A distributed fibre-optic sensing monitoring platform for CCUS

Michael Mondanos[1]*, Pierpaolo Marchesini[1], Anna Stork[1], Carlos Maldaner[1], Garth Naldrett[1] and Thomas Coleman[1], present a measurement, monitoring and verification (MMV) framework for CCUS.

Introduction

Carbon Capture, Utilisation and Storage (CCUS) is expected to play a crucial role in reducing CO_2 emissions and meeting global climate targets. Leading organisations including the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and Intergovernmental Panel on Climate Change (IPCC) have all produced long-term energy outlooks that rely on a rapid expansion of CCUS in order to limit global temperature rise to 1.5°C.

Carbon Capture and Storage (CCS) technology offers an opportunity to prevent CO_2 emissions to the atmosphere by capturing and injecting it underground in depleted oil and gas fields, coalbeds, or saline geological formations where it is securely stored (Figure 1). There are three main requirements for a geological formation to be suitable for CO_2 storage: high-volume *capacity,* good *injectivity,* and CO_2 *containment* provided by overlying caprock formations.

To reach a 1 Gt CO_2/year of global capture capacity by 2030, in line with the net-zero emissions scenario, would require on average 160 Mt CO_2/year of capture capacity and 140 Mt CO_2/year of storage capacity to start the planning stage each year until 2026 (IEA Net Zero Roadmap). Regulatory frameworks governing geological CO_2 storage are being developed worldwide and the rapid acceleration in the number of large-scale CCS projects will require additional policy support for site-specific technologies. This includes measures to encourage investment in key enabling infrastructure such as CO_2 storage facilities, demonstration and commercialisation of emerging technologies, and creation of a larger global market for low-emission products.

A series of monitoring requirements exists during CO_2 injection operations. These requirements focus on mitigating risks arising from the injection of large volumes of CO_2 under high pressure in deep reservoirs. The evaluation of storage performance and containment is captured under a Measurement, Monitoring and Verification (MMV) framework.

The main risks identified and illustrated in Figure 2 are:
- Migration of CO_2 along faults and fractures.
- Migration of CO_2 plume outside of the storage reservoir.
- Induced seismicity.
- Interactions with, or impacts on, other natural resources such as drinking water or hydrocarbons.

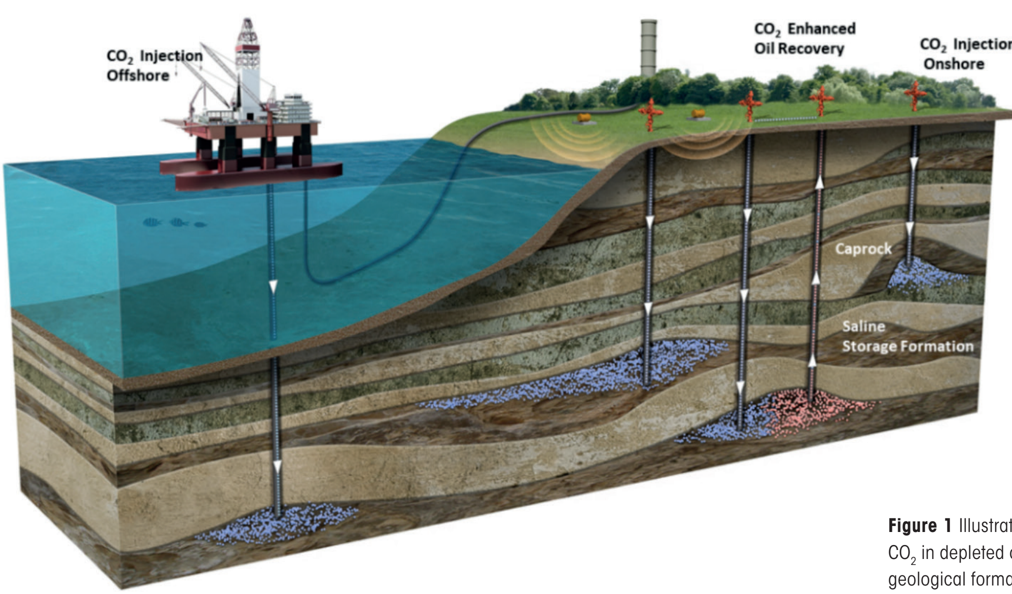

Figure 1 Illustration of permanent storage options for CO_2 in depleted oil and gas fields or in deep saline geological formations.

