Deliverable 4.4

Optimizing Fibre-Optic Monitoring: A Case Study in the Norwegian North Sea

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High-level Summary

This report provides an overview of monitoring technologies for CO_2 storage being considered in the ACT SHARP Project. SHARP is a research project funded under the ERA-NET ACT programme for accelerating Carbon Capture and Storage (CCS). The overall aim is to "Improve the accuracy of subsurface CO_2 storage containment risk management to a level acceptable to both commercial and regulatory interests".

Within the SHARP project, Work Package 4 (WP4) has the overall goal of developing more intelligent methods for monitoring rock strain and fluid pressure. To focus on this effort, we set up a more specific objective to 'Design improved monitoring schemes using right-time and right-place detection.' The initial tasks in WP4 were to understand the rock failure risks for each case study site (Deliverables 4.1 and 4.2). These studies form the basis for the monitoring parts of WP4.

Depending on the storage site at hand, CO_2 storage monitoring might involve various techniques and methods such as seismic data acquisition, utilizing pressure and temperature sensors, gravity and magnetic surveys, electro-magnetic surveys, and/or well logging tools. This report provides an overview of novel fibre optic (FO) monitoring technologies and focus on how FO monitoring systems might be optimized combined with conventional technologies. We use examples from the Norwegian North Sea case study area to show how a 'right-time and right-place detection' system could work, utilizing both conventional data but especially new emerging FO sensing technologies.

The primary focus of this report is on monitoring for containment risk management. Conventional approaches to CO_2 storage site monitoring often focus on monitoring the migration of the CO_2 plume (i.e. saturation monitoring) which is an essential part of both containment and conformance monitoring. Here we shift the focus to how the rock system responds to CO_2 injection, specifically monitoring of pressure, strain and temperature. As CO_2 injection proceeds, changes in fluid pressure will result in various geomechanical effects, including elastic deformation and potentially permanent deformation (e.g. in-elastic strains and fractures). If several storage sites are located in the vicinity of each other, they might impact each other's stress field due to changes in fluid pressure. There is a need for monitoring and handling this potential interaction. Initial assessments of stress and pore pressure effects can be done by rock mechanical testing (see SHARP WP3), but we also need to monitor how the rock system responds to pressure changes. This can be achieved using a combination of microseismic monitoring and downhole measurements of pressure, strain and temperature. It is important to emphasize that while monitoring of fluid displacement is usually a primary objective, in this report we mainly focus on monitoring the effects of geomechanical changes.

Containment risk management encompasses leakage risk management, but it is broader than that, with seismicity monitoring playing a crucial role. Seismic monitoring is also essential for public perception. In the case of significant seismic activity (e.g., events with magnitudes above 2), it is vital to distinguish between CO_2 injection-induced events and natural seismicity. Operators must localize such seismic events and determine, for example, if they occur within the reservoir or beneath it. Therefore, reducing depth uncertainty is a crucial risk mitigation step for maintaining public trust and regulatory approval.

The report demonstrates the benefits of integrating existing offshore installations, such as Permanent Reservoir Monitoring (PRM) systems and telecom and power cables, into the monitoring technology to reduce the depth uncertainty in seismic event localization.

A Norwegian North Sea case study illustrates how earthquake detection and seismic monitoring capabilities of the Norwegian National Seismic Network (NNSN) improve with the integration of additional monitoring technologies. Selected stations from two PRM systems streaming data to the NNSN in near real-time significantly enhance earthquake location accuracy. Incorporating the HolsNøy Array (HNAR) and the concept of array processing into this integrated system can reduce seismic location uncertainties by about 50%. Furthermore, the integration of Distributed Acoustic Sensing (DAS) technology utilizing surface optical fibers in submarine telecom infrastructure further reduces depth uncertainty to about 2 km, compared to approximately 10 km uncertainty using the NNSN alone.

In general, the utilisation of FO sensing as a CO_2 storage monitoring solution is emerging fast and can include fibres both at surface and downhole. FO sensing can be used in several ways: (a) changes in temperature can be measured using distributed temperature sensing (DTS), (b) direct changes in rock strain can be recorded downhole using distributed strain sensing (DSS) and distributed acoustic sensing (DAS); (c) passive detection of microseismic events can be done using FO DAS cables, as well as (d) active seismic monitoring and seismic imaging.

We aim to illustrate with examples from published research and field trials from various regions worldwide, how combining these various monitoring technologies can create an enhanced monitoring scheme that provides a holistic understanding of subsurface dynamics in the Norwegian North Sea region.

Focusing on the feasibility of DAS and its detectability, it was demonstrated in a field trial in Canada that microseismic events with magnitudes lower than -0.6 are detectable at distances exceeding 10 km when the DAS fiber was deployed in an injection well cemented behind casing. Experience from the geothermal sector show that utilizing low-frequency DAS downhole allows for the direct observation of microseismic events linked to fracture openings, with observed strain changes of about 0.5 nanoStrain. Current DAS technologies measure strain changes with picoStrain resolution, enabling the detection of these fracture openings and other signals related to CO_2 injection when deployed in a well. The overall strains which occur in response to CO_2 injection are about 2 milliStrain in formations and typically in microStrain range when the fiber is deployed in or cemented between formation and casing.

Additionally, DAS in surface fibers can measure seismic anisotropy and by this infer stress field changes. This capability was demonstrated by measuring icequake-induced seismic events in Antarctica. It is shown that DAS surface fibre can image the arrival of both fast and slow shear waves, and thus the delay time can be measured with high temporal and spatial accuracy (e.g., with a slowness resolution of about 0.1 s/km)

Permanent Reservoir Monitoring (PRM) systems provide high-resolution measurements capable of detecting subtle changes, such as variations of approximately 200 microseconds time shift, indicative of pressure, strain, and temperature alterations. Additionally, stress field estimates utilizing shear wave anisotropy provide crucial inputs for stress field estimations updating geomechanical models, facilitating the development of preventative monitoring strategies.

The primary advantage of FO monitoring lies in its continuous real-time monitoring and high-resolution measurements, facilitating the early detection of subsurface changes. Although real-time monitoring is valuable since it enables prompt decision-making, changes in the stress field may also result in delayed fault reactivation, which is not immediately evident in the real-time data. This means that merely including FO as advanced monitoring solution as such is not sufficient. It is important to monitor the right parameters at the right time and place to record important input parameters for predictive geomechanical modelling.

For instance, various studies demonstrate that human activities, such as fluid injection or withdrawal, can trigger earthquakes. This poses risks in industries like geothermal energy production where it was observed that horizontal stresses were shifting by tens of mega Pascals, potentially leading to prolonged induced seismicity even after operations cease. Emphasized in the report by Williams *et al*. (2022) are the stress history, seismicity, and rock mechanics parameters, which serve as crucial inputs for geomechanical modelling and predictive analysis. It is imperative to complement real-time monitoring with preventative monitoring to identify potential risks before their manifestation in real-time data.

The data obtained from FO monitoring can be integrated into geomechanical modelling workflows, providing calibration and ground truthing of models as projects develop. This will enable a more comprehensive understanding of the subsurface behaviour. Such predictive geomechanical modelling empowers operators to devise proactive strategies, enables early identification of potential issues and enables the implementation of preventive measures to mitigate adverse events.

Furthermore, as technological advancements in CO_2 storage and monitoring continue to evolve, especially the use of FO sensing, there is a growing recognition that existing regulations may need to be updated to incorporate these innovations. Integrating fiber optic technologies into regulatory frameworks can significantly enhance the accuracy and reliability of monitoring efforts.

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1 Introduction

1.1 Motivation

CO_2 storage is an important tool for enabling decarbonisation of our society, and currently the interest in this technology is growing fast and the rate of deployment is accelerating. While putting captured sources of CO_2 surface emissions back underground is clearly a positive action, there are concerns about the long-term safety of CO_2 storage. Could the injected CO_2 leak back to the surface or could the injection process induce fractures or trigger earthquakes? How could storage sites located in the vicinity of each other impact each other? Addressing these underlying questions about storage safety leads to the topic of stress and strain and the interplay of rock mechanics and fluid pressure. This is what we are focusing on in the SHARP Storage research project, where we investigate 'Stress History and Reservoir Pressure for improved quantification of CO_2 storage containment risks.'

Work Package 4 of the SHARP project is focused on the monitoring aspects of this problem, where we focus on developing smart or novel monitoring solutions directed especially at monitoring of *rock strain*. In the field of geomechanics, strain is how rocks respond to changes in the effective stress.

1.2 Basic principles in rock mechanics

To briefly summarize the underlying principles, stress, σ, is related to strain, ε, via Young's Modulus, E, such that $\underline{\sigma} = E\,\underline{\varepsilon}$ (where the underline signifies a mean value). The Young's Modulus E describes the resistance of a material against deformation – i.e. it is a physical property describing the mechanical stiffness. (Note that this equation only applies to a linear elastic system and assumes an isotropic medium.)

Most rocks have some mechanical strength, meaning that we need to consider the three components of the tensorial stress field, $\sigma_1\ \sigma_2\ \sigma_3$ and the three components of the strain tensor, $\varepsilon_1\ \varepsilon_2\ \varepsilon_3$. Then, as proposed originally by Terzaghi in 1936, the failure of a rock system is controlled by the effective stress, σ', where:

$$\sigma_1' = \sigma_1 - P, \quad \sigma_2' = \sigma_2 - P \quad \text{and} \quad \sigma_3' = \sigma_3 - P$$, where P is the pore pressure.

Note that this concept strictly only applies to cohesionless soil systems with incompressible grains but has been extended by Biot in 1941 to include poro-elastic systems with compressible grains.

To estimate the point of failure of a rock, we also need to quantify a deviatoric stress, τ_{dev}, also called the shear stress (this is the non-isotropic part of the stress field). The Mohr diagram is the most common way of expressing this behaviour graphically (i.e. the state of stress relative to failure), where the effective normal stress is plotted against the deviatoric stress, such as in the example shown in Figure 1. The question is then at what point does the rock system reach the failure curve, which will be different for intact rock with some degree of cohesion as compared with a critically aligned fault with no cohesion. Note that most rocks will fail in a shear mode, but tensile failure can also occur with very high fluid pressure. For further reading on these rock mechanics principles see, for example, Jaeger *et al*. (2007).

It is also worth emphasizing, that before rock failure occurs there will always be some elastic deformation – the restorable linear deformation that occurs with any stress change. We can then separate the elastic and non-elastic parts of rock strain. In general, some elastic response of the rock system will always occur. Furthermore, some non-elastic deformation can also be acceptable, such as micromechanical damage and small-scale movements of natural fractures and joints, or bedding-parallel shear. And then there are certain higher levels of rock failure that are clearly undesirable, such as a small fault which is stimulated to slip enough to create a felt earthquake. Monitoring of rock strain then concerns what rock deformation is acceptable and expected versus larger rock deformation that could be of concern or potentially unacceptable. It may also be possible to use the observation of "acceptable strains" constructively, such as to optimize injection processes, as suggested by Grande et al. (2024).

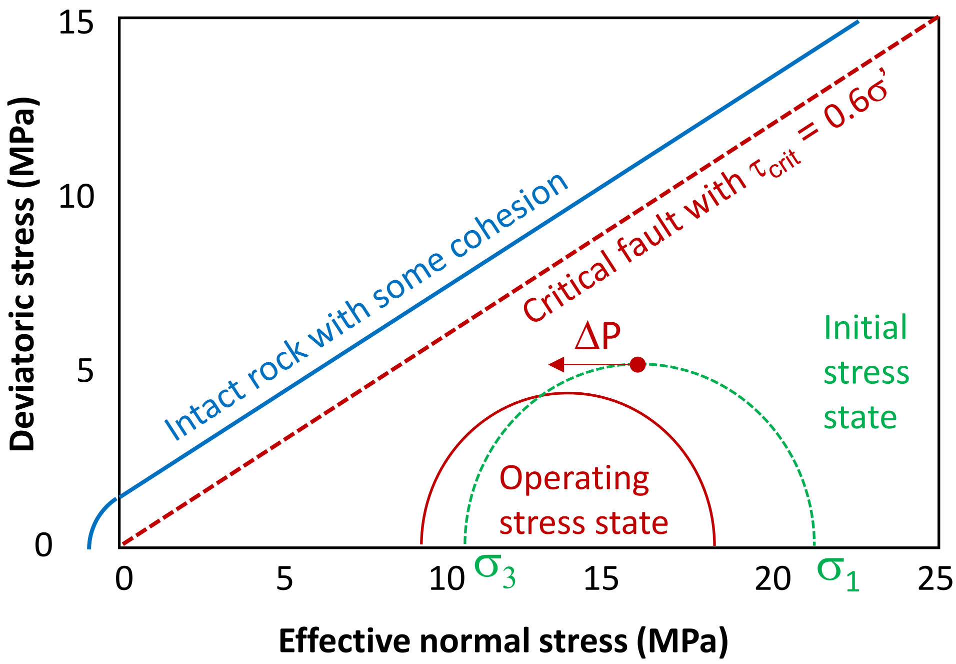

Figure 1 *– Mohr Diagram, showing stress states for a rock system, where the initial stress state is modified by an increase in pore pressure ΔP. Diagram modified from Vilarrasa and Carrera (2015).*

1.3 Monitoring objectives – the bigger picture

In the ACT SHARP project, we are investigating how site monitoring could help an operator to manage risks – specifically how to avoid unwanted degrees of rock fracture or how to monitor expected levels of rock strain. We can potentially measure rock strain directly using downhole strain gauges, or fibre optic measurements of strain, or using surface measurements of strain (such as InSAR). We can also measure strain remotely, by listening to acoustic events occurring at depth. Small acoustic events are like 'creaks and groans' of the rock mass and would have magnitudes of less than zero on the 'Richter scale'. Larger acoustic events are called 'earthquakes' which can be minor earthquakes, moderate-sized earthquakes, or occasionally major earthquakes (Figure 2). Micro-seismicity is a term used to describe events generally lower than magnitude 3 and not felt by humans at the surface. Microseismic monitoring is therefore useful for monitoring rock strain in and around a CO_2 storage site, but also important for understanding when and where larger seismic events occur. In general, some larger events could be quite acceptable, such as natural earthquakes in the wider region around the injection site, while other events could be less acceptable, like for example, a moderate sized earthquake triggered by the injection activity. It is important to emphasize, that these are only general concepts, and each project would need to assess what levels of seismicity may or may not be acceptable according to a risk evaluation carried out for each specific site.

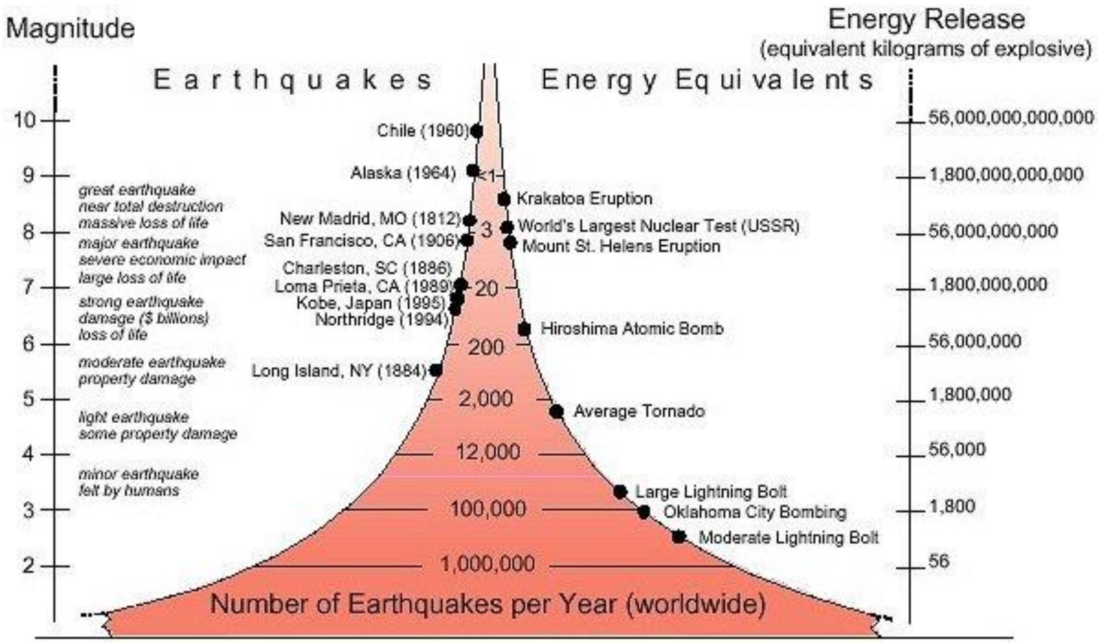

Figure 2 – Graph showing the average annual occurrence and equivalent energy release for earthquakes of different magnitudes. Source: Public domain p*lot from the Incorporated Research Institutions for Seismology.*

1.4 Background and Objectives of this study

The SHARP Project is a research project funded under the ERA-NET ACT programme for accelerating Carbon Capture and Storage (CCS) with the overall aim to improve the accuracy of subsurface CO_2 storage containment risk management.

Work Package 4 is focused on developing targeted strategies for monitoring rock deformation and fluid pressure impacts resulting from CO_2 storage operations and has the overall objective to: "Design improved monitoring schemes using right-time and right-place detection".

The main objective of this report is to assess current monitoring practices, to propose enhancements, and to evaluate the effectiveness of specific monitoring technologies. We aim to identify the gaps or limitations in current monitoring practices that necessitate further research or improvement. We have a special focus on the use of fibre optic (FO) sensing, which is a fast-emerging CO_2 storage monitoring solution, offering a multi-use solution. FO sensing can be used in several ways including direct measurement of rock strain using distributed strain sensing (DSS), active seismic monitoring using FO distributed acoustic sensing (DAS) utilizing telecom and power cables as detectors, and passive detection of microseismic events on FO DAS systems. Distributed temperature sensing (DTS) is another important class of FO sensing, which exploits the inelastic Brillouin and Raman scattering measurements as compared to elastic Rayleigh scattering used for DAS.

We also emphasize the need for safe and effective monitoring practices and include learnings from the geothermal sector and fracking operations. The understanding of the geomechanical response to CO_2 injection is crucial in the operation of CO_2 storage projects. Key considerations involve preventing significant rock failure (e.g., fracturing of sealing formations) and ensuring that the levels of induced seismicity are at a very low level. It is also important to note that these monitoring strategies are generally aimed at avoiding or preventing potential 'loss of containment' events. It is better to modify injection plans before a breach of containment occurs rather than wait until it is too late! This is essentially why monitoring of acceptable levels of strain/seismicity is done – we want to mitigate against unacceptable levels of strain/seismicity.

1.5 Monitoring requirements for safe CO2 storage

The overall objective of a Monitoring, Measurement and Verification (MMV) programme is to verify storage and minimise the risk of leakage, as outlined in the European Directive (EC, 2009). Jurisdictions outside the European Economic Community may have different legal terms but will generally use the same conceptual framework. We will here use the European legal framework as a reference, as this is relevant for most of the field sites used in SHARP. The overall monitoring objective can be subdivided into two main goals: *Conformance* to verify storage performance and *Containment* to ensure the CO_2 is contained within the storage complex. A third important aspect of an MMV programme is the concept of *Contingency* which is the ability to respond (for example to potential leakage events). For further information on regulatory and legal aspects we refer to Dixon and Romanak 2015 and Dixon *et al*. 2015. We will here mainly focus on containment monitoring, as the main purpose is to explore how monitoring can be used for dynamically detecting changes in subsurface stress and modelling geomechanical changes.

The EU legislation does not specify what kind of monitoring system(s) should be employed, but states that the parameters to be monitored should fulfil the purpose of monitoring. A list of minimum number of parameters to monitor is also provided.

