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Stage 2C of the CO₂CRC Otway Project: Seismic Monitoring Operations and Preliminary Results

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Abstract

The CO₂CRC's "Otway Stage 2C project" is a test injection of 15,000 tons of supercritical gas mixture (80 mole% CO₂ & 20 mole% CH₄) at the CO₂CRC Otway site in the Australian state of Victoria. The objective of this test is to examine the limits of surface seismic detection and to conduct detailed pressure monitoring of the injection. A key design feature of the project is injection near the bottom of a highly permeable formation, thereby allowing for buoyancy driven flow to thicken the plume and enhance seismic response. The project is specifically targeting observation of the development of the gas plume through a combination of multi-vintage 4D seismic surveys acquired with a buried seismic receiver array, 4D Vertical Seismic Profiling (VSP) and pressure measurements. Using both time-lapse seismic data and reservoir simulations, we aim to not only detect the plume but also demonstrate its eventual stabilisation. In this paper we discuss the technical aspects of the Otway Stage 2C seismic monitoring program and the initial results.

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1. Introduction

Time lapse (TL) seismic is playing an important role in Monitoring and Verification (M&V) operations of many CO₂ geosequestration projects [1-5]. TL seismic is used for both monitoring of the plume evolution and as an assurance monitoring technique, demonstrating absence of significant leakage of the injected carbon dioxide out of the primary containment [6]. In order to optimize use of seismic monitoring for these purposes it is important to understand limitations in TL imaging resolution and sensitivity of the method to detect small quantities of CO₂ in different geological formations. An important special case is injection or leakage of supercritical CO₂ into brine aquifers.

Several field experiments reported different degrees of success in detection of small carbon dioxide injections into the saline aquifers. A strong signal from injection of as low as 1600 tons of supercritical fluid was observed at the Frio site using time-lapse zero-offset and offset VSP surveys [7, 8]; however this was done by placing geophones in the well passing through the CO₂ plume both above and below the injection interval. Surface seismic was successfully deployed to monitor ~22,000 tons of gas at the CO2SINK project [9], while no clear TL signal was observed from an injection of ~70,000 tons CO₂ at the Illinois Basin Decatur experiment using a 4D VSP survey [3].

Another set of issues affecting applicability of TL seismic to commercial CO₂ geosequestration projects (especially those which are being conducted on land) are related to cost, land access and ability to conduct continuous or on-demand seismic monitoring operations. To address these or similar issues, permanently deployed receiver arrays and continuously operating seismic sources can be employed [2, 10].

The CO2CRC Otway project is the first Australian demonstration of carbon dioxide geosequestration. The project site is located ~240 km West of Melbourne, Victoria, Australia. Development and testing of M&V technologies, including seismic monitoring, is one of its focus areas.

Stage 1 of the project was carried out in 2006-2010. At that stage ~66,000 tons of supercritical CO₂/CH₄ mixture was injected to a depleted gas reservoir located at ~2 km depth. A 4D seismic program consisting of 3 land surveys (2007/08, 2009 and 2010) and TL 3D VSP acquired concurrently with 2007/08 and 2010 surveys was a major component in an assurance monitoring program to monitor the CO₂ plume. In addition, a set of zero-offset and offset VSPs was trialed as a less expensive alternative. No strong seismic TL signal was observed at the injection interval. By combining results of forward modelling with the analysis of the observed TL noise, we demonstrated that a secondary accumulation of 5,000-7,000 tons of CO₂ should be visible in the overburden [6, 11]. It was also demonstrated that the main factors affecting the TL noise level on surface geophone data are related to high ambient noise and seasonal variations in the ground conditions [12]. It was also noticed that 4D VSP has a superior repeatability compared to the surface seismic.

The focus of Stage 2 of the Otway project, which commenced in 2010, is storage of CO₂ in saline aquifers. A part of this stage, Stage 2C is targeting demonstration of stabilization of a small plume injected into the Paarattee formation, a Cretaceous sequence of stacked deltaic sandstones, at 1.5 km depth through a series of TL seismic surveys in conjunction with matching modelling results. Another important goal of Stage 2C is to assess the seismic detectability threshold for small supercritical CO₂ injections, which can be considered representative of gas migration into overlying layers of commercial scaled storage projects.