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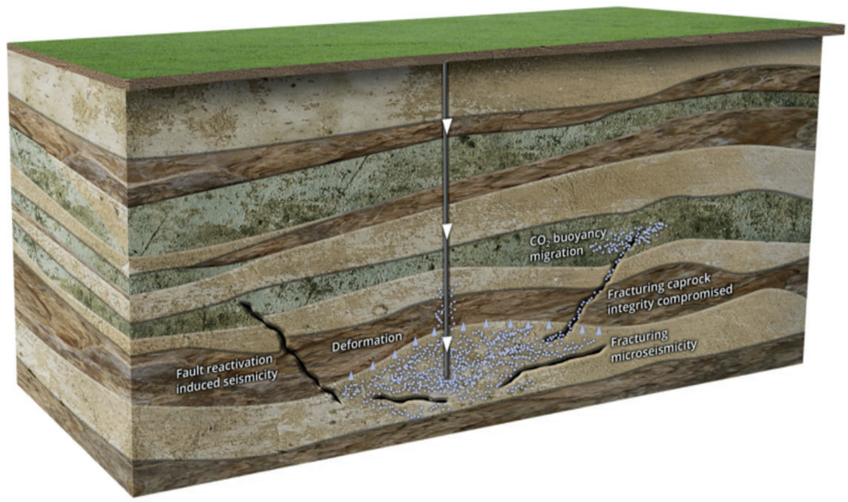

Figure 2 Risks arising from the injection of CO_2.

Identifying potential risks during site characterisation, baseline, or subsequent monitoring operations allows targeted actions to mitigate the impact of identified risks or to prevent their occurrence. During CO_2 injection operations and after site closure, the stored CO_2 and the decommissioned injection infrastructure should be monitored for the following reasons:

- Conformance monitoring: to ensure the CO_2 plume distribution and migration is tracked and understood.
- Containment monitoring: to ensure that injected CO_2 remains within the storage formation.
- Contingency monitoring: to ensure that the contingency measures to stop movement of CO_2 out of the storage formation are performing according to their design and requirements.

Distributed fire-optic sensing

Distributed fibre-optic sensing (DFOS) based survey methods focus on near surface and subsurface monitoring. These methods can greatly enhance the spatial and temporal resolution of the data acquired over the full lifecycle of a project, while reducing overall monitoring costs, improving data quality, and increasing asset longevity when compared to standard solutions which use point sensors such as geophones or downhole temperature and pressure gauges. Monitoring can also be carried out utilising permanent fibre-optic cables typically installed behind casing which limits the risk and cost of intervention while also providing spatio-temporally continuous sensory capability which is not feasible using alternative permanent sensors.

DFOS solutions can be used to characterise site specific temperature, strain and seismic baselines, and enable monitoring of the injection and post-injection activities due to the long-life expectancy of the optical fibres in the downhole cable. Applications include CO_2 plume distribution monitoring based on time-lapse vertical seismic profiling (VSP) surveys (e.g., Pevzner et al. 2021; White et al., 2019); microseismic monitoring for natural baseline and induced seismic activity (e.g., Stork et al., 2022); and temperature and acoustic monitoring for well integrity applications (e.g., Ricard, 2020). The system can run autonomously and continuously, and it is compatible with permanent seismic sources located at fixed positions (Isaenkov et al., 2021). Additionally, as the optical fibre is the sensor, there is minimum maintenance requirement and low risk for failure.

Permanent CO_2 storage monitoring system

The development of a permanent and proven distributed sensing-based monitoring system, the Carina Carbon Secure system, provides a solution that reduces CCS monitoring costs throughout the lifetime of a project. With minimal environmental impact, the system provides a reliable autonomous and continuous or on-demand monitoring solution for both offshore and on land projects. It ensures CO_2 injection safety and long-term MMV capabilities for efficient management of the storage reservoir. Apart from the numerous operational benefits, the system also has the potential to facilitate faster CCS adoption by the industry and society. An illustration of an onshore CCS monitoring system is given in Figure 3.

