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20 years of monitoring CO_2-injection at Sleipner

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Abstract

The Sleipner CO_2 injection project was the world's first industrial offshore CO_2 Capture and Storage (CCS) project with more than 16 Mt CO_2 injected since 1996. Key monitoring insights from Sleipner are the dual interpretation of seismic and gravimetric monitoring surveys to quantify the free CO_2 mass changes and plume geometry development as a function of time. The learnings from Sleipner have contributed to making guidelines for monitoring future CCS injection projects, showing that selection of monitoring technology and the timing and extent of monitoring surveys should be case specific and risk based, while also taking into account the long term nature of CCS projects.

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Keywords: Sleipner; CO_2-injection; CCS; monitoring; time-lapse seismic; time-lapse gravimetry

1. Introduction

The Sleipner Vest gas field (Figure 1) was discovered in 1974, and put on stream in 1996, in a combined development with the Sleipner Øst condensate gas field. One challenge was the high CO_2 content (approximately 9 %). To meet the sales gas requirements, avoid pollution to the atmosphere and in response to the Norwegian CO_2 emissions tax, Statoil and partners decided to capture and inject the CO_2 into the saline, highly porous Utsira Fm. aquifer near the Sleipner Øst production platform [1], [2], [3]. CO_2 injection commenced through injection well 15/9-A-16 on September 15[th] 1996. During the first year of injection there were challenges related to injectivity, caused by sand influx, but these challenges were remediated by a re-perforation and installation of a gravel pack in August 1997 [3]. Since then injection has been stable, with a yearly rate of approximately 0.9 Mt during the first

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years, reducing slightly during later years, due to reduced gas flow from Sleipner Vest. Since 2014, CO_2 from the Gudrun gas field has also been processed via the Sleipner CCS facility.

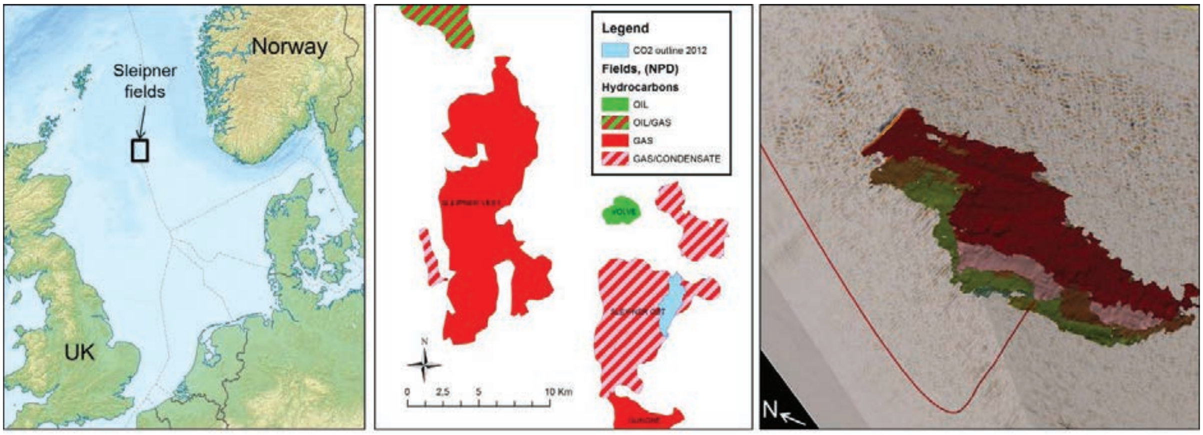

Figure 1: Left: location map (courtesy of Uwe Dedering). Middle: the Sleipner fields with the outline of the CO_2 plume in 2013 indicated (base map courtesy of NPD). Right: A seismic difference section illustrating the extent of the CO_2 plume in 2013.

An extensive geophysical and environmental monitoring programme has been deployed, as further described below. None of the monitoring data have indicated any CO_2 release from the storage unit. As there were no monitoring guidelines or regulations in place at the start of the Sleipner injection, Statoil and partners chose to test a large range of methods, with frequent repeats and dense coverage. Suggestions for drilling a dedicated monitoring well were rejected early on in the project on the grounds of cost and added risks, and the project has successfully focused on use of remote geophysical monitoring methods.

In this paper we will focus on the lessons learned from monitoring during these 20 years, with particular emphasis on seismic monitoring and the latest gravimetric results. We will examine the specific learnings and its implications for reservoir understanding, but we will also discuss how the experiences from Sleipner can be employed when planning new CCS projects.

Nomenclature

Mt	million metric tons

2. CO_2 storage monitoring

Sleipner CO_2 injection is conducted under the Norwegian Petroleum Law, and CO_2 storage and monitoring was first included explicitly in a regulation announced December 8 2014 and since then a formal permit is in place. The wording in the Norwegian law is consistent with the EU directive 2009/31/EC. The monitoring objectives fall into three main categories:

- Conformance monitoring: ensuring that the behaviour of CO_2 in the reservoir is understood.
- Containment monitoring: ensuring that CO_2 stays within the storage unit.
- Contingency monitoring: assessing effect of contingency measures in the case of leakage.