Preparation for the Stage 2C commenced in 2009-2010. A TL seismic signal was predicted and sensitivity of various surface and downhole seismic acquisition geometries was evaluated through a series of simulations. We used a number of different workflows [13-15] trying to take into account principal factors that could affect the level of the signal, such as properties of the injection interval and technical parameters of the seismic survey (geometry, frequency content, etc.). In order to reduce the TL noise level (which was largely controlled by the presence of ambient noise) we successfully trialed burying the geophones in 2012 [16], demonstrating a noise floor reduction of 20 –30 dB. These tests also included an early look at distributed acoustic sensing (DAS) capabilities [17].

Based on the results of these studies, in early 2015 we designed and installed a buried receiver array at the CO2CRC Otway site, which includes both high-sensitivity geophones and DAS. Our initial concept of performing a series of active surveys was expanded to include passive seismic monitoring and TL monitoring using permanent fixed position surface seismic sources. This array is being used to monitor the Stage 2C injection through a series of 3D seismic surveys and is also paired to two permanently deployed surface orbital vibrators (SOVs). In this paper

we discuss the design of the array, seismic monitoring program and preliminary results obtained from the baseline and first three monitor surveys conducted in 2015-2016.

2. Stage 2C seismic monitoring program

The CO2CRC Otway Stage 2C experiment includes the following activities:

- Design and installation of the buried receiver array
- Acquisition of the baseline seismic data
- Injection of 15,000 tons of supercritical CO₂/CH₄ gas mixture into the saline aquifer (Paaratte Formation) located at 1.5 km depth
- Acquisition of two monitor seismic surveys during the injection and one survey at the completion of the injection to detect the injection and observe the plume evolution
- Acquisition of two additional post-injection surveys (one and two years after commencement of the injection). This data is supposed to be used in conjunction with fluid flow simulations to demonstrate plume stabilization.

All but the last item was completed by April 2016.

In order to both evaluate seismic detectability limits and obtain sufficient quality of the image to resolve stabilization of the plume, significant effort has been expended to improve the quality of the TL seismic image. Other factors affecting the monitoring program design, effectiveness and completeness include usual land access issues and survey cost optimization.

The CO2CRC Otway site is located in an active cattle farming area in rural Victoria. As a result, we opted to use relatively small vibroseis trucks (Inova UNIVIB, Houston USA), leaving minimal impact on the ground when operated during the November to April time window (corresponding to summer in Australia), when the ground is dry and hard. From previous experience, we also knew that the presence of seismic cables on the surface during seismic acquisition is incompatible with farming activities. The buried receiver array shortened the mobilization period, and working with the local farmers we staged the source effort to minimize the impacts of the frequent repeat surveys.

As a result, the seismic monitoring program is based on the 4D surface seismic acquired using the buried receiver array concurrently with 4D VSP. These two methods provide superior image quality in combination with minimal operational disruptions to the landowners. Similar to Stage 1, zero-offset and offset VSP is used to evaluate the performance of a less expensive monitoring technique.

2.1. Buried receiver array design and deployment

Key parameters of the buried receiver array are provided below [18]:

- Eleven receiver lines are instrumented with seismic sensors (Figure 1). Distance between the lines is ~100 m, receiver spacing along the line is 15 m. Due to the differences in the line lengths, each line has 60-95 geophones with the total of 908 geophones deployed.
- High-sensitivity Sercel SG-5 geophones in marsh-line casings are deployed in PVC cased wells at the depth of 4 m. Each geophone is connected to an individual field data recording unit.
- The recording units and all of the cables are deployed in 0.8 m deep trenches.
- The permanent seismic system is built on the Sercel 428 XL platform (Sercel, Nantes, France). Each receiver line contains one cross-line unit located roughly in the middle of the line to distribute power to the individual field recording units and transmit the data to a central recording facility located near the CRC-2 well. Cross-line units themselves are connected by both power and data cables to the recording facility; with the cables housed in the backbone trench. The central recording facility is designed such that the whole system can be controlled remotely to allow unmanned operation for passive seismic experiments with seismic records having GPS time stamps.

