SUBsurface CO$_2$ storage - Critical Elements and Superior Strategy

Geophysical monitoring

FME SUCCESS Synthesis report Volume 4

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SUBsurface CO$_2$ storage - Critical Elements and Superior Strategy
Carbon Capture and Storage (CCS) is considered an essential mitigation strategy in order to reduce anthropogenic CO₂ emissions. To meet the 2°C target set in the Paris Agreement, decarbonization of the global power sector by the 2030s and the heavy industry sector beyond that is critical. CCS is currently the only option for decarbonizing the steel, chemical and cement industries.

CCS is a proven method (e.g. at Sleipner, Snøhvit, In Salah, Weyburn, Boundary Dam, Quest). There are remaining technical challenges related to upscaling, however, and cost is a critical factor in large-scale deployment of CCS.

In order to stimulate relevant research, the Norwegian Research Council has established a scheme of Centers for Environment-friendly Energy Research (FME) to develop expertise and promote innovation by focusing on long-term research in selected areas of environment-friendly energy, including CCS.

The FME SUCCESS center
The SUCCESS center for Subsurface CO₂ storage was awarded FME status in 2009 and was formally inaugurated on 1 January 2010.

Key to public acceptance and successful deployment of CCS, the FME SUCCESS center focuses on effective and safe storage of CO₂. To meet the regulatory requirements for Measurement, Monitoring and Verification (MMV), the SUCCESS center seeks to provide a sound scientific base for CO₂ injection, storage and monitoring in order to fill gaps in strategic knowledge, and to provide a system for learning and development of new expertise. Such knowledge is vital in order to ensure conformance (concordance between observed and predicted behavior), containment (proving storage performance in terms of security of CO₂ retention) and contingency (leakage quantification and environmental impacts).

The following objectives were defined in the FME SUCCESS application:

- To improve our understanding and ability to quantify reactions and flow in carbon storage.
- To develop advanced modeling tools for multiphase flow and reaction.
- To investigate the integrity of sealing materials, and test their retention capacity.
- To improve our understanding and develop new models for the relationship between saturation, flow and geomechanical response.
- To improve our understanding and develop new models for geochemical and geomechanical interactions.
- To improve our understanding and modeling tools for flow and reaction in faults and fractures.
- To test, calibrate and develop new monitoring techniques and instrumentation.
- To improve the understanding of shallow marine processes and the ecological impact of CO₂ exposure, and develop marine monitoring methods.
- To reduce risk and uncertainties in sub-surface CO₂ storage.
- To facilitate extensive and high-quality education on CO₂ storage.

Field excursion Unis CO₂ lab workshop, Svalbard 2012.
One of the strengths of the FME SUCCESS center is its expertise within fundamental, theoretical research, which is internationally recognized; the center hence focuses on basic research, interpreting the results of field and laboratory experiments in order to predict the long-term effects of CO₂ storage. In particular, the center has used the theoretical platform to address critical and relevant scientific issues related to CO₂ storage.

Upon inauguration, the SUCCESS center was organized into six scientific work packages and one educational work package:

**Mid-term evaluation**

In 2013, the Norwegian Research Council conducted a mid-term evaluation of the FME centers. The mid-term evaluation of the SUCCESS center concluded that the center needed to undertake major changes in the organization and operational structure to secure integration and industry relevance.

Following the recommendations of the mid-term evaluation, the SUCCESS center re-organized the scientific activities into three work packages:
- Work Package 1: Reservoir
- Work Package 2: Containment
- Work Package 3: Monitoring

An integration Work Package, WP0, was also established for the final two year-period of the center. WP0 aimed to test and verify new knowledge and methodology developed at the SUCCESS center in connection with two case studies. The Skade and Johansen formations were originally chosen as case studies. The Johansen Formation was later replaced by the Smeaheia project case, which is the selected reservoir candidate for Norwegian full-scale demo project.

**Final reports**

As part of the center's scientific reporting, the center's partners and board agreed that a set of reports would be written and
summarize the major scientific findings and achievements. These reports have been referred to as Long-term Deliverables (LTD).

Knowledge and lessons from the two field pilots, Snøhvit and Sleipner, have been synthesized in separate summary reports (Volume 6 and 7). Lessons from the Longyearbyen CO₂ Lab, which has been an important test site for the SUCCESS center, have been and will be published in dedicated summary volumes of scientific journals.

The case studies on the Smeaheia fault block (deep, confined reservoir) and the Skade Formation (shallow, saline aquifer) in the North Sea are presented in separate reports in order to demonstrate the value of the results achieved at the SUCCESS center and associated projects, and determine how they can be applied to better quantify the storage feasibility of untested aquifers. They allow testing of the lessons and knowledge from the Snøhvit and Sleipner field pilots, and may constrain the range and use of the methods and models developed.

The LTD reports (5) include the SUCCESS center final reporting, and they aim at synthesizing results and findings of the SUCCESS center and relate directly to the objectives of the SUCCESS center.

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The LTD reports cover the following topics:

1. **Storage capability (Volume 1)**
   - This report summarizes the SUCCESS center's work on storage capability, which is the ability of a formation to safely store CO₂. An important objective of this center has been to identify geological factors and the hydro-geomechanical processes that are most important for determining storage capability. The most important factor is whether the storage reservoir is open or closed.

2. **Injectivity (Volume 3)**
   - Summarizing the results from field, experimental and theoretical studies of potential leakage mechanisms and their relevance to CO₂ storage site risk assessment, this report demonstrates that viscous deformation of the shales can play an important role in their ability to keep CO₂ contained and that material properties and their dynamic behavior in response to the stress introduced by CO₂ injection need to be evaluated in order to safeguard operations.

3. **Containment (Volume 2)**
   - Summarizing the results from field, experimental and theoretical studies of potential leakage mechanisms and their relevance to CO₂ storage site risk assessment, this report demonstrates that viscous deformation of the shales can play an important role in their ability to keep CO₂ contained and that material properties and their dynamic behavior in response to the stress introduced by CO₂ injection need to be evaluated in order to safeguard operations.

4. **Conformance (Volume 4)**
   - The LTD reports cover the following topics:
     - **Geophysical monitoring (Volume 4)**
       - The geophysical monitoring report summarizes the SUCCESS center’s work on rock physics related to pore pressure and saturation and estimating these two parameters via geophysical monitoring. By estimating their spatiotemporal distribution, we can monitor the migration of injected CO₂ and determine whether the containment of storage complex is secure.

5. **Contingency (Volume 5)**
   - This report synthesizes relevant knowledge and data regarding marine monitoring methods and strategies for inorganic carbon in the water column, based on modeling and observational work. A cost-effective strategy for a marine monitoring program should optimize the probability of detecting a leak.
Relevance of work
The collective work of the SUCCESS center addresses various groups of stakeholders and the reporting structure is relevant to different communities. The report on storage capability is particularly relevant to storage site selection and Norwegian CO₂ storage capacity estimates, based on better constrained trapping efficiency and immobilization potential. The leakage risks report addresses important issues regarding safe operation of CO₂ storage and risk management. The report on injectivity provides valuable knowledge on the planning of CO₂ operations and reservoir utilization. Finally, there are two reports on monitoring: the report on geophysical monitoring addresses methods for measurement, monitoring and verification (MMV) of the subsurface; while the report on marine monitoring is particularly relevant to risk management and mitigation in the event of leakage to the water column.

Future work and recommendations
CO₂ storage has been successfully demonstrated at Million-tonne scale, but needs to be ramped up to Giga-tonne scale in order to achieve global emissions reductions targets. A shown in the report on Large-scale Storage of CO₂ on the Norwegian Shelf, there are no technical showstoppers for ramping up CO₂ storage (Tangen et al., 2014). However, ramping up to Giga-tonne scale requires 1) better estimate of storage capacity, 2) better pressure management strategies, and 3) smart methods for controlling and optimizing CO₂ injection (Nøttvedt, A., pers. comm. "Mission innovation workshop", 2017).

