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Processing four-dimensional vertical seismic profiling in the CO2CRC Otway Stage 4 Project

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Abstract

Long-term containment assurance is critical for regulatory approval and public acceptance of geological carbon dioxide (CO₂) storage, placing strict requirements on the repeatability and robustness of time-lapse seismic monitoring over multi-year operational periods. Multi-well vertical seismic profiling (VSP) using distributed acoustic sensing (DAS) offers a compact, repeatable monitoring option; however, long-term deployments can be compromised by non-geological changes, such as altered surface optical routing, interrogator artifacts, or fiber integrity loss. The CO2CRC Otway Stage 4 Project provides a relevant test case because non-repeatable acquisition conditions occurred between the baseline and monitor surveys. This study presents the processing and initial evaluation of a four-dimensional (4D) VSP dataset acquired in February 2025, following the injection of approximately 10 kt of CO₂-rich gas into the Paaratte Formation (~1,500 m depth) via the CRC-3 injector. Processing was adapted from the previous Otway DAS-VSP monitoring workflow, with cross-vintage comparability improved through well-specific channel alignment, including correction for time-varying channel shifts. The workflow further included cross-equalization and Wiener matching to reduce residual source–signature differences and improve repeatability, wavefield separation, and in-house Kirchhoff migration. Time-lapse analysis of migrated volumes and root mean square difference attributes computed over the injection interval shows coherent anomalies at CRC-4 and CRC-5 that are geometrically consistent with the Stage 4 injection interval, although no usable 4D data were available from the injector well CRC-3. CRC-6 exhibits no coherent anomaly. An anomaly near CRC-7 is spatially separated from the injector and is likely due to the continued evolution of CO₂ plumes from previous Otway injections. These results demonstrate that multi-well 4D DAS-VSP can provide robust qualitative detection and delineation of plume-related seismic anomalies under substantial acquisition non-repeatability, strengthening conformance monitoring workflows for long-term CO₂ storage.

Keywords: Four-dimensional vertical seismic profiling; Distributed acoustic sensing; Carbon dioxide storage

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1. Introduction

Climate change remains one of the key global challenges requiring integrated solutions in the energy and industrial sectors. The latest international assessments identify carbon capture and storage as a necessary component of large-scale decarbonization pathways for achieving net-zero emissions.^{1,2} Deep saline aquifers offer the largest theoretical storage capacity among geological options; however, demonstration of long-term containment is required to secure regulatory approval and public acceptance.³ Therefore, effective carbon dioxide (CO₂) injection monitoring is essential for tracking plume evolution and detecting potential leakage.

Time-lapse (four-dimensional [4D]) seismic imaging is widely regarded as an effective tool for detailed characterization of the CO₂ plume evolution and containment.⁴ Time-lapse seismic has been successfully used in numerous saline aquifer storage projects, demonstrating the ability of repeated seismic surveys to track plume dynamics. Vertical seismic profiling (VSP) with fiber-optic distributed acoustic sensing (DAS) enables frequent and repeatable seismic monitoring around wells, providing a robust approach for CO₂ storage applications.⁵⁻⁷ Using DAS in VSP surveys replaces discrete downhole geophones with a permanently installed optical fiber that is interrogated to measure axial strain or strain-rate along the well at meter-scale spacing, yielding densely sampled VSP gathers with a small operational footprint and excellent repeatability.^{8,9} Compared with surface 4D seismic, DAS-VSP offers receiver-side repeatability because the permanently installed fiber remains fixed in the borehole, and the downhole receiver geometry places measurements closer to the reservoir, supporting high-resolution imaging around the wells and reducing the operational footprint. In contrast, surface seismic provides broader areal coverage and is therefore advantageous for regional plume tracking, but it typically requires a larger acquisition footprint and is more exposed to survey-to-survey variations in near-surface and receiver conditions. Compared with repeated retrievable borehole-geophone deployments and large-footprint surface 4D seismic, DAS-VSP is a more cost-effective and less disruptive monitoring option that can be repeated without well intervention and has been demonstrated in walkaway and three-dimensional (3D) VSP acquisition geometries.