In addition to high sensitivity geophones, we also deployed optical fiber cables to every receiver line trench to permit DAS recording [19]. A total of ~38 km of optical fiber was connected to two iDAS interrogators manufactured by Silixa. The buried receiver array and DAS network was installed at the Otway site in February 2015.

2.2. Acquisition of the baseline and monitor surveys

2.2.1. Surface seismic and 3D VSP

Baseline data was acquired in March 2015, immediately following the deployment of the receiver array. The injection commenced in December 2015, so three monitor surveys occurred between January and April 2016, after injection of 5000, 10000 and 15000 tonnes (we denote them as M1, M2 and M3, respectively).

Acquisition parameters remained constant for the three surveys. We used 3003 source points (in the baseline survey) grouped into 27 lines (Figure 1), with source line spacing varying from 50 m to 100 m. Denser source coverage on the North-East was used to partially compensate for the presence of large inaccessible areas. Source spacing along the line was 15 m. To acquire the data, we used single 24 s 6-150 Hz sweeps with 0.5 s cosine tapers and 5 s listen time on every shot point. Two Inova 26,000 lbs vibroseis units were operating in flip-flop mode to speed up the acquisition.

During the monitor surveys ~0.5% of the source points acquired in the baseline survey were inaccessible due to surface obstructions or soft ground conditions.

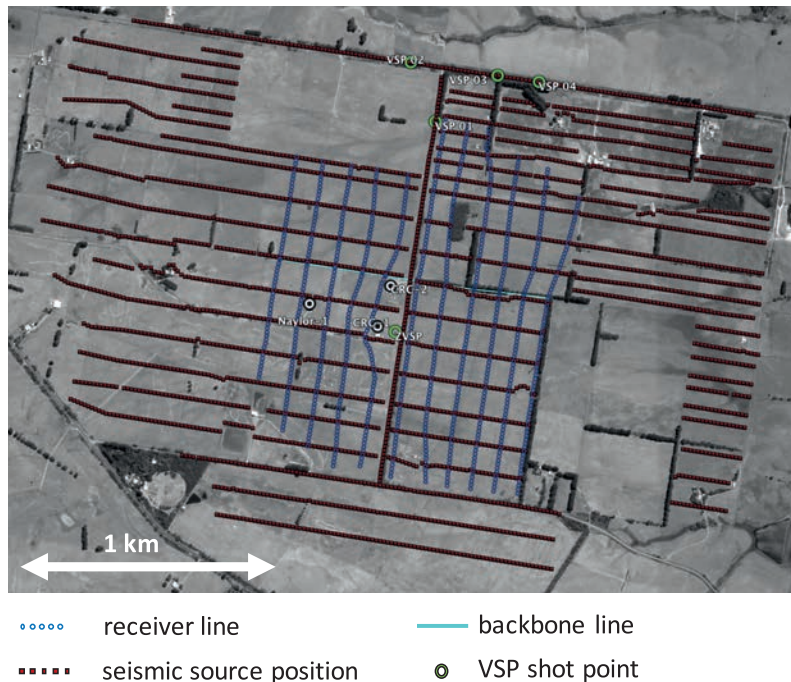


Fig. 1. CO2CRC Stage 2C experiment location scheme.

It took 10 days of acquisition time to conduct the baseline survey. Monitors 1 and 2 were completed in 7 days each and the post-injection survey took 6 days to complete. It was important to shorten the monitor surveys as all seismic operations and injection needed to be complete within the dry season.

3D VSP data was acquired concurrently with the surface data. To do this, a 10 level 3C geophone string with 15 m spacing between the shuttles was deployed in the CRC-1 well at the depth interval of 760 – 895 m. In addition, optical fiber in CRC-2 well was also used for DAS acquisition concurrently with the 2D DAS surface array).

Due to technical issues with the downhole equipment during the first monitor survey, 3D VSP acquired with 3C geophones recorded only ~30% of the total source effort. The other two monitor surveys have complete 3D VSP source coverage.