Better estimate of storage capacity requires more reliable forecasting of CO₂ migration and trapping processes, with range of uncertainties. This, in turn, requires improved physics and chemistry-based understanding of CO₂ flow and transport processes at multiple scales within heterogenous rock media.

Better pressure management strategies imply control on pressure limits at both near-well and reservoir scales and quantification of allowable pressurization. Consequently, better understanding of the effects of stress field, pressure history, reservoir/caprock heterogeneities, including faults and fractures, is needed.

Smart methods for controlling and optimizing CO₂ injection include effective control and handling of transmissivity, near-well geochemical processes, formation damage, etc. Well stimulation and next-generation well technologies need to be demonstrated to enable large-scale CO₂ injection. Future advances in CO₂ storage will likely occur at the interface between industry and academia and be coupled to the execution of ramp-up CO₂ storage projects.
Geophysical monitoring
# Table of contents

The FME SUCCESS center on CO$_2$ storage .......................................................... 2
Preface .................................................................................................................... 8
Abstract ............................................................................................................... 9
Introduction ........................................................................................................ 10

## CO$_2$ rock physics and advanced laboratory work

- The effect of sub-core scale heterogeneities on geophysical properties .................. 13
- Multidirectional and multilevel acoustic and resistivity measurements ................. 15
- CO$_2$ flow through a natural fracture .................................................................. 15
- Temperature and pressure-dependent velocity of CO$_2$-saturated sandstones ........ 16

## Methods for geophysical data analysis

- Shape representation and identification ............................................................. 17
- Multilevel parameter estimation ....................................................................... 18
- Uncertainty quantification and ensemble-based methods ................................. 18
- Joint use of disparate geophysical data types ................................................. 19

## Field case studies

- CSEM data study on the Sleipner CO$_2$ storage site ........................................ 21
- Gravity and subsidence monitoring of CO$_2$ injection at Sleipner ...................... 22
- Skade synthetic data study .............................................................................. 22

## Conclusion and recommendations ................................................................... 27

## Reference ........................................................................................................ 30

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Preface

This document is a synthesis report on the geophysical monitoring work under Work Package (WP) 3 at the FME SUCCESS center, summarizing the main findings from all of the activities during the past 8 years. The other part of WP3 (marine monitoring) is available in a separate synthesis report.

This report begins with a brief introduction of the motivations and objectives of WP3, geophysical monitoring. The next two sections explain the main results and findings from 1) CO₂ rock physics via advanced laboratory work and 2) joint geophysical data inversion algorithms, respectively. A series of field-scale case studies with real and synthetic data are presented next, and we demonstrate how all the lessons learned at the SUCCESS center can be applied to industrial-scale operation. The report concludes with a list of recommendations that can serve as good guidelines for monitoring upcoming CCS projects.

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"A series of field-scale case studies with real and synthetic data are presented next, and we demonstrate how all the lessons learned at the SUCCESS center can be applied to industrial-scale operation."
Abstract

Carbon Capture and Storage (CCS) should be based on multidisciplinary science and engineering. With this in mind, the SUCCESS center has planned its 8-year program and contributed to the development of CCS through activities like development of theory, laboratory experiments, numerical simulations, field-scale studies, etc. This report summarizes the activities and main findings under WP3, geophysical monitoring.

Measurement, monitoring and verification (MMV) describes a set of activities designed to verify the conformance and containment of a CO₂ storage site by estimating injected volumes and the potential extent and location of sequestered CO₂. The SUCCESS center has therefore focused on increasing its understanding of the rock physics related to pore pressure and saturation, and on estimating the two most important parameters via geophysical monitoring. By estimating the spatiotemporal distribution of these two in situ parameters, we can monitor the migration of injected CO₂ and also safeguard the containment of the storage complex. Unexpected barriers can also be encountered, e.g. when the migration observed differs from the predictions.

We have learned the following through our geophysical monitoring in WP3. P-wave amplitude is more sensitive to minor changes in fluid migration patterns than P-wave velocity. This suggests that full waveform inversion (FWI) may be an important tool in order to increase the accuracy of seismic data interpretation. We have also found that the electrical resistivity method is crucial to CO₂ plume monitoring, particularly when the fracture flow is the dominant mechanism for migration and storage. A novel inversion approach is developed by solving CSEM or gravity sequentially, then seismic AVO inversions, and is shown to be more accurate than AVO inversion alone. Finally we provide a set of recommendations that the SUCCESS center believes are important for an industrial-scale framework for CCS geophysical monitoring.

"... the electrical resistivity method is crucial to CO₂ plume monitoring, particularly when the fracture flow is the dominant mechanism for migration and storage. A novel inversion approach is developed by solving CSEM or gravity sequentially, then seismic AVO inversions, and is shown to be more accurate than AVO inversion alone."
Carbon Capture and Storage (CCS) is a proven technology which can significantly reduce the amount of anthropogenic greenhouse gas emissions to the atmosphere, and can meet the demands in e.g. the European Commission’s Energy Roadmap (2011) and the Paris Agreement (2015). The technology initially had three main activities: capturing, transporting and storing. Application is also gaining importance.

One of the challenges associated with CCS is to deal with the Earth’s natural variations, particularly in relation to storage. It is well known that fluid can be produced from or injected into the subsurface, which has been a petroleum industry practice for over a century. However, due to the enormous uncertainties in the information available about the Earth’s subsurface, such a long-term practice still requires great scientific and engineering expertise, whenever and wherever it is executed.

The FME SUCCESS center has focused its efforts on increasing human understanding of the behavior of the planet’s subsurface during the process of CO$_2$ injection and migration. With such a high ambition, the FME SUCCESS center is divided into 3 work packages (WP): reservoir, containment, and monitoring. WP3 Monitoring in turn is composed of two parts: Geophysics and Marine. This report summarizes the activities and deliverables from Geophysical monitoring.

Monitoring should therefore be based on broad-ranging activities. The operator must continuously (and in real time) compare the actual (or observed) and modeled behavior of CO$_2$ and formation water in the storage site in order to quantify whether or not there are any significant irregularities, barriers or anomalies, and also to detect any CO$_2$ migration and leakage towards the surface. In both the short and long term, the operator should also update the assessment of the safety and integrity of the storage complex, including the assessment of whether the CO$_2$ stored will be completely and permanently contained. Through such extensive efforts, the operator can fulfill its duty of risk assessment and risk management in relation to injectivity, capacity, conformance and containment (Pawar et al., 2015).

In the context of monitoring, the geophysical data contribute most and directly to the last two themes. Conformance means ensuring the performance of the CO$_2$-injected reservoir by verifying that all observations during the injection operation are within the range of expectation and prediction. For example, the CO$_2$ plume distribution in Sleipner observed through seismics in the early stage was very different from what had been predicted before injection, e.g. in connection with the interlayering structures in the Utsira Formation.

"This report summarizes the activities and deliverables from Geophysical monitoring."

... we need to acquire and analyze useful physical parameters that can tell us what is happening in the subsurface, so that we can react if and when necessary.
Geophysical monitoring

"The CO₂ saturation allows us to validate whether or not the subsurface and injection operation work as planned or according to predicted models ...."

Containment means showing that there are no signs of hazards throughout the CO₂ storage complex, including the reservoir, caprock, over/underburden and the water column. One of the main concerns is caprock integrity, including the fault reactivation risk, and eventually leakage to the surface and/or contaminating ground water. The injection at well KB-502 of the In Salah project is believed to have reactivated an existing vertical fault across the injection perforation. However, there is no evidence in the literature that this has developed further and caused a leakage to the surface (White et al., 2014).

The measurement, monitoring and verification (MMV) obligation will be deemed to have been met once all of the steps above are fully assessed and documented.

In order to execute the monitoring duties described above, we need to acquire and analyze useful physical parameters that can tell us what is happening in the subsurface, so that we can react if and when necessary. Such parameters should be quantitative rather than qualitative, so that e.g. associated uncertainties can also be estimated (Jenkins et al., 2015).