The CO₂CRC Otway International Test Centre (OITC) in Victoria, Australia, offers a unique testbed for exploring and improving carbon capture and storage monitoring methods.¹⁰ OITC has been used for a series of CO₂ injection and monitoring experiments to observe plume movement. The studied interval at OITC is part of the Late

Cretaceous Paaratte Formation of the Sherbrook Group in the onshore Otway Basin. At the site, the interval of interest lies at approximately 1,500 m depth and comprises sandstone, siltstone, and mudstone, including cemented and carbonate-cemented intervals. The two studied parasequences are interpreted as coastal-to-shallow-marine deposits and comprise delta-front, distal mouthbar, proximal mouthbar, and distributary-channel facies.¹¹ Exploring CO₂ storage in the Paaratte Formation began in the Stage 2C Otway Project with the injection of 15 kt of CO₂-rich gas (a mixture of supercritical 80 mol% CO₂ and 20 mol% methane, produced from the nearby Buttress gas field) through the CRC-2 well. This injection was monitored using 4D surface seismic with a buried geophone array and conventional surface seismic sources.^{12,13} During the next experiment, the Otway Stage 3 Project, 4D surface seismic was replaced with multi-well 4D DAS-VSP surveys, which were conducted before and after 12.5 kt (out of a total of 15 kt) of CO₂-rich gas was injected via CRC-3 well, resulting in high-quality time-lapse seismic datasets.¹⁴ The current experiment, the Otway Stage 4 Project, includes 10 kt of CO₂-rich gas injected 50 m above the Stage 3 interval from November 2024 to January 2025 using the same CRC-3 well, followed by a multi-well 4D DAS-VSP survey acquired in February 2025.

Stage 3 results demonstrated high-quality imaging and repeatability of multi-well 4D DAS-VSP for monitoring CO₂ migration in the Paaratte Formation. However, long-term deployment introduces practical challenges that can directly affect time-lapse consistency, and Stage 4 differs from Stage 3 in both the injection interval and acquisition conditions. In particular, changes in surface optical routing, interrogator behavior, and fiber integrity can compromise baseline-monitor comparability and must be accounted for prior to time-lapse analysis. This study presents the processing and initial evaluation of the Stage 4 time-lapse dataset relative to the Stage 3 baseline. The objectives are to determine whether reliable time-lapse response can be recovered under non-equivalent DAS channel-depth mapping and acquisition artifacts between vintages, and to characterize the geometry and extent of the Stage 4 seismic anomaly associated with the shallower injection interval. This supports long-term containment and conformance monitoring at the OITC.

2. Methodology

2.1. Data acquisition

As part of the Stage 4 monitoring and verification program, a time-lapse 3D VSP monitor dataset was acquired. Under the Otway project's established time-lapse survey identifiers that distinguish individual acquisition vintages across

multiple injection projects, this monitor survey is called M9. In Stage 2C, the program comprised a baseline survey and monitor surveys M1, M2, and M3 acquired during the injection, followed by post-injection monitor surveys M4 and M5.¹⁵ In Stage 3, the 4D VSP program included M6, M7, and M8 surveys acquired during injection.⁸ M8 also serves as a baseline for Stage 4, while M9 is the monitor. Figure 1 illustrates the M9 survey acquisition layout, along with interpreted CO₂ plume contours from previous stages.

The survey was acquired after the injection of approximately 10 kt of CO₂-rich gas into a saline aquifer via the near-vertical injection well CRC-3 into the Paaratte Formation at approximately 1,500 m depth (approximately 50 m shallower than in the Stage 3 injection).

The plan for the M9 survey was to use 4,185 point locations to match the M8 survey from Stage 3, which served as the baseline survey for Stage 4. In total, 4,044 shot points were acquired, as some planned source shot points had to be skipped during the survey due to the

presence of certain farming crops or inaccessibility. The survey employed two 26,000-lb INOVA UniVib vibrators. Each shot used a single 24 s linear sweep from 6 to 150 Hz at 70% of the vibrator's rated maximum force of 26,000 lbf (115 kN). The sweep was tapered with 0.5-s cosine ramps and followed by a 3-s listen time. Shot points were spaced at 15 m along source lines separated by approximately 100 m, replicating the M8 Stage 3 acquisition geometry.