Fibre-optic cables are permanently deployed in boreholes to provide on-demand surveys and long-term monitoring capabilities. High-quality distributed acoustic sensing (DAS) data, with up to 20 dB noise floor improvement over standard DAS data are provided by the engineered Constellation fibre. The unique fidelity of this system provides the capability to acquire repeatable active seismic data and record small microseismic events with improved signal-to- noise ratio (SNR). Continuous and real-time microseismic monitoring delivers a detailed picture of seismicity than traditional technologies to mitigate potential seismic hazards. Given the system's extreme sensitivity, active seismic surveys can be efficiently conducted with smaller seismic sources or fewer stacks providing early warning of potential CO_2 leakage pathways. Wellbore integrity and plume breakthrough can also be monitored with Distributed Temperature Sensing (DTS), DAS configured with a high sampling frequency and Distributed Strain Sensing (DSS) systems on the same fibre-optic cable.

Real-time data processing conducted using an edge processing platform maximises the on-site processing capabilities and operational flexibility. The approach allows for remote and efficient QC/QA, data analysis, and multi-physics data integration and avoids high bandwidth requirements for offsite data transmission. The DAS, DTS and DSS interrogators can run continuously or be activated at specific times to perform on-demand surveys. When acquisition is performed without supervision, a log of performance metrics (Key Performance Indicators, KPIs) is kept and displayed. Advanced functionality includes alarms and notifications if necessary.

Data bandwith, resolution, and processing requirements are determined by the applications deployed for the specific site. The processing modules are grouped in nodes to process data received from the relevant interrogator units. If a unit is used for multiple operations, then it must be configured to accommodate different set up parameters under a scheduler operation. Potentially, there may be different acquisition settings for a single interrogator depending on the applications.

One of the first DFOS autonomous systems for CO_2 storage monitoring was implemented at the CO2CRC Otway Project in Australia, and the preliminary results have been published by Isaenkov et al. (2021). This monitoring system includes fibre-optic cables deployed in multiple boreholes extending across the injection interval and also trenched on surface. Combined with permanent Surface Orbital Vibrator (SOV) seismic sources, the DFOS system has provided near-continuous monitoring of injected CO_2. Isaenkov et al. (2021) highlighted that the 'monitoring system allows acquisition of seismic vintages every two days in an automated manner. The permanent installation requires no human effort on-site and thus drastically reduces the monitoring cost'. The system has operated continuously for months at a time over several years. The best measurement performance has been achieved with cables cemented behind casing, but other installations with the fibre-optic cables on tubing and suspended have shown near comparable performance. The introduction of the optical fibre monitoring system has been estimated to have a 75% cost saving, and a substantial reduction of CO_2 emissions, over traditional monitoring technologies.

A significant number of offshore CO_2 storage projects are under development, and it is expected that the number of these projects will grow rapidly in the coming years (Global CCS Institute, 2023). In addition to the cost and emissions reduction, a further benefit of permanent monitoring is the reduced personnel required on site. While several offshore production platforms have DFOS monitoring systems installed, the monitoring of subsea wells has only recently become feasible. By using an engineered fibre with high optical scattering in the subsea well the interrogator unit can be located onshore, or on a host Floating Production Storage and Offloading (FPSO) or platform and connected to the subsea well via standard umbilicals. Operating through standard single mode fibres and remotely operated vehicle (ROV) wet mate connectors in the umbilical, few modifications and no customisation is required to standard equipment. Reliability is also ensured by using qualified, field-proven technologies. As the interrogator is located on the host facility it reduces installation costs, simplifies data transfer, allows system upgrades over the installed life, improves reliability, and reduces power and communication interface requirements within the subsea production system.

Such offshore monitoring systems have been successfully installed in several deepwater wells in the Gulf of Mexico, as well as the North Sea. In February 2023, bp presented the results of its first deepwater DAS 3D seismic acquisition, showing a significant enhancement in frequency content and resolution at the target and better ties to the well log, compared to the surface seismic (Soulas et al., 2022). In the context of CO_2 injection this improvement would allow for higher resolution timelapse imaging of the CO_2 plume.

Edge processing monitoring platform

In general settings, a permanent real-time monitoring system for CCS consists of a network of optical fibre cables installed in the injection and monitoring wells and a processing platform where operations are performed onsite at the edge of the system, and results can be accessed remotely and transferred over the network (Edge-based architecture). Figure 4 shows the system architecture with two monitoring and one injection well and also a mesh of fibre cables installed in the near surface.