At the SUCCESS center we therefore chose two in situ physical parameters for CO₂ saturation and pore pressure in the whole subsurface of a CCS project site, not just next to wells. The CO₂ saturation distribution tells us how much of the injected CO₂ is migrating away from an injection well e.g. when interacting with barriers and where it is migrating to. The CO₂ saturation allows us to validate whether or not the subsurface and injection operation work as planned or according to predicted models (conformance with respect to e.g. injectivity, capacity).

We can also find unknown subsurface barriers or new fluid migration paths. The pore pressure, on the other hand, indicates how the injected CO₂ physically influences the reservoir and caprock, e.g. whether it initiates favorable or unfavorable fractures/deformation (containment). Once the two spatiotemporal parameters have been established, we may apply a multiphysics approach of combined flow and geomechanics, and we may evaluate physical interaction between the injected CO₂ and the subsurface (the reservoir, caprock/overburden, faults, fractures, etc.) in more quantitative terms.

This was one of the main activities in WP1 and WP2 at the SUCCESS center (for the Sleipner, Snøhvit and In Salah fields) (as mentioned in page 4). If there is any deviation from the scenarios expected, which should not be any surprise, considering that Sleipner, Svelvik, Snøhvit, In Salah, etc. all had unexpected observations, the injection plan must be modified and, if needed, the whole subsurface should be re-evaluated in order to make sure the injection operation is safe and optimized. For example, the Snøhvit project experienced a persistent increase in pressure, eventually reaching the estimated minimum fracture pressure. In 2011, injection therefore moved from the Tubåen Formation to the Stø Formation, and the injection operation subsequently stabilized. Geophysical time-lapse data played an important role in providing reservoir-scale distribution of pressure and saturation (Grude et al., 2013).

Knowing (or estimating directly) the in situ CO₂ saturation and pore pressure is nonetheless not a trivial task. The injection data (bottomhole pressure and temperature) are always available, albeit only providing information for near the injection wells (or even points), which does not provide reliable parameters for the whole subsurface. The injection data also provide the injected volumes. The injection data alone do not tell us if all of the injected CO₂ is contained within the reservoir as planned. In addition, even if it is all within the reservoir, we cannot know how it is distributed within the reservoir, whether there is any risk to the caprock integrity away from the injection points or potential leaks or pressure build-up through faults, or whether any new subsurface features are identified (e.g. new barriers). It is also important to note that the pressure induced by injection propagates much faster and farther from the injection well than the CO₂ saturation. It is therefore important to not only understand but also to distinguish the effects of pore pressure and CO₂ saturation.

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In order to achieve the goals mentioned above, the SUCCESS center’s WP3 geophysical monitoring group has focused on the following two scientific aspects:

- Development of CO₂-related rock physics and mechanics based on advanced laboratory tests.
- Development of joint geophysical data inversion algorithms.

Rock physics and mechanics are two critical elements that link geophysical data to the spatiotemporal distribution of the physical parameters that we need to know (i.e. saturation and pore pressure). CO₂ injection introduces a multiphase flow phenomenon to the subsurface, and the interactions between different fluids and between fluids and rock formations become complicated. Such questions can be answered through advanced laboratory tests under in situ stress conditions (e.g. High Pressure High Temperature (HPHT) triaxial cell, CT imaging, multidirectional measurement). This was the first area of focus of WP3 geophysical monitoring.

The second area of focus was the development of optimized inversion algorithms in order to handle different data sets jointly maximizing the amount and quality of information extracted from the geophysical data acquired. The main objective was to discriminate the effects of pore pressure and saturation on the geophysical data. We therefore developed an innovative approach of sequentially inverting different geophysical data. We then applied the achievements to a set of field case studies using both real and synthetic data, and performed a further evaluation.

The two field cases of Sleipner and Skade were considered. This work and the results are summarized in the following sections. Section 2 describes the work related to the rock physics laboratory tests and models. Section 3 explains the joint inversion algorithm development, by combining seismic, gravity and electromagnetic (EM) data. Section 4 demonstrates how we applied what we have learned to a field-scale environment, by utilizing both real and synthetic data. Section 5 concludes the document by making recommendations.
Within the geophysical monitoring group at the SUCCESS center’s WP3, we have developed and applied a set of advanced rock physics laboratory facilities in order to improve our understanding of the physical behavior of CO$_2$ in relation to multiphase flow (CO$_2$ pressure, temperature, saturation and distribution-pattern), and its effects on geophysical parameters under the subsurface storage environment.

We have also investigated CO$_2$ flow behavior in both matrix and (natural) fracture in sandstones. Such scientific findings are essential for effective monitoring (MMV), where field-scale geophysical parameters such as density, seismic velocity and electrical resistivity are analyzed further and interpreted in order to estimate changes in pressure, temperature, saturation and distribution in a CO$_2$ storage subsurface.

The advanced laboratory tests have led to detailed findings on the relationship between these physical parameters, and we are evaluating them with respect to existing rock physics models. More work needs to be done, but we are now ready to interpret the geophysical data acquired from CO$_2$ injection sites and quantify the fate of the injected CO$_2$. With future developments e.g. at the Norwegian CCS Research Center or other platforms, we will keep learning and improving our ability to understand, interpret, model and apply rock physics principles for monitoring the behavior and extent of CO$_2$ in a storage reservoir.

**The effect of sub-core scale heterogeneities on geophysical properties**

Sub-core scale heterogeneity in a rock formation governs the physical behavior of the subsurface when CO$_2$ is injected and stored. Such effects must be taken into account during geophysical data interpretation, but were previously not much investigated using high resolution sub-core scale imaging together with measuring both acoustical and electrical properties, mostly either acoustics or resistivity (e.g. Nakatsuka et al., 2010). The SUCCESS center therefore explored the effects of sub-core scale heterogeneity on CO$_2$ flow patterns and saturation, and the acoustical and electrical properties of a typical reservoir rock by performing drainage and imbibition flooding tests with CO$_2$ and brine (Alemu et al., 2012). An industrial X-ray CT scanner was therefore deployed and used to map 3D images of CO$_2$ distribution and saturation levels during the flooding tests. The geophysical properties (acoustical velocity and electrical resistivity) were measured concurrently. The results show how the bedding and flooding directions influence the multiphase fluid distribution and saturation.

For a given saturation level resulting from the CT image interpretation, the measured changes in the acoustical and electrical parameters have been found to be affected by both the fluid distribution pattern and the bedding orientation, relative to the measurement direction. Most importantly, we learned that the P-wave amplitude and the

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electrical resistivity are more sensitive to small changes in the fluid distribution patterns than the P-wave velocity (Figure 1).

The fact that the amplitude is more sensitive to changes than the wave velocity suggests that full waveform inversion (FWI) will be a sought-after tool in the future. Furthermore, the change in amplitude was most affected by the bedding orientation and the resulting fluid distribution patterns.

In some cases, the change due to the fluid distribution pattern was higher than the variation caused by the change in CO$_2$ saturation. As a result, it is not straightforward, albeit still feasible, to apply Gassmann’s relation based on a ‘uniform’ or ‘patchy’ saturation pattern for prediction of P-wave velocity variation. Overall, the results demonstrate the importance of core imaging by improving our understanding of fluid distribution patterns and the associated effects on measured rock-physics properties (what to monitor). We must now scale up the findings to the reservoir and field scale.

The P-wave amplitude and the electrical resistivity are more sensitive to small changes in the fluid distribution patterns than the P-wave velocity.

The geophysical property change due to the fluid distribution pattern was higher than the variation caused by the change in CO$_2$ saturation. As a result, it is not straightforward, albeit still feasible, to apply Gassmann’s relation based on a ‘uniform’ or ‘patchy’ saturation pattern for prediction of P-wave velocity variation.

Figure 1 (Left panel) P-wave velocity variation against calculated CO$_2$ saturation; (Middle panel) Amplitude of first-break P-wave variation versus CO$_2$ saturation, normalized with respect to that with full brine saturation; (Right panel) Rock resistivity variation against calculated CO$_2$ saturation. Note that all the upper rows apply to the perpendicular to bedding sample and all the lower rows to the parallel to bedding sample.