The purpose of monitoring is according to Article 13 (EU CCS Directive 2009):

> *"1. Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex (including where possible the CO2 plume), and where appropriate the surrounding environment for the purpose of: (a) comparison between the actual and modelled behaviour of CO2 and formation water, in the storage site; (b) detecting significant irregularities; (c) detecting migration of CO2; (d) detecting leakage of CO2; (e) detecting significant adverse effects for the surrounding environment, including in particular on drinking water, for human populations, or for users of the surrounding biosphere; (f) assessing the effectiveness of any corrective measures taken pursuant to Article 16; (g) updating the assessment of the safety and integrity of the storage complex in the short and long term, including the assessment of whether the stored CO2 will be completely and permanently contained."*

The minimum parameters to monitor are given by ANNEX II (EU CCS Directive 2009):

> ”… *continuous or intermittent monitoring of the following items: (e) fugitive emissions of CO2 at the injection facility; (f) CO2 volumetric flow at injection wellheads; (g) CO2 pressure and temperature at injection wellheads (to determine mass flow); (h) chemical analysis of the injected material; (i) reservoir temperature and pressure (to determine CO2 phase behaviour and state)*”.

It is up to the operator to design a monitoring plan adhering to these requirements, and to get it approved by the authorities. Due to the large diversity of potential storage sites, the actual monitoring programmes will consequently span a wide range of methods, spatial coverage and timing. The operator is typically responsible for monitoring the storage during and after operations, until the responsibility is handed over to the authorities (in EU legislation this generally corresponds to a period of between 20-50 years, while in the USA it is normally 50 years).

Storage sites should be selected in locations where the geological leakage risk is minimal, and all measures should be taken to minimise the risk of leakage during operation. Consequently, risk management has a major focus both before, during, and after storage operations, and monitoring should be used actively to minimise risks. Due to the wide variety of potential storage sites (homogeneous/heterogeneous storage units, deep/shallow sites, saline aquifers/depleted reservoirs, sandstones/carbonates/others) the risks will also vary considerably, and the monitoring programme will consequently need to be tailored to the relevant risks. In addition to technical leakage risks, there are risks related to public perceptions, and the potential need for monitoring technologies that might not directly impact technical decisions but might still be relevant for obtaining a license to operate. Refer to SHARP WP 5 “Risk quantification” for further discussions of risks related to CO2 storage.

When designing monitoring programmes, the operator is often in a situation with a need to distinguish “nice to have” from “will impact operational decisions”. In a position with a strong focus on cost prudency, every monitoring technology must be argued for. Questions that need to be addressed are typically related to in which cases there is a need for intermittent or continuous real time monitoring, whether a technology addresses the full storage complex (e.g. time-lapse seismic, gravimetry) or whether a limited volume (e.g. FO in-well or near well applications, surface monitoring) will be sufficient.

From the regulations described above a minimum requirement is to monitor the plume migration (CO_2 saturation) in the storage complex. In addition, there might be a need to monitor the pressure front (depending on degree of expected pressure buildup). The pressure front typically extends far beyond the CO_2 plume and can be manifested both as pore pressure buildup, and as geomechanical changes in the surrounding subsurface rocks. Both plume and pressure monitoring typically requires some kind of remote monitoring technology, usually some variation of seismic velocities, gravimetric, or electromagnetic monitoring. Questions related to areal extent and timing are highly relevant for this type of subsurface monitoring, given an extensive need for receivers and/or sources for these technologies. There are efforts to develop more cost-efficient tools (such as small, continuous seismic sources, FO listening devices, FO strain monitoring *etc*).

The risk of well leakage is often considered to be higher than the risk of geological leakage, and the consequences larger, though often easier to mitigate (provided there is access to the well). Wells are generally suitable for integrating FO technologies such as DAS, DTS, and DSS, but these will generally map a relatively confined area near the well. FO cables can be installed cemented to casing, clamped on tubing, or even hanging loose in the wellbore and the quality varies correspondingly. DAS can be used either as part of an active seismic survey, or as a passive listening device in combination with other passive seismic monitoring sensors. The deployment of fiber optic cables presents technical challenges and requires careful consideration of costs, with various pros and cons to weigh.

For example, many of the CO_2 injectors in the North Sea are anticipated to be subsea developments, which come with higher completion costs, especially when integrating fiber optic downhole systems—potentially even more costly than platform wells.

1.6 Monitoring technology in CO2 storage

CO_2 storage monitoring is typically performed using a combination of equipment and techniques to ensure comprehensive monitoring. Some commonly used methods include seismic data acquisition (e.g. marine streamers, surface acquisition or ocean bottom node (OBN) systems), pressure and temperature sensors, gravity and magnetic surveys, electro-magnetic surveys, downhole FO sensing and well logging tools. Overall, a combination of these geophysical techniques is used to ensure comprehensive monitoring of CO_2 storage sites and to mitigate any potential risks associated with the process. A full review of experience and options for the monitoring of CO_2 storage sites is beyond the scope of this report, and is covered elsewhere (e.g., Chadwick *et al*., 2010; Jenkins *et al*., 2015; Furre *et al*., 2017; Harvey *et al*., 2022; Ringrose *et al*., 2013; Ringrose 2020). Figure 3 shows an example where downhole FO sensing was successfully used at the onshore CO_2 storage site at Quest in Canada (from Harvey *et al*. 2022) where the main objective was monitoring the expansion of the CO_2 plume via time-lapse DAS VSP (vertical seismic profiling).

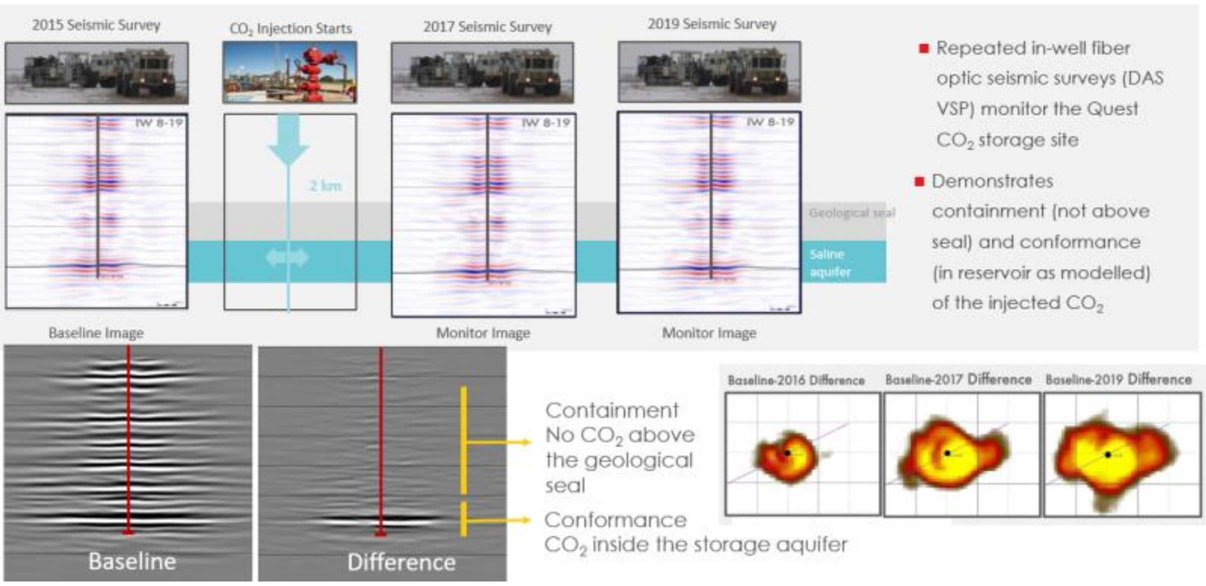

Figure 3 – In-well fibre optic technology utilized for conformance and containment monitoring. Time-lapse DAS VSP showing CO2 plume in the expected location, source Harvey et al. 2022, https://jpt.spe.org/twa/best-practices-for-risk-based-measurement-monitoring-and-verification-in-ccus-projects

Recent advancements in monitoring CO_2 storage sites have an increased focus on observing the geomechanical effects of CO_2 injection, which requires measurements of rock mechanical properties and stress field assessments. This involves a combination of microseismic monitoring and downhole measurements of pressure and strain.

For onshore CO_2 storage sites, microseismic monitoring has been widely deployed (e.g., see Verdon *et al.* 2013, Goertz-Allmann *et al.* 2014, Dando *et al.* 2021). Monitoring with downhole geophones close to the storage site offers the best possibilities to detect small microseismic events near the injection wells. Good location estimates can be achieved by combining downhole geophones together with supplementary seismic nodes on the surface and by application of advanced processing methods (e.g., Goertz-Allmann *et al*. 2023).

The deployment of a seismic network around a CO_2 storage site is important for many reasons. Firstly, it is needed to assess the general level of seismic risk in the region (which is part of the site selection and appraisal process). Secondly, it plays an important role in analysing earthquake source mechanisms, potentially allowing for the clarification of the causal connections between the stress field and fault rupture. This capability also offers valuable insights into the geomechanical properties of the subsurface, facilitating a comprehensive assessment of geomechanical changes induced by CO_2 injection activities.

The next important role of a seismic detection network is to provide a baseline against which possible induced seismicity can be assessed. Differentiating between natural seismicity and induced seismic events is a critical aspect in CO_2 storage operations. Integrating seismicity data with regional stress information and geomechanical datasets is paramount for gaining a nuanced understanding of natural seismicity patterns and assessing the potential for induced seismicity.

Such integration not only aids in characterizing the nature of seismic events but also facilitates the management of geomechanical risks associated with CO_2 injection operations. The recent study by Zarifi *et al.* (2023) shows how this assessment of background seismicity has been done for the offshore Horda platform region (where the Northern Lights CO_2 injection project is soon planned to start).

A fast-emerging monitoring technology is the use of FO sensing both at surface or downhole. Several onshore CO_2 storage sites have deployed FO monitoring, such as Distributed Acoustic Sensing (DAS) in injection wells to monitor the CO_2 plume using time-lapse DAS vertical seismic profiling (Figure 3) whereby FO cables are utilized as seismic receivers (e.g. Harris *et al.*, 2016, Bacci *et al*., 2017). It has also been argued that it might be beneficial to use pressure gauges for absolute measurements in combination with DAS to monitor small pressure and strain changes in the subsurface close to the injector well (e.g. Ringrose *et al*. 2018). An introduction to FO technologies will be given in the following chapter along with a discussion of the potential applications. Figure 4 shows a sketch highlighting the potential for a 'multi-physics' approach to CO_2 storage monitoring – could we cost-effectively monitor saturation, pressure and rock strain using one integrated system? And, what role could FO sensing play in achieving this?

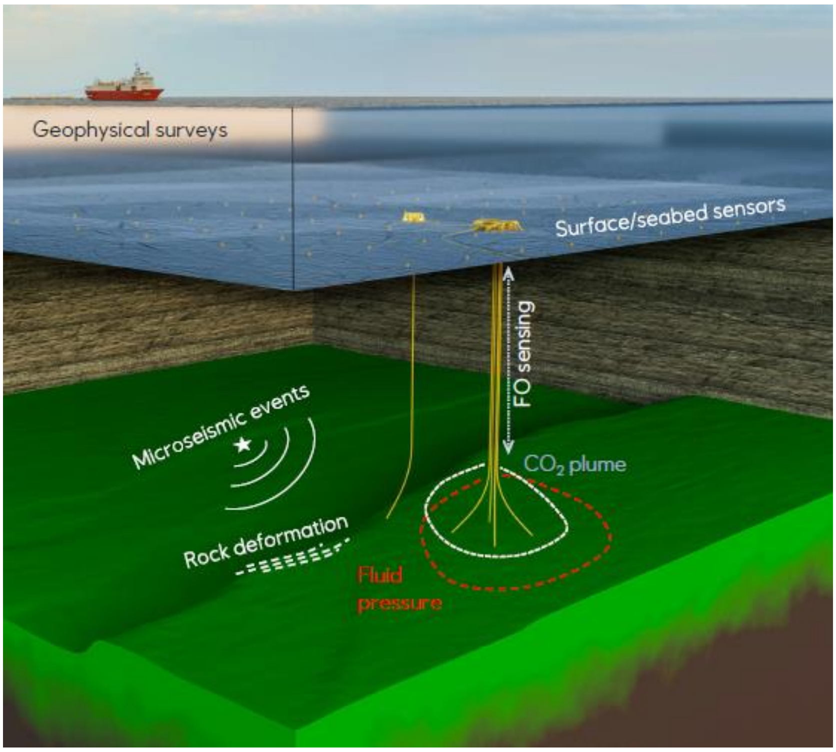

Figure 4 *– Sketch illustrating CO_2 storage monitoring in an offshore setting, (modified from Ringrose 2023).*

1.7 Fibre optic technology

In this section, we aim to provide an introductory overview of the fundamental concepts surrounding fibre optics, laying the groundwork for readers to comprehend the potential applications of this technology. This foundation will serve as a framework for delving deeper into the specific utilization of the FO technology for CO_2 storage monitoring later in the report.

The evolution of distributed optical fibre sensors (DOFS's) from conceptualization in the early 1980s to their widespread usage today underscores their significance in modern technology. These sensors have revolutionized monitoring practices, particularly in boreholes for geothermal and hydrocarbon production. Unlike traditional sensors that measure parameters at a single location, DOFS's provide insights into the temporal and spatial distribution of a measurand along lengthy fibre sections. The advancements in optical fibre technology during the early 1970s paved the way for rapid development, including low-loss fibres and sophisticated transmitting/receiving electronics design (e.g., Hartog 2017). Scientific literature during this period showcased the versatility of optical fibres, demonstrating their utility in measuring various parameters such as chemical composition, acoustic signals, temperature, pressure, and strain. This versatility enabled the creation of lightweight sensors adaptable to space, power, and environmental constraints, particularly crucial for hostile environments like high-temperature borehole applications. Consequently, distributed sensing technologies like Distributed Temperature Sensing (DTS), Distributed Pressure Sensing (DPS), Distributed Acoustic Sensing (DAS), and Distributed Strain Sensing (DSS) emerged as practical solutions.

Permanent Reservoir Monitoring (PRM)

Permanent Reservoir Monitoring (PRM) systems which typically utilize FO technology represent an advanced method for continuously monitoring subsurface conditions within oil and gas reservoirs.

It's essential to clarify that Optowave PRM systems, such as used in prominent projects like Ekofisk, Johan Sverdrup, Johan Castberg, and Libra/Mero, are actually not DOFS's (although often named as such), as DOFS's specifically refer to distributed sensing. Instead, Optowave PRM systems represent FO sensing solutions with integrated point sensors. It is a 4C system combining several seismic stations that consist of 3 accelerometers and 1 hydrophone based on a unique FO sensing technology (utilizing Fibre Bragg Gratings). The 4C sensor cable network is installed on the seabed and the interrogation unit is installed on the platform/FPSO. A key advantage of fibre optic sensors compared to electrical sensors is their independence from electronic components and electrical power at the sensing point. All electronic elements are located above water, where data recording occurs. This inherent design enhances safety and reliability significantly.

PRM systems offer several advantages over traditional monitoring techniques. They provide high-resolution data with enhanced sensitivity, allowing for precise detection of reservoir changes. Additionally, the permanent installation of fibre optic cables ensures continuous monitoring throughout the lifespan of the reservoir, enabling long-term data collection and analysis. These systems play a crucial role in reservoir management by providing valuable insights into reservoir behaviour, such as fluid movement, pressure changes, and reservoir depletion. By continuously monitoring key parameters, PRM systems help optimize production strategies, enhance reservoir recovery, and mitigate operational risks.

The Ekofisk field, operated by ConocoPhillips, installed a PRM system in 2010, which was claimed to be the world's largest at that time. The deployment represents a notable advancement in acquiring precise 4D seismic data, allowing for precise observation of subsurface changes and measuring subtle changes in velocity, now with variations of around 0.2 milliseconds being observable (Folstad *et al.* 2015). This marks a significant breakthrough compared to previous time shift resolutions, which typically ranged between 2-3 milliseconds (within a positioning error margin of about 2 milliseconds). The observed time shifts can be attributed to various factors, including the response of the reservoir to water injection, and increased pressure in the reservoir (positive time shifts) or factors like reservoir compaction, depletion, or reduced pressure (negative time shifts). This system represented a significant advancement in reservoir monitoring technology, providing operators with crucial insights into reservoir behaviour and facilitating informed decision-making for optimized reservoir management and production strategies.
The data obtained from 4D seismic surveys conducted at Ekofisk, utilizing both early streamer surveys and the PRM system, are valuable for various operations ranging from optimizing well paths, containment integrity and monitoring reservoir waterfront dynamics (e.g., Folstad *et al.* 2015). The utility of PRM extends beyond daily operations to encompass activities such as reservoir mapping and identifying new well targets. Since its installation, more than 25 PRM surveys have been conducted at Ekofisk.

In recent years, Equinor has implemented PRM systems in major fields such as Snorre and Grana, and PRM systems based on FO technology at Johan Castberg and Johan Sverdrup, which play pivotal roles in the company's high recovery strategies on the Norwegian Continental Shelf (NCS), aiming for recovery rates of 60% and 70%, respectively. These fields marked the first instances globally where PRM systems were installed ahead of production commencement, driven by the pursuit of operational efficiency and economic benefits.

In the future, PRM systems present promising potential for CO_2 monitoring applications. During the injection phase of CO_2 storage, it can be instrumental in mapping the CO_2 front, akin to how water fronts are mapped.
By enabling the mapping of the CO_2 plume front, this technology ensures effective containment and conformance monitoring, essential for successful CO_2 storage operations. Additionally, it empowers the monitoring of injected CO_2's influence on regional stress field changes, thereby enhancing the understanding and management of geomechanical risks associated with CO_2 storage.

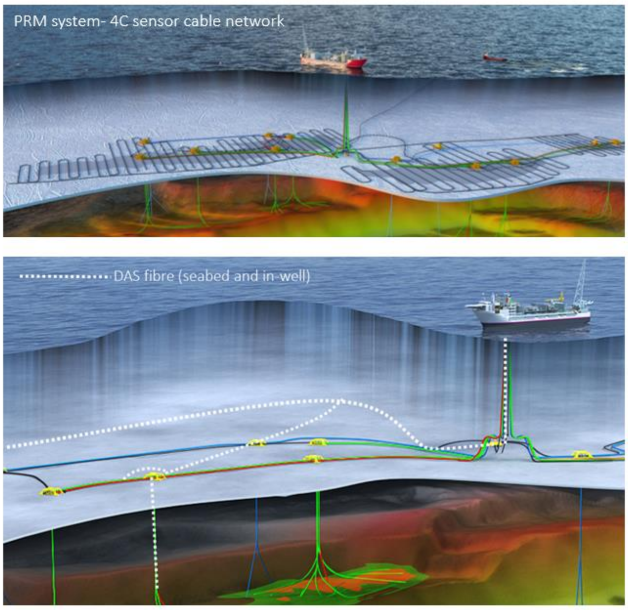

Figure 5 – Illustration of fibre optic monitoring systems PRM and DAS with cortesy of Equinor (source: https://www.asn.com/energy-solutions)

Distributed Acoustic Sensing (DAS)

The technique utilizes optical fibres deployed for monitoring purposes or using fibres already included in submarine telecommunication and power cables to sense the marine environment. In DAS, a measurement instrument called an interrogator is connected to a fibre optic cable into which it sends a laser signal. A tiny fraction of this laser signal is backscattered by Rayleigh scattering.