The regulations specify detailed directions for monitoring the facilities and wells. For the wider storage complex there are no detailed requirements, giving an operator a degree of freedom in planning the monitoring programme.

We will in this paper focus on our experiences with conformance and containment monitoring, and in particular on remote geophysical monitoring. The best methods available both for containment and conformance monitoring are typically remote geophysical techniques. The experience from Sleipner mainly comes from towed seismic streamers and gravimetric surveys, but we will also discuss the potential of other remote sensing technologies. Seismic sensors and (where applicable) sources could be towed in the water, or placed on the ground, at seabed, or in wells. They could be retrievable or permanent. Both seismic and gravimetric methods have been used for monitoring oil and/or gas fields [4], [5], in addition to CO_2 injection sites [6] [7]. Repeated resistivity measurements in wells are also an established technology [8], [9]. Recent research indicates that under favourable conditions, CSEM can be used for monitoring CO_2 [10], [11], but CSEM has not yet been applied in the time-lapse sense, neither for monitoring CO_2, oil or gas fields. In an offshore setting, seabed and well operations are relatively expensive compared to surface operations and a case specific cost benefit analysis should be conducted to arrive at the best solution for a new CCS project.

At Sleipner a total of ten 3D seismic surveys and four gravity surveys have been acquired to date, and these have contributed to a detailed understanding of CO_2 behaviour in the storage unit. We discuss these in further detail below.

Wellhead pressure, temperature and rate have remained stable from production start-up, but due to the fact that the CO_2 at the wellhead is at the liquid/gas phase boundary, it is not possible to relate wellhead pressure to bottom-hole pressure without knowing the gas/liquid ratio. Down-hole pressure gauges would have been valuable, but the technology was not readily available in 1996.

A Controlled Source Electromagnetic (CSEM) test line was acquired over the field in 2006, but the resolution was found inferior at the time. As it was challenging enough to detect the CO_2 plume, this line was consequently not repeated. The seabed has been surveyed with high-resolution acoustic imaging and photo mosaic, to investigate the potential of escape release structures. Finally chemical sampling of sediments and water column has been conducted, to search for potential increased CO_2 levels. None of the above monitoring techniques have indicated any leakage from the Sleipner CO_2 injection site.

3. Seismic - ideal for containment monitoring

When entering the reservoir, CO_2 is normally in supercritical state. This provides a strong sonic velocity contrast to the initially brine filled reservoir and favourable conditions for seismic monitoring. The seismic monitoring programme at Sleipner consists of repeated 3D towed seismic surveys, acquired in 1999, 2001, 2002, 2004, 2006, 2008, 2010, 2013, and 2016, respectively. The 2016 dataset was not available for analysis at the time of writing. These repeated surveys form, together with a base survey from 1994 (prior to injection start) a unique dataset which images the plume development [12, 13]. The early surveys were mostly conducted as research projects, while during later years the asset owner has been in charge of the monitoring.

Seismic acquisition technology has improved significantly over the last two decades. Most surveys were acquired using conventional streamers, with increasing number of receiver cables over time. Also source and receiver configurations, and even tow direction have varied over the years. The six first acquisitions were combined with other seismic acquisitions in the area to save cost, and tow depths were not optimized for the CO_2 monitoring at shallow depths, neither in the initial base line nor the later repeats. Two surveys were acquired using broadband technologies; dual source in 2010, and slanted cable in 2013. The repeated datasets have all been through a common time-lapse processing to enhance repeatability. Consequently, the image quality of the broadband surveys might be suboptimal, because all datasets were time-lapse processed to match the quality of the base survey. Despite these challenges related to variation in acquisition parameters and image quality, all surveys have been valuable for understanding the CO_2 plume development. This favourable outcome is attributed to the time-lapse processing and the large contrast in acoustic properties between the *in-situ* saline aquifer and the injected CO_2.

The seismic response arising from this large acoustic impedance contrast is illustrated in Figure 2, which shows a vertical seismic section along the crest of the gentle anticline below which CO_2 is injected. Already at the time of the first time-lapse repeat survey (in 1999) nine bright reflections were identified. These reflections are interpreted as interfaces between sand layers saturated with CO_2, and thin shale layers. The sand layers are between 20-30m thick with the shales being typically 1-1.5m thick [2]. Well data confirm that thin shale layers which could act as flow baffles exist internally in the reservoir, but with the exception of one thicker [c. 6m thick] shale near the top of the storage reservoir it is not possible to correlate these shale layers between wells [2], or to identify them in the baseline seismic survey. CO_2 thus acts to illuminate the internal reservoir architecture, similar to the use of contrast dye in medical imaging.

In the early years the CO_2 signatures in the shallower layers (6-9) were spatially small, and the deeper reflectors were easy to interpret. In more recent data, imaging is better for layers 5-9, whereas layers 1-4 are challenging to interpret (Figure 2). The reason for this degradation of the deeper signals is probably a combination of inelastic attenuation, transmission loss of signal through the CO_2 layers and CO_2 migration/dissemination [14].