2.2.2. Zero-offset and offset VSP

Zero offset and four offset source positions were used to acquire VSP data using 3C geophones in CRC-1 and DAS in CRC-2 wells. The receiver interval in CRC-1 was set to 15 m. Receiver range was varied between 180-1800 m and 630-1800 m for different vintages. For every receiver station, three to four sweeps were recorded, excluding noisy records.

Total acquisition time for zero-offset and offset VSP was 2 days for the baseline survey and 1 day for the three monitor surveys (excluding the time to rig down the tool).

2.3. Continuous monitoring

In order to conduct continuous monitoring of the CO₂/CH₄ gas injection, we employed both passive and active seismic monitoring. Active seismic monitoring was performed using a combination of two permanently deployed SOVs designed by LBNL and DAS/geophone arrays. The location of the SOVs near Naylor-1 and CRC-2 wells was chosen based on forward modeling of the plume illumination. SOVs were in operation for 120 days covering the time frame from September 2015 to June 2016 with some gaps. Preliminary results of the continuous monitoring are promising [20, 21].

3. Fast-track data 4D seismic data processing and analysis

The amount and diversity of data acquired during the experiment is significant. The field operations on the third monitor survey finished only a few months ago, so in this paper we focus only on fast track results arising from the analysis of the active 4D seismic data acquired using the buried geophone array.

3.1. Effect of burying geophones on the ambient noise level

The main objective of the installation of the geophone array at a depth of 4 m was to drastically reduce the ambient noise level. So it was prudent to verify if we were able to achieve that goal. In order to do this, we installed six surface geophones above buried geophones. Geophones of the same type SG-5 as used in the wells were connected to wireless Sercel Unit RAU-eX3 recorders, which allowed us to conduct direct comparison to the data acquired with FDU-428.

Figure 2 shows the comparison of a single common receiver gather obtained using buried and surface geophones and the source line oriented in a north-south direction in Figure 1. It is quite obvious that the ambient noise level is significantly lower on the buried geophone data.

The ambient noise level obtained from uncorrelated geophone data as a function of frequency is presented in Figure 3. Within the sweep frequency range, we see a noise reduction by 10-50 dB, with most of the useful frequency range exhibiting a noise floor decrease of 20-30 dB. This matches with our previous experiments conducted in 2012. Very low frequencies do not show any change in the ambient noise level because they are mainly contaminated by the surface waves, which do not decay at 4 m depth, while higher frequencies are mainly affected by wind noise.

3.2. Fast track processing of 4D seismic data

We applied the same processing flow to all 4 datasets; parameters of the flow are presented in Table 1. This is a variation of the processing flow designed for Stage 1 4D seismic data acquired in 2007-2010. Despite not being a

true amplitude processing at this stage, it would still allow us to produce a high quality image in a short time. The processing flow was verified on the 4D FDTD synthetic dataset in order to ensure that we do not damage the TL signal or introduce misleading artifacts [15]. We also use surface consistent static corrections computed for one vintage and applied the correction to all four surveys.