Rayleigh scattering is an elastic process caused by localised inhomogeneities in the fiber. When a section of the optical fibre is subjected to strain, the light propagating through will experience an optical phase delay. By analysing the back-scattered signal a DAS interrogator can determine the fibre strain induced along each section of the optical fibre. Everything that impacts the cable strain, can be measured. Example causes of strain changes in the submarine environment are strain changes are caused by acoustic vibration, but also tidal forces, ambient temperature changes, pressure changes due to ocean swells produced by storms, and physical impacts on the cable e.g., due to dragging anchors and fishing trawls (e.g., Lindsey *et al.* 2019, Rørstadbotnen *et al.* 2023, Wienecke and Brenne 2023).

Note that, Distributed Strain Sensing would, however, be a better description than Distributed Acoustic Sensing, but for historical reasons the name DAS is kept in order to distinguish the method from Distributed Strain Sensing based on Brillouin scattering.

In the following, we aim to showcase a diverse array of applications to demonstrate the versatility of DAS technology, akin to a multifunctional Swiss army knife. While the primary focus in this report lies in its utility for CO_2 storage monitoring, DAS also holds promise for a range of other applications. These include enhancing security and safeguarding infrastructure, contributing to climate research endeavours, and advancing the field of marine biology. Through exploring these varied applications, we seek to underscore the broad spectrum of possibilities offered by DAS technology.

In a 2018 field trial, DAS technology was deployed on a subsea telecommunication cable provided by Tampnet, ranging from Lowestoft, UK, to a platform located in the North Sea. This trial demonstrated the interrogator's remarkable ability to detect strain vibrations with high sensitivity over distances of up to 130 km. Vessels and boats emitting acoustic noise near the cable can be detected and localized within 10 km distance sideways from the cable. Bottom trawls can be detected above the ambient noise and localized within distances of about 2.5 km sideways from the cable (Rønnekleiv *et al.* 2019).

Vessel tracking data from the Automatic Identification System (AIS) available during the periods of DAS recording allowed comparison of vessel tracking positions with DAS localization results. These were found to be in very good agreement. The technology detected vessels and trawls also in cases when no signal was sent to AIS. These field trial results qualify the feasibility of long-range DAS interrogation for integrity monitoring of submarine telecommunication cables and associated infrastructure. Real-time cable threat monitoring capabilities enable early warning and therewith allow for risk mitigating actions to prevent potential cable damage (Morten *et al.* 2023). The field experiment increased our understanding that DAS has valuable capabilities to offer to the marine biology and geoscientific community with high temporal and spatial resolution and very broadband measurements detecting a large variety of acoustic signals (Wienecke and Brenne 2023). For example, the understanding of the real-time ship tracking capabilities using long-range DAS and the fact that ship-strike injuries are recognized as one of the most critical anthropogenic threats to cetaceans, motivates to develop other types of applications such as localizing and tracking of cetaceans.

Two field trials conducted in 2020 and 2022 at Svalbard demonstrated the utilization of long-range DAS as an acoustic monitoring tool for cetaceans, complementing existing techniques (Landrø *et al.* 2022, Rørstadbotnen *et al.* 2023). The trials verified a significant signal-to-noise ratio (SNR) gain achievable through extended aperture array processing, facilitating the construction of high-quality audio waveforms. This enhancement enabled the auditory and spatial differentiation of cetacean individuals and identification of call types across species. Observations revealed that whale vocalizations could be detected at a minimum strain of approximately 20 pico-strains, thereby defining the maximum detection range. Empirical estimations placed the DAS detection range at approximately 9.4 km on either side of the cable for all whale tracks, with localization errors of about 100 m.

Moreover, the trials confirmed DAS's capability to measure various ocean-bottom pressure responses and detect microseismic events within the 0.02-0.5 Hz frequency band. These microseismic events were found to correspond to ocean swells generated by distant storms (Taweesintananon *et al.* 2022).

Results also indicated that the extended antennae provided by submarine cables, particularly when curved, offer a complementary method for seismic source localization. Near-field beamforming techniques were applied to enhance the SNR of recorded seismic signals and better extract P- and S-wave phase arrival times. Hereby the apparent velocity and angle was estimated to find the optimal number of traces that could be stacked coherently for different segments of the cable. The SNR for a segment of the FO cable (61 km) could be increased from 10.7 dB to 30.5 dB for P-wave signals, and from 20.4 dB to 40.6 dB for S-wave signals. For earthquake analyses, DAS-recorded events exhibited good agreement with conventional seismometer data. Seismograms derived from DAS measurements closely matched those from the KBS seismic station in Ny-Ålesund, part of the Global Seismograph Network, depicting P, S, and SS arrivals with excellent correspondence (Rørstadbotnen *et al.* 2023).

The findings from these field trials underscore the remarkable sensitivity and potential of DAS for CO_2 storage monitoring, which holds considerable relevance for such applications. The ability to detect whale calls even within the complex underwater environment, where the FO cable is encased within a protective metal tube and situated deep beneath the seafloor, highlights the system's capacity to discern acoustic signals. This sensitivity extends to identifying acoustic emissions indicative of leakage in CO_2 injection wells, a topic to be further explored in Chapter 4.3.

Moreover, the trials demonstrate the practicality of leveraging existing infrastructure for cost-effective monitoring solutions (Wienecke *et al*. 2024). Pre-injection monitoring of natural seismicity in the vicinity is essential for establishing a baseline against which any induced seismicity from CO_2 injection can be evaluated and communicated to the public effectively. Additionally, the trials illustrate the potential of DAS for pinpointing the locations of micro-seismic events and earthquakes, whether they occur within the reservoir or in the underlying basement. These capabilities are crucial for comprehensive monitoring and risk assessment in CO_2 storage operations.

DAS observing seismic anisotropy

Passive seismic imaging can illuminate structure in the subsurface in multiple ways, one of which is the observation of seismic anisotropy. As seismic waves propagate, they can encounter structures and crystalline fabrics that cause wave speed to vary as a function of propagation direction. This effect of seismic anisotropy can be measured by careful examination of the arrival of seismic phases. Mostly the shear S-waves are studied as their inherent polarisation makes them particularly sensitive to linear structures that cause anisotropy. One unambiguous effect of seismic waves passing through an anisotropic medium is shear-wave splitting (SWS). In this case, as S-waves pass through the anisotropic region, they split into a fast and slow shear wave, the fast polarised in alignment with the structure, and the slow perpendicularly polarised. Both the polarisation of the fast shear wave (or "fast direction"), and delay time between the fast and slow, can be measured and used to infer information about the structure along the ray path.

DAS methods have now been used to measure SWS in multiple settings. Hudson *et al*. (2021) demonstrated the ability of DAS to measure seismic anisotropy from icequakes during a passive seismic experiment on ice sheets in Antarctica. Several fibre geometries were employed, and the effectiveness of each was compared. It was shown that DAS fibre can image the arrival of both fast and slow shear waves, and thus the delay time can be measured with high temporal and spatial accuracy. The DAS measurements were compared to those from 3-component broadband seismometers for validation.

Slowness analysis can be used on fibre geometries to find both delay time and fast S-wave polarisation direction. In Hudson *et al*. (2021), the ratio of strain rate amplitude is used on two sides of a triangular array to infer shear wave polarisation (show in Figure 6 below). The amplitude ratios are used to find the best fitting fast direction based on model arrivals from a range of S-wave sources. Fast and slow polarisations are fit independently, and verified if the two angles are close to 90 degrees apart. Delays times are computed using the average delay observed on the three sides of the array, to approximate the delay that would be observed at the centre. These splitting results were directly comparable to those found by conventional measures of SWS (Smith *et al*., 2017)

Using DAS methods for measurements of anisotropy are, however, highly dependent on fibre geometry. Whilst delay times can be measured by picking both the fast and slow shear waves (and their respective moveouts) on DAS record sections, due to the single component nature of DAS recordings, polarisation information, and thus a measure of fast shear wave polarisation direction, is more difficult to acquire. It requires a fibre geometry that can capture the 2-D horizontal wavefield over a small spatial area, and corrections that account for event slowness in the S-wave arrivals, as shown in Hudson *et al*. (2021). Whilst this is a complicating factor, it can be overcome using post processing of the event data. However, the primary advantage of DAS systems is greater spatial sampling of the wavefield, often over much larger distances than would be suitable for SWS analysis. Thus, it seems unlikely that DAS arrays will often be employed to measure seismic anisotropy in this manner. If measures of SWS were an objective for a large aperture DAS array, small, azimuthally varying 2-D segments of fibre would need to be employed.

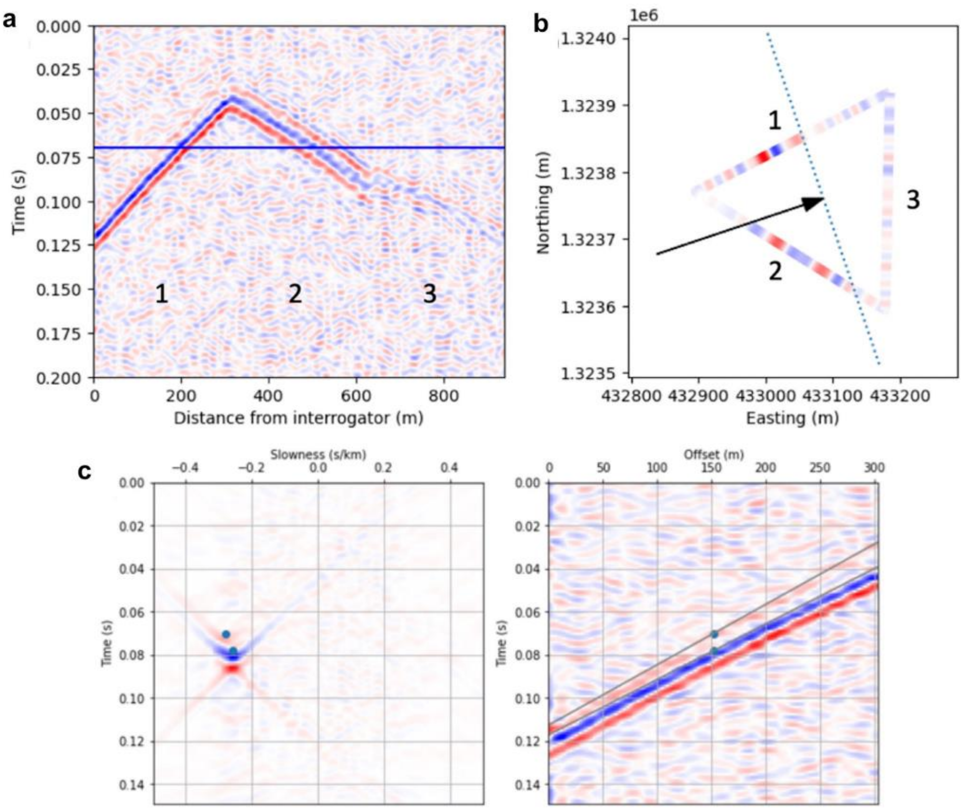

Figure 6 *– An example of DAS-recorded shear wave splitting from Hudson et al. (2021). (a) shows an example of an icequake recorded on a DAS fibre, the geometry of which is shown in (b). The colour scale in (b) shows the strain at a snapshot in time which is shown as the blue line in (a). (b) also shows the propagation direction and wavefront location found from the recorded slowness, as the black arrow and dotted blue line respectively. The slowness analysis is shown in the left panel of (c), using data from the side of the triangular denoted by 1 in both (a) and (b), shown in detail on the right of (c). Two discrete S-wave arrivals can be observed in the slant stack,*

with arrival times shown by the blue dots in (c). The two grey lines on the right panel of (c) indicate the moveout of the fast (higher amplitude) and slow (lower amplitude) shear wave arrivals.

DAS in comparison to other technologies

In 2019-2020, a fibre-optic Permanent Reservoir Monitoring (PRM) system was installed at Johan Sverdrup. To compare PRM and DAS responses a field trial was performed where data were recorded in co-located PRM and DAS recording cables, trenched at the sea bottom. Active seismic data were collected simultaneously for both DAS and PRM systems, with the fibre-optic cable trenched together with the PRM array cable. Figure 7 shows the PP migrated image in the time domain. Surprisingly at that time, the DAS system provided a seismic image of good quality. Because of the higher sampling, the lateral resolution above 0.5 seconds is higher and more detailed seismic information compared to the PRM system can be obtained. This was notable despite DAS being a single-component (1C) system, in contrast to the 4C sensors used in the Optowave - PRM system. In the depth domain it is observed that the spatial resolution is much higher, allowing for the detection of small-scale faults below 12m (in the past referred to as sub-seismic faults). However more research and field trials are needed to investigate if this could be attributed to the DAS acquisition samplings parameter of a small gauge length (*e.g.,* 4m) and/or the higher sampling frequency (*e.g.,* above 800 Hz).

Another surprising finding was that despite the DAS system utilizing a much weaker seismic source (approximately four times weaker than the standard source used for the PRM system), DAS provided a very comparable image to PRM imaging results for the shallow subsurface. However, it is crucial to recognize that for a PRM system, seismic imaging primarily targets the reservoir depth rather than detailed overburden imaging. Additionally, a DAS system exhibit lower signal to noise levels compared to a PRM.

Regardless of lacking certain advantages of PRM systems, DAS on submarine cables presents a cost-effective alternative for a monitoring solution.

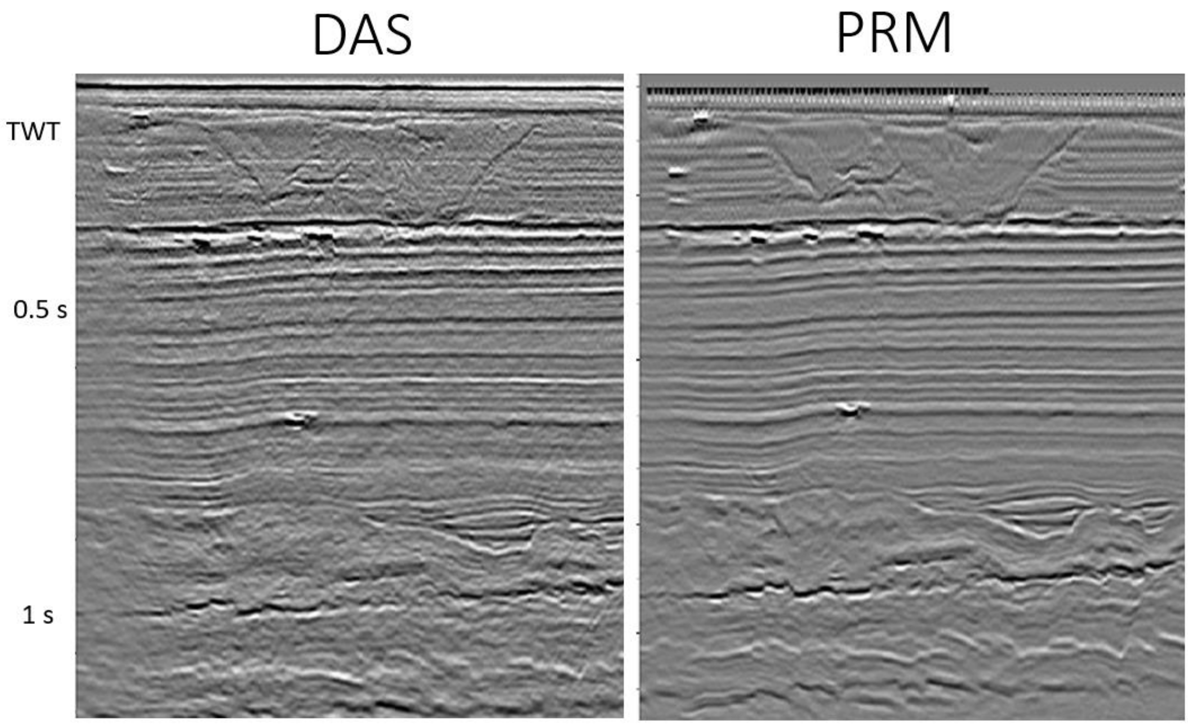

Figure 7 *– Seismic imaging results for DAS and PRM (Optowave). Active seismic was simultaneous collected, with the fiber-optic cable trenched alongside the PRM array cable. DAS exhibited higher spatial resolution and detailed seismic imaging compared to PRM in the overburden, despite being a single-component system using a weaker seismic source. Modified from Pedersen et al. (2022), image courtesy of Equinor, Aker BP, Petoro and TotalEnergies*

PRM systems, with their higher sensitivity and suitability for time-lapse reservoir monitoring due to fidelity and 4C capability, remain advantageous. However, DAS technology shows considerable promise. Nonetheless, extensive research and field trials are imperative to validate this technology fully. Furthermore, understanding signal amplitude quantification in depth and comparing it to conventional seismic sensors is essential for its widespread adoption and effective utilization.

DAS exhibits considerable potential when compared to conventional technologies such as geophones and seismometers. While DAS may have limitations in microseismic detection and source localization compared to conventional instruments (e.g., Hudson *et al*. 2021), it outperforms geophones in source spectra and full-waveform source mechanism inversion.

Hubbard *et al*. (2022) demonstrated that DAS and geophone measurements exhibit consistent phase and amplitude characteristics, when the gauge lengths correspond to the spatial distance between the geophones. Visualizing the time series through power spectra offers a more comprehensive comparison between DAS and geophones, with power spectra being a function of distance from the seismic source. DAS generally exhibits higher signal power across the frequency band, particularly above 45 Hz.

In comparison to conventional seismometers, Lior *et al*. (2023) investigated magnitude estimation using a telecommunication cable offshore Chile. Their findings suggest that DAS can reliably provide real-time magnitude estimation and ground motion prediction, offering significant advantages over standard point-sensors, particularly in offshore earthquake scenarios. The comparison between predicted and observed magnitudes illustrates an improvement over time, highlighting the potential of DAS technology for seismic monitoring applications.

Further research is imperative to fully explore the potential of the DAS technology. While it shows significant promise, thorough validation is required to ensure its reliability. It is crucial to quantitatively characterize DAS measurements, considering factors such as coupling mechanisms, installation configurations, and cable properties, to understand signal amplitude quantification in depth and compare it with conventional seismic sensors (e.g., Wienecke *et al.* 2023). Various field trial results indicate that telecom cables, whether buried or unburied, remain sensitive enough to detect earthquakes and monitor seismicity, even offshore in deep water environments, as demonstrated by experiences offshore Brazil (Browaeys 2024).

A key focus of future research should be on sensitivity and detectability. It is essential to investigate whether strain changes caused by CO_2 injection, or other induced alterations in rock properties are detectable. Insights from downhole DAS experiments, such as those with Quest, suggest that 4D Vertical Seismic Profiling (VSP) is sensitive enough to monitor CO_2 plumes. However, additional laboratory testing and research are necessary to address the fidelity of DAS measurements and further refine its capabilities for CO_2 storage monitoring. The main benefit of DAS are continuous real-time monitoring and high-resolution measurements enabling us to detect small changes in the subsurface early on. But, real-time monitoring, while valuable, falls short in fully addressing the complexities and challenges associated with safe CO_2 storage. The behaviour of CO_2 in the subsurface is influenced by various factors, including geological heterogeneity, pressure changes, temperature, and fluid flow. Real-time monitoring may not capture the intricate interplay of these factors and their long-term effects, and it is crucial to complement real-time monitoring with predictive modelling allowing for the identification of potential risks before they manifest in real-time data.