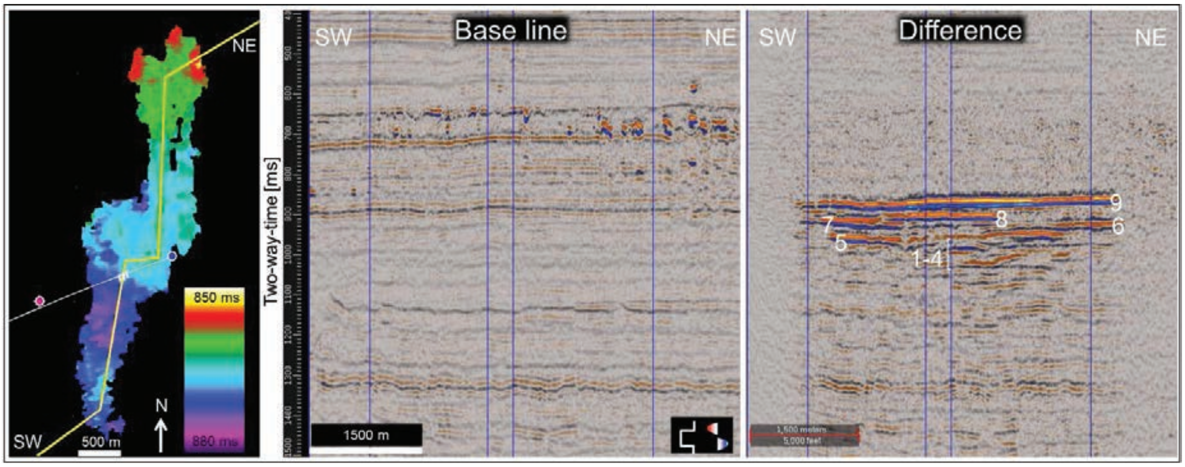

Figure 2: Left: Map of the two-way time interpretation of the uppermost layer of the CO_2 plume, interpreted on the 2013 seismic time-lapse processed data. The yellow line corresponds to the position of the vertical sections in the middle and right vertical plots, representing the 1994 baseline and the difference between the 2013 and 1994 seismic data, respectively. The white line on the map represents the injection well, with perforation interval indicated as parallel white lines, whereas the magenta circle represents the nearest exploration well.

Up until approximately 2008, the temporal thicknesses of the CO_2 filled layers were below maximum seismic tuning, and layer thicknesses are nearly proportional to amplitude [12] [15]. Using an amplitude-thickness relationship, layer thicknesses down to meter scale can be observed, however, temporal thickness (separating top and base) of such thin layers cannot be separated. For the conventional time-lapse seismic data, having a dominant frequency of approximately 35 Hz, the temporal tuning thickness between top and base layer is approximately 10 ms [16].

Several attempts have been made at increasing the seismic resolution, both through acquisition and data analysis. A 2D seismic survey was acquired in 2006, using source and receiver tow depths of only 3 m, as opposed to 6 m and 8 m for most of the 3D surveys. This pushes the frequency notches beyond the spectrum of the reflected pulses from the CO_2 target. Despite the fact that the 2006 2D data could not be 3D migrated, they proved the potential of better resolving the CO_2 layering in the reservoir, having a peak frequency of approximately 50 Hz, and giving a temporal tuning thickness of approximately 7 ms [17]. The 2010 dual streamer data was studied using image processing in addition to the time-lapse processing, which permitted pre-stack wave field separation and removal of the receiver ghosts. This enabled a retrieval of higher frequencies, with a peak frequency of 50 Hz, similar to the 2D dataset [12]. Recent developments in spectral decomposition analysis have further enhanced the lower resolution limit of the seismic data, utilizing the broader frequency spectrum [17] [15].

While resolution is limited, another important limitation is the seismic wave sensitivity to compressional velocities. Velocities change significantly as the fluid changes from pure brine to a brine with low CO_2 saturation; much less as CO_2 saturation increases further. Repeated seismic data is therefore an excellent containment monitoring tool to identify small CO_2 saturations in the reservoir, and potential leakages, but less successful in quantifying further CO_2 saturation increases. Seismic data are also an important tool for conformance monitoring, although additional data (especially reservoir rock properties and in situ fluid properties) are also important for that purpose.

4. Gravity monitoring – contributing to conformance monitoring

In contrast to velocity, density is linearly related to saturation. High-precision gravity monitoring offers an independent measurement of density changes, and consequently of saturation. In 2002 permanent seabed benchmarks were installed over the CO_2 plume at Sleipner and a baseline for gravity monitoring was acquired the same year [7]. Subsequent surveys were conducted in 2005, 2009, and 2013 [18]. The outline of the benchmarks is shown in Figure 3. In the original outlay only benchmarks 1-30 were installed, based on the need for calibration points (stations 1-20) and the plume extent at the time (estimated from seismic data; stations 7-10, and 21-30). The western part of the calibration line was acquired to compensate for gravity effects caused by water influx into the deeper gas condensate reservoir at Sleipner Øst (outlined in green). The eastern part of the line acts as reference stations in an area undisturbed both by injection and production. As the CO_2 plume has expanded over time, new benchmark stations have been installed (stations 31-43), covering a larger area.