An extensive geophysical monitoring programme is necessary to demonstrate plume containment and conformance. High survey costs and increased temporal resolution requirements are driving the development of continuous or on-demand reservoir monitoring techniques that allow for cost-effective, autonomous, and remotely managed operations. The large data volume produced requires on-site processing capabilities to minimise data volumes transfer to off-site locations.

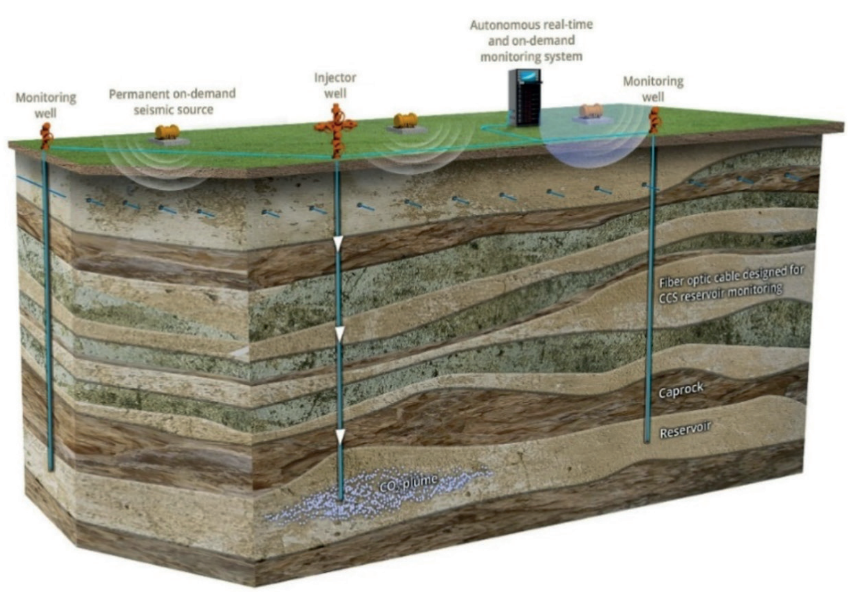

Figure 3 Integrated and autonomous fibre-optic distributed sensing monitoring system for CCS projects.