2 Preventative monitoring solution

In this section, we aim to elaborate on ways to improve current monitoring solutions to achieve an enhanced monitoring solution focused on improved subsurface risk management. More specifically, how can we put in place a strain monitoring system that anticipates and avoids unwanted rock deformation. We do not only want to monitor 'unacceptably large' seismic events – rather we want to prevent such events occurring by 'watching' the injection process. Monitoring seismicity can highlight the location of potential active faults, but it can also be used to characterise the faulting style or assess the *in situ* stresses, which can help in anticipating risks at potential storage sites. Furthermore, monitoring seismicity alone may be insufficient; we also want to monitor changes in the fluid pressure and stress field in order to update geomechanical models and develop predictive solutions. To explain the potential of this approach, we describe a published study from the geothermal sector.

2.1 Objectives of preventative monitoring

Conventional monitoring methods often fall short in monitoring the parameters which are crucial inputs for geomechanical modelling and predictive analysis needed for anticipating long-term effects. Including FO sensing into the monitoring toolbox is very beneficial. One of the main benefit of FO sensing data is the real-time monitoring aspect. However, it is important to mention that the enhancement of monitoring solutions with real time monitoring for fast decision making is not enough to improve the risk management by itself; some degree of predictive modelling is needed in both time and space, akin to weather forecasting. For example, where are fractures likely to occur and when?

It is important to clarify that the presence of fractures and faults does not necessarily imply leakage. Most faults found *in situ* are likely to be sealing if there is a strong enough presence of seal in the lithology. A storage site is only selected if it has sufficient sealing formations, typically mudrocks, shales, or salt, all of which exhibit creeping behaviour. This means faults extending into the overburden are generally self-healing under typical stress conditions. Additionally, sealing lithologies within the fault zone itself can retard flow. While more brittle and porous rocks might be dragged into the fault zone, potentially allowing for across and along fault flow, such occurrences are usually localized. The behaviour of faults and fractures is complex, depending on the lithologies present at the site and the structural history.

An important containment risk for CO_2 storage is the possibility of leakage, arising for example from well failure, or the presence of undetected faults leading to leakage. However, it is important to recognize another key risk namely induced seismicity. Some degree of low-level seismicity will be acceptable, but higher levels may cause concern or even indicate leakage risk.

Monitoring seismicity and localizing seismic events are crucial for public perception. Advancing technology to reduce the uncertainty in depth localization is essential to mitigate the risk of falsely attributing natural seismic events to CO_2 storage activities.

However, numerous studies have shown that human activities in the subsurface, such as fluid injection or withdrawal can induce seismicity, posing potential hazards in various sectors including hydrocarbon extraction, geothermal energy production, and wastewater disposal. For example, The US National Research Council (2013) published a major review of *Induced seismicity potential in energy technologies* or see Keranen and Weingarten (2018) for another review. While the likelihood of a larger seismic event might be low, the resulting consequences can be substantial, making induced seismicity an important risk to account for.

For instance, Schoenball *et al*. (2014) highlight findings from the geothermal sector, demonstrating how significant hydromechanical processes can follow the shut-in of wells. In the Soultz-sous-Forêts geothermal system, significant changes in stress orientation and magnitude were observed, with horizontal stresses shifting by tens of megapascals, potentially leading to seismic deformation on a large scale. This research shows evidence for a hydromechanical response after well shut-in, where earthquake focal mechanisms were used to invert for stress changes in time and depth. The study concludes that there is a risk of induced seismicity persisting for months after operations are stopped.

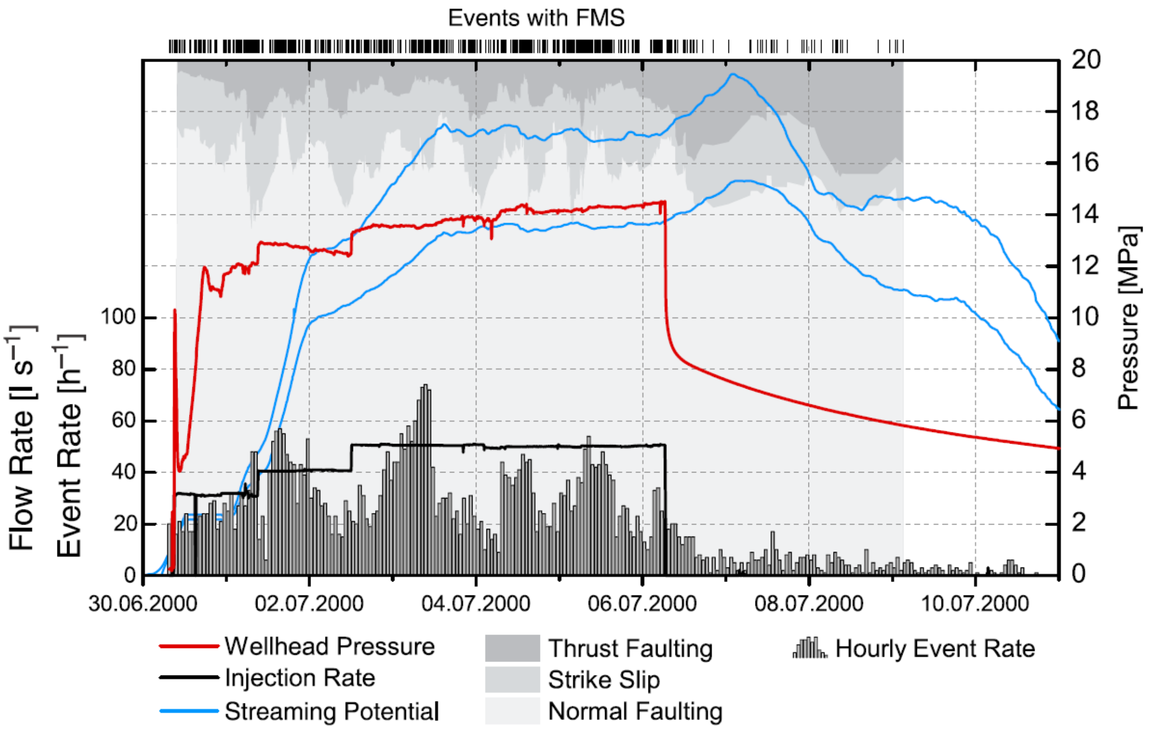

Figure 8 *– Example from Schoenball et al. 2014, showing change of stress regime during geothermal reservoir stimulation.*

Utilizing this knowledge and deriving lessons from these findings is crucial. Although the lithology, and stress generating mechanisms of this geothermal system may differ from those of the CO2 storage complex, it underscores the significance of addressing geomechanical risks in CO_2 storage endeavours. It highlights the need for preventative monitoring and expert guidance to mitigate risks effectively.

As emphasized in the report by Williams *et al*. (2022), the stress history, seismicity, and rock mechanics parameters are crucial inputs for geomechanical modelling and predictive analysis.

One of the primary technical objectives of the SHARP Project includes establishing a framework for a cost-effective monitoring scheme. While past efforts focused on improving seismic networks (see more in chapter 3), combining DAS on submarine telecommunication cables offshore and seismic networks onshore offers enhanced monitoring capabilities (see chapter 4, paragraph 4.2). A recent field trial showcased that utilizing DAS measurements improves the localization of seismic events and significantly enhances event detection, as evidenced by Bremaud *et al*. 2023. DAS, unlike conventional seismometers, allows for the observation of the entire wavefield, providing more comprehensive subsurface information (see paragraph 4.1 , Figure 14)

Combining different available technologies is crucial for effective monitoring. The broadband DAS data combined with conventional seismic observations (e.g. from geophones, OBN, broadband seismometer) enhances the understanding of the geological conditions and seismic risk factors in the storage area. The strain data obtained from FO monitoring can be integrated into geomechanical modelling workflows, providing calibration and ground truthing of models as projects develop. This will enable a more comprehensive understanding of the subsurface behaviour. This integration would enable operators to develop a more proactive method, for example to simulate different injection scenarios and assessing their potential seismic impact, aiding in the development of safer operational practices. It facilitates the early detection of issues and the implementation of mitigation strategies to prevent adverse events, such as leakage or unexpected subsurface reactions. The precise methodology for achieving this remains a topic for future research and is beyond the scope of this report.

An example of a workflow for fault stability assessment is presented in Choi and Skurtveit (2021). The geomechanical model can address regional stress changes at the reservoir. Detailed information about the fault strength and applicable failure criteria (cohesion and friction) is usually associated with high uncertainties and should be carefully addressed in risk assessments. A full geomechanical analysis requires multidisciplinary inputs, including a detailed geological model for geometries (2D or 3D), a reservoir simulation for saturation and pore pressure distribution (and temperature if applicable), petrophysical properties, stiffness, and strength for the reservoir and surrounding model area (e.g., Goertz-Allmann *et al.* 2014).

2.2 Key parameters for preventative monitoring

In our report, when we refer to "key parameters" we mean fundamental variables crucial for monitoring and understanding subsurface behaviour impacting the stress field. These parameters include temperature, pressure, and strain, both elastic and non-elastic, which are pivotal for long-term monitoring.

Our focus on seismicity lies within the broader context of enhancing our understanding of rock deformation and integrity, aiming to develop a more comprehensive enhanced monitoring solution. We envisage an improved and adaptive traffic light system that can better assess and respond to changing subsurface conditions.

Therefore, it is imperative not only to monitor seismic activity in terms of magnitude and occurrence but also to track key parameters for refining the geomechanical model and advancing monitoring capabilities. In addition to conventional monitoring of seismicity using geophones, FO technologies can provide information on the following:

- Time shifts resulting from compaction or dilation of storage reservoirs, or from velocity pushdown effects beneath CO_2 plumes and velocity changes resulting from emplacement of subsurface CO_2 plume (e.g., Harvey *et al*. 2022)

- Overburden stress anisotropy (such as observed by Ridder *et al*., 2015 at Ekofisk)
- Pressure, temperature and strain close to injection wells in conjunction with downhole pressure and temperature gauges (as illustrated e.g. by Ringrose *et al*., 2018, or Haavik and Constable 2023)
- Seismic imaging (e.g., Pedersen *et al*., 2022, Raknes *et al*., 2023)
- Acoustic Emissions (indicative of leakage in CO2 injection wells, as described by Grande *et al*., 2024)

The key parameters that can be monitored using FO technologies therefore relate to temperature, pressure, velocity and strain, all of which are likely to evolve during CO_2 injection operations. The impact of reservoir and overburden deformation can be both elastic and non-elastic, with non-elastic deformation potentially occurring later during storage site development. This may have implications for the monitoring period, with long-term monitoring deployments required to identify the transition from elastic to non-elastic deformation.

The potential applicability of seismicity monitoring methods have been demonstrated at several operational CCS projects (Verdon *et al*. 2013). One of the aims of seismicity monitoring is to develop improved models for rock deformation/failure. In this context, monitoring the key parameters listed above in addition to seismicity, will enable the use of geomechanical modelling as a predictive modelling solution. Recording the evolution of these key parameters along with information on the increase in magnitude or occurrence of seismicity during storage operations, would enable iterative updating of geomechanical models to understand the causal mechanisms controlling the seismic response more fully. Initial rock failure models such as those outlined in SHARP Deliverable 4.1 (Williams *et al*. 2022) can then be validated and updated accordingly.

3 Norwegian North Sea Case Study

The Norwegian North Sea is situated in a tectonically stable environment, with tectonic stress primarily influenced by post-glacial rebound and ridge push forces from two distant plate boundaries. Despite a relatively low risk of seismic hazards, it remains imperative to monitor seismicity, particularly in the context of ongoing CO_2 storage operations. The potential for injection-induced seismicity underscores the importance of a clear understanding of natural seismicity rates. The identification and differentiation of induced seismic events, as well as the assessment of the probability of induced fault reactivation, demand a robust monitoring solution. This necessitates the use of adequate instrumentation to effectively capture and characterize active regions of microseismicity at local scales.

In our report, we advocate for the development of seismic networks that extend beyond earthquake detection to include monitoring key parameters essential for refining geomechanical models. We aim to harness the fast-emerging FO technology to optimize monitoring schemes alongside traditional seismic networks. Our focus will be on the Norwegian part of the North Sea, specifically the Horda area, Aurora, and Smeaheia. We will utilize the dataset from the Horda platform as a case study and draw upon published examples to illustrate the added value of incorporating new and improved monitoring systems.

Our approach involves leveraging seismic networks such as the Norwegian National Seismic Network (NNSN) and the HolsNøy Array (HNAR) array, not only for seismicity monitoring but also as input for geomechanical models, facilitating the development of preventative monitoring solutions. We will examine the additional information that can be obtained from Permanent Reservoir Monitoring (PRM) systems and quantify the improvements in detection threshold and location accuracy they provide.

3.1 Monitoring with the Norwegian National Seismic Network (NNSN)

Norwegian National Seismic Network (NNSN) consist of 44 broadband onshore seismic stations, where deployed in the mainland Norway and Norwegian arctic islands (Figure 9). Data from these seismic stations streams in real time to monitor seismicity in Norway. The NNSN catalogue presents list of earthquakes in the Norwegian territory since 1964, besides sparse historical seismicity. A uniform earthquake magnitude (in M_L) is just available in this catalogue since 2002.
Horda platform to the west coast of Norway, currently hosts three planned large scale CO_2 storage sites on Smeaheia, Aurora and Luna. The NNSN seismic stations near the Horda platform (FOO, HYA, SUE, ASK, BER, ODD1, BLS5 and KMY), have the main contribution on detecting seismicity in this area (Figure 9). These stations are located to the east of the Horda platform, and therefore detection threshold and location accuracy of seismicity suffers from lack of azimuthal coverage. Since 2018, in a collaborative effort between industry and the NNSN, selected stations from offshore Permanent Reservoir Monitoring (PRM) systems (see section 3.3) on Grane and Snorre oil/gas field streams data in near real time to the NNSN, which improves azimuthal coverage for seismicity monitoring in the Horda platform.

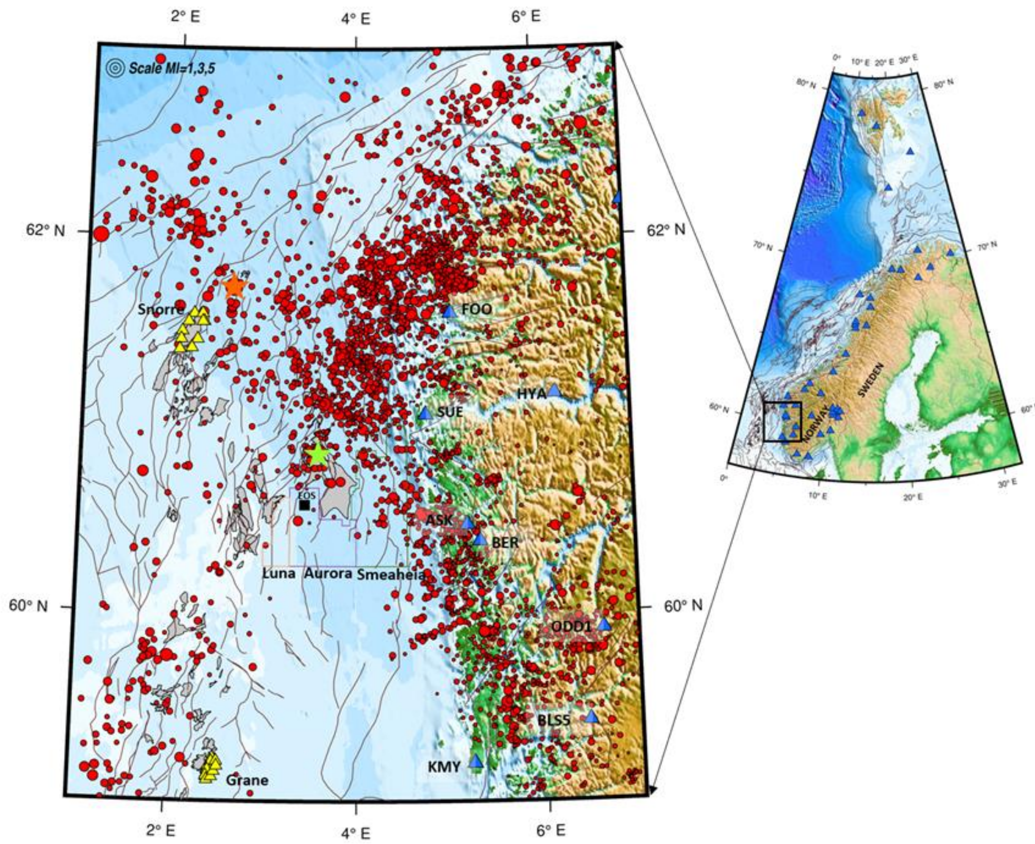

***Figure 9** –Left- Seismicity in and around the Horda platform (NNSN, 2002-2024). Right (Inset)- Location of NNSN seismic stations. The Horda platform currently hosts three CO_2 storage sites in Smeaheia, Aurora and Luna. The largest earthquake in the Horda platform is the 8th June 1980 earthquake (ML=4.5, green star), located 50 km to the NNE of EOS well in Aurora license. The largest recent earthquake around Horda platform is the 21st March 2022 earthquake (ML=4.6, Orange star) located to the NW of the area of interest. Blue triangles are the broadband stations from the NNSN. Yellow triangles are selected geophones from offshore PRM on Grane and Snorre fields, which are integrated with the NNSN since 2018.*

The Horda platform is marked with moderate rate of natural seismicity, mainly associated with the Øygarden fault system, but also to the North of the Horda platform. The G-R relationship suggests a b-value of ~1.0 and Magnitude of Completeness (MC) of 1.5 (M_L) (*Zarifi et al. 2022*). Although majority of seismicity in this area are small in magnitude, but a few moderate size earthquakes with $4.5 < M_L <$ ~5.0 reported in the NNSN catalogue. The *8th June 1980 earthquake with (M_L=4.5) is* largest event near the Aurora license, located about 50km to the NNE of the CO_2 injector (the EOS well). The most recent earthquake near the Horda platform (towards the NW, and about 120km west of Florø (FOO seismic station) is the 21st of March 2022 event with M_L=4.6 (M_w=5.1). The location of these two events, based on NNSN, is marked with green and orange stars in Figure 9, respectively.

Although the expansion of the NNSN network in recent years, in terms of number of seismic stations and integration of selected offshore geophones from PRM, has improved the detection threshold and lateral location accuracy, but depth of seismicity remains inaccurate with uncertainty of about 10km. This major uncertainty raise difficulty to associate seismicity with the future CO_2 injection.