The 4D VSP dataset was acquired using six wells instrumented with fiber-optic DAS arrays: CRC-3, CRC-4, CRC-5, CRC-6, CRC-7, and CRC-8. Data acquisition used a DAS system connected to optical fibers installed in the wells. The full DAS system configuration is summarized in Table 1. Multiple interrogators were deployed during the survey; however, this study focuses on data from the Silixa iDAS-v3 Carina units, as baseline data (M8) are only available for these instruments.

The processed data were recorded on individual fiber-optic receiver arrays in each well, comprising the

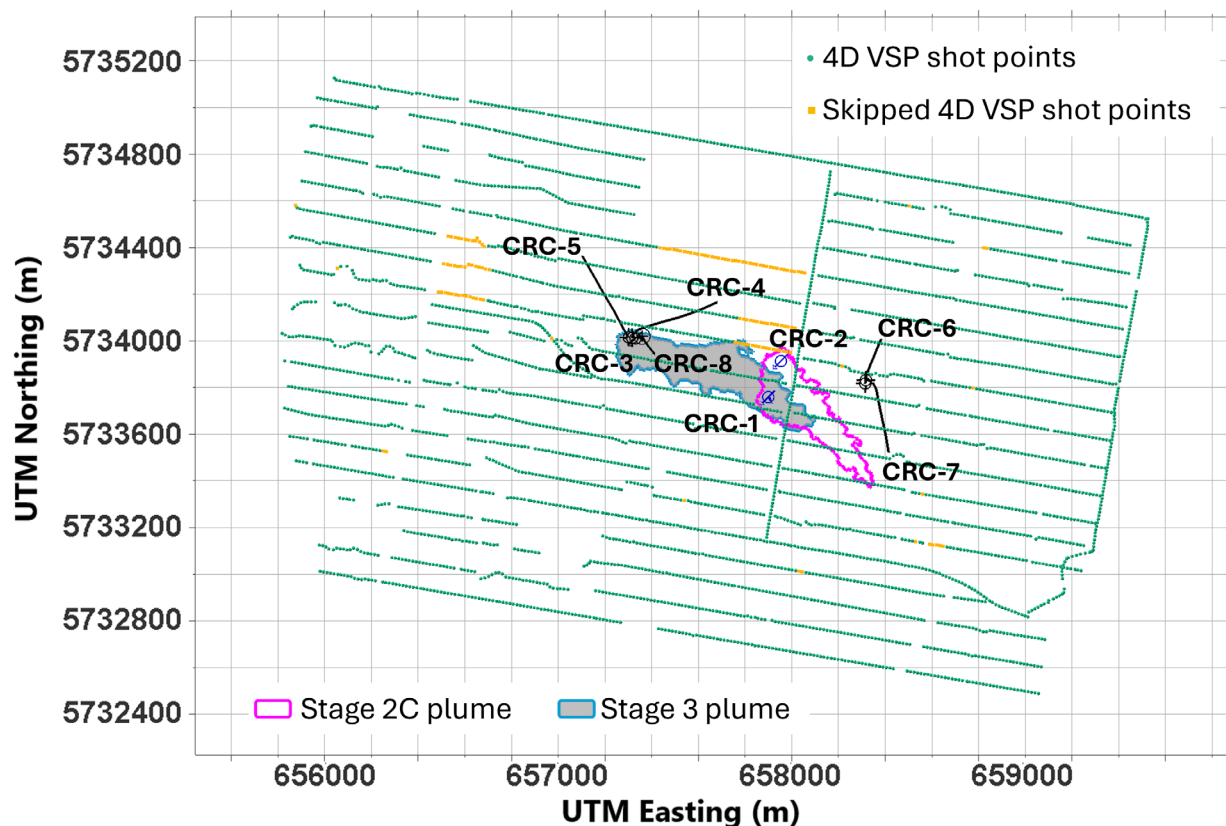


Figure 1. Acquisition geometry for the Stage 4 time-lapse 3D VSP (M9 Seismic Survey) at the Otway site, showing the surface projections of the well locations (black solid lines), 4D VSP shot points (green circles), and skipped shot points (orange squares), as well as previously interpreted extents of the Stage 2C (magenta line) and Stage 3 (blue line, grey filled area) CO₂ plume in the Paaratte Formation.

