The increase in reservoir pressure due to injection of $CO_2$ may induce deformation in the overlying strata causing the surface to rise. If $CO_2$ is sequestered on land, surface deformation may affect buildings or infrastructure. Potential ground motion due to $CO_2$ storage would usually be a broad uplift dome which would typically not lead to damages in buildings or infrastructure. However, surface deformation may be a sign that the reservoir is not behaving as expected, e.g., that the overburden is not as rigid as modelled or that $CO_2$ is migrating along a fracture zone, making ground motion monitoring an important tool for handling the safety in $CO_2$ projects. One important example of the use of ground motion monitoring is the In Salah project in Algeria, where observed uplift during $CO_2$ injection indicated movement along an unmapped fracture zone, as described below. This observation lead to the suspension of the project in 2011 due to concerns about the integrity of the reservoir seal (e.g., Rinaldi and Rutqvist, 2013).

## Surface deformation in Denmark

Denmark is located in a region with relatively little ground deformation, however, some processes are affecting the surface. A regional uplift is caused by glacio-isostatic rebound following the last deglaciation that started at 22 000 years before present, causing uplift of 0-2 cm/year in Denmark. Local ground movement is mostly seen as subsidence in coast-near cities built on reclaimed land. In addition, seasonal variations in the density of the troposphere globally causes a vertical signal, on the order of +/-1 cm in GNSS time series in Denmark (S. A. Khan, DTU, pers. comm., 2019).

Monitoring of ground motion of the planned $CO_2$ injection site should be initiated well ahead of the onset of injection as to establish a base line for the deformation. At least one year of base line monitoring is needed to document seasonal variations as well as local variations from the known regional deformation pattern.

A number of factors influence the risk of inducing surface deformation due to $CO_2$ sequestration, such as the type of reservoir, depth to the reservoir, the stiffness of the overlying strata, and the rate of $CO_2$ injection.

## Experiences from CCS projects worldwide

Surface deformation monitoring has been implemented in a number of $CO_2$ storage projects globally, such as Weyburn-Midale (Petroleum Technology Research Centre, 2015), Aquistore (Worth et al., 2017) and Quest (Larkin et al., 2019) in Canada, Decatur (Finley, 2014) and SECARB (Advanced Resources International, 2017) in USA, and In Salah in Algeria (e.g. Onuma and Ohkawa, 2009; Vasco et al., 2010).

While some projects have been in operation for years without causing measurable surface deformation, uplift have been observed in others. Ground motion caused by $CO_2$ sequestration have been observed in at least two incidences, the SACROC project in Texas, USA, and the In Salah project in Algeria.

In the SACROC enhanced oil recovery field in Texas, more than 175 million tons of $CO_2$ have been sequestered since 1972. The $CO_2$ is injected into a limestone reef mound formation at 2000 m depth. Injection rates were increased after 2004 to approximately 7.5 Mt per year, leading to surface uplift of up to 10 cm during 2007–2011 (Yang et al., 2015). Despite the fairly large rate of uplift, the SACROC project is functioning without any major safety issues.

In the In Salah $CO_2$ storage project in Algeria injection of $CO_2$ started in 2004. During the first years, 0.5–1 million tonnes $CO_2$ per year were injected at 1800-1900 m depth in a carboniferous reservoir overlain by more than 900 m low-permeability mudstone (e.g., Rutqvist et al., 2010). Prior to injection, surface deformation was not expected due to the fairly small volume of $CO_2$ injected compared to the overburden, however, the injection during the first five years produced a measurable uplift of approximately 5 mm/year, clearly correlated to the three injection sites (Fig. 1)(Vasco et al., 2010). One of the injection sites showed a double-loped uplift pattern, indicating that permeability was affected by an intersecting fault or fracture zone (e.g., Rinaldi and Rutqvist, 2013), which led to the suspension of $CO_2$ injection in 2011.