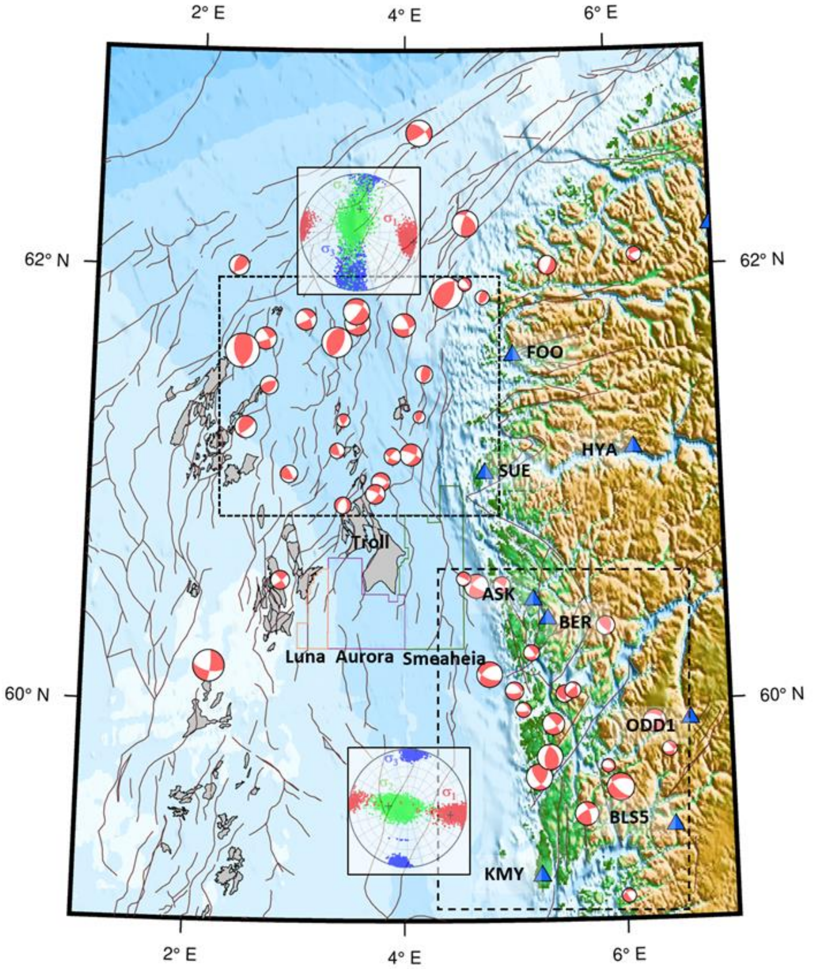

Figure 10 *– Focal Mechanism (FM) earthquakes in the Horda platform and surrounding based on by Tjaland and Ottemoller (2018) and GCMT. Zarifi et al. (2023) used group of FMs to the SW (mostly onshore) and North of Troll(offshore) field in Focal Mechanism stress inversion (presented in solid black boxes). The maximum horizontal stress is dominantly northwest–southeast to east–west over the entire area*

Moderate size of earthquakes in the Horda platform and surrounding areas makes the Focal Mechanism (FM) determination challenging, nevertheless the source mechanisms of some of these earthquakes could be analysed. The report by Tjaland and Ottemoller (2018), marked the most reliable FM determined in this area. Figure 10, shows these reported FMs, plus a few earthquakes reported by Global CMT solution. Most of the onshore earthquakes presents a strike slip and occasionally normal faulting, where this trend changes to mainly reverse faulting in the offshore setting. Zarifi *et al*. (2023) used these data in Focal Mechanism stress inversion and confirmed that the direction of maximum horizontal stress is dominantly northwest–southeast to east–west over the entire area. The trend and plunge of the three principal axes of stress to be (98.8°, 26.9°) for σ_1, (−83.8°, 63.1°) for σ_2, and (8.3°, 1°) for σ_3, onshore, in the southeast of the Troll field. These values change slightly to (100.1°, 57.31°) for σ_1, (3.5°, 57.3°) for σ_2, and (−167.3°, 32°) for σ_3, offshore, in the north-northwest of the Troll field (Figure 10). In addition, the inversion provides an estimate of the stress ratio. The relative stress ratio is higher in the southeast near the Norwegian cratonic basement and lower in the northwest, suggesting some degree of stress relaxation in the sedimentary basin package compared with the basement. Analysis of focal mechanism and tectonic stress regime determination is the subject of further work in WP2.

More efforts on the stress regime, fault stability and containment related geological risks in Smeaheia and Aurora, have been performed in recent studies by Skurtveit *et al*. (2018), Wu *et al*., (2022) and Thompson *et al*. (2021; 2022a; 2022b).

3.2 Including the HolsNøy Array (HNAR), and OBS deployments in the Horda platform

In June 2020, a CLIMIT demo project, HNET, has deployed a dedicated seismic array to improve detection threshold of seismicity in the Horda platform. This array called HNAR, HolsNøy Array, consists of 9 broadband seismic stations, distributed in a circular layout with an approximate radius of 2km in the Holsnøy island to the east of the Horda platform.

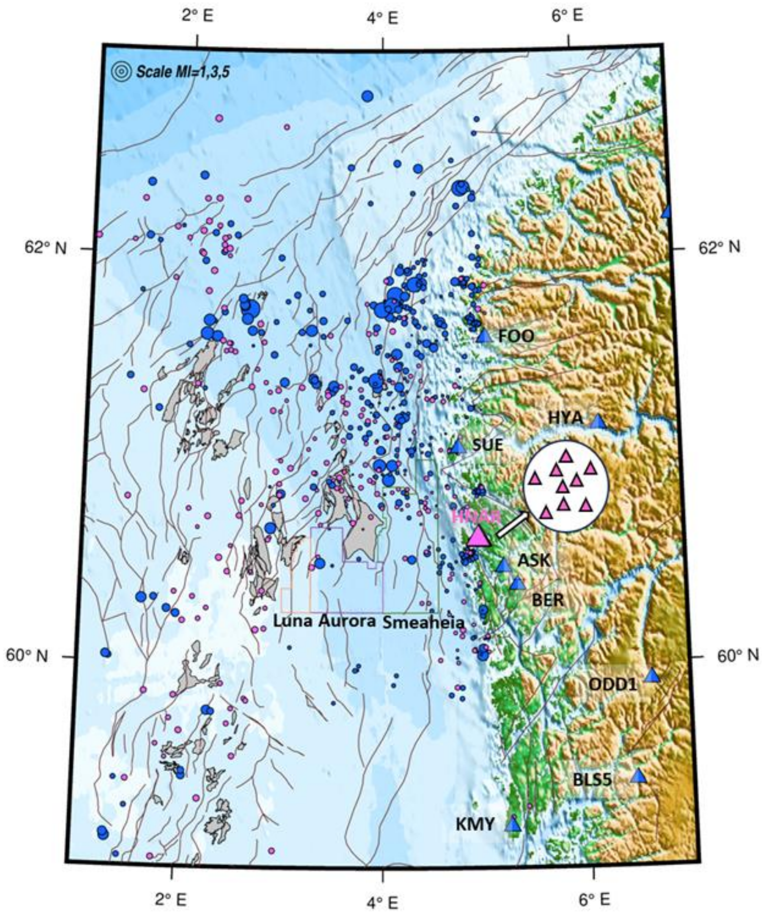

Figure 11 *– Recorded seismicity between June 2020 and April 2024, by the NNSN in blue and by the HNAR array in Purple. Totally 265 minor earthquakes detected by the HNAR, which were not detected by the NNSN. The inset in white circle shows the layout of the HNAR array.*

In period of June 2020- April 2024, 265 earthquakes have detected by HNAR, which was not present in the NNSN catalogue. These events are mostly minor earthquakes with $M_L \leq 1.5$ (Figure 11, see also Oye *et al.*, 2021; Zarifi *et al.*, 2023). The HNAR array has clearly improved the detection threshold of seismicity in the Horda platform. The ability to detect smaller earthquakes using HNAR, can positively impact local seismic hazard analysis in addition to detection and analysis of possible future induced events for geomechanical risk assessments.

In an additional effort, the HNET project deployed three Ocean Bottom Seismometers (OBS), Between October 2021 and September 2022, to the south of the Troll field. The aim of this deployment was to verify the observed low level of seismicity rate in Aurora license boundary. By integration of these stations after retrieval with the NNSN stations, and application of ML algorithm, about 380 small earthquakes (many with $M_L \leq 0.5$, but also slightly larger events) have been detected where none were located in the Aurora license (Figure 12). This result can confirm the importance of OBS deployment in this area. However, since OBS data could be analysed just after their retrieval from seabed, the OBSs could not be part of real time seismicity monitoring in this area.

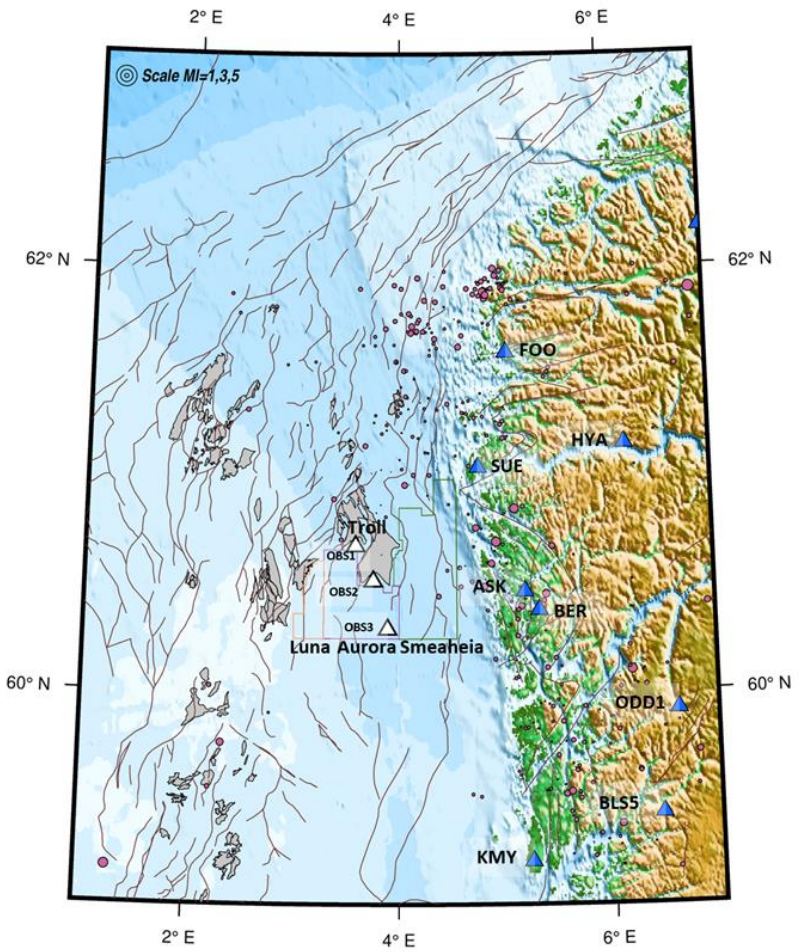

Figure 12 *– Three Ocean Bottom Seismometers (White triangles, OBS1, OBS2 and OBS3) deployed for period of about one year (October 2021- September 2022) to the south of Troll field, to be able to verify the observed low level of seismicity in the Aurora license. By integration of these stations with the NNSN stations, and application of ML algorithm, about 380 small earthquakes (many with ML ≤ 0.5) have been detected.*

3.3 Including Permanent Reservoir Monitoring (PRM) systems

Permanent Reservoir Monitoring (PRM) systems are mainly aimed to monitor dynamic of reservoirs in oil/gas fields through 4D seismic acquisition. However, the very same instruments can be used for passive seismic monitoring between two active vintage acquisition. Snorre and Grane PRM with more than 10000 and 3500 geophones, respectively are located to the NW and SW of Horda platform. Using selected geophones from these two PRMs and its integration with the onshore NNNS stations to the east of Horda, could provide better azimuthal coverage to improved detection and lateral location accuracy of seismicity in this area. Since 2018, 10 selected stations from each Snorre and Grane are streaming data to the NNSN in near real time (see Figure 9). Zarifi *et al*. (2022) confirmed that this integrated system can improve the location accuracy of earthquakes. Adding the HNAR array and the concept of array processing into this integrated system can reduce location uncertainties of seismicity by about 50% (Zarifi *et al*. 2022).

Exploring further potentialities in addition to seismicity monitoring, literature offers examples of utilizing PRM systems to estimate the stress state in reservoirs. This opens up for new possibilities for leveraging surface fibre optic cables arranged in specific geometries to achieve similar outcomes. However, substantial research is needed to investigate whether the sensitivity of such systems is adequate for stress state estimation, and additional field trials are indispensable for the advancement of this application. Ridder *et al*. (2015) applied seismic tomography to analyse Scholte waves measured with the PRM system at Ekofisk. Anisotropic seismic wave velocities were leveraged for overburden monitoring and stress field estimation (Figure 13). The fast directions of anisotropic Scholte waves overlaid on the velocity field revealed a large circular pattern, with higher velocities observed in the centre. This ring pattern correlates well with the observed seafloor subsidence bowl exceeding 9 meters, attributed to years of hydrocarbon extraction and pressure depletion from water injection. The observed extensional stresses stemming from subsidence contributes to a weakening of the overburden. These findings hold implications for CO_2 storage monitoring, emphasizing the importance of updating geomechanical models to develop preventative monitoring solutions.

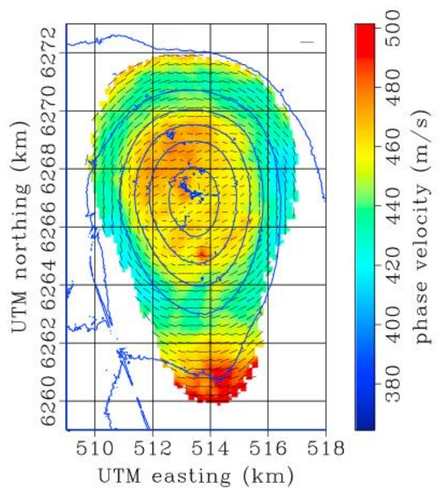

Figure 13 *– Stress field estimates at Ekofisk using anisotropic seismic wave velocities for overburden monitoring. Scholte wave phase velocities ranging from 400 m/s (blue) to 500 m/s (red). The fast velocities (indicated by blue lines) are overlain on the velocity field. The large circular pattern correlates with the observed subsidence of the sea floor. Figure source modified after Ridder et al. 2015.*

4 Further monitoring enhancements

In this chapter we will present examples from published research and field trials to demonstrate the added value of information derived from multiple applications of fibre optic cables.

We aim to show how integrating various monitoring technologies can enhance the overall monitoring scheme and how a preventative monitoring solution would look like that provides a holistic understanding of subsurface dynamics in the Norwegian North Sea region.

4.1 Including downhole DAS

The results from a field trial conducted at an operational CO_2 storage site at Quest (Goertz-Allmann *et al*., 2022) showcase the remarkable sensitivity of Distributed Acoustic Sensing (DAS) monitoring technology.

Microseismic events were detected with magnitudes lower than -0.6, at a distance of more than 10 km and occurring at depths of approximately 10 km. By employing advanced processing techniques, the detectability of these events can be enhanced, highlighting the potential for further refinement through data post-processing. Integrating DAS measurements with observations from geophone arrays within wells proved advantageous, providing a comprehensive view of the subsurface wavefield, and yielding valuable insights into local geological structures.

Despite having a lower signal-to-noise ratio compared to geophones, DAS offers a more thorough depiction of the complex wavefield due to its dense spatial sampling. Additionally, the ability to discern details on reflected and converted wave types enhances our interpretation of subsurface features. Up to date, the combination of DAS with conventional technologies is essential for accurately quantifying signal amplitudes, thereby improving the reliability of monitoring data. However, this may change in the future, when the DAS technology is further developed in terms of fidelity and more research is carried out (for example about the effect of installation, coupling and material properties on the strain transfer function)

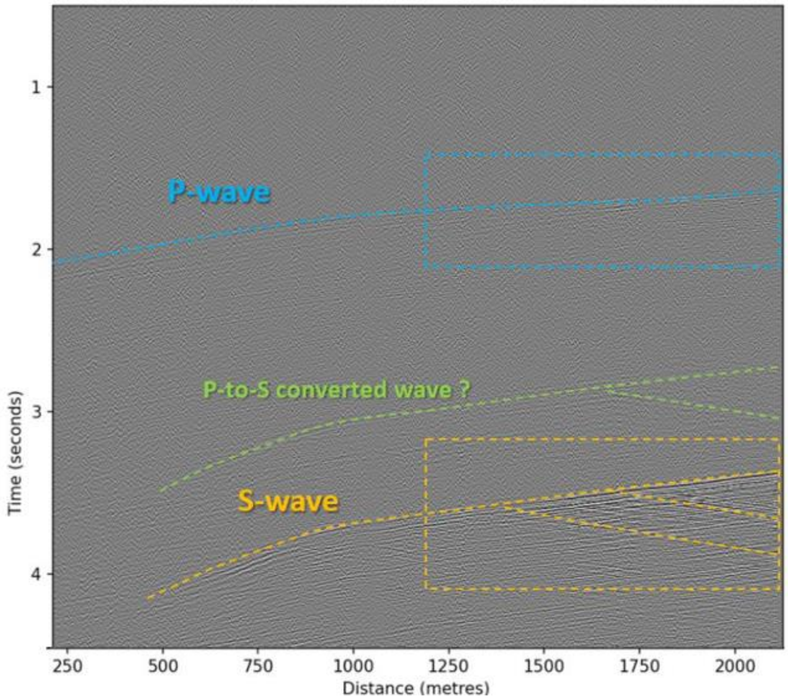

Figure 14 *– DAS downhole on single mode fibre in CO_2 injection well at Quest, small magnitude event 0.8 occurring more than 10km away capturing the entire wavefield, including details on reflected waves and P to S converted waves, Fig source (Goertz-Allmann et al., 2022, Wienecke et al., 2023)*

Real-time monitoring capabilities enable the optimization and fine-tuning of data acquisition procedures, facilitating proactive management and prompt decision-making. For instance, the detection of microseismic events in real-time allows for the monitoring of pressure build-ups during CO_2 injection activities. Initial results underscore the significant potential of DAS technology for CCS monitoring, demonstrating its sensitivity and large detection distance (>10 km) at operational CO_2 storage sites, even for events of small magnitudes (0.8).

The detectability of events using algorithms like Short Time Average/Long Time Average (STA/LTA) further underscores its efficacy to develop future warning algorithm (Wienecke *et al*. 2023). Looking ahead, continued advancements in post-processing methods, signal classification techniques, and the integration of machine learning (ML) and artificial intelligence (AI) algorithms hold promise for further enhancing the detectability and accuracy of DAS-based monitoring systems. Leveraging detection algorithms like STA/LTA will continue to play a crucial role in detecting seismic events efficiently.

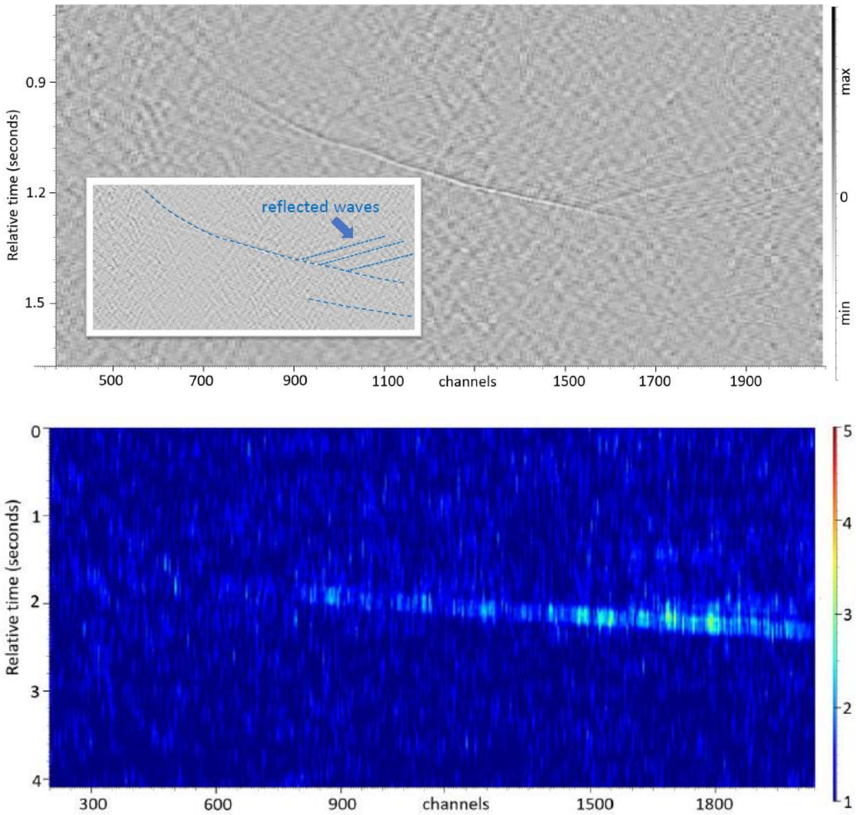

Figure 15 *– Raw DAS data display: event with magnitude –0.679, at edge of detectability (top), using algorithms like Short Time Average/Long Time Average (STA/LTA) further underscores its efficacy to develop future signal detection algorithm (bottom)*

Recent studies have highlighted the advantages of utilizing low-frequency Fibre Distributed Acoustic Sensing (LF-DAS) measurements, as demonstrated by Ma *et al*. 2023 in their study on hydraulic fracturing. The figure presented in their publication (see Figure 16) displays the time-depth distribution of LF-DAS fibre strain over a 4-hour period at the perforation depth, revealing distinct patterns of strain rate indicating the opening (red colours) and closing (blue colours) of fractures. Hypocentres of microseismic events (orange dots) are overlain from both geophones (top) and DAS (bottom) to determine if event locations correspond to observed fracture growth.