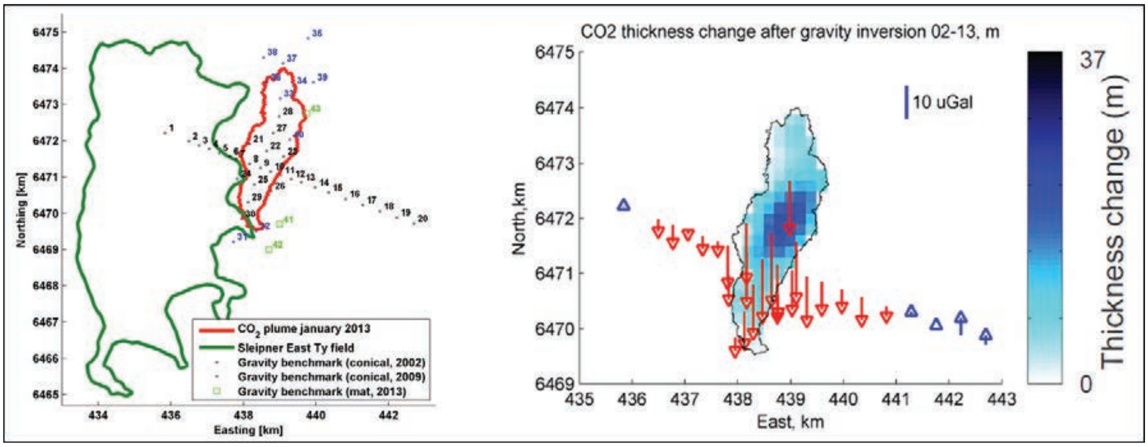

Figure 3: Left: The gravity survey layout, with contours of the CO_2 plume and the deeper Sleipner East Ty gas-condensate reservoir. Right: Inverted CO_2 thickness change based on gravity change from 2002 to 2013, along with the CO_2 outline from seismic in 2013. Red arrows show decrease in measured gravity, blue arrows increase. The signal from Ty Fm. has been removed along with other signals mentioned in the text.

Gravimeters need repeated measurements due to instrumental drift. This calibration was performed by frequent visits to the eastern benchmark stations of the calibration line. Further error reduction was achieved by making redundant measurements, both through repeated visits at each station, and by using several gravimeters. In addition to density changes in the Utsira Fm, the gravity measurements are influenced by several other factors, which will need to be accounted for in order to identify the pure CO_2 response [7], [18]. First, ocean tidal fluctuations are accounted for using pressure gauges both on the gravity survey tool and stationary reference pressure gauges on the seafloor. Second, scouring by sea-bottom currents has lowered some of the benchmarks more than 10 cm into the sediments over time. This was also compensated for using the stationary pressure gauges. In addition, to reduce this error in the future, the new 2013 benchmarks were formed as mats instead of the conical shape which was used previously. The final effect influencing the gravimetric signal is hydrocarbon production and water influx in the deeper condensate reservoir at Sleipner Øst (the Ty and Hugin Fms). This leads to a gravity field increase with higher amplitude and longer wavelength than for the CO_2 influx in the Utsira Fm.

All these effects were inverted for during data processing to obtain the true gravimetric response of CO_2 replacing water in the Utsira Fm. This response is in the order of tens of μGal, whereas gravity repeatability has improved from maximum 4.3 μGal in the earlier surveys to 1.1 μGal in 2013. Based on the gravimetric measurements, and the plume geometry from seismic data, a mean in situ CO_2 density of 720±55 kg/m^3 is found, neglecting the effects of dissolution of CO_2 into the formation water.

The gravimetric measurements can also be used to estimate an upper bound for the CO_2 brine dissolution rate, by assuming that the temperature in the reservoir is known. Within measurement uncertainty this gives a dissolution rate between 0 % and 2.7 % per year. This adds an important constraint to laboratory estimates of CO_2 dissolution in the formation water [19], an important process which reduces the long-term risk of leakage, because brine with CO_2 dissolved is heavier than pure brine and will sink to the bottom of the formation. In conclusion, within the measurement uncertainty the current amount of supercritical CO_2 in Utsira Fm. detected from gravity monitoring is the same as the injected amount of CO_2.

5. Lessons learned

Containment monitoring of CO_2 at Sleipner has been demonstrated by a total of nine repeated seismic surveys. Both seismic and gravimetric data have contributed to conformance monitoring. An important spin-off from the project has been the wealth of knowledge that has evolved through monitoring, and which has been shared with the scientific community over the twenty years of operation. Statoil and the Sleipner Licence partners have released all the seismic, gravity, and CSEM data acquired up to and including 2009. These data are available upon request and have been used for a wide range of applications, such as improving reservoir characterization, constraining flow modelling, and developing new techniques for seismic inversion and spectral decomposition. More than 150 scientific papers, conference abstracts, and several PhD and Master theses have used data from the Sleipner CO_2 project datasets.