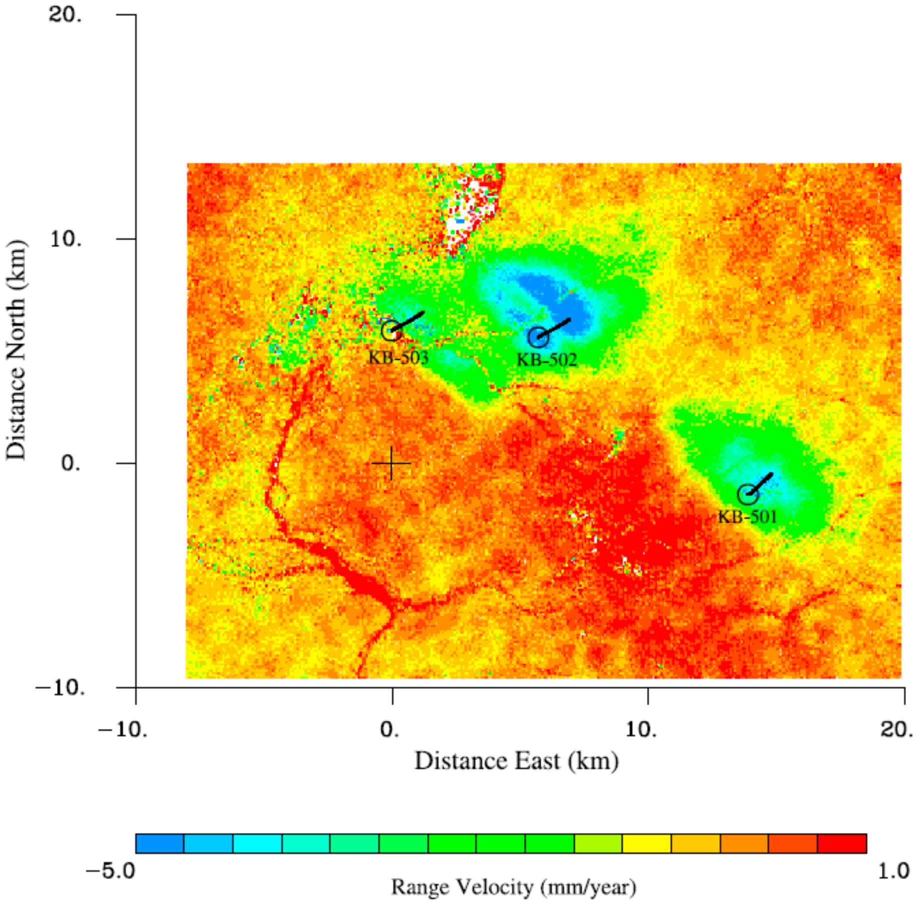

Fig. 1: InSAR displacement measured towards the satellite in mm/year for the In Salah field in Algeria, from year 2003 to year 2007. The three $CO_2$ injection wells are labelled (KB-501, KB-502, KB-503). The cross, which signifies the origin of the local coordinate system, is located at longitude 2.137° East and latitude 29.114° North. Figure reproduced from Vasco et al. (2010). See description if the InSAR method below.

Other $CO_2$ storage projects have been operating for years without causing measurable surface deformation. One such example is the Aquistore $CO_2$ storage project in Saskatchewan, Canada, where injection of $CO_2$ started in 2015 into a permeable sandstone interval approximately 150 m thick at 3200 m depth at a rate of 0.05 million tonnes $CO_2$ per year (Worth et al., 2017). Another example is the Midwest Regional Carbon Sequestration Partnership Michigan Basin, where $CO_2$ is been injected into an oil-depleted carbonate reef at a rate of up to 0.2 million tonnes $CO_2$ per year without causing measurable surface deformation (Gupta et al. 2017).

## Pre-injection modelling of surface deformation

The expected surface movement can be assessed by modelling prior to injection. Analytical models have the advantage of providing a quick assessment, whereas detailed numerical models can incorporate the structural and rheological complexity of the injection site.

A number of analytical models are available in the literature that can be used to fit geodetic data and infer source location and parameters, or, conversely, to predict surface deformation due to known source location and pressure change (e.g. Battaglia and Hill, 2009). Four such models are: 1. A point source simulating a small spherical expansion source (Mogi, 1958). 2. A finite spherical pressure source (McTigue, 1987). 3. A finite dipping prolate ellipsoidal pressure source (Yang et al., 1988). 4. A disk-shaped source simulating a finite, pressurized, horizontal circular source (Fialko et al., 2001). The analytical models typically make simplifying assumptions that the crust is elastic, homogeneous, and isotropic, however, careful use of the analytical models together with high quality data sets can in many cases produce accurate reproductions to observed surface deformation.