Observations from this analysis suggest that fractures originate at the perforation depth and propagate both upwards and downwards (as indicated by the black dashed line), with the ultimate fracture height estimated to reach approximately 200 meters above the perforation depth. The discussion highlights the significance of the broad aperture provided by DAS fibres, which are advantageous for characterizing microseismic sources and achieving good agreement between event depth and fracture opening.

A direct cause-and-effect relationship between fracture opening and the occurrence of microseismic events is evident from the data. However, it is essential to note that the significance of fracturing for the operation varies depending on whether it occurs in the caprock or the reservoir level. While fracturing can sometimes be beneficial, particularly in enhancing reservoir permeability, its implications must be carefully evaluated, particularly concerning the integrity of the caprock and containment of injected fluids.

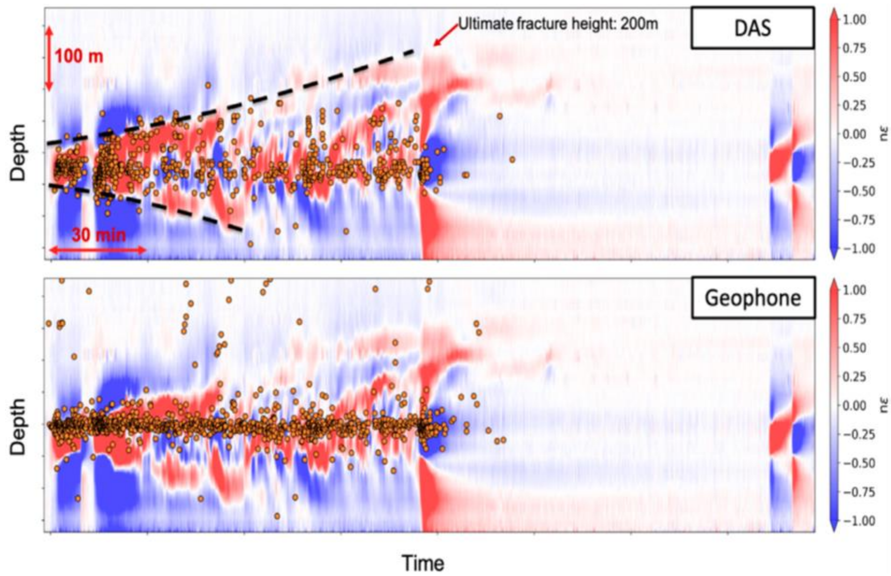

***Figure 16** – Low frequency DAS utilizing the low frequency band of DAS measurements – published example, Ma et al., 2023 hydraulic fracturing, Figures display time-depth distribution of LF-DAS fibre strain over 4h around the perforation depth , observed strain rate shows opening of fracture (red colours) and closing (blue). Hypocentres of microseismic events around perforation depth (orange dots) are overlain from geophones (top) and DAS (bottom)*

Conclusively, DAS downhole technology offers significant value despite its lower signal-to-noise ratio compared to traditional geophones. Its dense spatial sampling provides a more comprehensive understanding of the complex wavefield, particularly valuable for interpreting local structures and identifying various wave types. However, its integration with conventional technology is crucial for signal quantification. Real-time monitoring and near-real-time data display enable optimization and fine-tuning of data acquisition, facilitating proactive management and rapid decision-making. Initial results demonstrate the promising potential of DAS for CCS monitoring, with successful technology demonstrations during daily operations of the CO_2 injection site at Quest (Wienecke *et al.* 2023). DAS exhibits excellent sensitivity and a wide detection distance at operational CCS sites. Utilizing low frequency DAS would allow for the direct observation of microseismic events linked to fracture openings with observed strain changes of about 0.5 nanoStrain. Current DAS technologies measure strain changes with picoStrain resolution, enabling the detection of these fracture openings and other signals related to CO2 injection when deployed in a well.

Overall, DAS measurements could enhance our understanding of subsurface processes and improve management of geomechanical risks in CCS operations.

4.2 Including seabed FO cables

A recent field experiment (Breamaud *et al.* 2023) demonstrated the sensitivity of standard telecommunications fibre optic cables deployed at the seabed (partly buried and unburied) for passive seismic (DAS) monitoring systems. The 90km cable, arranged in two perpendicular lines of 45km each, connects the Troll platform to the Oseberg platform near the Northern Lights injection well.

DAS data was continuously acquired over a period of nine months, and events detected by the HNAR were stored for analysis and comparison with NNSN. This facilitated an investigation into the potential enhancement of earthquake localization within this region, which traditionally relies solely on onshore seismic networks, with recent potential additions of PRM systems (typically also located in limited clusters).

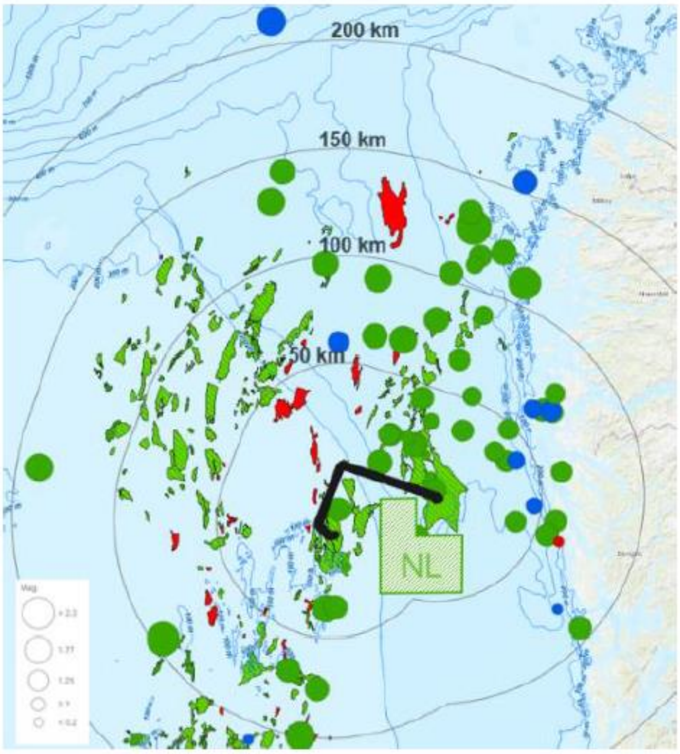

Figure 17 *– Location of DAS field trial utilizing telecom cables at the Troll platform as passive seismic monitoring system. See text for more description. Source: Breamaud et al. 2023*

In the context of fiber optic detection, locations of seismic events from the NNSN (Norwegian National Seismic Network) onshore sensors catalogue are visualized on a map, as shown in Figure 17. These seismic events are categorized based on their detection outcomes using the fiber optic cable. Seismic events that are successfully detected by the fiber optic system are represented as green and blue on the map. Events with a smaller detection signal through the fiber are depicted as blue. This suggests that the signal-to noise ratio is a bit smaller, possibly due to various factors such as distance from the fiber optic cable or signal attenuation. Seismic events that show no detection signal through the fiber optic system are shown in red on the map.

Breamaud *et al.* (2023) emphasized the importance of signal processing techniques, particularly denoising procedures, in enhancing the signal-to-noise ratio and facilitating the precise detection of seismic and microseismic events. Employing a denoising technique involving spatial Gaussian smoothing and median removal by time stamps, as depicted in Figure 18, the DAS data undergoes successive noise reduction. These processing techniques play a crucial role in extracting valuable information from raw data, enabling more accurate and detailed study and analysis of seismic events.

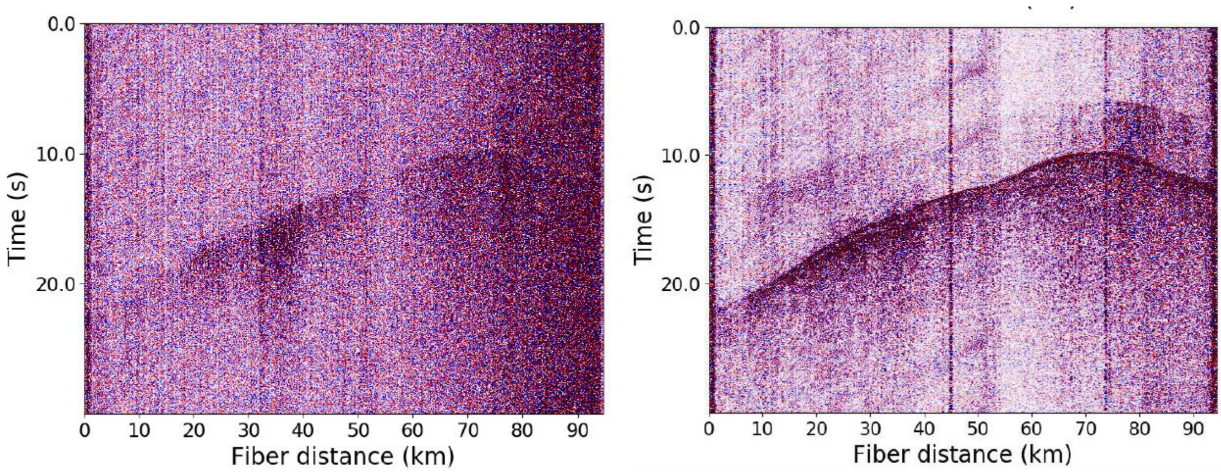

Figure 18 *– Figure modified after Bremaud et al. 2023, example of processing a magnitude 1.3 earthquake- plot show recording along 90 km and arrival of P and S wave. On the left: raw data, on the right: after denoising technique- spatial gaussian smooth and median removal by time stamps.*

Upon comparing the earthquake location derived from DAS data with the onshore sensor location, noticeable differences emerge. The new location reveals discrepancies of approximately 13 km east-west, 5 km north-south, and 7 km in depth compared to the location provided by the NNSN network alone. These differences underscore the potential benefits of employing fibre optics cable for seismicity monitoring, particularly in proximity to the CO_2 storage complex.

Bremaud *et al.* (2023) concluded therefore that the integration of DAS technology utilizing surface fibres in telecom infrastructure with onshore passive seismic networks may provide a robust and valuable monitoring solution, encompassing both detection and source location of microseismic events.

The FO system demonstrated effectiveness by successfully detecting earthquakes ranging from magnitudes 0.5 to 2.2 up to a large distance of 200 km from the cable. Bremaud *et al*. states that it outperformed onshore sensors, detecting ten times more earthquakes over a period exceeding one month, highlighting its robust seismicity detection capabilities. However, a study on true versus false positive event classification was not presented.

Nevertheless, Bremaud *et al.* (2023) concluded that the fibre optic cables provided enhanced earthquake location accuracy when compared to reliance on onshore sensor arrays alone. The improved localization is crucial for accurately identifying the origin of earthquakes, distinguishing between natural tectonic events and those induced by CO_2 storage.

An additional example showing the advantages of utilizing DAS on submarine surface fibres is the application for seismic imaging, particularly ultralong offset scenarios, which prove beneficial for Full Waveform Inversion (FWI) techniques. This application was demonstrated in a field trial conducted by Raknes *et al*. (2023) at the Ula platform operated by AkerBP. The trial, conducted in 2022, served as proof of concept for utilizing existing telecom infrastructure to acquire long-offset seismic data of high quality.

Remarkably, the infrastructure, installed 25 years ago for unrelated purposes, now serves as an excellent seismic sensor. DAS data was acquired using a 130 km telecommunication cable deployed at the Ula platform offshore Norway. Active DAS data collection involved utilizing a seismic vessel to generate shots along the cable's length. Concurrently, streamer data was acquired for comparative analysis.

Analysis of the frequency spectrum revealed significant differences between DAS and streamer data. Notably, the DAS data exhibited a richer frequency content, particularly in the low-frequency range (<10Hz), which is particularly valuable for Full Waveform Inversion (FWI) and velocity model building. Conversely, streamer data displayed larger notches in its frequency spectrum, suggesting limitations in capturing certain frequency components compared to DAS.

The availability of such rich low-frequency content in DAS data enhances its suitability for FWI applications, facilitating more accurate velocity model construction and improved seismic imaging outcomes. This example underscores the potential of repurposing existing infrastructure for seismic monitoring applications, highlighting opportunities to leverage telecom assets for scientific research and technological advancements in the field of geophysics.

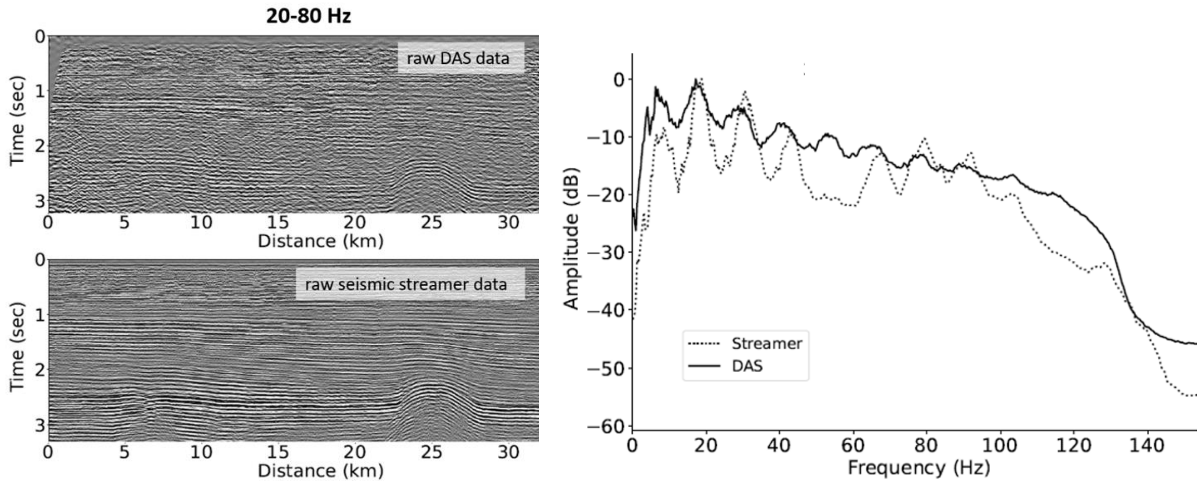

Figure 19 *– DAS versus streamer data Ula Platform (modified after Raknes et al. 2023)*

4.3 Including multiple use FO cables

A major emerging field in monitoring technology is the multiple use of distributed FO sensing both at surface and downhole. The huge benefit is that multiple parameters can be monitored at the same time and place, and its interconnection can be better understood- which in turn leads to a better understanding of the subsurface processes.

Recent advancements in Distributed Sensing Systems (DSS) coupled with Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) technologies have enabled continuous data collection along wells, presenting opportunities for multi-physics monitoring. For instance, low-frequency DAS measurements can be correlated with temperature variations and directly juxtaposed with measurements obtained from DTS and DSS within the same wellbore. The variations observed in temperature, strain, and acoustic signals along the wellbore are intricately linked to changes induced by pore pressures and temperatures resulting from CO_2 injection fluid, as well as the elastic and strength properties of the storage reservoir.

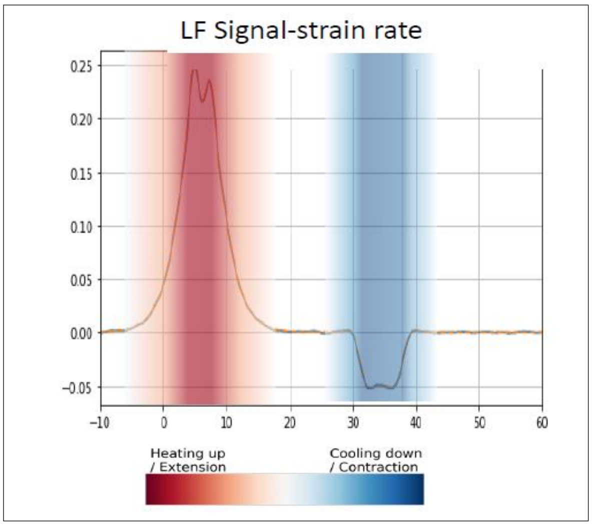

Figure 20 *– Schematic illustrating how temperature changes will be reflected as strain changes, as heating up will result in expansion of the fiber (red colour) and cooling down effects will correspond to contraction of the fiber (blue colour), Figure source: Haavik and Constable 2023*

DAS measures in principle any signal that impacts the strain at the fiber optic cable. Extension and contraction at the fibre measured with DAS can be qualitatively correlated to temperature changes (Figure 20). This integrated approach to monitoring allows for a comprehensive assessment of dynamic changes occurring within the storage complex, aiding in the characterization of reservoir behaviour and the evaluation of injection processes.

It is important to acknowledge that DAS provides only qualitative measurements, necessitating a deeper understanding of how to interpret data both qualitatively and quantitatively to harness its potential as a valuable tool for risk management. The installation of fibre optic cables in wells varies in quality, ranging from being cemented to casing, clamped on tubing, or loosely hanging in the wellbore, and this variability significantly impacts the costs and measurement quality.

Investigating the quality of coupling between the fibre and various materials is an important task for future research, as it directly influences the detectability and quality of measurements obtained. Unlike conventional seismic sensors and fibre-optic permanent reservoir monitoring (PRM) systems, which ensure fidelity, there is a lack of such assurance for measurements conducted with DAS. To utilize FO measurements fully, the transfer function of the strain depending on the coupling needs to be described which differ for cement, casing steel, fluid, and tubing. Furthermore, the impact of nonlinearities, failure modes, fracture dynamics, and changes in permeability on the measurements are not fully understood. Because of this knowledge gaps the FO data can only be interpreted qualitatively and should be combine with other measurements, such as pressure and temperature gauges.

