DAS seismic monitoring of the shallow CO$_2$ controlled-release experiment at the South West Hub In-Situ Laboratory

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SUMMARY
Carbon Capture and Storage (CCS) remains one of the most viable short-term options for halting the increase in atmospheric concentration of greenhouse gases. Assurance of storage safety is an essential part of the process required to maintain a community operations licence. Ability to understand the migration behaviour of CO$_2$ in the shallow subsurface and faults is essential for leakage detection and mitigation. Here we present the results of the successful detection and monitoring of a shallow injection of extremely a small quantity of carbon dioxide into a fault zone using a borehole seismic technique with fibre optic sensors. The experiment was conducted at the South West Hub In-Situ Laboratory in Western Australia.

Key words: CO2 monitoring, DAS, borehole seismic.

INTRODUCTION
The South West Hub In-Situ Laboratory is a dedicated facility designed to perform experiments focusing on the controlled release of a small amount of CO$_2$ into a shallow fault zone and monitoring evolution and movements of the plume. The project’s focus is on studying the impact of faulting on carbon dioxide migration patterns in shallow geological conditions and to design the monitoring approach for early detection and monitoring of a potential out-of-storage CO$_2$ leakage. The research site is located in Western Australia approximately 150 km south of Perth. A major fault zone with a maximum throw of up to ~1000 m is crossing through the site and providing favourable geological settings for the research activities (Michael et al., 2018b).

The project utilises two wells for the intended tests and trials. The Harvey-2 well is a stratigraphic well that was previously drilled for the geological characterization program of the South West Hub CCS initiative. After the drilling, the well was cemented to 400 m depth to seal the fault zone and, later, recompleted and perforated as an injector. A new geophysical monitoring/observation well was drilled ~6 m to the northeast from the injection well and completed with a fiberglass casing to a depth of ~370 m (Michael et al., 2018a). The Harvey-2 well is instrumented with a fibre optic deployed on production tubing and a set of a downhole pressure gauge. The monitoring well has a number of receivers cemented behind the casing; a fibre optic cable with single and multimode cores, 3 pressure gauges, 8 three-component geophones and 32 electrodes. Injection into the fault zone of ~38 tons of food grade carbon dioxide has been completed into a six meters perforated interval at a depth of 336-342 m.

Borehole seismic technology is a recognized approach for the time-lapse surveillance of a reservoir, offering excellent repeatability (Pevzner et al., 2010) as receivers are positioned in generally stable conditions inside a bore. It also often has fewer issues with accessing areas for the onshore acquisitions, as there is no need to redeploy surface equipment apart from sources. Examples of the observation of small quantities of carbon dioxide using vertical seismic profiling (VSP) in offset and 3D geometries using conventional three-component geophones were published by Tertyshnikov et al. (2017) and Tertyshnikov et al. (2018). They have tracked ~5 kt of the supercritical mixture of CO$_2$/CH$_4$ injected into a formation 1500 m deep within the CO2CRC Otway project experiments.

Distributed acoustic sensing (DAS) techniques have experienced a rapid development in instrumentations, sensing cables and general application to seismic exploration. The approach uses fibre optic cables to record seismic energy; such receivers have a certain directivity pattern, in which they are more sensitive to seismic waves propagating along the cable axis compared to energy arriving broadside (Correa et al., 2017). For borehole seismic applications using VSP geometry, the fibre sensors are positioned favourably along the well’s axis.

In this paper, we present the results of the seismic monitoring program at the In-Situ Laboratory controlled release experiment, more specifically, detection of a small volume of gas using walk-away borehole seismic acquired with distributed fibre optic sensors in the monitoring well.

ACQUISITION OF OFFSET VSP DATA
As a part of the first shallow controlled-release test within the In-Situ Laboratory Project at the Harvey-2 site, a comprehensive seismic monitoring program was conducted by the Curtin University geophysics team. The injection (of total ~38 t of carbon dioxide) experiment and seismic surveys were conducted over two weeks’ time at the beginning of February 2019. Here we focus on results obtained from the DAS data acquired with the hybrid cable cemented behind the casing of the entire length of the monitoring well. A single mode core of the installed cable was interrogated using an IDAS v2 interrogator (Silixa Ltd, UK) unit during the surveys.

The offset VSP monitoring acquisition setup was designed as a series of azimuthal lines extended from the monitoring well with the maximum offset ~200 m and the nearest offset of 40 meters from the well. (Figure 1). Shot points locations were limited to accessible land around the observation well to the north-eastern section. In total 128 shot positions were planned for the monitoring offset VSP surveys. The light seismic source – a 45 kg accelerated weight drop – has been chosen for the monitoring offset VSP acquisition due to the shallow depth of the injection (~350 m). To increase signal to noise ratio of the...
collected data eight source excitations per shot point were performed during the surveys.

The baseline survey was acquired just before the commencement of the injection. All offset points were repeated every day during a six days period of the injection. At the start of the injection the nearest offset circle of shots was repeated again to form an additional dataset for these points. The last monitoring survey was acquired five days after the end of the injection.

**DATA PROCESSING AND RESULTS**

The express processing flow parameters were consistent across the vintages in order to achieve acceptable level of repeatability. For the fast assessment of detectability of the injected volume, the processing was focused on data from the closest offset (shots located 40 m away from the monitoring well).

The shot points around the monitoring well at the constant nearest offset resemble the case of zero-offset VSP geometry that allows stacking them all to a single gather for improvement of signal-to-noise ratio. The wavelet for deconvolution has been estimated for each vintage separately; the wavefield separation has been performed and seismograms were NMO corrected. Figure 2 shows the results of the processing: panels from left to right represent baseline data and all monitoring datasets respectively. Clear signal from the injected gas could be observed starting from the fourth vintage at the two-way time around 300 ms at the corresponding depth of ~350 m (area highlighted with red in Figure 3). We observe significant brightening of the reflector corresponding to the injection interval in successive surveys. Figure 3 displays deconvolved gathers (stack of all shots at the offset of 40 m) of the baseline dataset, monitor 8 vintage and their difference. Significant time-lapse signal is clearly manifested on the difference seismogram (highlighted by a red arrow) at the injection depth. This provides solid evidence that the CO₂ plume has reached the monitoring well and such small quantities can be monitored using a borehole seismic approach with installed fibre optic sensors.

**CONCLUSIONS**

Borehole time-lapse seismic in offset VSP configuration using fibre optic sensors demonstrated a robust detection of as little as 38 tons of carbon dioxide injected at the depth of ~350 m during the controlled release experiment at the South West Hub In-Situ Laboratory site. Given the low power of the accelerated weight drop source, and the general sensitivity of DAS, which lags behind conventional sensing technologies, we were surprised by the high quality of the monitoring data. The results suggest that the downhole seismic using a combination of inexpensive and scalable fibre optic receivers and small sources provides a reliable and cost-effective surveillance solution for early warnings in an event of unwanted leakage of gas from a CO₂ reservoir.

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**REFERENCES**


Figure 2. Seismograms showing NMO corrected upgoing wavefield. From left to right: Baseline data – 0; Monitors data – 1-8. Red square indicates times of a reflection from the injection interval.

Figure 3. Time-lapse images of the CO2 plume on VSP sections. Left panel: monitor 8 seismogram; Centre panel: baseline seismogram; Right panel: differences of the baseline and monitor data. Red arrow indicates clear response from the injected gas.