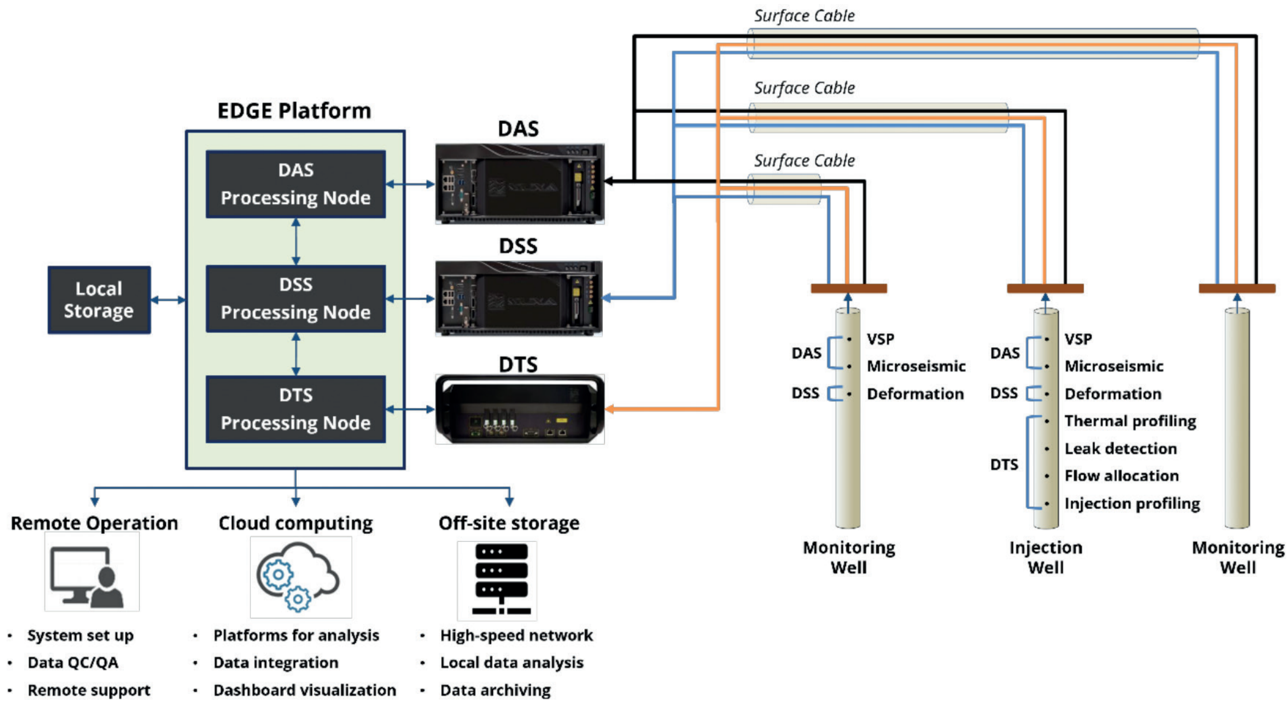

Figure 4 Edge-based architecture for remote, automated, and real-time systems for CCS projects.

The autonomous monitoring system produces microseismic event catalogues, flow profiles, and wellbore integrity analyses in real-time using an Edge processing architecture to avoid high bandwidth requirements for offsite data transmission and limiting raw acoustic data storage requirements. Combined with geomechanical deformation, wellbore integrity and leaks, thermal response, and cross-well applications enabled, a permanent reservoir monitoring programme to be employed. Seismic shot extraction and pre-processing of active survey data can also be performed in the Edge system on-demand. The processed data and results are made available on a cloud server, can be accessed on cloud services, or transferred offsite while the user can remotely operate the equipment and schedule the monitoring scheme.

The monitoring system can be enhanced with permanent seismic sources and DFOS receivers within an architecture based on Edge processing maximising the in-situ processing power and operational flexibility. It allows remote and efficient QC/QA, data analysis, and multi-physics data integration. The approach is attractive to operators due to cost-effective deployments, less time-consuming operations, superior spatial coverage, enhanced data quality compared to conventional technology, and it represents the next step towards affordable and truly continuous reservoir monitoring for CCS.

Plume monitoring

Tracking the CO_2 plume over time is important task in any CCS MMV program. Changes in the seismic response to a CO_2 plume can be monitored and assessed by time-lapse seismic surveys. Images of the subsurface are generated through either 3D VSP, multiple 3D surface, or 2D cross-well surveys to track and quantify the migration of plume over time. Distributed fibre-optic sensing methods provide denser spatial coverage compared to standard methods, decreased acquisition costs without compromising on data quality, and enhanced data repeatability to allow imaging of CO_2 plume distribution and saturation around injection and monitoring wells.

Pevzner et al. (2021) show how a small volume CO_2 injection (15 kT) can be monitored with time-lapse DAS VSP surveys using permanently installed surface orbital vibrators (SOV) and fibre-optic cable cemented behind the casing. Having both source and receivers permanently installed enables us to perform VSP surveys more frequently with low costs providing early detection of CO_2 plume, tracking the rapid distribution changes and monitoring potential leakages out of the target reservoir. Other recent examples of SOV DAS-VSP surveys have provided comparable results to conventional time-lapse seismic with vibroseis and geophones (Correa et al., 2018; Yavuz et al., 2021).

The CO_2 plume evolution over time at the CO2CRC Otway project after several injection stages from March 2017 to March 2021 is shown Figure 5 (Glubokovskikh et al. 2022). The plume boundaries were generated by picking the P-wave first arrivals. A fluid-induced microseismic event at reservoir depth is also shown relatively close to the plumes.

In Pevzner et al. (2022), the simultaneous analysis of travel time shifts and amplitude variations in DAS-VSP settings allows not only to delineate the presence of the CO_2 plume at early stages but also to formulate observations on its characteristics as it is forming. Thanks to its relatively low cost, 4D VSP with DAS is an attractive proposition for frequent seismic monitoring around monitoring and injection wells.

Wellbore integrity

CCS MMV programs required demonstration of wellbore integrity by proving that any CO_2 is escaping to shallow geological formations. DTS and DAS can provide the dataset required to prove integrity of the injection system. The temperature difference between the injected CO_2 and the reservoir temperature serves as a tracer to indicate locations of (either intended or accidental) CO_2 flow along the wellbore (Figure 6a). Temperature data from DTS systems can also be collected continuously to monitor the status of cement location and quality during cementation of the casing (Figure 6b). The dense receiver coverage provided by fibre-optic cables allows capturing temperature anomalies with sub-metre resolution (down to 25 cm).