Numerical simulation of the surface response to reservoir pressure change can be obtained by coupled reservoir-geomechanical models (e.g., Rutqvist et al., 2010; Bissel et al., 2011; Morris et al., 2011; Shi et al., 2013). Such models allow incorporation of varying rheological properties of the geological layers at the injection site, fracture zone, anisotropic permeability, temperature and initial fluid pressure and stress.

## Data and instrumentation

*Interferometric Synthetic Aperture Radar (InSAR)* is a satellite-based technology capable of detecting mm-scale surface deformation in the line-of-sight of the radar (e.g., Massonnet and Feigl, 1998; Burgmann et al., 2000). The radar transmits electromagnetic pulses and receives the reflected signal. By interfering two images of the same area it is possible to map any changes in the line-of-sight distance from the satellite to ground between the acquisitions. The SAR satellites travel in polar orbits with side-looking geometry, hence the data are divided into ascending (moving towards North) and descending (moving towards South) geometries. By combining data from the two geometries, it is possible to resolve vertical and east-west ground motion. The method is less sensitive to north-south motion.

The method allows all-weather and day-and-night imaging. It works best where the ground reflectivity is high, i.e., in areas with sparse vegetation and objects such as houses or outcropping rocks. In areas with few or no natural reflectors, it is possible to install low-cost and low-maintenance corner reflectors (Fig. 2), to ensure good measurements at desired localities. Displacement time-series of corner reflectors and natural reflectors are obtained by processing multi-temporal SAR images using specialised processing techniques called Persistent Scatterer Interferometry (PSI) (Ferretti et al., 2001; Colesanti et al., 2003).

Fig. 2: Left: Corner reflector optimised for Sentinel-1 ascending and descending acquisitions. The reflector is 1 m wide and mounted in an agricultural field on three screw pegs inserted 1,5 m into the ground, Photo: Marie Keiding, GEUS. Right: GNSS station mounted on concrete pillar for long-term or permanent monitoring. Photo: UNAVCO.

A number of different SAR satellites have been operating since the early 90'ies. Two high-resolution SAR satellites, Sentinel-1A and -1B, were launched in 2014-2015 by the EU Copernicus Earth Observation Program. The satellites provide SAR imagery with a ground resolution cells of 5 x 20 m and revisit times of 6 days over Europe. Most of Denmark is covered by two overlapping satellite tracks in both geometries, hence data are acquired every three days in both ascending and descending geometry. All Copernicus data are available for full and free download, making InSAR a valuable and cost-effective tool for monitoring ground deformation for future $CO_2$ storage facilities.

*Global Navigation Satellite System (GNSS)* refers to a constellation of satellites that transmit positioning and timing data to GNSS receivers on ground. High precision GNSS receivers and double-difference processing of the signals can provide the three-dimensional location and displacement with time with sub-millimetre precision. InSAR and GNSS are often used together, because InSAR typically have a high spatial sampling while permanent GNSS stations have full temporal resolution. In addition, GNSS data provide the full 3-dimensional displacement data, which also helps interpreting the InSAR data in line-of-sight from satellite to ground.

*Levelling* is a simple but precise method to measure the heights of specified points or benchmarks relative to a datum. Repeated measurements of the same points can show the change in height, e.g., due to uplift. Levelling benchmarks are usually deployed in arrays. The levelling technique has been used extensively for both land inspection purposes and research for more than a century (e.g., Sturkell et al., 2008; Kierulf et al., 2012), but is today gradually being taken over by other, less time-consuming geodetic methods.

*Tiltmeters* are highly sensitive instruments that measure very small changes in inclination. When deployed along the sides of an uplifting (or subsiding) area, tiltmeters can provide very precise measurements of the vertical change. The instruments can be deployed either at surface or in shallow boreholes (Fig. 3). Tiltmeters are typically deployed in an array located at a range of radial distances from the injection well. In the Aquistore project in Canada, for example, an array of six tiltmeters have been deployed in 30 metre boreholes (Worth et al., 2014).


Fig. 3: Installation of tiltmeter in a shallow bore hole. Photo: UNAVCO.