Figure 2 P-wave velocity and electrical resistivity versus injected CO$_2$ in pore volume (PV), measured simultaneously at different levels/points and directions during CO$_2$ flooding test with Gres Des Vosges (GDV).
Multidirectional and multilevel acoustic and resistivity measurements

A novel apparatus has been developed to measure not only simultaneously acoustical velocity and electrical resistivity, but also to measure in multiple directions (axial and radial) and multiple levels (top, middle, bottom) along a core sample (Omolo, 2016; Tran, 2016). The new apparatus can therefore provide useful heterogeneity parameters as well as anisotropy.

Such apparatuses can be found in the literature but providing only acoustic or electrical measurement (e.g., North et al., 2013). In addition, particularly in connection with CO₂ flooding tests, it can monitor how the injected CO₂ flows through a core (breaking through at different levels) by directly measuring geophysical parameters (velocity and resistivity), which can complement the 3D image interpretation of the X-ray CT scanner.

Two MSc students at the University of Oslo (UiO) worked with the SUCCESS center’s geophysical monitoring group and conducted extensive experiments with the new apparatus, covering the Gres Des Vosges, Red Wildmoor and Berea sandstones. The core sizes were similar, but the flow properties (porosity, permeability) were different. The resulting data sets were large, and are still being analyzed. Figure 2 shows an example of processed data, where it can be clearly seen that the multidirectional and multilevel novel apparatus does a good job of capturing the flow flooding steps at the different levels, which is indicated through sudden drops (in velocity) or increases (in resistivity) (Soldal et al., 2015). In addition, the velocities and resistivities are different at each level, indicating the strong sub-core scale heterogeneity. When combined with CT image analysis, the novel apparatus would maximize the information extraction for laboratory tests. Furthermore, this multiple-point and multiple-level data can be used for upscaling or homogenization.

The new apparatus can provide useful heterogeneity parameters as well as anisotropy. In addition, particularly in connection with CO₂ flooding tests, it can monitor how the injected CO₂ flows through a core (breaking through at different levels) by measuring directly geophysical parameters (velocity and resistivity).

The velocities and resistivities are different at each level, indicating the strong sub-core scale heterogeneity. When combined with CT image analysis, the novel apparatus would maximize the information extraction for laboratory tests.

CO₂ flow through a natural fracture

Most rock formations include fractures which can serve as fluid migration paths and/or storage spaces. With respect to CO₂ storage, it is therefore important to know how the fracture influences CO₂ fluid migration or storage capacity, and see how we can monitor the process, not only the matrix (e.g., Aluem et al, 2012; Nakatsuka et al., 2010). In order to investigate fracture flow properties and to evaluate changes in geophysical responses (velocity and resistivity), a PhD student at UiO together with the Norwegian Geotechnical Institute (NGI) rock physics group conducted simultaneously fluid flow and geophysical measurements on a single naturally-fractured tight sandstone core plug using the multidirectional and multilevel apparatus (Nooraiepour et al., 2018). They tested a low-porosity low-permeability naturally-fractured core sample of the De Geerdalen Formation acquired from the Longyearbyen CO₂ research laboratory in the Arctic (Svalbard, See Figure 3). The geophysical moni-

Figure 3 (left) Illustration of naturally-fractured De Geerdalen sandstone core plug studied with fracture plane extracted from CT scanning; (middle and right) Changes to normalized geophysical properties during drainage of brine by CO₂ out of the fracture.
The observed velocities at different T and P conditions for (upper row) the Red Wildmoor sandstone core plug and (lower row) for Knorringfjellet sandstone core plug.

"Seismic velocity changes were mainly linked to significant changes to CO₂ density and the corresponding bulk rock moduli over the critical point."
methods for geophysical data analysis

Geophysical monitoring of CO₂ sequestration has a number of important objectives related to both operational safety and efficiency, such as to verify proper CO₂-plume placement and use of storage capacity, to provide warnings about potentially hazardous pressure build-up in the aquifer, to provide warnings about a potential CO₂ leakage towards the seabed, and to verify fluid-flow simulation results used in the design of the CO₂ injection. As written in the FME SUCCESS synthesis report on Potential Leakage Mechanisms, CO₂ migration through an intact shale takes a very long time (about 1000 to 10,000 years for 100 m thick caprock).

However, if there is leakage through induced pathways, the migration or flow rate would be much faster, and should be detected by geophysical monitoring. These objectives suggest that the following scientific challenges should be addressed when developing data analysis (inversion) methodology: quantification of saturation and pressure changes from time-lapse geophysical data, or quantification of the effects of saturation and pressure changes on elastic parameters and electric conductivity.

Quantification of uncertainty regarding these results should also be addressed. Furthermore, the computational complexity involved should be manageable, so that the methodologies involved are practical in an operational setting.

Literature review shows that a methodology for quantification of saturation and pressure changes based on linearization of the rock-physics model and calibration with respect to laboratory and in situ well measurements has been developed (Landrø, 2001). The core of this methodology has been applied in order to discriminate the pressure and saturation changes for CO₂ storage at the Snøhvit field (Grude et al. 2013). On the other hand, the methodology developed in the SUCCESS center does not rely on a linearization of the rock-physics model or calibration with respect to laboratory and in situ well measurements.

Part of the methodology (ensemble-based methods) provides quantification of the uncertainty in the estimated quantities as an integral part. It allows for a sequential approach where data with lower resolution (EM, gravimetry) can be applied in order to improve the prior model for the inversion of a data type with higher resolution (seis-mics). It has been applied in order to improve discrimination between the effects of pressure changes and saturation changes on seismic P-velocity changes (see Figs. 9–12 in the current section, and the Skade synthetic data study in Section 4.) The methodology has several novel aspects which are described below in greater detail.

Shape representation and identification

We illustrate the concept of shape representation in Figure 5 using three examples. The figure shows an artificial ‘true’ geological strata sequence and two ways of representing the strata for the purpose of numerical calculations: grid-cell representation and approximate region-based (shape) representation. A grid-cell representation may not be an economical choice when seeking to identify this type of geology (for example, too many grid-cell values could be required). It seems more natural to seek to identify the strata boundaries directly using a region-based representation of the geology.

A similar situation occurs with geophysical monitoring of CO₂ sequestration. Although the particular spatial locations where saturation and/or pressure changes occur should be quantified, it could be computationally challenging to achieve this with grid-cell precision. As an alternative, we there-

Figure 5 ‘True’ geological strata (left), grid-cell representation (middle), approximate shape representation (right).
fore seek to identify the approximate shape and location of regions where saturation and/or pressure changes occur, while internal variation within these regions is modelled using significantly fewer parameters than with a grid-cell parameterization. This means that we primarily view these inverse problems as shape identification problems. The particular shape representation methodology we use was proposed in Berre et al. (2009) and further developed in Berre et al. (2011), and Tveit et al. (2015a, 2015b).

A shape representation approach uses significantly fewer inversion parameters than a grid-cell parameterization.

**Multilevel parameter estimation**

During the first part of the SUCCESS project period, we applied sensitivity matrix-based optimization methods in conjunction with shape representation in order to solve the inverse problems involved in geophysical monitoring. The number of unknown parameters should be moderate in order for sensitivity matrix-based optimization methods to be computationally feasible and stable. In addition, many cases require strong restrictions on the type of solutions to the inverse problem that are acceptable (regularization). For geophysical monitoring, the restrictions are far from obvious. A moderate number of parameters seems hence desirable, also for stability reasons.

The number of parameters applied in the shape representation will, however, influence the representation’s ability to faithfully portray the true shapes of the regions sought. This can be seen in Figure 5, for example, where the shape representation (right) has too few parameters to fully represent the true geology (left). This illustrates that one should aim to work with as many parameters as allowed with respect to stability and computational complexity issues. As that number is unknown prior to the inversion, we have further developed multilevel parameter estimation strategy proposed in Grimstad et al. (2003).