In addition to DTS, the flow of high-pressure fluids through well perforations has a well-defined acoustic signature that can be captured using high-frequency DAS surveys. Acoustic data can be monitored with high-resolution for the onset and evolution of such flow signals. The location of potential leakage is easily identifiable in the acoustic data, and the flow can be parameterised by the power distribution of the frequency spectrum. The information can be coupled with DTS information to refine and characterise any leakage signature (Figure 7).

Reservoir deformation due to the pressure build up can also be assessed using DAS and DSS methods to inform about wellbore integrity and minimise the risks associated with casing failure during and post injection.

By detecting anomalies or unexpected increases in regions of the wellbore with DTS, DAS, and DSS, it is possible to identify and locate leaks within the borehole with high-resolution and in real time. If readings occur outside the expected range, alarms are sent to the operators to assess the data and take any required actions.

Microseismic monitoring

Induced seismicity can occur due to an increase in stress on pre-existing faults or because of lubrication of faults due to increases in pore pressure. Reactivation of faults could result in leakage pathways for CO_2 and lead to potential migration of CO_2 and native fluids to the shallow subsurface.

Microseismic monitoring as a tool for fracture network characterisation and imaging developed with the rise in hydraulic

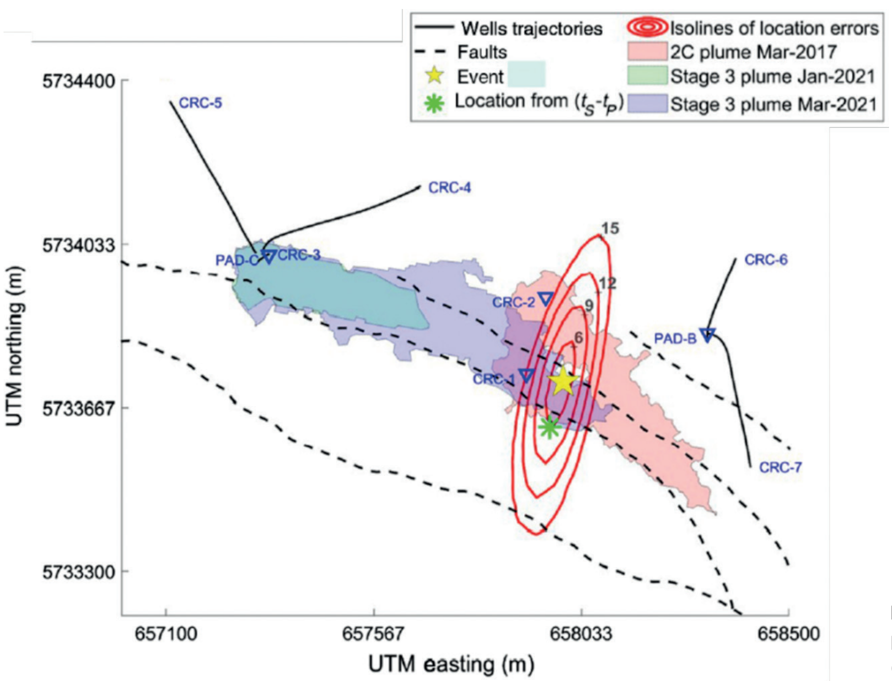

Figure 5 Evolution thought injection stages of CO2 plume boundaries delineated from P-wave travel time (modified from Glubokovskikh et al., 2022).