## Underwater geodetic methods

The methods described above cannot be use underwater, however, geodetic methods have been developed specifically for monitoring sea bottom deformation, for example, to monitor inflation of ocean bottom volcanoes.

Tiltmeters have been specially designed for ocean bottom measurements (Fig. 4), some with possibility for acoustic data retrieval (Shimamura and Kanazawa, 1988). Such instruments can measure sea floor tilt and acceleration with very high precision (Fabian and Villinger, 2007), and may be relevant for offshore $CO_2$ storage projects.

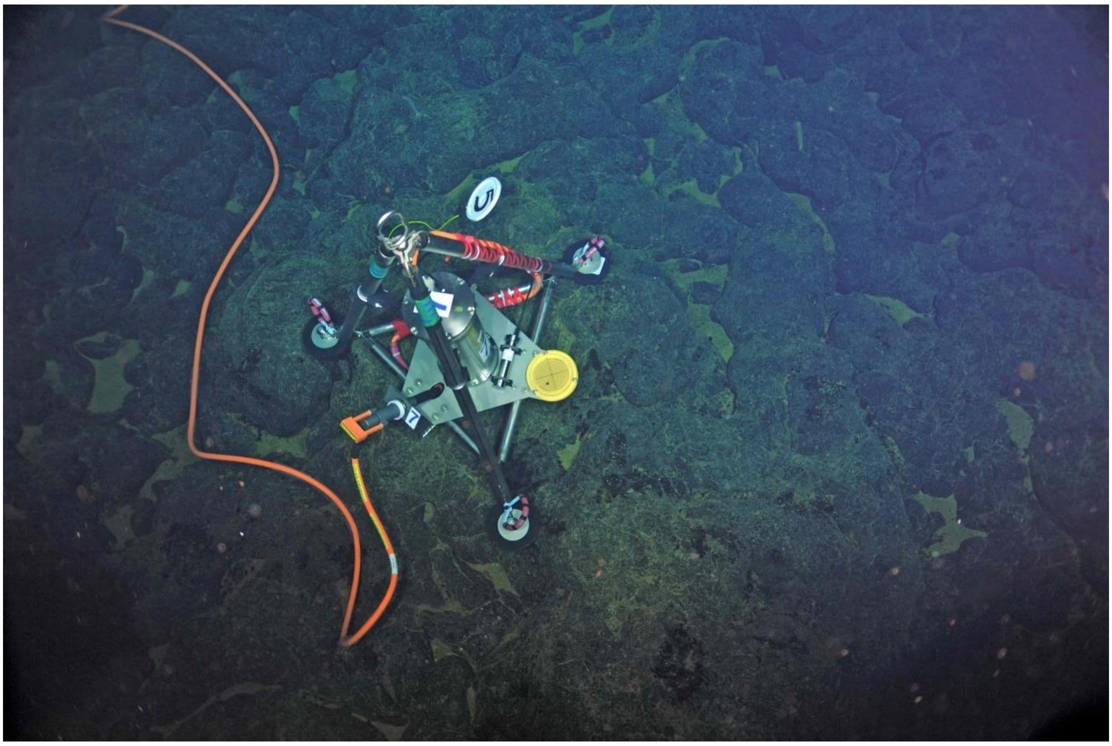

Fig. 4: Combined ocean bottom pressure and tiltmeter mounted on a tripod and deployed at a submarine volcano. Picture from the Ocean Observatories Initiative.

Other techniques for sea bottom geodesy are ocean bottom pressure recorders, which record ambient pressure as a proxy for seafloor depth (e.g., Chadwick et al., 2006), or acoustic ranging between pairs of instruments or combined GPS/acoustic positioning from ships (e.g., Obana et al., 2000). However, the uncertainties of these methods are on centimetre scale, making them little useful for monitoring uplift due to $CO_2$ sequestration at sea.

# Tracking $CO_2$ plume migration

Geophysical methods, often developed for monitoring of oil/gas reservoirs, have proven very useful to monitor the development and migration of the $CO_2$ plume in $CO_2$ projects globally. The methods described below include 3-dimensional seismic surveys, gravimetry, pressure monitoring, electrical resistivity and electromagnetic surveys. Each method is based on the change in bulk rock physical properties that results from the injection of $CO_2$. In each case, baseline data must be acquired prior to the start of injection, and the surveys must be repeated with the same configuration one or more times to map the change with time. Such repeated surveys are called time-lapse, e.g. time-lapse seismic, and applies to all the methods described below.