The basic idea of multilevel estimation is to solve a sequence of inverse problems where the number of unknown parameters is gradually increased until the stop criteria advise that the inverse problem will become unstable if more parameters are introduced. Multilevel shape representation applied to a synthetic CO$_2$ plume is illustrated in Figure 6, while the final results from a multilevel estimation are compared to those from single-level estimation with the same number of parameters as in the last level in the multilevel estimation in Figure 7. The importance of performing the estimation in a multilevel manner in order to avoid instabilities is evident.

A multilevel parameter estimation strategy was proposed so that the number of unknown parameters is optimized with respect to the inversion problem stability.

**Uncertainty quantification and ensemble-based methods**

With the Bayesian framework for parameter estimation, all quantities involved are represented by probability density functions (PDF), thus allowing for uncertainty quantification of the parameter estimates. A PDF for the unknown quantities is basically defined using information that is available but which is not to be applied in the inversion itself (the prior PDF). The inversion is then performed by taking into account both the prior PDF and the available data, resulting in an updated PDF for the unknown quantities (the posterior PDF). If the mathematical forward model is linear and the prior PDF is Gaussian, the posterior PDF will be Gaussian as well; i.e. a closed-form solution to the inverse problem is obtained.

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*Figure 6* Part of true CO$_2$ plume boundary (solid curves), Level 1 representation (left, dashed curve), Level 2 representation (middle, dashed curve), Level 3 representation (right, dashed curve).

*Figure 7* True plume (left), multilevel estimation (middle), single-level estimation (right).
all other cases, the posterior PDF can only be characterized through sampling. Markov chain Monte Carlo methods are able to sample correctly from the posterior PDF, but are currently too computationally complex to be practical for forward models with a computational cost like those involved in geophysical monitoring. Ensemble-based methods (Evensen, 1994) sample fairly correctly from the posterior PDF and have an acceptable computational cost.

During the last part of the SUCCESS project period, we worked almost entirely with ensemble-based methods (as opposed to the sensitivity matrix-based methods earlier on at the SUCCESS center). The main advantages of ensemble-based methods are that: 1) they facilitate uncertainty quantification; 2) their computational cost does not depend on the number of parameters to be inverted (it depends on the number of unknowns in the forward model, however); 3) they are easy to implement, as no sensitivity calculations need to be implemented within the forward model.

With a basic ensemble-based method, the process starts by selecting a sample (an ensemble) of parameter vectors from the prior PDF. Each ensemble member is then input into the forward model and the forward model is run, resulting in an ensemble of forward model output vectors. The ensembles of parameter vectors and forward model output vectors will provide the empirical covariance between the parameter vector and the forward model output vector. This covariance matrix is then applied — along with the data and other relevant covariance matrices — in order to update the parameter-vector ensemble into an approximate sample from the posterior PDF.

In general, the empirical covariance between the parameter vector and the forward model output vector plays a similar role in ensemble methods as the sensitivity matrix in optimization methods. There are two important consequences associated with replacing the sensitivity matrix by an empirical covariance. First, the computational cost of ensemble-based methods scales as the number of ensemble members multiplied by the cost of a forward model run while they are independent of the number of parameters used to represent the unknown quantity in the inversion. Ensemble-based methods are non-intrusive with respect to computer programming, as they treat the forward model as a ‘black box’, meaning that they are very flexible for application to different forward modeling software.

Joint use of disparate geophysical data types

Various forms of joint use of disparate geophysical data types are viable, and the choice of approach depends on the problem at hand. When the data types are sensitive to the same unknown quantities, a joint inversion involving the data types can be run concurrently. (One example is inverting for saturation and pressure changes...
from time-lapse seismics and electromagnetic data.) If this is not the case, but the unknown quantities have been established as functions of the same underlying variables, one may perform the inversion so that dependencies between the disparate unknown quantities are introduced in order to guide the inversion, see e.g., the review by Gallardo and Meju (2011). One example is the inversion for seismic velocity changes from time-lapse seismic data and for electric conductivity changes from electromagnetic data. The cross-gradient method (Gallardo and Meju, 2003) is perhaps the more renowned of such methods. Our group has developed another methodology within this class (Lien, 2013), which is used when pressure effects on seismic data can be expected to be negligible.

More recently, we have also developed an ensemble-based Bayesian approach with shape representation of the unknowns for estimation of saturation and pressure fronts (Tveit et al., 2016), where we take into account the fact that the spatial resolution of results from inversion of electromagnetic data cannot be expected to be as good as that for inversion of seismic data. This suggests a sequential approach where Step 1 consists of inversion for electric conductivity from electromagnetic data, while Step 2 consists of inversion for seismic velocity from seismic data using the results from Step 1 in the construction of the prior model for Step 2. This approach will be illustrated through an example where CO₂ is injected from the left, creating a situation where a pressure front is located to the right of a saturation front at a certain time instance. The two fronts are reflected in the seismic P-velocity (Figure 9 (left)), while only the saturation front is reflected in the electric conductivity (Figure 9 (right)), as electric conductivity is nearly independent of pressure according to Archie’s law.

The results from Step 1 are shown in Figure 10, while the results from Step 2 are shown in Figure 11. These results can be compared to the results from the inversion of seismic data without using information from the electromagnetic inversion in the design of the prior model for the seismic inversion (Figure 12). The estimated front in seismic P-velocity corresponding to the pressure front is not identified as well as the corresponding front estimate resulting from the proposed two-step approach, even though the prior mean for that front was closer to the true mean than for the two-step approach.
Field case studies

CSEM data study on the Sleipner CO₂ storage site

We thoroughly investigated the marine controlled-source electromagnetic (CSEM) data acquired above the Sleipner CO₂ storage site, in order to study the data set in detail and conclude the feasibility of marine CSEM for offshore CCS monitoring (Park et al., 2016). There are certain challenges associated with CSEM in this particular area: a strong airwave influence (due to regional shallow water depth, about 80 m); the potential for weak and thin resistivity anomalies; the pipeline network on the seabed; and the shallow target depth. The most critical issue is the pipeline network on the seabed which interferes greatly with the data. To minimize the influence of the seabed pipeline on the CSEM data, we identified and muted some of the data and receivers near the pipeline network on the seabed (Bøe et al., 2017). We were still able to extract useful information, further interpret the CSEM inversion results by combining seismic data, and to extract the in situ resistivity and saturation of CO₂ in the Utsira formation by applying a rock physics model. The results are highly consistent with the seismic data, and the estimated total mass of CO₂ matches the injection data (Figure 13). In addition to what was observed in the laboratory tests (Section 2), this study confirms that marine CSEM data can be a critical tool for offshore CO₂ storage monitoring, most likely not on its own, but when combined with both seismics and gravity. This is a new and unique achievement regarding the Sleipner CCS project associated with the SUCCESS center, compared with previous studies (e.g. Girard et al., 2011), and can be considered a recent monitoring technology development since the IPCC Special Report on CCS (IPCC, 2005). Finally, near-future large-scale CCS projects in the North Sea would require extensive infrastructures such as seabed pipelines and templates, etc. This study demonstrates that CSEM technology may even work with such infrastructures in place. Finally, the results and experiences from this study will be transferred to the new Norwegian CCS Research Centre (under Task 12).