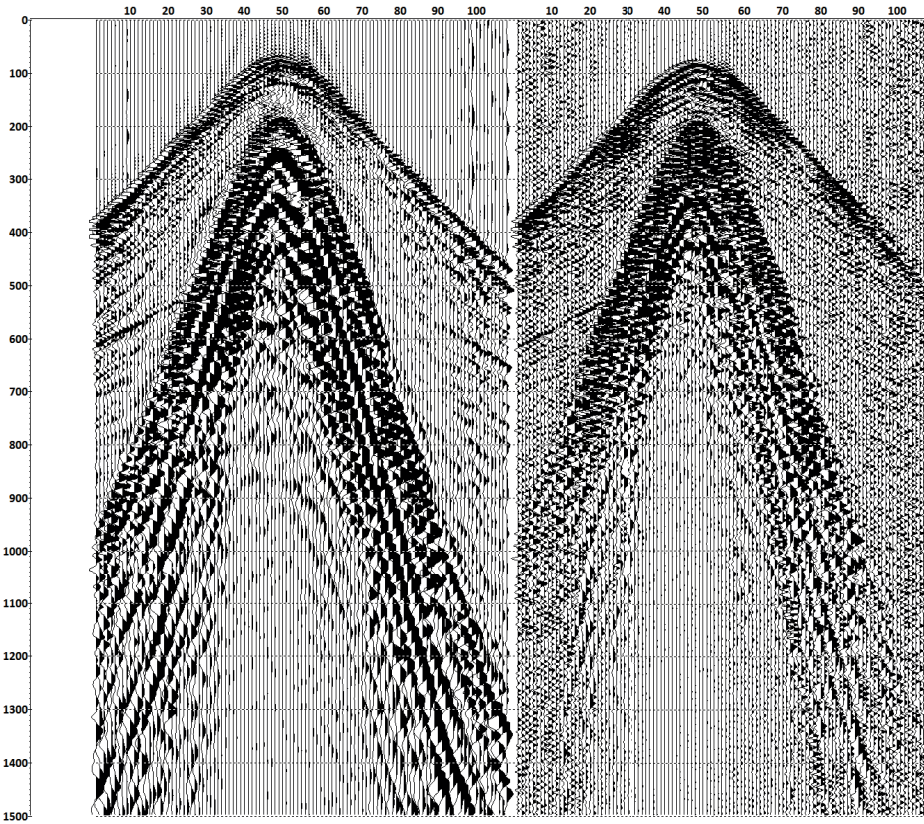


Fig. 2. Comparison of buried (left) and surface (right) geophone data

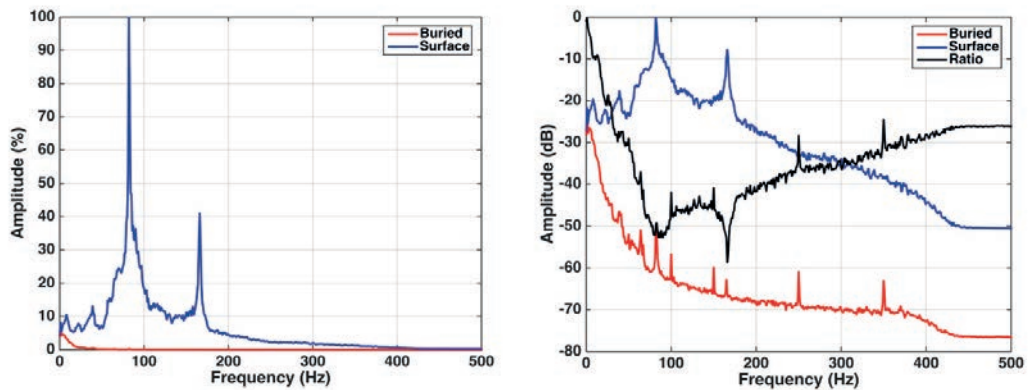


Fig. 3. Comparison of ambient noise level on buried and surface geophone data in linear (left) and logarithmic (right) scales

The work on the final true amplitude time-lapse processing flow requires good control on surface amplitude corrections, which honor temporal variations on the near surface conditions. Our ongoing analysis will rely upon joint surface and time-lapse VSP data analysis to constrain surface amplitude corrections.

Table 1. Processing flow chart.