## 3-dimesional seismic

Repeated 3-dimensional seismic surveys, i.e., time-lapse 3-dimesional surveys (sometimes called 4-dimensional seismic surveys), have proven to be an important component of $CO_2$ storage operations. The technique has been used extensively by petroleum engineers since the 1990'ies to monitor changes in fluid saturation in oil and gas production fields (e.g., Staples et al., 2007), and can be used to monitor the replacement of brine by $CO_2$, also called $CO_2$ saturation, in a saline aquifer (Fig. 5). It has been implemented for $CO_2$ plume monitoring in, e.g., Sleipner, Norway (e.g., Arts et al., 2004; Chadwick et al., 2009; 2010), Ketzin, Germany (Juhlin et al., 2007; Ivanova et al., 2012;), Weyburn-Midale (White, 2009; 2011) and Aquistore, Canada (White et al., 2014), Cranfield (Ajo-Franklin et al., 2013) and Frio, USA (Daley et al., 2008), Otway, Australia (e.g., Pevzner et al., 2017), and Nagaoka, Japan (Saito et al., 2006). To date, seismic monitoring is the most powerful method for tracking of subsurface $CO_2$ plume migration due to its high spatial resolution and low detection threshold for $CO_2$ saturation (e.g., Fabriol et al., 2011).

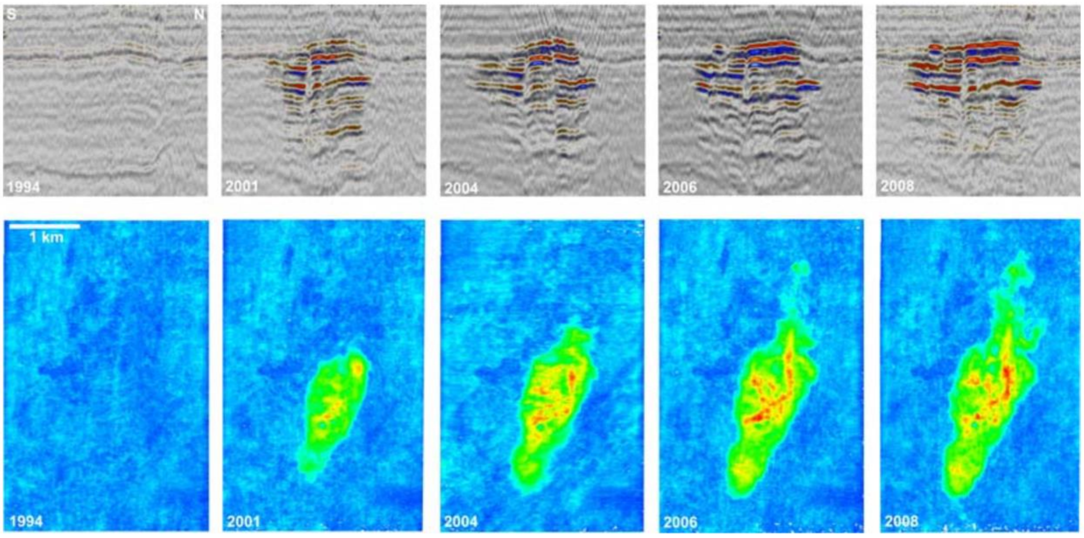

Fig. 5: Time-lapse seismic images of the Sleipner $CO_2$ plume during 1994-2008. Top panel: north-south section of the seismic data. Bottom panel: map view of total reflection amplitude in the plume. Figure from Chadwick et al. (2010).

In saturated porous rocks, the net seismic characteristics of the rock reflects the characteristics of the rock matrix (e.g., stiffness, porosity, and density), the nature of the fluid occupying the pore space, and the effective stress (the difference in confining pressure and pore pressure). Two types of seismic waves exist: compressional and shear waves. Compressional wave velocity of a rock or fluid is proportional to its bulk modulus and inversely proportional to its density, where the bulk modulus is a measure of the rock/fluid's incompressibility. The density varies little between fluid $CO_2$ and brine, and density will, therefore, have little effect on the seismic properties. The bulk modulus, on the other hand, varies considerably with a bulk modulus of $CO_2$ which is much smaller (G~0.3 GPa) than that of brine (G~3.0 GPa) and typical reservoir rocks (10-15 GPa). Thus, the overall rock stiffness will be strongly influenced by the composition of pore fluid, and even a small amount of $CO_2$ will result in an observable reduction in the compressional wave velocity. The compressional wave velocities typically decrease 6-10 % due to injection of $CO_2$ into a water-saturated porous sandstone (Xue and Ohsumi, 2004; Shi et al., 2007).