5.1. Improved reservoir understanding

The data from the Sleipner CO_2 project have been widely used as constraints for reservoir flow modelling since project inception. In 2011 a benchmark reservoir model was made available to the scientific community ([20], [21] and references therein). This first benchmark model covers only the uppermost layer, whereas subsequent reference models cover the two uppermost layers [20]. The reason for focusing model efforts on the upper layers is that only these layers could be interpreted on the baseline seismic survey, prior to injection start, thus forming the basis for surface grids in the reservoir model. Reservoir properties were provided as part of the models [20], and the released repeated seismic data from injection start until 2008 act as a reference for the simulation results.

The time-lapse seismic data show that the upper CO_2 layers tend to follow topographic highs. After some years of accumulation underneath the topographic high above the injection point, the CO_2 has spread in a relatively narrow corridor, and started accumulating below a structural high approximately 3 km north/north-east of the injection point. In general, results from several modelling studies have found it difficult to match the details of the time-lapse seismic [22], [23], [20], [21], [14], [24], [25]. This is due partly to challenges understanding the underlying physics of the CO_2 flow, and partly due to uncertainties in geological assumptions. On the microscopic scale the CO_2 injection into brine filled sandstone in the Utsira Fm is a drainage process but imbibition can occur with plume migration. There is still some debate on whether the upscaled flow process is dominated by viscous or gravity forces, although increasingly a gravity-dominated interpretation is being proposed [26, 27]. Viscous dominated models will typically not be able to reproduce the northwards corridor observed in the later seismic surveys [23], [25], whereas gravity dominated models predict an affinity to travel too far north too early [21], [25]. Geological assumptions, such as the number of feeder channels up to the top layer, permeability, a correct representation of the top seal topography, and temperature distribution will all have a strong effect on the final flow pattern, and contain some uncertainty [25]. It is not within the scope of this paper to conclude on the way forward for flow simulations, but the Sleipner time-lapse seismic data have been crucial for generating new insights that are valuable for later CO_2 injection projects.

Similarly, the excellent time-lapse dataset has spurred scientists to use it for developing and testing new inversion schemes, both inverting from seismic amplitudes to impedances, and further to rock physics properties. The data have been used for full, partial, and pre-stack 2D and 3D inversions, and in later years also Full Waveform Inversion (FWI), and joint inversion between seismic and gravimetric data [28], [29], [30], [31], [32], [33] [34], [35].

Seismic inversion studies can at their best lead to improved understanding of the reservoir and time-lapse observations because they provide a quantitative estimate of elastic properties. The effect of the seismic wavelet is removed, so that elastic property changes are confined to where they belong, and not smeared out by wavelet effects. Further, with a good rock physics model, inversion for saturation changes can also be conducted. However, the limitations in the available Sleipner data mean that only inversion for compressional velocity will give meaningful results. Inversion for shear velocity or density will be too error prone. Due to uncertainty in choice of saturation model, compressional velocity sensitivity to gas saturation is uncertain, meaning that without additional constraints, CO_2 saturation estimates are not conclusive from purely seismic inversion [31]. Because of this the Sleipner inversion studies have been mainly used for method development, but seismic inversion could be a complementary tool in CO_2 monitoring.

5.2. Optimising monitoring programmes

CO_2 monitoring regulations give the site operator considerable freedom, and consequently a large responsibility, when designing a monitoring programme to satisfy the overall requirements. The main factors to take into account are which technologies to use, and the spatial and temporal sampling intervals; factors that influence both cost and information content. We will discuss the specific learnings from Sleipner, and go on to discuss monitoring in more general terms.

The experience from Sleipner has shown that seismic monitoring is the most efficient containment monitoring tool, due to the ability to remotely cover a large area, the strong response expected even for small CO_2 saturations, and consequently the ability to detect small changes (of order one meter vertically and 5-10 meters laterally). Seismic survey interval at Sleipner was quite short; two-three years. No big surprises have emerged from one survey to the next. This dense series of data points can be used to estimate the error introduced by dropping one or more surveys [36], and consequently to evaluate the overall cost of the monitoring programme compared to the gain of retrieving more frequent data. The most recent survey at Sleipner was acquired four years after the previous one, reflecting confidence in previous measurements.

With the experience gained from such a well-behaved case as the Sleipner injection site we suggest that the monitoring strategy for CO_2 injection sites could be adjusted in future. For Sleipner we had fairly frequent seismic repeats for the first 15 years of injection (on average every second year), and then increased the time between surveys to four years. One approach for future monitoring projects could be to have the first repeat as soon as possible after injection start (depending on expected response perhaps after about one year), but to increase the survey interval if the injection goes according to plan. Such a programme should anyway be designed flexibly, so that if other monitoring devices indicate anomalies (*e.g.* anomalous well pressure behaviour or indications of leakage at the surface) new seismic surveys could be mobilized.

Industry experience demonstrates that seismic acquisition prices have varied considerably over time (for the Sleipner injection the seismic prices have varied by an order of magnitude during the project's lifetime). A robust monitoring project must therefore account for net present value and varying survey prices.