Procedure	Parameters
Data Input	SEG-D data input
Correlation with sweep signal	Linear sweep 6-150 Hz, length of sweep 24 s, output trace length 5 s
Geometry assignment	Applied from field acquisition reports and GPS processed coordinate files
Binning	Bin size 7.5 m x 7.5 m
Trace Editing	Kill bad traces/seismograms
Radon Renumeration	New headers were calculated with respect to binning grid orientation
Radon Filtering	Number of P-values – 700, modelled noise subtraction, applied in cone window
Automatic Gain Control	500 ms, applied before radon filter and removed after
Statics	500 ms shift, applied before radon filter and removed after
Elevation Statics	Final datum elevation – 30 m (MSL), Replacement Velocity – 1800 m/s
Surface Wave Noise Attenuation	900 m/s, 6-35 Hz
Automatic Gain Control	500 ms, applied before deconvolution and removed after
Spiking Deconvolution	Zero-phase spiking, Operator length – 200 ms, ‘white noise’ level – 0.1 %, applied in gates
Air Blast Attenuation	Energy with velocity of 330 m/s was attenuated
Interactive Velocity Analysis	2 iterations, VA Grid – 100 m x 100 m 30% - NMO muting
Residual Static Correction	2 iterations, Max Power Autostatics
Automatic Gain Control and NMO	AGC window -500 ms, NMO muting – 30%
Bandpass Filter	Ormsby, zero-phase, 6-10-100-150 Hz
CDP stacking	Stacking method – Mean, Power scalar for stack normalization 0.5
Pad 3D Stack Volume	INLINES 1-219, XLINES 1- 266
FXY-deconvolution	Wiener Levinson filter, 7 inlines x 7 xlines, 4-180 Hz
FK Filter	Applied in polygon
Migration	Post-stack phase shift time migration

Processed 3D volumes corresponding to the baseline and three monitor surveys were cross-equalized using only post-migration static correlation base shifts computed using a 0-1100 ms time window. All monitor vintages were brought to the baseline. These volumes were used for derivation of the difference volumes.

The result of processing and cross-equalization is presented in Figure 4. Panels on this figure contain (left to right) the baseline data and difference volumes obtained for M1-M3 surveys.

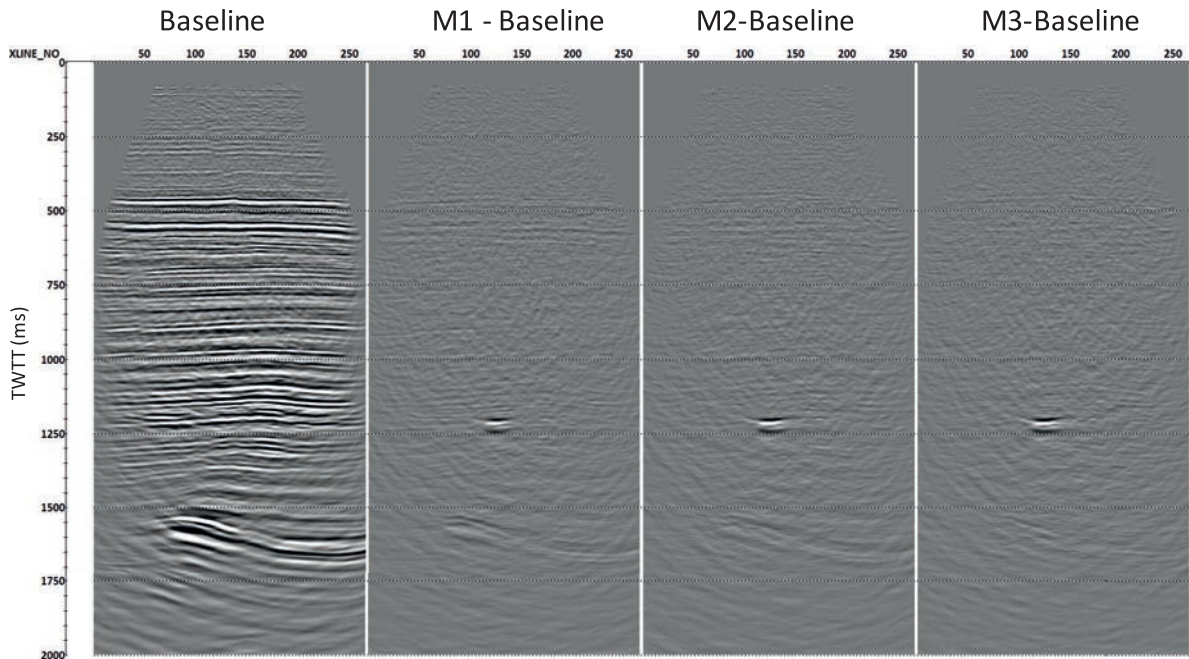


Fig. 4. Fast-tracked time-lapse processing results, an inline passing through the CRC-2, left to right: baseline data and three difference volumes corresponding to 5000, 10000 and 15000 tons of injection.