Marine CSEM data can be a critical tool for offshore CO₂ storage monitoring when combined with both seismics and gravity. This study demonstrates that CSEM technology may work well even with interfering surrounding infrastructures (e.g. seabed pipelines).

\[ M_{\text{CO}_2} = \sum_{\text{inversion grid}} \rho_{\text{CO}_2} \phi S_{\text{CO}_2} V = 10.3 \text{M-ton} \]

Figure 13 Inversion results of vertical resistivity (\( \rho_v \)) and anisotropic ratio (\( \rho_v/\rho_h \)) shown above the seismic images from late 2007; CO₂ saturation (\( S_{\text{CO}_2} \)) distribution obtained by the 3-step procedure and the converted total mass of 10.3 M-ton. Note: \( \rho_{\text{CO}_2} \) (CO₂ density) is assumed at 700 kg/m³, \( \Phi \) (Utsira porosity) is also assumed at 0.37, each grid volume (V) is 50 m x 250 m x 800 m. The final result is \( M_{\text{CO}_2} = 10.3 \text{ million ton}, \) which is highly consistent with the total injected CO₂ by the time of the 2008 CSEM survey; i.e. early September (Hagen, 2012).
Gravity and subsidence monitoring of CO₂ injection at Sleipner

The Sleipner field illustrates the value of gravity as a geophysical monitoring variable for CO₂ storage. CO₂ injection began in 1996, and gravity and subsidence measurements were conducted in 2002, 2005, 2009 and 2014 (Skalmeraas, 2014). While time-lapse seismics maps CO₂ plumes with fine spatial resolution, gravity provides quantitative information on the lateral distribution of mass changes. This in turn can be used to estimate the CO₂ density and the fraction of dissolved CO₂ in the formation water (Alnes et al., 2011).

Three Sintrex CG-5 relative gravimetry sensors are used to measure relative gravity data during a gravity and subsidence survey. Each sensor is mounted inside a pressure container together with a paroscientific pressure gauge. The three identical instrument packages are mounted on a frame which is handled by a remotely-operated vehicle, and the instruments are operated in real time from the vessel. A survey typically lasts for 20 minutes.

Thirty stations were initially deployed at Sleipner above the Utsira Formation with some overlap on the Ty Formation covering the CO₂ plume in 2002. Ten additional stations were deployed for the 2009 survey (Alnes et al., 2011) in order to replace damaged stations and provide better coverage of the plume. The concrete stations are shaped as cones, with a diameter of 80 cm at the top and 160 cm at the bottom, and serve as stable platforms for placing instruments on the seabed (Stenvold, 2008). The distance between the stations is up to 500 m (Alnes et al., 2011). During a survey, each station is visited in loops that start and end at the same station, which has a central location on the field. This is done in order to reduce uncertainties from instrumental drift. In subsets of stations, tide gauges are deployed for the whole survey in order to correct the pressure measurement for tides and other oceanographic effects. The corrected pressure data can then be converted into the station depth, which in turn allows the monitoring of subsidence with a precision of a few millimeters.

The temperature dependency is a challenge when estimating the CO₂ density at Sleipner (Stenvold, 2008; Alnes et al., 2011). At Sleipner, the CO₂ in the Utsira Formation is supercritical and close to the critical point. A slight change in temperature could significantly change the density (Alnes et al., 2011). The CO₂ temperature at the well bottom is estimated to be 48°C and the hydrostatic pressure approximately 105 bar, decreasing to formation temperature away from the well (Alnes et al., 2011). History matching the time-lapse gravity and subsidence data with the reservoir model of the field is the main method for interpretation of gravity data (Stenvold, 2008; Alnes et al., 2008; 2011).

At Sleipner, the forward gravity models are fitted to a set of reservoir models for both production and gravity data and are history matched with acquired time-lapse gravity data from 2002–2009. The best-fit average CO₂ density at Sleipner is found to be 530 kg/m³ using vintage 2002 and 2005 data (Nooner et al., 2007; Stenvold, 2008) and 760 kg/m³, after revisiting the data in 2008 (Alnes et al., 2008). The difference in the best-fit average is mainly due to better processing software and new sensor calibrations of the different gravity data vintages (Alnes et al., 2008). When the 2009 vintage was included, the best-fit average CO₂ density was adjusted to 720kg/m³ (Alnes et al., 2011). Following Alnes et al. (2011), the rate of dissolution of CO₂ into brine is less than 1.8% per year. In their analysis of the Sleipner data, using Bayesian inversion combined with seismic information to constrain the model, Hauge and Kolbjørnsen (2015) found that the upper limit for the rate of dissolution of CO₂ is 1.76%.

While time-lapse seismics maps CO₂ plumes with fine spatial resolution, gravity provides quantitative information on the lateral distribution of mass changes, which can be used to estimate the CO₂ density and the fraction of dissolved CO₂ in the formation water.

Skade synthetic data study

A geophysical monitoring study involving a synthetic data set of seismic, CSEM and gravity methods was conducted for a CO₂ injection scenario in the Skade formation. The Skade formation is one of the best candidates for large-scale North Sea storage suggested by the Norwegian Petroleum Directorate (2011). The SUCCESS center decided to perform an exercise to apply what the SUCCESS center had learned and developed to the Skade synthetic case study, and evaluate the performance. WP1 and WP2 developed the Skade subsurface model, and WP3 worked on it further in order to investigate how joint utilization of CSEM, gravity, and seismic data (Section 3) could improve the monitoring of inversion results over performing seismic inversion. In addition to generating geophysical models from reservoir simulation results, the over and underlying geophysical models needed to be designed. As little geological information is known about the area where Skade is located, over and underlying models were devised by extrapolating remote well logs. The over and underlying geophysical models, together with the converted models from the reservoir simulations, were used as input when we generated the synthetic observed data for the monitoring study.

First, 3D reservoir simulation was performed using 3 CO₂ injection wells over a 250-year period (2020–2270) with an injection period of 50 years (2020–2070) and about 20 Mton/year injected into each well (in total 3 Gton). We extracted saturation and pressure at regular time intervals on a 2D cross section through the three wells (in the east-west direction) and converted them into geophysical parameters using rock physics relations. The 2.5D resistivity models were devised by first converting saturation into horizontal resistivity using Archie’s equation and then using empirical parameters from the Sleipner EM data study (Park et al, 2017). Vertical resistivity was subsequently determined with an anisotropy factor of 2. The 2D density models were designed by converting the saturation change to the density change in the formation. Finally, the 2D P-wave velocity (Vp) model was generated from the saturation and pressure using Landrè’s approach (2001); the S-wave velocity (Vs) was then generated from Vp by using a Poisson ratio of 0.3.

For joint use of the geophysical data, we employed the sequential inversion strategy described in Section 3:
1. Invert CSEM or gravity data to get an approximate location of the CO₂ saturation front.
2. Invert seismic data, with prior information on the CO₂ saturation front from Step 1, in order to estimate both saturation and pressure.

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As we can get information about the CO₂ saturation from either CSEM or gravity data in Step 1, we conducted two separate studies using the sequential inversion strategy: one where Step 1 was performed using CSEM data and one where Step 1 was performed using gravity data. It is well known that gravity surveys are cheaper than CSEM surveys, and it was thus useful to compare the performance of both data types in Step 1, and subsequently compare the final results of Step 2. Following the objective of the monitoring study, we also compared the results from Step 2 with the results of seismic inversion without any prior information from CSEM or gravity data.

In order to focus our inversion studies, we set the inversion domain to only encapsulate one out of the three CO₂ injection wells. We also assumed that the over and underlying geology were known and only inverted for geophysical parameters inside the Skade formation. To perform all the inversions, we used the ensemble-based methodology described in Section 3.

In order to represent the geophysical models to be estimated in the inversion studies, we used the shape representation described in Section 3. For CSEM, gravity, and seismic inversions, one region’s boundary was used to represent the CO₂ saturation front/plume. The parameter values for the two regions separated by the region boundary (one inside and one outside the CO₂ plume) were estimated by two constant functions for the CSEM and gravity inversions, while they were estimated by two smoothly-varying functions for the seismic inversion. The reason we used smoothly-varying functions for the seismic inversions is that the Vp depends on both the saturation and pressure distribution, and the pressure distribution had a smooth gradient in the reservoir simulations. On the other hand, we used constant functions for the CSEM and gravity inversions, since conductivity and density were not sensitive to the pressure distribution.