As discussed above, streamer seismic is a good compliance monitoring tool. Gravimetric measurements can provide a good supplement for shallower cases, because of their ability to detect mass changes. The main limitation of gravimetric monitoring is the spatial resolution, which is low compared to seismic resolution. Gravimetric measurements have continuously improved precision over time as the technology has matured.

The Sleipner CO_2 injection site has been a unique playground for monitoring, due to its long history with regular operations, and favourable geological conditions. The high-permeable and large reservoir at Sleipner may, however, be less representative of more heterogeneous, complex reservoirs where higher pressure build-up could cause a stronger stress response. During the Snøhvit CO_2 injection, pore pressure build-up was significant [37]. In such a case, the need for extracting pressure information from the remote monitoring becomes stronger. Attempts have been made at separating pressure and saturation effects from the seismic data [38], [39].

It is possible to take remote CO_2 injection monitoring one step further, by installing sensors on the sea bed instead of operating streamer surveys. The added value of three component data would provide separation of compressional and shear waves, which could in turn provide aid in pressure and saturation separation. The ability to monitor geomechanical changes through shear-wave splitting is an important new use of multicomponent seismic data [40] [41]. Retrievable Ocean Bottom Seismic (OBS) surveys are, however, usually several times more costly than streamer surveys, meaning that retrievable systems are not realistic from a cost perspective. Permanent Reservoir Monitoring (PRM) seismic systems on the other hand could be an option. Though these have relatively high initial installation costs, they might over time be competitive with towed streamer surveys, depending on sampling frequency. A permanent seismic system in listening mode could detect potential microseismic activity [42], and could act as a trigger to acquiring a repeated seismic survey. Permanent systems usually have superior repeatability over retrievable systems, and could in passive mode be used for noise analysis. Several oil- and/or gas fields in operation are monitored by such PRM systems today [43] [44], [45] [46]. A permanent layout could in particular compete with towed streamer data if there are sea surface installations at the field. Such installations would prevent the towed streamers from accessing the area near the installations, which would in turn require expensive undershoots. A permanent system should also be planned in a flexible way, such that if the CO_2 moves towards the border of the survey area, a new lay-out could be added on to the existing one.

6. Conclusions

The CO_2 injection project at Sleipner has been both a technical and economic success. Remote geophysical monitoring has convincingly demonstrated that the CO_2 stays safely in the storage unit. Overall the monitoring experience at Sleipner shows that:

- CO_2 stays safely in the storage unit
- Downhole pressure and temperature gauges are needed for obtaining good control of the injection in-situ conditions and should be implemented for future CO_2 injection projects.
- Repeated seismic surveys have been crucial for ensuring both containment and conformance monitoring. Currently no good technology alternative exists.
- By acquiring both gravimetric and seismic monitoring, it is possible to combine the free CO_2 mass change and plume geometry data, and make an estimate of dissolution in formation water. This is important for longer term predictions. Together the datasets give much richer information than when handled separately.

Further learnings for future projects is that evaluations of specific monitoring design details (such as selection of monitoring technology, timing and extent of monitoring surveys) should be case specific and risk based. The monitoring strategy should be flexible, providing the opportunity to combine planned and triggered repeats, and taking into account the long term nature of CO_2 injection projects. The monitoring strategy should also be able to adapt as technology improves, as it has done over the 20-year Sleipner monitoring history.

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References

[1] A. Baklid, R. Korbøl and G. Owren, "Sleipner Vest CO_2 disposal, CO_2 injection into a shallow underground acquifer," in *SPE Annual Technical Conference and Exhibition,* Denver, 1996.

[2] P. Zweigel, R. Arts, A. E. Lothe and E. Lindeberg, "Reservoir geology of the Utsira Formation at the first industrial-scale underground CO_2 storage site (Sleipner area, North Sea)," in *Geological Storage of Carbon Dioxide for Emissions Reduction*, S. Baines, J. Gale and R. Worden, Eds., London, Geological Society, 2004, pp. 165-180.

[3] H. Hansen, O. Eiken and T. O. Aasum, "Tracing the path of carbon dioxide from a gas-condensate reservoir,

through an amine plant and back into a subsurface acquifer. Case study: The Sleipner area, Norwegian North Sea," in *SPE Offhsore Europe*, Aberdeen, UK, 2005.

[4] M. Landrø, O. A. Solheim, E. Hilde, B. O. Ekren and L. K. Strønen, "The Gullfaks 4D seismic study," *Petroleum Geoscience,* vol. 5, no. 3, pp. 213-226, 1999.

[5] O. Eiken, T. Stenvold, M. Zumberge, H. Alnes and G. Sasagawa, "Gravimetric monitoring of gas production from the Troll field," *Geophysics,* vol. 73, no. 6, pp. WA149-WA154, 2008.

[6] R. Arts, A. Chadwick, O. Eiken, S. Thibeau and S. Nooner, "Ten years' experience of monitoring CO_2 injection in the Utsira Sand at Sleipner, offshore Norway," *First Break,* vol. 26, no. 1, pp. 91-96, 2008.

[7] H. Alnes, O. Eiken and T. Stenvold, "Monitoring gas production and CO_2 injection at the Sleipner field using time-lapse gravimetry," *Geophysics,* vol. 73, no. 6, pp. WA155-WA161, 2008.