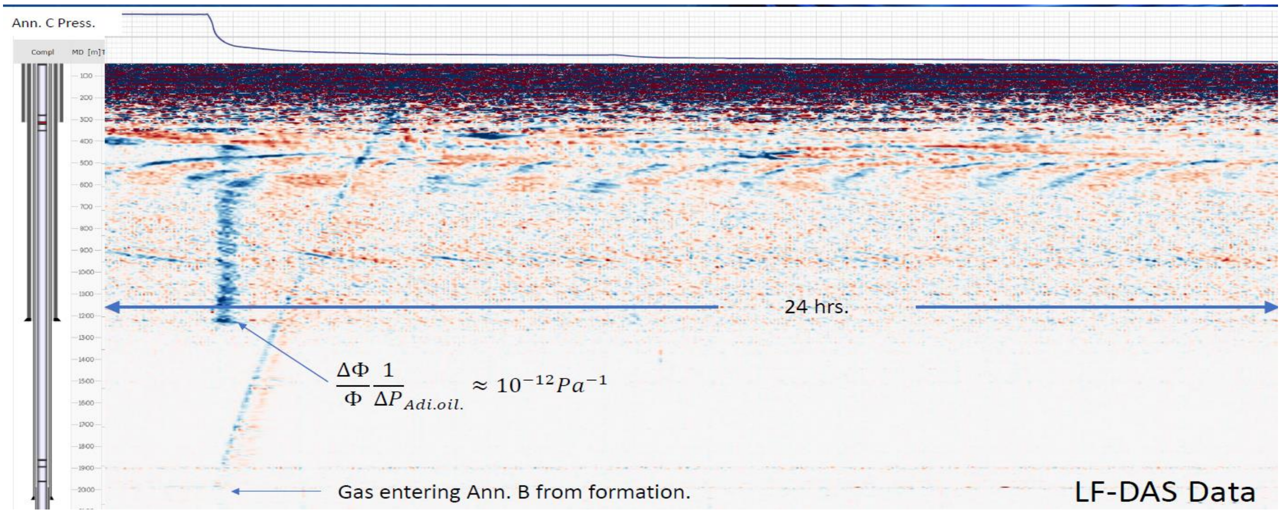

Figure 21 *– Using low frequency DAS data for well surveillance monitoring. Data is displayed as depth over time, for the duration of 24h. It shows events that correlate with the depth of the annulus that can be qualitatively interpreted as a cooling down event (related to a pressure change) and gas entering annulus B from formation. Figure source: Haavik and Constable 2023*

In their recent study, Haavik and Constable (2023) demonstrated the significance of low-frequency DAS for well surveillance monitoring, which offers valuable insights into liquid level detection, confirmation of leaks, and inference of leak paths.

The Raw DAS data (strain rate) underwent low-pass filtering (≤0.6Hz) and was resampled in accordance with signal theory, enabling meaningful interpretation for well surveillance monitoring purposes. In the low-frequency (LF) DAS data, a positive strain rate corresponds to fiber heating or extension (red colour), while a negative strain rate corresponds to fiber cooling or contraction (blue colour). Figure 21 illustrates LF-DAS data plotted against well depth over a 24-hour period, revealing an instantaneous event (depicted in blue) indicating a cooling down event associated with a pressure change, as well as a diagonal line originating at the depth of annulus B, indicating gas entry into the annulus from the formation.

The LF-DAS capability holds potential for application in the monitoring of CO_2 storage operations. Drawing from the proven value demonstrated in the oil and gas production sector, such as in well optimization and pressure control, there exists a compelling business case for leveraging LF- DAS for CO_2 storage monitoring. Specifically, this technology can be employed to enhance operational efficiency and ensure optimal pressure control. Moreover, its application in leak detection can reduce the need for interventions, thereby minimizing operational disruptions and associated costs.

Amer *et al.* (2022) suggest that integrating the three measurements (DTS, DSS, and DAS) could provide a cost-effective approach for multi-purpose data acquisition and real-time monitoring techniques in geological CO_2 storage. In particular, DSS strain measurements demonstrated the high accuracy of 1 microStrain in the casing mechanical integrity monitoring. If successfully installed, DSS fibre optic cable embedded in cement behind casing may provide information on strains transferred from the deforming formation (storage sandstone, sealing units or shallow traps) to the cement as a response to CO_2 injection. Furthermore, combinations of fibre optic DSS and DAS in well may be utilized to quantify elastic vs. inelastic strains. The elastic and inelastic response in formation due to changes in pore pressure and temperature is expected to vary as a function of depth, lithology type (sand, sandstone, clay, mudstone), drainage condition (drained vs. undrained), stiffness of rock and the gradient between CO_2 injection fluid and formation (Park *et al*., 2022).

In the SHARP project, geomechanical analysis is used to assess the impact of pore pressure and cooling on the stress path, elastic and in-elastic strain. Namely, analytical Mohr-Coulomb-based approach are used to evaluate stress path relative to failure criteria in sand and sandstones (Grande *et al*., 2024). Granular lithologies such as sand and sandstones are expected to be more acoustic responsive compared to sealing clay rich lithologies, and the changes in seal close to well may be derived indirectly from in the dynamic changes of strains and acoustics in the reservoir. It was found that in shallow uncemented sands and weakly cemented sandstones, the response from cooling is dominated by elastic expansion, however, for deep stiff sandstones cooling induced contraction, in-elastic damage, and small-scale fracturing may occur, resulting in a source for acoustic emission (AE) and micro seismic events (MS). Hence, DSS may be utilized for characterizing total strain (the direction along wellbore) and DAS may be used to further constrain the in-elastic component derived from recording AE and MS. For quantitative use in seal integrity, the strain and AE information must be analysed through incorporating the coupled responses of well system (casing, cement) and formation, which further requires thermal-hydromechanical modelling, constitutive behaviours of the formation and noise reduction algorithms (noise from inside well flow, i.e. Haavik *et al*., 2023).

The overall strains from CO_2 injection are typically small and in the range of a few milliStrain (<2mS) and stress path caused by CO_2 injection will reduce the mean effective stresses which could cause some energy to be released during failure which both may give some challenges for monitoring the actual strain and noise transferred to the fibre optic cable (Grande *et al*., 2024). Current DAS technologies measure strains within picoStrain (10^{-12}) resolution, so it should be feasible to detect signals related to CO_2 injection at the milliStrain (10^{-3}) level in the formations, at the microStrain (10^{-6}) level in the well casing and something in-between in the cement between formation and casing.

Finally, the DTS method can measure the temperature change between the injected CO_2 and the subsurface, and temperature anomalies may be interpreted as a potential vertical migration of CO_2 along the wellbore, and hence DTS could provide high-resolution information useful for well integrity monitoring including early warning of leakage along well, casing corrosion or cement degradation (Amer *et al*., 2022).

However, regarding the North Sea setting there are several limitations for sub-sea developments (read more in chapter 6 Challenges and limitations). The fiber lead-in length limitations for DTS, DSS and DAS are very different and fiber behind casing is usually not installed on sub-sea wells which means that the noise levels are much higher. For example, DAS measurements from a fiber inside tubing require post-processing using advanced noise reduction algorithms (that need to be developed in the future) removing e.g., noise from the inside well flow during injection.

5 Benefits and Impact

The seamless integration of diverse monitoring technologies, encompassing FO systems, ocean bottom nodes, onshore seismic networks, and downhole measurements, stands as pivotal for robust monitoring and risk management in CO_2 storage operations. By integration of these various measurements and inferred parameters, operators can achieve comprehensive data collection and analysis, empowering them to foresee, identify, and mitigate potential risks associated with CO_2 storage. The broadband DAS data together with seismic sensors (e.g. geophones, OBN, broadband seismometer) enhances the understanding of the geological conditions and seismic risk factors in the storage area. The data obtained from FO monitoring can be integrated into geomechanical modelling workflows, providing calibration and ground truthing of models as projects develop. This will enable a more comprehensive understanding of the subsurface behaviour. Such predictive geomechanical modelling empowers operators to devise proactive strategies, enables early identification of potential issues and enables the implementation of preventive measures to mitigate adverse events such as leakage or unanticipated subsurface responses.

5.1 Safety and risk mitigation

Risk is typically quantified as the combination of the likelihood of an adverse event happening and the severity of its consequences. Effective risk management involves monitoring specific parameters at precise locations and times, contributing to a comprehensive understanding of potential risks. Ensuring the safety of CO_2 storage operations necessitates the adoption of appropriate monitoring methods to assess conformance and containment.

Many researchers have sought to comprehend elusive risks or uncertainties (Kim, 2012) and have adopted the framework of knowledge quadrants, including known knowns, known unknowns, unknown knowns, and unknown unknowns (which represent risks of which we are unaware). Project managers strive to maximize known knowns by uncovering as many unknown knowns as possible, as early as possible. However, it is impossible to anticipate all risks in advance.

For instance, the implementation of a new technology may disrupt operations, a challenging risk to manage as it cannot be mitigated until it is identified. Identifying gaps in knowledge about specific subproblem areas may indicate the presence of unknown unknowns but cannot pinpoint them (Loch *et al.*, 2007). While a likely event may not be considered an unknown unknown because it is already identified, its consequences may fall into that category. Foreseeing an event such as a natural disaster is relatively straightforward, but predicting or estimating its impact is challenging.

Finding more unknown unknowns means converting them to known unknowns so that they become manageable using project risk management. With sufficient monitoring and measuring the key parameters we minimize the unknowns – the risk can be understood and therefor better managed.

For example, to enhance risk management, integrating technology such as geophone arrays or fibre optic cables within injection wells enables real-time monitoring of the injection process. This approach aligns with insights from human psychology, particularly the work of Kahneman (2011), emphasizing the importance of making informed decisions based on updated models rather than relying solely on intuition.

The main technical risk associated with CO_2 Storage is the potential for leakage, stemming from factors such as inadequate preparation, suboptimal site selection, injection well failure, undetected faults, fractures, and seal failure, as well as mineral dissolution. Nonetheless, it's imperative to recognize another notable risk—induced seismicity. Consequences from induced seismicity could be for example increased risk of leakage, damage to infrastructure/habitat, negative public perception, negative media coverage, loss of license to operate. Our conclusion emphasizes the equal significance of geomechanical risk in CO_2 storage operations, highlighting the necessity for proactive monitoring and expert guidance to effectively mitigate these risks.

Numerous studies indicate that human activities such as fluid injection or withdrawal can trigger earthquakes. Schoenball *et al*. (2014) demonstrated significant hydromechanical processes occurring after well shut-ins, with notable stress changes where horizontal stresses shifted by tens of megapascals. These alterations could potentially lead to prolonged induced seismicity even after operations cease. As emphasized in the report by Williams *et al*. (2022), the stress history, seismicity, and rock mechanics parameters as crucial inputs for geomechanical modelling and predictive analysis. Although real-time monitoring enables prompt decision-making, changes in the stress field may result in delayed fault reactivation, with increased seismicity not immediately evident in the real-time data. Enhanced monitoring strategies, akin predictive geomechanical modelling, are vital for anticipating and managing such risks to ensure safe CO_2 storage.

5.2 Environmental impact of the monitoring scheme

The environmental impact of CO_2 monitoring solution involves both a *footprint*, representing the negative effects, and a *handprint*, encapsulating the positive contributions and solutions. The footprint comprises for example the energy consumption, resource utilization, and potential emissions associated with CO_2 storage monitoring activities. This includes the energy required for data acquisition, processing and storage, the materials that are used to build the equipment and instrumentation used for monitoring, and any emissions resulting from staff travelling, the transport of the monitoring equipment, the installation and other things associated with the storage field operation. However, to provide a full life cycle is out of the scope of this report.

Efforts to minimize the footprint of CO_2 monitoring involve adopting energy-efficient technologies, optimizing resource use, and employing sustainable practices in the manufacturing and operation of monitoring equipment.

The handprint becomes important to mention when considering the broader positive impact. Enhanced monitoring solutions for safe CO_2 storage contribute to informed decision-making and therefore improved risk management (for example facilitating targeted interventions to keep levels of induced seismicity as low as possible.)

Enhanced monitoring solutions including FO offer valuable benefits beyond CO_2 storage monitoring. DAS technology has applications in security and protection, allowing for integrity monitoring and detection of potential threats to underwater cables and infrastructure. Furthermore, it was shown that DAS utilizing submarine telecom cables can be applied for monitoring of ocean currents and temperature changes (e.g., Ide *et al.* 2021) essential for climate research and UNESCO's efforts to safeguard ocean health.

The Decade of Ocean Science for Sustainable Development, as outlined in the UN' Agenda 2030 and ratified by 150 countries, entails various actions, including substantial reductions in marine pollution, protection of marine ecosystems and coastal areas, and mitigation of human activities that pose threats to marine life. It was demonstrated that DAS enables the monitoring of marine life, such as whales, acoustic pollution and the detection of unsanctioned anthropogenic activity (Rørstadbotnen *et al*. 2023, Thiem *et al.* 2023, Wienecke *et al.* 2023).

This dual consideration of both footprint and handprint emphasizes the importance of balancing the negative environmental impacts with the positive contributions that an enhanced monitoring scheme brings to the overall goal of environmental sustainability in mitigating climate change.

5.3 Regulatory compliance

Given the relative immaturity of the regulations governing CO_2 injection, there is a need to develop understanding and guidelines for operations. This must be done in cooperation with authorities. It is important for operators to demonstrate compliance with regulations and control over the injection site, to obtain a license to operate. Especially in the early projects there might be a need with a more extensive monitoring plan than necessary, with the option to modify it as experience builds and advanced technology solutions are developed.

The monitoring plan at Quest (Canada) is an example of this, where operations and monitoring demonstrated that the initial comprehensive seismic monitoring programme with full 3D seismic monitoring, planned for a relatively early stage could be delayed in the favour of several 2D seismic surveys, employing both surface geophones and in-well DAS for VSP purposes (Bourne *et al.* 2016, Harvey *et al.* 2022).

Furthermore, as technological advancements in CO_2 storage and monitoring, such as fiber optic sensing, continue to evolve, there is a growing recognition that existing regulations need to be updated to incorporate these innovations. Integrating fiber optic technologies into regulatory frameworks can significantly enhance the accuracy and reliability of monitoring efforts, providing real-time data that supports improved decision-making and risk management. Advanced DAS technology, for instance, can improve the detection and localization of microseismic events (reducing the depth uncertainty from about 10km to 1km), enabling a clearer distinction between seismic events occurring in the reservoir and those in the basement below. This distinction is crucial for differentiating between CO_2 storage-induced seismicity and natural seismic events.

It is also important to leverage the capabilities of FO technologies in assessing site suitability and ensuring the long-term containment of injected CO_2. Additionally, new risk mitigation protocols could be developed to utilize fiber optic sensing for the rapid identification and response to potential risks, such as unexpected pressure and regional stress changes, thereby preventing significant environmental impacts.

In conclusion, while current regulatory frameworks have laid a solid foundation for the safe and effective implementation of CO_2 storage projects, there is a need to update these regulations to incorporate state-of-the-art monitoring technologies. Doing so will not only enhance the safety and efficiency of CO_2 injection and storage operations but also build public confidence in the environmental responsibility of such initiatives.

6 Challenges and limitations

Fibre-optic monitoring in a Norwegian North Sea setting involves both technical challenges and limitations. These will depend on whether the focus of the monitoring campaign is on detection of temperature and pressure changes, leakage, acoustic emissions, seismicity or on mapping CO_2 plume migration, and if the fibre optic cable(s) will be deployed at sea floor or downhole. The technical challenges and limitations will always be part of the quality assurance phase of a monitoring campaign, to ensure that the injected CO_2 is stored in a stable and secure reservoir.

6.1 Technical challenges

Monitoring a fibre optic cable in a location like offshore Norway includes several technical challenges of different levels of severity. First, one must select a location for the DAS system (interrogator and recording unit), where the choices presently are either at an offshore installation or at a land-based location. The marination of interrogators is currently under discussion again. In that regard it's noteworthy that some companies with over 160 years of submarine infrastructure installation expertise, have highlighted the superiority of fiber optic sensors over electrical ones due to their autonomy from electronic components and power sources at the sensing point. With all electronic elements situated above water, this inherent design greatly enhances safety and reliability.

If the DAS unit is located at an offshore installation e.g. a platform it will be difficult to access in case of repair and replacements, however the distance from the DAS interrogator to the target area is shorter, enabling a near full usage of the distance limitation for data acquisition.

If the DAS unit is placed at a land location, it will have easy access for repair and replacement, but the distance to the target area might be very large and therefor limiting the length of available fibre optic cable that can be utilized for strain sensing. For instance, certain interrogators are limited to a maximum sensing range of approximately 70km. This implies that if the location of the target area exceeds this distance from the shore, the DAS data measurements will not cover the CO_2 storage area. The maximum interrogation range of a fibre optic cable depends on the interrogator model and the attenuation of the laser signal.

The laser signal that is emitted by the interrogator into the optical fibre will lose energy as it travels through the fibre optic cable. The attenuation is normally about 0.2 dB/km, but connectors and cable bending also reduce the energy of the traveling laser signal, which limits the maximum length of the fibre optic cable that can be used for sensing. Normal lengths to be reached are about 50-70km, however new advances in long-range DAS report operating lengths up to 175 km (Waagard *et al.* 2021, Wang *et al.,* 2014 and Kislov and Gravirov, 2022). Comparison between conventional and long-range DAS systems reveals distinct differences in their interrogation methods and noise characteristics. Long-range DAS (such as OptoDAS) relies on frequency swept interrogation, while conventional DAS utilizes laser pulse interrogation. A comparison of noise curves, with all curves maintaining a spatial resolution of 10 m, demonstrates notable distinctions. In long-range DAS, instrument noise remains consistently low along fibre lengths of up to 90-100 km, characterized by a flat curve attributed solely to laser noise rather than shot noise (Figure 22). Notably, several key parameters influence the noise level, including spatial resolution or gauge length, sampling frequency, total fibre loss, and bandwidth.

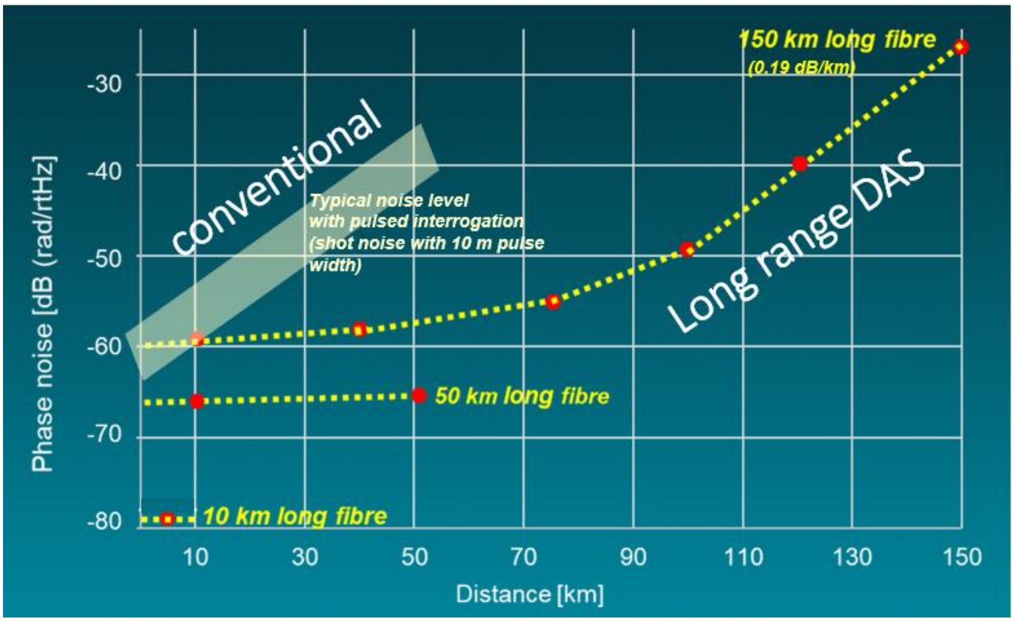

***Figure 22** – Noise curves are for a spatial resolution of 10 m (GL=10m) and with a fibre loss of 0.19 dB/km. Long range DAS (OptoDAS) instrument noise is mainly caused by laser frequency noise for distances up to about 100 km. Beyond 100 km, the instrument noise is determined by shot noise.*

One of the major barriers for utilizing long-haul telecommunication infrastructure for DAS is the presence of repeaters usually installed at distances of 60-120km. These repeaters are designed to amplify the optical signal and extend data transmissions over long distances. However, they do not support bi-directional propagation, which inhibits the backscattering of laser signals required for DAS interrogation. As a result, sensing is not possible beyond the first repeater (Wienecke and Brenne 2023).

Additionally, dark fibres are uncommon in long-haul submarine telecom systems with repeaters. This necessitates the coexistence of DAS sensing with live data transmission signals. Because telecom systems operate in the C-band (optical spectrum), an L-band version of the OptoDAS interrogator has been designed for enabling DAS sensing in coexistence with live telecom data transmission. This enables DAS sensing to operate alongside live data transmission without interference.