The time-lapse signal from the injection is clearly seen at the difference volumes at ~1200 ms (or ~1500 mMD at CRC-2 location). The location and the size of the anomaly broadly matches model predictions. We also see some lateral growth of the gas plume as the injection progresses from 5000 (M1) to 15000 (M3) tons.

It is important to notice that we do not see any other amplitude anomalies in the difference volumes comparable in magnitude. It hints that the level of time-lapse noise is very low. Figure 5 contains the NRMS [22] histogram computed for all difference volumes, revealing NRMS values predominantly below 0.2. This dataset can be regarded as “precision 4D seismic” as defined in [23].

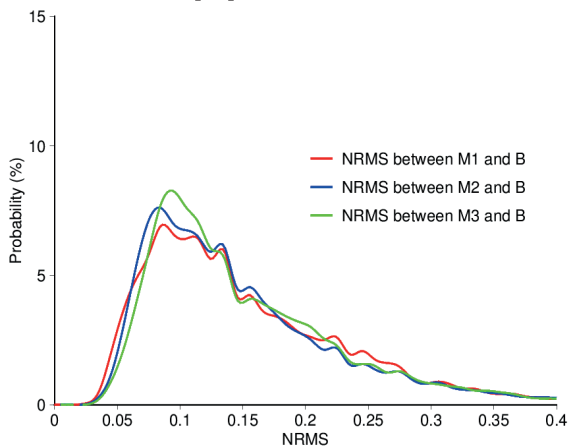


Fig. 5. NRMS histogram computed for 1135 ms time slice using 60 ms window.

Absence of the the strong amplitude anomalies outside (more specifically, above) the primary containment also means that we do not see any indications of vertical migration of the injected gas.

4. Discussion and conclusions

As a part of Stage 2C of the CO2CRC Otway project, 15,000 tons of the supercritical CO₂/CH₄ mixture were injected into the subsurface. In order to monitor the injection, an extensive seismic monitoring program was employed, which includes 4D seismic conducted using the permanently deployed receiver array, time-lapse borehole seismic, an areal DAS network and trial of continuous seismic monitoring.

The monitor 3D surveys were acquired during and immediately after concluding gas injection, January-April 2016. To date we conducted fast track data processing and analysis. While more detailed time-lapse processing and analysis is still ongoing, it is possible to conclude that the data quality is sufficient to claim seismic detection of as low as 5000 tons of CO₂/CH₄ injection and observation of the plume evolution.

By using the buried high sensitivity geophone array we achieved better signal to noise ratio than achievable using a surface array, gaining 20-30 dB in ambient noise reduction and higher repeatability, with NRMS measure on average below 0.2.

Another benefit of using a permanent receiver array is lower impact on landowners. We spent less than a month to install the array and only 30 days of actual acquisition time for all four vintages of the TL 3D data. During the installation of the array, only a small portion of the area was affected at any time as the array was deployed on a landowner by landowner basis. Acquisition of data was also conducted by sequentially completing the source points located at the land parcels belonging to the different landowners with small vibroseis trucks and no cables lying in the paddocks.

Deploying geophones and electronic components underground, one the other hand, complicates access to them if maintenance would require. However, fixing minor localized faults is not excessively invasive as the electronic components are located relatively shallow.

Drastic reduction of acquisition time and minimal crew required to conduct the survey results in significant cost reduction of seismic monitoring. Further cost reduction can be achieved by using less expensive DAS-based receiver arrays and unmanned continuous monitoring (both active and passive).

Our future steps include thorough time-lapse processing of all of the data acquired during the experiment and integration of the results. The high quality of the data is likely to allow application of modern quantitative interpretation techniques to facilitate temporally and spatially estimating gas saturation in the plume. Seismic monitoring results will be used by the reservoir engineers involved in the project to perform history matching using dynamic models. By combining seismic monitoring results with the fluid flow modelling we plan to further investigate seismic detection thresholds for pure CO₂ in comparison to the lower density mixed gas we injected.

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