Abbreviations: 3D: Three-dimensional; 4D: Four-dimensional; CO₂: Carbon dioxide; UTM: Universal Transverse Mercator; VSP: Vertical seismic profiling.

engineered constellation fiber (CF) (Silixa Ltd, United Kingdom) with enhanced backscattering. All downhole fiber sections used in this 4D VSP study were permanently installed behind casing and cemented in the wells. The unit iDAS-v3 P06 was connected to a single-mode fiber (SMF) on the cable in the CRC-4 well, spliced to the CF core at the bottom of the CRC-4 well, and then to the CF core on the cable cemented in the CRC-3 well. The iDAS-v3 P08 unit was connected to four fiber sections: an SMF section, followed by a CF section in the CRC-7 well, and then a CF and an SMF section in the CRC-6 well. The iDAS-v3 P22 unit was connected to SMF and CF sections in the CRC-5 well, followed by a horizontal section of a Silixa-branded helically wound cable buried in a shallow trench. The total fibre length per unit was less than 6 km. As in M8, the acquisition was done with a 10 m gauge length, a 5 m pulse length, a 16 kHz pulse repetition frequency, and 1 m channel spacing. All recording systems were synchronized and triggered via radio links through the Sercel 428 system (Sercel, United States) installed on-site. Data from DAS interrogators were continuously acquired, and shot gathers were extracted from the global positioning system time on the Sercel 428 system, which was used to launch the signal excitation.

2.2. Rerouting of surface cables

Between Stage 3 and Stage 4 projects (i.e., between the M8 and M9 surveys), all fiber-optic surface cables from the wells to the acquisition cabin were rerouted, resulting in a different optical path compared with the Stage 3 layout. This rerouting affected the mapping between DAS channels and

physical locations along the wells. In addition, the P06 unit experienced a recording issue that manifested as a random temporal channel shift during acquisition. Figure 2 shows the root mean square (RMS) amplitudes for the M8 and M9 surveys recorded by the iDAS-v3 units; the red arrows mark the beginning of the fiber after the interrogators in M8.

To restore consistency and enable a valid comparison of the datasets, a uniform shift was applied to each channel within each well (for iDAS-v3 P06, this was combined with a temporal shift correction). The shift values differed between wells and were determined by manually aligning recognizable features between the M8 and M9 surveys. To align M9 with M8, 1–16 channels were subtracted from the M9 channel numbers, depending on the well. The random temporal shift observed in the P06 interrogator was corrected by adding approximately 25 channels.

2.3. Constellation fiber damage in CRC-3

During the reperforation of CRC-3, the CF cable was damaged. The inflowing fluid caused fiber degradation, rendering it practically unusable for seismic monitoring. Figure 3 illustrates a comparison of 4D VSP data acquired during M8 and M9 surveys in CRC-3 and CRC-4. CRC-4 fiber data showed consistent data quality across the time axis; in contrast, CRC-3 data showed a broad band of channels losing integrity, as evidenced by noisy, incoherent traces across a range of channel numbers. Although the first arrival remained visible in the affected interval, the increased noise floor prevents identification of weaker coherent events. Consequently, CRC-3 CF data from M9

Table 1. List of distributed acoustic sensing interrogators and system configuration

Interrogator	Vendor	Connected Well 1	Connected Well 2	Connected Well 3
iDAS-MG	Silixa	CRC-8 (SMF↓↑)	-	-
iDAS-v3 P06	Silixa	CRC-4 (SMF↓ CF↑)	CRC-3 (CF↓)	-
iDAS-v3 P22	Silixa	CRC-5 (SMF↓ CF↑)	HWC (CF)	-
iDAS-v3 P08	Silixa	CRC-7 (SMF↓ CF↑)	CRC-6 (CF↓ SMF↑)	-
OptoDAS	ASN	CRC-8 (SMF↓↑)	CRC-4 (SMF↓↑)	CRC-3 (SMF↓↑)
Treble+	Terra15	CRC-8 (SMF↓)	-	-

Note: Arrows indicate the downgoing and upgoing segments of the borehole optical path.