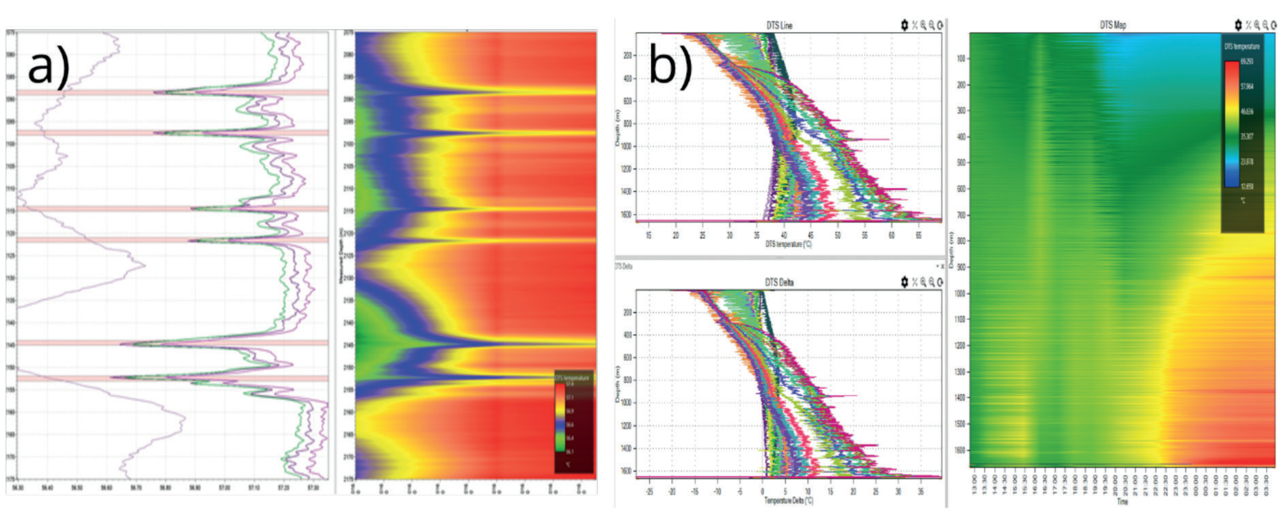

Figure 6 a) Example of DTS temperature profile indicating fluid zonation. b) Thermal monitoring during casing cementation.

fracturing for unconventional oil and gas production (Maxwell, 2010). The application of DAS for microseismic monitoring has matured rapidly with improved data quality and acceptance of the technology as an important geophysical tool (e.g. Boitz and Shapiro, 2024; Staněk et al, 2022; Stork et al., 2020; Tuinstra et al., 2023). Real-time continuous microseismic monitoring is required to monitor caprock integrity and induced seismicity risk for CCS projects, requiring efficient processing of large datasets.

Such a continuous DAS monitoring system has been successfully trialled on major CCS projects, for example at Quest CCS (Vera Rodriguez et al., 2023) with event detection results available in real time. Ideally, the inclusion of engineered fibre provides enhanced detection capabilities with high SNR data.

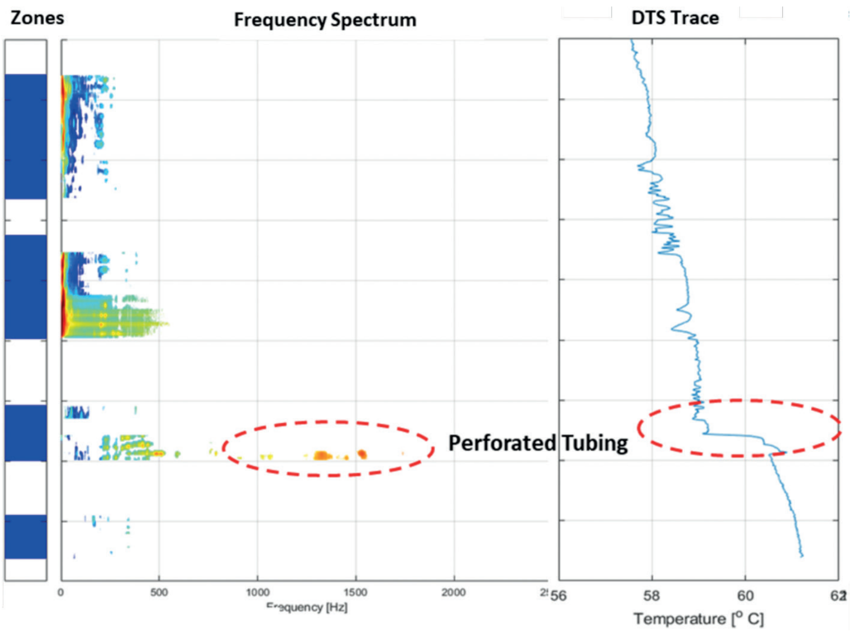

Figure 7 Tubular failure identified by acoustic (left) and temperature (right) anomalies.