DAS interrogation in coexistence with live telecom traffic in high-capacity networks was successfully validated through lab and field tests. The first test, conducted on a 10,025 km line with a net fibre capacity of 11.2 Tb/s, and the second test on a 3,031 km line with a net fibre capacity of 22.4 Tb/s, showed no impact on the transmission line's Q-factor confirming the long-term stability of data transmission (Brenne *et al.* 2023a). These results demonstrate that DAS measurements can be obtained with the same range, sensitivity, and fidelity as with DAS interrogation on dark fibres, without interfering with live telecom traffic. Field experiments conducted on the *2Africa network* for 2 weeks at the Marseille landing segment demonstrated consistent high sensing sensitivity over 100 km, with various signals detected from sources such as surface vessels, seabed fishing gear, earthquakes, and marine life (Brenne *et al.* 2023b).

The use of DAS technology adds great value to a telecom infrastructure for asset owners, regulatory instances for environmental monitoring, safety, and risk management applications enabling early warning methods and protecting the shore-end of long-haul networks from potential damage (Wienecke and Brenne 2023). Using the submarine infrastructure that is already in place and connecting an interrogator onshore provides a convenient solution to monitor the coastal areas of more than 130km distance from the shore. These presented technological advances now make it possible to utilize the submarine infrastructure as a smart surveillance tool (Wienecke *et al.* 2024).

For CO_2 storage monitoring, various infrastructure components such as DCFO, power cables, telecommunication systems, and subsea templates are typically installed prior to field development, offering opportunities for DAS.

The oceanic environment and how the fibre optic cables should be deployed on the seafloor is another challenge to solve. If the fibre-optic monitoring utilizes submarine fibres in shallow waters, the dynamics of the sea floor should be considered. Studies in shallow waters in the Belgian part of the North Sea show that the sea floor bathymetry can change by several meters over a decade (Montereale-Gavazzi *et al*., 2018). Tidal forces and sediment transport in shallow water environments pose a threat to buried fibre optic cables, potentially leading to damage and loss of ground coupling, which can adversely affect seismic monitoring quality. Conversely, in deep-water settings, utilizing unburied fibre optic cables offshore Brazil (Browaeys 2024), showed that high-quality measurements can be obtained. Given the substantial costs associated with cable burial, if unburied cables demonstrate sufficient sensitivity, they present a more economically feasible solution.

Regarding subsea developments in the North Sea, downhole fiber optic measurements face several significant limitations. The installation of fiber during completion presents considerable challenges, often making the cons outweigh the pros. One major issue is that optical fiber cemented behind casing is rarely installed in subsea wells due to concerns over cement integrity and leakage risks. Additionally, DAS measurements from a fiber inside the tubing exhibit much higher noise levels compared to fibers cemented behind casing. To address these challenges, future advancements in noise reduction algorithms, potentially leveraging machine learning techniques, are necessary to mitigate issues such as injection noise. Moreover, the measurement range limitations for Distributed Temperature Sensing (DTS) and Distributed Strain Sensing (DSS) typically range from 50 to 80 km. However, performance declines with increasing range, resulting in lower temporal, spatial, and thermal data resolution (Mathew *et al.* 2024). Recent technological advancements suggest the potential to extend these ranges beyond 100 km.

New developed long-range DAS interrogators enable versatile in-well monitoring systems, facilitating different interrogation scenarios. These scenarios include subsea wells connected via extended lead-in fibres exceeding 50 km, simultaneous interrogation of up to four platform wells with a single unit using time multiplexing, and wells through subsea templates, albeit with higher optical losses.

In comparison between platform wells and long step-out subsea wells, experiments conducted in North Sea fields demonstrate the resilience of standard single-mode fibres over extended lead-in distances (Brenne and Olsen 2022). Lead-in distances of 50 km and 75 km exhibit minimal deterioration in DAS data quality, while a lead-in distance of 100 km results in significant noise increase, thus not recommended for well monitoring.

However, technical challenges persist, particularly concerning FO installation in wells, including issues with installation on subsea Xmas trees and navigating the fibre past packers to access the active injection zone.

Another technical challenge concerns the timing and handling large data volumes. Timing of the recorded strain or strain rates is of great importance, e.g. if the target is micro seismicity and especially if the data is combined with other data of known seismic sources. It is therefore often required to have a time stamp on the data with accuracies in the order of milliseconds. Using global navigation satellite system (GNSS) is today a standard way of timestamping data and will give higher timing accuracy than e.g. NTP (Network Time Protocol) (see e.g. Shinton, 2020).

Real-time monitoring capabilities facilitate proactive management and prompt decision-making. However, a significant challenge arises from the large volumes of fibre optic data (for example 10 Tb a day). To address this challenge, effective data processing methods are essential, including de-noising and event detection, which are vital for developing automatic signal detection algorithms and advancing real-time monitoring techniques. The efficacy of event detection algorithms, such as Short Time Average/Long Time Average (STA/LTA), underscores their potential for developing future warning systems (e.g, Wienecke *et al.* 2023). Up to date it is crucial to establish efficient processing methods to handle massive data volumes and store only valuable information. This is essential for future data processing in near real-time, including approaches such as edge computing, but also the development of data compression algorithm.

6.2 Cost considerations

In the context of building an enhanced monitoring solution, initial costs can be high, but over the long term, it proves to be cost-efficient, particularly when considering the need for monitoring even after field site closure for up to 20 years.

Given the expansive areas and extended timeframes involved in CO_2 storage monitoring, a cost-effective solution is imperative. One approach to addressing these challenges is leveraging existing infrastructure such as telecom and power cables including optical fibre. However, these may lack the sensitivity required to detect small changes, underscoring the importance of considering the Value of Information concerning Health, Safety, and Environment (HSE) risks to maintain operational licenses, contingent upon the storage site. It is crucial when assessing the value of information to consider a 20-year timeframe (and even more), along with the benefits of additional HSE applications (as for example oceanographic monitoring, well integrity monitoring and safeguarding of the infrastructure).

PRM systems emerge as an advanced safety option, even though they entail higher costs, because they provide high-resolution measurements capable of detecting subtle changes, such as variations of approximately 200 microseconds in velocity, indicative of pressure, strain, and temperature alterations. Additionally, stress field estimates utilizing shear wave anisotropy provide crucial inputs for updating geomechanical models, facilitating the development of enhanced monitoring strategies.

Dean and O'Brien (2024) from Shell stated that for risk-based measurements, monitoring, and verification in CCUS projects "Fibre-optic in-well sensing is lower cost compared with traditional 4D surface seismic methods for conformance and containment monitoring near the wells. It records time-lapse, distributed-acoustic-sensing (DAS), vertical-seismic-profiling (VSP) data." The cost-effectiveness of this technology was successfully demonstrated at Quest, which is an onshore site in Canada.

Application of FO sensing offshore is more challenging than onshore as usually higher costs are involved. Ringrose *et al*. (2018) presented the potential for cost-effective monitoring of CO_2 storage offshore. Their proposed monitoring solution integrates cost-effective strategies at offshore sites, utilizing high-quality seismometers arranged in array configurations in nearby coastal regions, along with the deployment of Ocean Bottom Node (OBN) nodes employing DAS FO cables within wells. In their proposed monitoring solution DAS on submarine cables where not considered, because this technology was less well developed at the time. However, this fast-emerging technology offers significant advantages, as detailed in Chapter 4.

The introduction of new submarine cables laid on the seafloor for monitoring solutions, necessitates consideration of whether they should be buried or left unburied. Buried cables offer improved coupling, enhancing sensitivity and Signal-to-Noise Ratio, albeit at potentially higher costs, especially if trenching is required due to inadequate sensitivity. Furthermore, buried submarine cables offer better protection against cable damage caused by fishing trawlers in shallow water and abrasive forces from ocean currents and tidal waves.

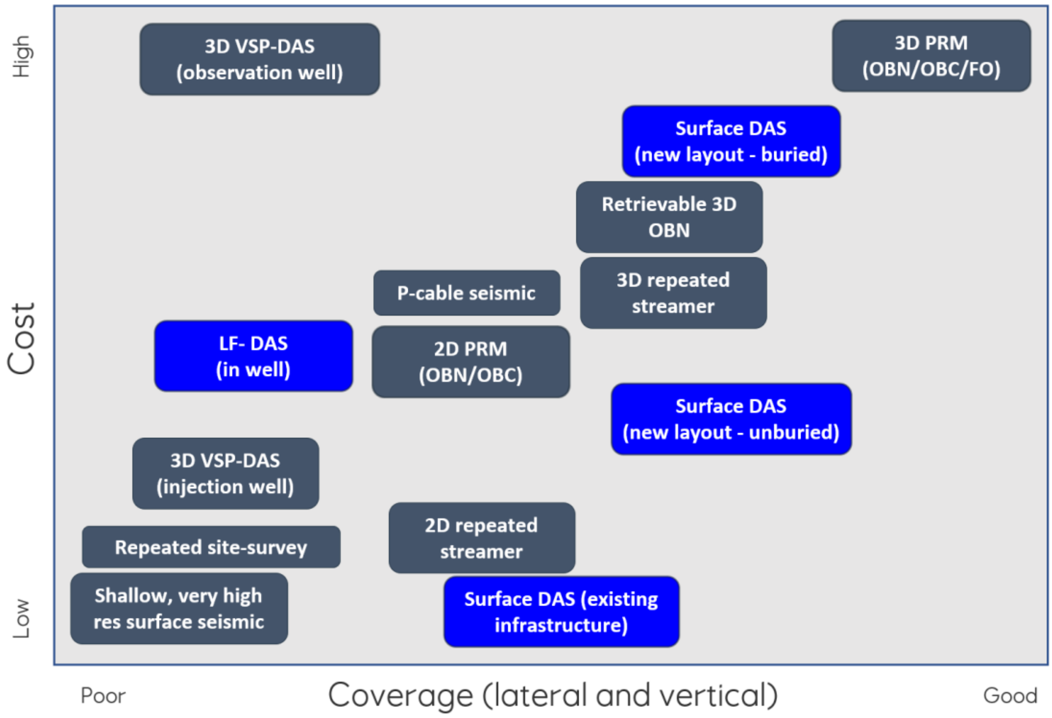

Figure 23 – Example of cost-benefit evaluations related to data coverage. Figure modified after Furre *et al.* 2020.

Evaluating the value of information is a critical aspect of cost considerations in geophysical monitoring. It assesses how much useful information a technology provides relative to its cost, helping to determine the most efficient allocation of resources. Cost-benefit evaluations are essential for comparing the economic feasibility of various monitoring technologies. These evaluations ensure that investments in new technologies, including recent advancements in FO systems, are justified by the enhanced data coverage and improved risk management they offer. Figure 23 presents a cost-benefit evaluation regarding the data coverage conducted by Furre et al. (2020) for various geophysical monitoring technologies. This updated figure includes recent advancements in fiber optic technology presented in this report, highlighted in blue-coloured boxes.

Cost considerations for technical equipment discussed in this report specifically address the DAS interrogator, as cost assessments for conventional technologies, data processing, fiber optic cables and other equipment have already been conducted (e.g. Paul *et al.* 1984, Ertunga *et al.* 2021, Khan 2023).

Estimation of the yearly cost of using DAS interrogators in a seismic monitoring system, depends highly on the lifetime and failure rate of the interrogator. The lifetime is determined by when the components in the interrogator no longer provide the data quality need for the seismic monitoring. Components in electrical systems will stop working at some point in time due to usage and environmental conditions. The failure rate or mean time between failure (MTBF) can be estimated by counting the number of failures over time when operation one or more interrogators. In a seismic monitoring system, some failures on data acquisitions units can be accepted, if the duration of the failure is short and if the monitoring is conducted by several units that independent collect data, reducing the total down time of the monitoring campaign. The data completeness for seismic networks is often close to 100 % since there is most often enough seismic stations running to detect and locate significant earthquakes, but each instrumental failure will lower the detection capabilities of the seismic monitoring and increase the estimated location and magnitude inaccuracy of the events in the area.

An example of mapping the lift time with respect to mean time between failure (MTBF) is given by power supply manufacture Elipse (2024). The MTBF value is a measure of reliability, but it is not a guarantee of reliability. It measures how frequently failures are expected to occur. For the DAS interrogators lifetime and MTBF estimates are important cost parameters that might differ for one manufacturer to another. If the DAS interrogator is handled using manufacturer recommendations, it could be assumed that the lift time and MTBF is comparable to that of a PC (see Elipse 2024). NKT Photonics that produce the Koheras laser for DAS interrogators state: "…we mean a typical lifetime of more than 10 years…" (NKT Photonics, 2024). Fibre optic cables have an average MTBF of 25 years or more, showing their long-term reliability.

It's crucial to acknowledge the wide range of valuable applications associated with FO technology, making it comparable to a versatile Swiss army knife. Beyond its primary benefit for CO_2 storage monitoring, fiber optic technology offers numerous additional benefits, which are significant for public perception and the overall environmental impact. These multifaceted utilities enhance its value proposition and justify the investment. It was demonstrated, for example, that DAS utilizing submarine telecom cables enables the monitoring of marine life, such as whales, and detection of acoustic pollution (Wienecke and Brenne 2023). Additionally, DAS can be applied for monitoring of ocean currents and temperature changes essential for climate research and UNESCO's efforts to safeguard ocean health. The protection of marine ecosystems and reducing the impact of human activities that are threats to marine life are important aspects of the SDG14 objective of the UN Agenda 2030 for Sustainable Development and Revitalization of the Ocean (United Nations 2022). The Intergovernmental Oceanographic Commission of UNESCO recognizes that healthy oceans and marine ecosystems are vital to a sustainable future. Moreover, the DAS technology has applications in security and protection, allowing for integrity monitoring and detection of potential threats to underwater telecom and power cables.

6.3 Public perception/acceptance

A social science study of public perception and acceptance in relation to a deployment and operation of a fibre-optic monitoring system in a Norwegian North Sea setting is beyond the scope of this project. In a study of the public perception and acceptance of telecommunications cables by Starosielski (2012), it is observed that the visual trace of the cable is an important factor. Especially the visibility of cable landing points is important. Often these are hidden, to mitigate potential threats or prevent public attention. Starosielski (2012) reports that the largest human threat to cables has been from anchors and trawling nets damaging the cables on the seafloor and that fisherman can lose equipment caught on the cable. Starosielski (2012) describes a strategy for mitigation from Morro Bay Area, USA, where a liaison committee between fishermen and the cable company is formed to share maps of laid cables and offer grants and financial resources for fishing communities.

In general, there could be several reasons why the public might be sceptical or even opposed to large-scale CO_2 injection and monitoring projects. In public perception, it seems that problems are often dealt with by sweeping them under the carpet: nuclear waste is buried underground, and now there's a proposal to do the same with CO_2. Other reasons may include concerns about environmental risks such as CO_2 leakage, groundwater contamination, and induced seismicity. Additionally, some members of the public may be doubting the effectiveness of CO_2 injection as a solution to climate change and may question the long-term viability of such projects. There may also be concerns about the potential impact on local communities, ecosystems, and property values. Lack of trust in regulatory bodies, transparency issues, and perceived conflicts of interest could also contribute to public opposition. Finally, misinformation, fear of the unknown, and opposition to perceived government or industry involvement may further influence public perception. However, if the technical solutions and guidelines for CO_2 storage monitoring are transparent, well-regulated, and effectively communicated to the public, they may be viewed more positively as essential tools for ensuring the safety and success of CO_2 storage projects.

Ultimately, public perception may be influenced by factors such as communication efforts, public engagement, access to accurate information, and the demonstration of tangible benefits and safety measures associated with monitoring solutions. As previously discussed in section 4.2, enhanced monitoring solutions extend beyond CO_2 storage monitoring. DAS technology presents applications in security and protection, facilitating integrity monitoring and detection of threats to underwater cables and infrastructure. Additionally, DAS on submarine cables as well as hydrophones can monitor marine life, acoustic pollution, ocean currents, and temperature changes, contributing to climate research and UNESCO's initiatives for sustainable ocean development and protection.

7 Conclusion

This report offers an overview of novel FO monitoring technologies in combination with conventional technologies crucial for the success of safe CO_2 storage. The project's primary objective within the framework of the ACT SHARP project, is to enhance the accuracy of subsurface CO_2 storage containment risk management to satisfy both commercial and regulatory interests.

Here we provide the main framework for the development of an enhanced monitoring solution that can be designed cost-effective and that monitors the right parameters used for predictive geomechanical modelling improving risk management. Following commissioning of a CO_2 storage site, rock failure models should be verified and updated based on operational data such as flow rates, pressure measurements, microseismic event detection. The focus of this report lies in monitoring for containment risk management, prioritizing the assessment of how the reservoir and overburden responds to CO_2 injection.

The utilization of FO sensing emerges as a promising monitoring solution, offering continuous real-time monitoring and high-resolution measurements. FO systems present opportunities for detecting seismic events, recording changes in strain, temperature and facilitating seismic imaging, thereby enhancing our understanding of subsurface dynamics. FO technology can complement other methods, and even potentially replace them in some specific situations. However, it won't serve as a universal solution for all scenarios.

Integration of various monitoring technologies, including FO systems (DAS-DTS-DSS), ocean bottom nodes, onshore seismic networks, and downhole measurements, is crucial for effective monitoring and risk management. These integrated approaches allow for comprehensive data collection and analysis, enabling operators to anticipate, identify, and mitigate potential risks associated with CO_2 storage operations.

Deploying downhole fiber optic cables presents technical challenges and requires careful cost consideration, with various pros and cons to evaluate. For example, many CO_2 injectors in the North Sea are expected to be subsea developments, which involve high completion costs when integrating fiber downhole. A more cost-effective solution is to use surface fibers inside existing infrastructure, such as submarine telecom and power cables. However, this approach offers less sensitivity (e.g., regarding pressure changes in the reservoir) and lower detectability compared to downhole fibers.

Our report emphasizes the importance of predictive modelling alongside real-time monitoring to anticipate and manage risks effectively. By continuously updating geomechanical models with data from enhanced monitoring systems, operators can make informed decisions and implement proactive measures to ensure the safety and success of CO_2 storage projects.

According to ANNEX II of the EU CCS Directive 2009, the minimum parameters for monitoring CO_2 storage facilities include fugitive emissions of CO_2, it's volumetric flow at injection wellheads, pressure and temperature at injection wellheads, chemical analysis of the injected material, and reservoir temperature and pressure. However, our analysis suggests these minimum parameters could be updated to strain monitoring. Moreover, the scope of strain monitoring should extend beyond the vicinity of the injection well to encompass regional impacts, with strain changes inferred from observed seismic velocity changes. As CO_2 storage and monitoring technologies evolve, existing regulations must be updated to incorporate these innovations.

The integration of DAS technology on surface and downhole fibers offshore with seismic networks onshore, for instance, can improve the detection and localization of microseismic events. Reducing depth uncertainty in seismic event localization is an important risk mitigation step for both containment and leakage risks, as well as for addressing public perception concerns.

Developing new risk mitigation protocols and updating regulations to include advanced monitoring technologies will enhance the safety and efficiency of CO_2 storage operations and build public trust in their environmental responsibility. Beyond CO_2 storage monitoring, the versatility of FO technologies extends to applications in security, climate research, and environmental protection, underscoring their broader societal benefits.

In essence, the findings presented in this report contribute to advancing monitoring practices and risk management strategies in CO_2 storage operations. By harnessing innovative technologies and fostering interdisciplinary collaborations, we aim to address environmental concerns while accelerating progress towards a sustainable future.

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