The synthetic observed data was taken from the end of the injection period in the year 2070. For CSEM inversion, 5% Gaussian noise was added to the synthetic observed data with the noise floor set to 1·10⁻¹⁵ V/Am². To generate the 2D synthetic observed CSEM data, we used COMSOL Multiphysics (Park et al., 2013) with a 3D finite element solver in the frequency domain. The data were real and imaginary parts of the inline (with the receivers) electric field. We used 8 sources and 26 receivers, and the frequency used was 0.25Hz. The forward model responses were generated using the 2.5D MARE2DEM simulator (Key, 2016).

For the gravity inversion, we added 10% Gaussian noise to the synthetic data, and used 45 receivers. The data observed were generated using COMSOL Multiphysics with an analytical formulation of the gravity equations. The data were given as the difference in vertical gravity acceleration between 2070 and 2020. The forward model responses were generated using an analytical formulation for polygonal density anomalies (Talwani et al., 1959), where the difference in density between 2070 and 2020 was input.

For seismic inversion, we added Gaussian noise with a fixed variance to the synthetic observed data. In order to study the robustness of inversion with and without the sequential inversion strategy with respect to data noise, we ran three inversions with data variance given as 5·10⁻⁵, 1·10⁻⁵, and 5·10⁻⁶. To generate the synthetic seismic data, we used a 2D AVO simulator, where the Vp, Vs, and density models were input (Buland et al., 2003). The data were P-wave to P-wave (PP) reflection coefficients. The PP reflection coefficients in the observed data were gathered at 6 incident angles from 5° to 30°. In order to generate forward model responses, we used the same AVO simulator that was used to generate the synthetic data. Note that we only estimate the Vp in this study, and keep the Vs and density fixed to their true model values.

We now present the results of the monitoring study. The inversion results were made using forward model simulators with different types of discretization grids. In order to make it easier to compare results from different geophysical inversions, we plotted all of the inversion results on a separate plotting grid. The plotting grid was made using equidistant cells in the x and z directions covering the inversion domain, where only the cells within the Skade formation are shown. Moreover, the figures have been vertically exaggerated.

The first inversion result is based on the sequential inversion strategy using CSEM data in Step 1. The prior model used for the CSEM inversion in Step 1 was designed sufficiently far away from the true model while still representing a reasonable scenario for the early stage of the CO₂ injection. Figure 14 shows the mean of the prior and final ensemble, and the true conductivity model. We see that the shape of the CO₂ plume, given by the low-conductivity shape, corresponds well to the true shape of the plume, with some deviations at the top of the formation. The conductivity of the CO₂ is estimated well, while the conductivity of the brine (high-conductivity part) is underestimated. In Step 2 of the sequential inversion strategy, we made the prior model for

Figure 14 Step 1: inversion of CSEM data. From left to right: mean of the initial and final updated ensemble, and the true conductivity model.
the seismic inversions as follows: the mean of the final ensemble from the CSEM inversion was used as the mean for the CO$_2$ saturation front when generating the initial ensemble for the seismic inversions. As the CSEM inversion does not provide information about the pressure distribution, we generated prior models for the smoothly varying functions inside and outside the CO$_2$ plume based on an assumed development of the pressure in the year 2070. Figure 15 shows the mean of the initial ensemble. Figure 16 shows the mean of the final updated ensemble for the three seismic inversions. We see from the figures that all of the inversions have produced results with accurate estimations of the true model (see Figure 16). This indicates that starting with a prior model generated from the CSEM inversion in Step 1 produces stable inversion results that are consistent with the true model.

Next we present the results using the inversion strategy with gravity data in Step 1. The prior model in Step 1 was made in the same manner as in the CSEM inversion. Figure 15 shows the mean of the initial and final ensemble. When compared to the true model, shown in Figure 15, we see that the shape of the plume is not well approximated. The difference in density inside the plume is well estimated, while it is slightly underestimated outside the plume (in the brine). For the seismic inversions in Step 2 of the sequential inversion strategy, we made the prior model in the same manner as for Step 2, with the CSEM inversion results above; see Figure 16 for the mean of the initial ensemble. Figure 18 shows the mean of the final updated ensemble for the three seismic inversions. We see that the inversion results correspond well with the true model, especially the CO$_2$ plume, and the right side of the plume is well approximated. The stability of the inversion results using the sequential inversion strategy is shown here again. If we compare the inversion results using CSEM and gravity data in Step 1 (Figure 17 against Figure 18, respectively), we see that the inversion results are comparable. Even though the CSEM inversion results in Step 1 provided a better representation of the CO$_2$ plume shape than the gravity inversion in Step 1, the gravity inversion results still provided useful prior information to the seismic inversions in Step 2.

Finally, we present the results from the inversion of seismic data without prior information from CSEM or gravity inversions. Here the initial ensemble was generated in a similar manner as for the CSEM and gravity inversions; Figure 19 shows the mean of the initial ensemble. In Figure 19, the mean of the final updated ensemble is shown for the three seismic inversions. We see that the result of inverting observed data with a fixed variance of 1·10^{-5} is a good approximation of the true model (c.f. Figure 16), while the inversion result with data variance of 5·10^{-5} does not estimate the shape of the right side of the CO$_2$ plume well. The version result with a data variance of 5·10^{-6} does not estimate the true model (see Figure 16) well. The results of the three inversions show that when we performed seismic inversion without prior information from either CSEM or gravity inversion, the inversion results were not robust.

As we discussed in Section 3, the objective of the sequential inversion strategy was to improve the discrimination between the effects of pressure changes and saturation changes on the Vp. In order to further quantify pressure and saturation changes, seismic and CSEM/gravity inversion results...
can be interpreted together (recalling that CSEM/gravity data are only sensitive to saturation changes).

Reducing the monitoring cost is an important issue in CCS projects, particularly for offshore cases. We therefore investigated how we can approach this issue by performing an inversion exercise with only the Skade CSEM synthetic data that were produced for the previous study. We gradually reduced the number of EM seabed receivers to see if we could obtain the same accuracy results. For this purpose, we used the inline electric fields at 6 frequencies of 0.1, 0.25, 0.5, 0.75, 1 and 2 Hz for the year 2024. The baseline for 2020 was obtained by inverting the 1 km spacing receiver configuration and the results for 2048 were obtained by inverting the upper part of depth <1500 m for different receiver spacings. Figure 20 shows the results of this exercise. We clearly see that the reduction in the number of receivers does not decrease the accuracy in the inverted CO\textsubscript{2} images. In fact, the convergences for the 2 and 4 km spacings are a bit faster than the 1 km spacing. The significant gain observed from this exercise would be the fact that we may reduce the number of receivers, which in turn would significantly reduce the survey acquisition cost. It would therefore be very useful to perform this type of exercise dur-

Figure 17 Step 2: Mean of the final updated ensemble from seismic inversion using results from CSEM inversion as a prior model. From left to right: Inversion results with data variance given as 5·10^{-5}, 1·10^{-5}, and 5·10^{-6}.

Figure 18 Step 2: Mean of the final updated ensemble from seismic inversion using results from gravity inversion as prior. From left to right: Inversion results with data variance given as 5·10^{-5}, 1·10^{-5}, and 5·10^{-6}.

Figure 19 Step 2: Mean of the final updated ensemble from seismic inversion without prior information from CSEM or gravity inversion. From left to right: Inversion results with data variance given as 5·10^{-5}, 1·10^{-5}, and 5·10^{-6}.
ing the CCS project planning stage, which would not be costly.

The results of the three different inversions show that when we performed seismic inversion with prior information from either CSEM or gravity inversion, the inversion results are much more robust than without CSEM or gravity-driven prior information.

Figure 20 Resistivity inversion results (left column) and inversion convergence (right column) for the year 2048, obtained by inverting only synthetic CSEM data and reducing the number of receivers for the Skade study: (a, b) for 1 km receiver spacing; (c, d) for 2 km receiver spacing; (e, f) for 4 km receiver spacing. Note that 1) the baseline (for the year 2020) is obtained by inverting the 1 km spacing receiver configuration and the results for the year 2048 are obtained by inverting the upper part of depth <1500 m; 2) the receivers are indicated by the reverse yellow triangles.
Conclusion and recommendations

During the 8 years that the SUCCESS center has been in existence, the WP3 geophysical monitoring group identified what was necessary in order to enhance our monitoring subsurface capabilities; and then delivered the new data, tools and algorithms that are presented in this report, which were achieved through the following two activities.