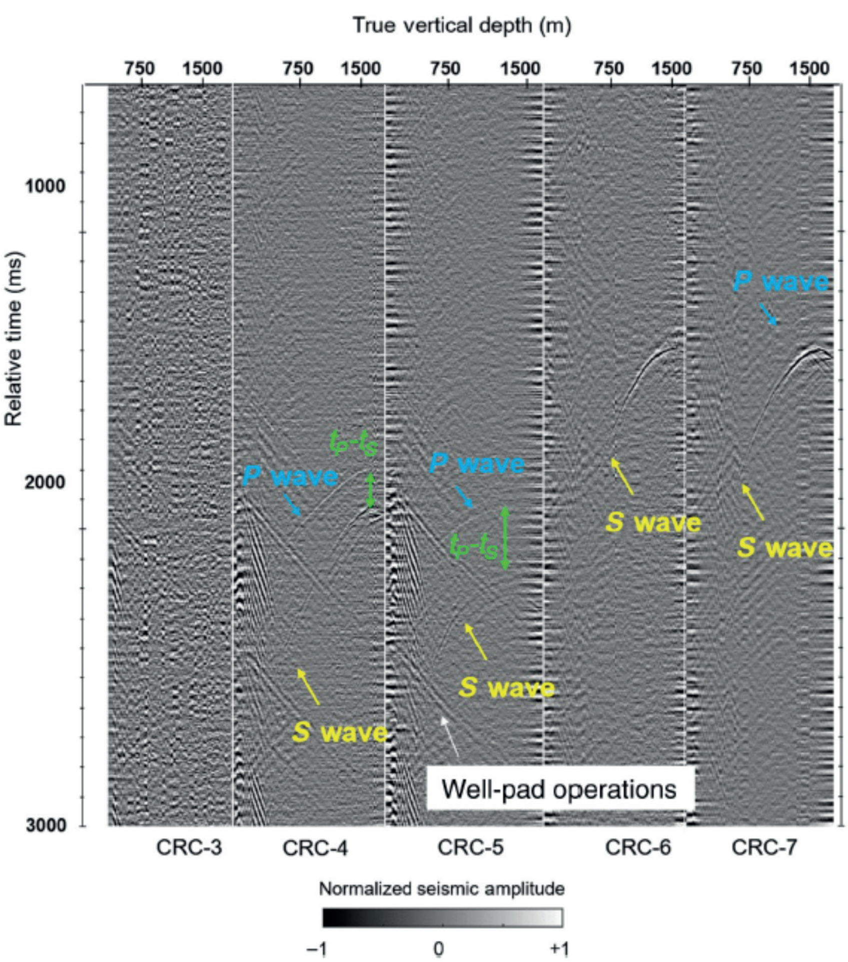

Figure 8 Strain-rate seismogram for weak microseismic events with Mw ~ −2. DAS array has sufficient sensitivity to pick the first P- and S-wave arrivals in all five boreholes. The relative location of the wells is shown in Figure 6 (from Glubokovskikh et al., 2022).

At the CO2CRC Otway site the installation of Constellation engineered fibre in the boreholes has facilitated the detection of small clusters of microseismicity associated with CO_2 injection at the site (Figure 5 and Figure 8; Glubokovskikh et al., 2022). These authors report that the borehole DAS monitoring system has sufficient sensitivity to detect and locate events with moment magnitudes, Mw, greater than −2 up to 1500 m away. An example recording of an Mw~-2 event is shown in Figure 8. This highly sensitive system facilitates a verification of the geomechanical response of the site to CO_2 injection and an improved understanding of any seismic hazards or caprock integrity risks. Surface cable deployments are also possible where wide area coverage is required (Stork et al., 2022).

Closing remarks

The mitigation of risks involved with CO_2 storage underground is possible with detailed site characteristion and advanced monitoring before, during, and after the injection period. Fibre-optic distributed sensing enables on-demand or continuous, multi-physics-based survey methods which reduce risk through closure of spatial and temporal geophysical and geomechanical information gaps. Cost is mitigated when compared to either standard intervention tools or arrays of discrete, permanent sensors through leveraging a single system for numerous monitoring applications, by limiting wellbore intervention and site mobilisations, and increasing system longevity. The fibre-optic distributed sensing monitoring system has been developed and tested over several years and it is currently being applied to numerous projects commercially.

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