The shear wave velocity of a rock is proportional to its shear modulus and inversely proportional to its density, where the shear modulus is a measure of the rock's rigidity. Since shear waves cannot travel in fluids, the shear wave velocity is little affected by the pore fluid changes due to saturation of $CO_2$. The pore pressure change caused by the $CO_2$ injection will affect the seismic properties by changing the confining pressure. A study from Weyburn-Midale indicated that the effect on the seismic velocities could potentially be on the same order as the effect of $CO_2$ saturation on the compressional velocity (Brown, 2002). However, inspection of compressional and shear wave velocities in the Weyburn field gave a variety of evidence that $CO_2$ saturation effects dominate over pressure-induced effects in the compressional wave time-lapse seismic images (White, 2009). Localized changes in fluid pressure may be associated with leakage, e.g., along a fault, in which case compressional and shear wave seismic data may be a useful as a detection tool (e.g., Chadwick et al., 2006).

Seismic surveys can be performed as surface seismic surveys, where both source and sensor are deployed on the surface in a field-scale area, or as cross-well seismic surveys, where the seismic source is deployed from one borehole and the signals are recorded by receiver sensors deployed in one or more monitoring bore holes. The cross-well seismic survey has the potential of providing very high spatial resolution in the near-well region and is an effective tool for determining $CO_2$ distribution for interwell distances of 10-100 m and thin reservoir units of 1-10 m (Daley et al., 2008).

Rock physics analyses must be conducted as part of the time-lapse seismic analysis, to establish the effects of the $CO_2$ saturation on the reservoir's seismic properties. This can be done by direct measurements on cores or well logs and by modelling. A theoretical basis for estimating the effect on seismic velocities due to replacement of the pore fluids is provides by the Gassmann's equations (Gassmann, 1951).

A recent development in seismic monitoring is the use of fiber-optic distributed acoustic sensing (DAS), in which fiber-optic cables are used sensors for seismic signals. DAS system has the potential of having thousands of sensors permanently deployed in the subsurface, at relatively low cost. The method is currently under development and is also been tested in $CO_2$ storage projects, such as the SECARB and Citronelle projects in USA, Otway in Australia and Ketzin in Germany (e.g., Daley et al., 2013; Harris et al., 2016).

## Gravimetry

Repeated measurements of the gravitational acceleration due to the distribution of mass within the subsurface can be used to detect changes in a reservoir due to $CO_2$ injection. Gravimetric instruments are highly sensitive and capable of detecting even small variations in gravity such as the replacement of a reservoir rock's pore fluid from brine to $CO_2$. Gravimetric measurements have proven useful in, e.g., Sleipner, Norway

(Chadwick et al., 2006; Nooner et al., 2007; Furre et al., 2017), SECARB, USA (Dodds et al., 2013), and Tomakomai, Japan (e.g., Goto et al., 2019). Sea bottom gravimetric measurements produces a spatial resolution which is lower than that of the seismic method, however, time-lapse gravimetry may be an important low-cost complementary to seismic monitoring.

Gravity measurements may be particularly useful for detection of leakage from the predicted reservoir, especially if the $CO_2$ plume is migrating to shallower depths (Wilkinson et al., 2017). The *in situ* density of $CO_2$ depends strongly on the pressure, i.e., the depth at which it is located. The density of $CO_2$ below 1000 meter is 600-700 kg/m3, but it decreases dramatically at shallower depths where part of the $CO_2$ turns to gas. Thus, migration to shallower depths may result in detectable reduction in the gravitational acceleration.