[8] T. Nakajima and Z. Xue, "Evaluation of a resistivity model derived from time-lapse well logging of a pilot-scale CO_2 injection site, Nagaoka, Japan," *International Journal of Greenhouse Gas Control,* vol. 12, pp. 288-299, 2013.

[9] C. Schmidt-Hattenberger, P. Bergmann, T. Labitzke and F. Wagner, "CO_2 migration monitoring by means of electrical resistivity tomography (ERT) - Review on five years of operation of a permanent ERT system at the Ketzin pilot site," *Energy Procedia,* vol. 63, pp. 4366-4373, 2014.

[10] S. Kang, K. Noh, S. J. Seol and J. Byun, "MCSEM inversion for CO_2 sequestration monitoring at a deep brine aquifer in a shallow sea," *Exploration Geophysics* , vol. 46, no. 3, pp. 236-252, 2015.

[11] O. Salako, C. MacBeth, L. MacGregor and E. Mackay, "Potential applications of time-lapse marine CSEM to reservoir monitoring," in *75th European Association of Geoscientists and Engineers Conference and Exhibition,* London, UK, 2013.

[12] A.-K. Furre and O. Eiken, "Dual sensor streamer technology used in Sleipner CO_2 injection monitoring," *Geophysical Prospecting,* vol. 62, no. 5, pp. 1075-1088, 2014.

[13] O. Eiken, P. Ringrose, C. Hermanrud, B. Nazarian, T. A. Torp and L. Høier, "Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit," *Energy Procedia,* no. 4, pp. 5541-5548, 2011.

[14] F. Boait, N. J. White, M. J. Bickle, R. A. Chadwick, J. A. Neufeld and H. E. Huppert, "Spatial and temporal evolution of injected CO_2 at the Sleipner Field, North Sea," *Journal of Geophysical Research,* vol. 117, no. 3, 2012.

[15] J. C. White, G. A. Williams and R. A. Chadwick, "Thin layer detectability in a growing CO_2 plume: Testing the limits of time-lapse seismic resolution," *Energy Procedia,* vol. 37, pp. 4356-4365, 2013.

[16] A.-K. Furre, A. Kiær and O. Eiken, "CO_2-induced seismic time shifts at Sleipner," *Interpretation* , vol. 3, no. 3, pp. SS23-SS35, 2015.

[17] G. Williams and A. Chadwick, "Quantitative seismic analysis of a thin layer of CO_2 in the Sleipner injection plume," *Geophysics,* vol. 77, no. 6, pp. R245-R256, 2012.

[18] H. Alnes, O. Eiken, S. Nooner, G. Sasagawa, T. Stenvold and M. Zumberge, "Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO_2 plume," *Energy Procedia,* vol. 4, pp. 5504-5511, 2011.

[19] H. Hassanzadeh, M. Pooladi-Darvish and D. W. Keith, "Accelerating CO_2 dissolution in saline aquifers for geological storage - Mechanistic and sensitivity studies," *Energy and Fuels,* vol. 23, no. 6, pp. 3328-33326, 2009.

[20] V. Singh, A. Cavanagh, H. Hansen, B. Nazarian, M. Iding and P. Ringrose, "Reservoir modeling of CO_2 plume behavior calibrated against monitoring data from Sleipner, Norway," in *Proceedings - SPE Annual Technical Conference and Exhibition,* Florence, Italy, 2010.

[21] A. Cavanagh, "Benchmark calibration and prediction of the Sleipner CO_2 plume from 2006 to 2012," *Energy Procedia,* vol. 37, pp. 3529-3545, 2012.

[22] M. Bickle, A. Chadwick, H. E. Huppert, M. Hallworth and S. Lyle, "Modelling carbon dioxide accumulation at Sleipner: Implications for underground carbon storage," *Earth and Planetary Science Letters,* vol. 255, no. 1-2, pp. 164-176, 2007.

[23] R. A. Chadwick and D. J. Noy, "History-matching flow simulations and time-lapse seismic data from the Sleipner CO_2 plume," in *Petroleum Geology Conference Proceedings*, London, UK, 2010.

[24] K. W. Bandilla, M. A. Celia and E. Leister, "Impact of model complexity on CO_2 plume modeling at Sleipner," *Energy Procedia* , vol. 63, pp. 3405-3415, 2014.

[25] C. Zhu, G. Zhang, P. Lu, L. Meng and X. Ji, "Benchmark modeling of the Sleipner CO_2 plume: Calibration to seismic data for the uppermost layer and model sensitivity analysis," *International Journal of Greenhouse Gas Control* , vol. 43, pp. 233-246, 2015.

[26] A. J. Cavanagh, R. S. Haszeldine and B. Nazarian, "The Sleipner CO_2 storage site: using a basin model to understand reservoir simulations of plume dynamics," *First Break*, vol. 33, no. 6, pp. 61-68, 2015.