The first activity in WP3 geophysical monitoring was Development of CO$_2$ related rock physics and mechanics based on advanced laboratory tests. CO$_2$ injection introduces the multiphase flow phenomenon to the subsurface (wetting and not-wetting phases), and the interactions between different fluids and rock formations become complex. Such issues can be resolved through advanced laboratory tests under the in situ stress conditions (e.g. HPHT triaxial cell, CT imaging, multidirectional measurement). The main findings are summarized in the following.

- P-wave amplitude and electrical resistivity are more sensitive to small changes in the fluid distribution patterns than P-wave velocity.
- A new lab apparatus offering multidirectional and multilevel measurement provides useful heterogeneity parameters and anisotropy. In addition, particularly for CO$_2$ flooding tests, it can monitor how injected CO$_2$ flows through a core (breaking through at different levels) by measuring directly geophysical parameters (velocity and resistivity), which can complement the 3D image interpretation of the X-ray CT scanner. Furthermore, this multiple point and level data can be used for upscaling or a homogenization approach.
- The resistivity geophysical method (e.g. CSEM) can be crucial for the purpose of CO$_2$ plume monitoring, particularly when fracture flow is dominant within the reservoir.
- Seismic velocity changes are mainly connected to significant changes of CO$_2$ density and the corresponding bulk rock moduli over the critical point when the phase of CO$_2$ changes.

The second activity was Development of a joint geophysical data inversion algorithm that can handle different data sets jointly, maximizing the amount and quality of information extracted from acquired geophysical data. The main objective was to discriminate the effects of pore pressure and saturation on the geophysical data. We therefore developed an innovative approach of sequentially inverting different geophysical data. The main findings are listed as follows.

- A shape identification inversion algorithm can be more efficient than a grid-cell parameterization algorithm, because the number of unknowns in inversion parameters is much lower in the former.
- The multilevel parameter optimization method is shown to be more efficient than the sensitivity matrix-based one. In addition, as the exact number of inversion parameters is unknown prior to the inversion, the multilevel parameter estimation strategy is more reasonable.
- Uncertainty quantification and ensemble-based methods are seen to be efficient and easy to implement, e.g. because they are not so dependent on the number of inversion parameters (robust) because any forward calculation engine can be combined as a black box (flexible).
- A novel approach that sequentially solves 1) CSEM data; then 2) seismic inversions is shown to be more accurate than seismic inversion alone.
"Joining different geophysical data such as seismic, gravity and electromagnetic (EM) data is strongly recommended in order to maximize our understanding of subsurface behavior."

We are now equipped with these innovative utilities, and have also demonstrated what could be done better now than before, through our extensive work with field-scale case studies. As mentioned earlier, the main target physical parameters, are pore pressure and CO\textsubscript{2} saturation and their migration in both time and space. We see that the innovations at the SUCCESS center can be efficiently applied for this purpose on an industrial scale.

The SUCCESS center makes the following recommendations for an industrial-scale framework for CCS geophysical monitoring.

- Rock physics and mechanics knowledge resulting from laboratory tests and models should be applied with a view to upscaling to the field scale and site-specific issues. Programs that consist of laboratory tests and data acquisition should also be done in coordination with characterization of reservoir and containment, and development of injection scenarios. The rock physics data and models will then be calibrated more properly for specific sites and expected stress ranges and paths (or history). Finally, monitoring programs can be optimally planned and launched with well-investigated expectations regarding the ranges of the main parameters of our interest. The ranges should be quantified with estimated uncertainty.

- Joining different geophysical data such as seismic, gravity and electromagnetic (EM) data is strongly recommended in order to maximize our understanding of subsurface behavior. The simultaneous acquisition of e.g. EM and seismic data will therefore be very useful and cost-efficient in terms of finally discriminating the effects of pore pressure and saturation, as shown earlier on in this report. How to proceed and how to combine seismic, EM and gravity data will depend on specific sites and data sensitivity to changes in the subsurface. Cost is also an important factor to consider. We should acquire what we definitely and necessarily need without redundancy. As shown in the Skade EM data modeling exercise, synthetic-data-based inversion studies are fairly inexpensive, yet they can help us achieve an optimized or cost-efficient survey layout (reasonable results with much smaller number of receivers). Such a synthetic data exercise should be organized by combining different geophysical data, which might reduce the monitoring costs even further.

- The SUCCESS center focused particularly on CSEM, because EM is still a fairly immature technology in the sense of practical application or utilization, particularly, in the onshore CCS community. We clearly saw that EM adds more value in addition to seismics and gravity, particularly in terms of discrimination between pore pressure and saturation. However, it has not been established whether it should be a necessary tool like seismics. This is mainly due to the cost factor. Seismics are also doing well enough in most cases at present, and CCS subsurface characterization and injection operations are now well established and considered low risk (i.e. CCS is a proven technology). Nevertheless, as shown at the SUCCESS center, there are a few cases where use of EM would be necessary and it would even outperform against seismic, e.g. monitoring fluid flow through fractures.

The points recommended above are based on the SUCCESS center’s experiences and findings, and should contribute to industrial monitoring operations in GCS projects. At the same time, as the realization of full-scale and large-scale CCS projects comes closer and closer, we are seeing additional needs for further technology development and also more specific knowledge gaps. We therefore need to carry out further research, development and innovation activities in order to respond to such needs and accelerate CCS project deployments.
As a reflection of our 8 years of experience and also the activities of other CCS communities through the world, we see the following potential future areas of research, among many others.

- Geophysical monitoring should be combined more closely with geomechanics, covering reservoirs, caprock and the overburden. Geomechanics is particularly key in relation to containment. However, the extent of available geomechanical data (stress, strength, pore pressure, etc.) is always very limited (e.g. only near-well or only near reservoir), which makes field-scale geomechanical analysis and results very uncertain. Close and streamlined integration of geophysical data (including micro-seismic data) and geomechanical analysis may fill this gap, which will eventually increase our confidence in the containment security and overburden management.

- Full-waveform inversion (for both seismics and EM) has already been the subject of extensive research. However, there is still some potential for further improvement. One is to increase speed, accuracy and resolution e.g. for applications to locate pressure build-up and monitor faults. Such weaknesses may mar the main advantage of geophysical data, its ability to cover a large area, not only near-well, without intrusion into the subsurface. This requires greater advances, not only in geophysics itself, but also in combination with the discipline of Big Data. When the needed speed, accuracy and resolution are achieved, so-called maximization of geophysical data application and information will also become reality.

- Downhole monitoring technology should be advanced further and become more cost-efficient, particularly with respect to detection of pressure build-up and leakage through wellbores. For large-scale injection scenarios (e.g. >10 Mton/year, which will be necessary in order for CCS to reduce greenhouse gas emissions that lead to global warming), the pressure build-up near wellbores and potential leakage through wellbores should be on a very different scale from any injections to date. In such cases, measuring pore pressure and temperature directly in the caprock (outside casing) will be highly beneficial. Some technology already exists in the market. However, more work is needed in order for such technologies to be applied more actively e.g. increasing accuracy and reducing cost in measurement and interpretation (Choi et al., 20).

- More integration is needed between deep and shallow-focused monitoring activities. For example, the two monitoring activities should be planned together, based on common potential leakage scenarios or pathways from reservoir depth to surface (as a risk), which will make the monitoring work more focused and efficient, and not cover any whole open system. Examples of available technology can be found in the literature (e.g. Dean et al, 2017). The SUCCESS center has also ventured into this field (to develop a leakage scenario), but more practical and realistic attempts are required.

"Downhole monitoring technology should be advanced further and become more cost-efficient, particularly with respect to detection of pressure build-up and leakage through wellbores. For large-scale injection scenarios, the pressure build-up near wellbores and potential leakage through wellbores should be on a very different scale from any injections to date."
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