## Pressure

The pressure changes in the reservoir caused by injection of $CO_2$ can be quantified with pressure sensors deployed in bore holes. The method was developed for groundwater hydrology and contamination studies but is now also being implemented in some $CO_2$ storage projects. In the Decatur Project in Illinois, e.g., multilevel pressure measurements show that the $CO_2$ remains largely confined to the depth interval into which it was injected, with no buoyancy flow towards shallower levels (Strandli et al., 2014).

The injection of $CO_2$ into a saline reservoir causes a pressure build-up and displacement of the brine, affecting subsurface volumes that may be significantly larger than the $CO_2$ plume itself. Simulated water fluxes show that ahead of the $CO_2$ plume, the displaced brine flows mainly horizontally, with a slight upward component directly in front of the $CO_2$ plume. Within the $CO_2$ plume, there is buoyant flow of $CO_2$ and downward flow of brine due to gravity segregation (Birkholzer et al., 2009). The pressure responses are evident long before the $CO_2$ arrives at the monitoring well (Strandli and Benson, 2013).

Cross well pressure tests must be performed before the start of $CO_2$ injection to characterize the hydraulic conditions of the reservoir (Hu et al., 2015). $CO_2$ is injected in a source well, and pressure changes are monitored in one nearby monitoring well that acts as a receiver. By use of a well packer system water or brine is injected at various depths to generate a set of measurements for various source-receiver combinations.

Pressure measurement can also be used as input to an inverse problem, called pressure tomography, to obtain a 3-dimensional image of the reservoir's flow properties (Hu et al., 2015). The replacement of brine by $CO_2$ will affect the flow properties by increasing the compressibility of the fluid. The flow properties are derived from fluid injection/extraction tests by pressure data analysis.

## Electrical resistivity and electromagnetic

Repeated electrical resistivity tomography (ERT) or controlled source electromagnetic surveys (CSEM) are other methods for monitoring the development of the $CO_2$ plume. Both are based on a quantification of the electrical resistivity of the rock, which is a measure of how strongly the rock resists an electric current. For rocks, the resistivity depends on chemical composition as well as physical properties of porosity and fluid composition. Brine, due to its salt content, is highly conductive to electric currents. The replacement of brine with $CO_2$, therefore, significantly increases the electric resistivity of porous sediments (e.g. Bergmann et al., 2012).

In electrical resistivity tomography, electrodes are usually deployed in wells as vertical arrays that measure the resistivity at multiple depth levels (e.g., al Hagrey, 2012; Christensen et al., 2018). The electric current is either injected from a dipole source in a well or at the surface to allow for any cross-well, surface-to-borehole or surface-to-surface measurements (Kiessling et al., 2010; Bergmann et al., 2012). The resistivity data are subsequently inverted to provide tomographic images of the subsurface at different times. While cross-well data provide the best resolution, surface-to-borehole or surface-to-surface allows imaging over a larger area.

In controlled source electromagnetic surveys, an electric source is used to induce electric and magnetic fields to the ground. The induced electromagnetic field will depend on the subsurface resistivity distribution, hence, the measured electromagnetic field can be used to model the subsurface resistivity. The receiver electrodes are deployed at the ground or sea bottom. In marine surveys the electric source is deployed in the water slightly above the sea bottom, taking advantage of the conductivity of the sea water. Land-based electromagnetic surveys may be limited by technical issues related to high-power current transmission and high levels of electromagnetic noise in populated areas from, e,g., gas pipes and high voltage power lines. However, in the Ketzin $CO_2$ storage project in Germany, the method proved its usefulness with measured electromagnetic signals ten times higher than the noise (Girard et al., 2011).

The increase in resistivity due to $CO_2$ saturation will depend on the chemical composition and porosity of the rock. A high clay content, e.g., will reduce the increase in resistivity by $CO_2$ saturation (Nakatsuka et al., 2010). Therefore, a $CO_2$ saturation - resistivity relationship must be established for a given site using petrophysical experiments on core samples (e.g., Kummerow and Spangenberg, 2011).

Electrical resistivity tomography has been used to monitor the development of the $CO_2$ plume, e.g., at the Weyburn-Midale, Canada (White, 2011), Cranfield (Carrigan et al., 2013) and SECARB, USA (Hovorka et al., 2011) and Ketzin, Germany (Bergmann et al., 2012; Schmidt-Hattenberger et al., 2016). Controlled source electromagnetic methods have been applied to, e.g., the Ketzin project in Germany (Fig. 6) (e.g., Girard et al., 2011; Streich et al., 2011) and Sleipner project in Norway (Park et al., 2017). Although the electric methods do not provide the same resolution and detection threshold as time-lapse 3D seismics, both may provide a useful and low-cost supplement to other methods in $CO_2$ projects (Fabriol et al., 2011).