[27] C. M. Oldenburg, S. Mukhopadhyay and A. Cihan, "On the use of Darcy's law and invasion-percolation approaches for modeling large-scale geologic carbon sequestration," *Greenhouse Gases: Science and Technology,* vol. 6, no. 1, pp. 19-33, 2016.

[28] A. K. Evensen and M. Landrø, "Time-lapse tomographic inversion using a Gaussian parameterization of the velocity changes," *Geophysics,* vol. 75, no. 4, pp. U29-U38, 2010.

[29] K. Delepine, N. Clochard, V. Labat and P. Ricarte, "Post-stack stratigraphic inversion workflow applied to carbon dioxide storage: application to the saline aquifer of Sleipner field," *Geophysical Prospecting,* vol. 59, no. 1, pp. 132-144, 2011.

[30] N. Dubos-Sallée and P. N. J. Rasolofosaon, "Estimation of permeability anisotropy using seismic inversion for the CO_2 geological storage site of Sleipner (North Sea)," *Geophysics,* vol. 76, no. 3, pp. WA63-WA69, 2011.

[31] M. Queißer and S. C. Singh, "Full waveform inversion in the time lapse mode applied to CO_2 storage at Sleipner," *Geophysical Prospecting,* vol. 61, no. 3, pp. 537 - 555, 2013.

[32] R. Ghosh, M. K. Sen and N. Vedanti, "Quantitative interpretation of CO_2 plume from Sleipner (North Sea), using post-stack inversion and rock physics modeling," *International Journal of Greenhouse Gas Control,* vol. 32, pp. 147-158, 2015.

[33] M. Jullum and O. Kolbjørnsen, "A Gaussian based framework for Bayesian inversion of geophysical data to rock properties," *Geophysics,* vol. 81, no. 3, pp. R75-R87, 2015.

[34] E. B. Raknes, W. Weibull and B. Arntsen, "Three-dimensional elastic full waveform inversion using seismic data from the Sleipner area," *Geophysical Journal International,* vol. 202, no. 3, pp. 1877-1894, 2015.

[35] V. L. Hauge and O. Kolbjørnsen, "Bayesian inversion of gravimetric data and assessment of CO_2 dissolution in the Utsira Formation," *Intepretation,* vol. 3, no. 2, pp. SP1-SP10, 2015.

[36] A. Kiær, O. Eiken and M. Landrø, "Calendar time interpolation of amplitude maps from 4D seismic data," *Geophysical Prospecting,* vol. 64, no. 2, pp. 421-430, 2015.

[37] O. Hansen, D. Gilding, B. Nazarian, B. Osdal, P. Ringrose, J.-B. Kristoffersen, O. Eiken and H. Hansen, "Snøhvit: The history of injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm," *Energy Procedia,* vol. 37, pp. 3565-3573, 2012.

[38] S. Grude, M. Landrø and J. Dvorkin, "Pressure effects caused by CO_2 injection in the Tubåen Fm., the Snøhvit field," *International Journal of Greenhouse Gas Control,* vol. 27, p. 178–187, 2014.

[39] J. C. White, G. A. Williams, S. Grude and R. A. Chadwick, "Utilizing spectral decomposition to determine the distribution of injected CO_2 at the Snøhvit Field," *Geophysical Prospecting* , vol. 63, no. 5, pp. 1213-1223, 2015.

[40] T. L. Davis, A. Bibolova, S. O'Brien, D. Klepacki and H. Robinson, "Prediction of residual oil saturation and cap-rock integrity from time-lapse, multicomponent seismic data, Delhi Field, Louisiana," *Leading Edge,* vol. 32, no. 1, pp. 26-31, 2013.

[41] T. L. Davis and R. D. Benson, "Monitoring production processes by 4-D multicomponent seismic surveys at Vacuum Field, New Mexico," in *SEG Technical Program Expanded Abstracts*, San Antonio, USA, 2001.

[42] J. E. Lindgaard and T. Matveeva, "Utilizing PRM systems for injection monitoring," in *2nd EAGE Workshop on Permanent Reservoir Monitoring: Current and Future Trends*, Stavanger, Norway, 2013.

[43] O. I. Barkved, K. Buer, T. G. Kristiansen, R. M. Kjelstadli and J. H. Kommedal, "Permanent seismic monitoring of the Valhall field, Norway," in *2005 International Petroleum Technology Conference Proceedings*, Doha, Qatar, 2005.

[44] A. Bertrand, P. G. Folstad, B. Lyngnes, S. Buizard, H. Hoeber, N. Pham, S. De Pierrepont, J. Schultzen and A. Grandi, "Ekofisk life-of-field seismic: Operations and 4D processing," *Leading Edge*, vol. 33, no. 2, pp. 142-148, 2014.

[45] R. M. Elde, S. S. Roy, C. F. Andersen and T. Andersen, "Grane Permanent Reservoir Monitoring - Meeting Expectations!," in *78th EAGE Conference and Exhibition 2016*, Vienna, Austria, 2016.

[46] M. Thompson, M. Andersen, S. M. Skogland, C. Courtial and V. B. Biran, "Time-lapse Observations from PRM at Snorre," in *78th EAGE Conference and Exhibition 2016*, Vienna, Austria, 2016.