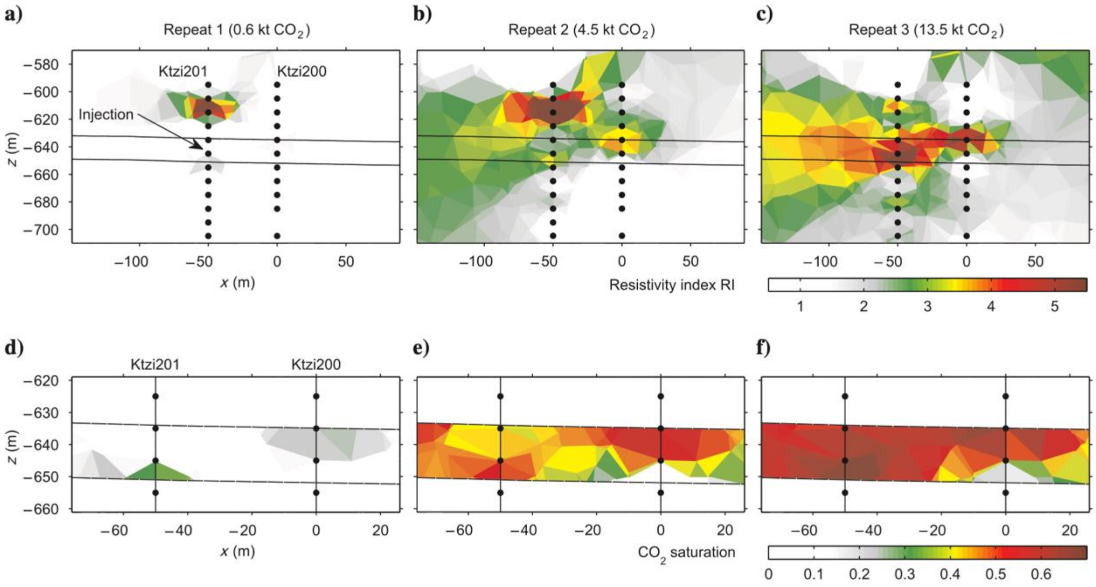

Fig. 6: Time-lapse resistivity tomography for the Ketzin site at three different times after start of CO2 injection. The black dots show location of receiver electrodes in two boreholes. The black lines delineate the approximate spatial extent of the reservoir sandstone. The resistivity index is the ratio of the repeat resistivity to the baseline resistivity. The high resistivity in the upper part of Ktzi201 might reflect problematic coupling conditions of the electrodes to the formation. Figure from Bergmann et al. (2010).

# Suggestions for supplementary investigations

The present overview is based on a literature review of state-of-the-art geophysical methods relevant for monitoring surface deformation and plume migration in $CO_2$ projects, with focus on $CO_2$ sequestration in saline aquifers. While many scientific papers have been published on the methods described herein, the published works do not provide a full overview of the experienced gained. E.g., results of surface deformation monitoring showing no deformation or methods tested without success may not have been published scientifically because of the "negative" results. We, therefore, suggest that a supplementary investigation should include direct contact to the companies/institutions responsible for geophysical monitoring at $CO_2$ projects to gain additional insight in the monitoring programs and experiences in relevant $CO_2$ projects globally.

Some geophysical methods have been developed to monitor gas leakage using acoustic sensors, e.g. in wells (distributed acoustic sensing) or from ship (multibeam). Further investigations should give a review of these methods.

Once a specific site for $CO_2$ storage has been selected, an appropriate monitoring program has to be defined based on the geological settings of the site and experiences from similar $CO_2$ storage sites. The proposed monitoring program must be evaluated with detailed feasibility analysis.

Baseline data must be acquired before start of injection for all geophysical methods that are intended to be used for the monitoring. We stress that surface deformation monitoring must be preceded with at least one year, and preferentially longer, of baseline data acquisition, in order to properly document any seasonal variations in the deformation field.

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