Abbreviations: CF: Constellation fiber; DAS: Distributed acoustic sensing; HWC: Helically wound cable; SMF: Single-mode fiber.

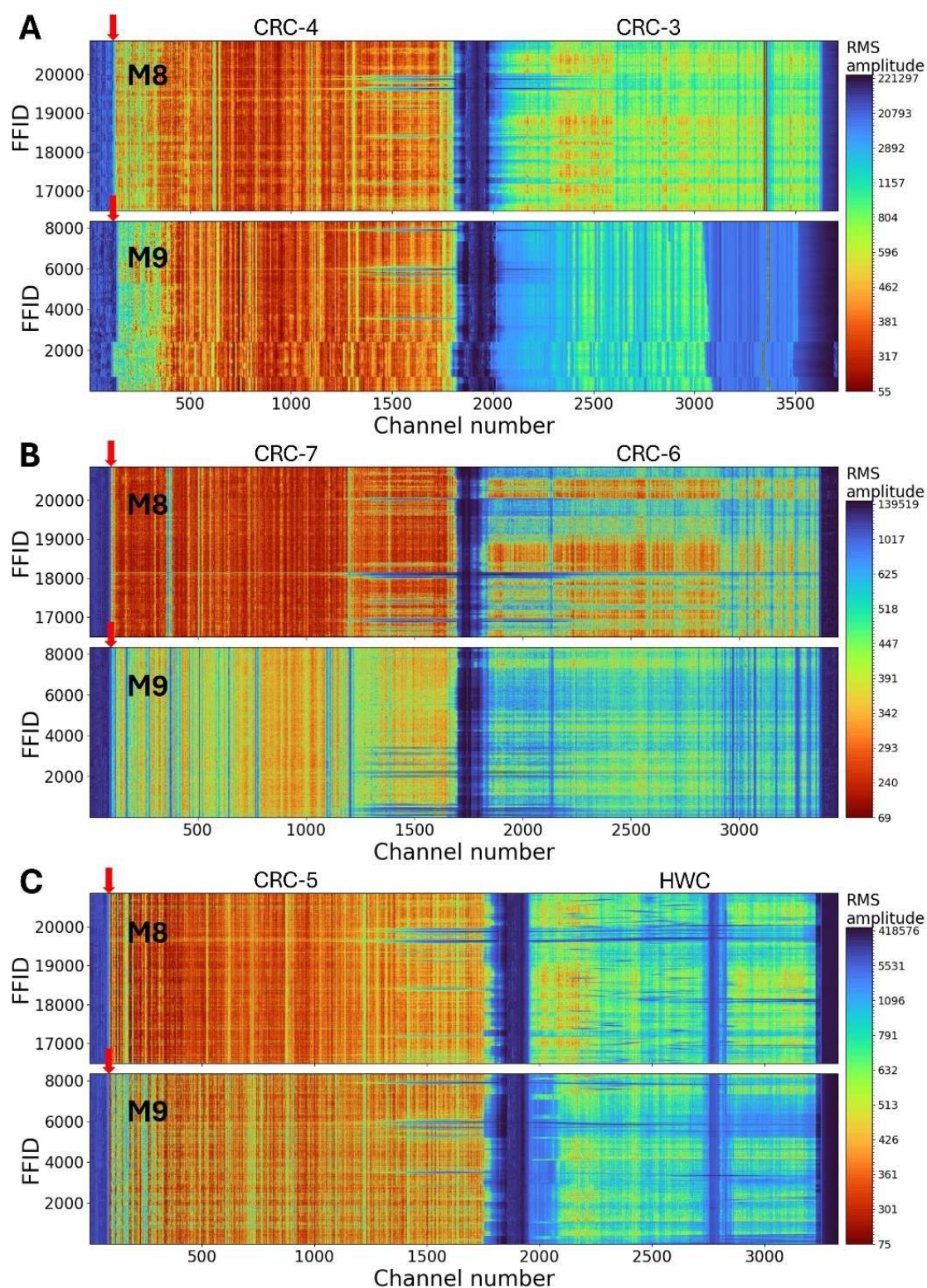


Figure 2. Root mean square (RMS) amplitudes of the Silixa iDAS-v3 Carina units. The red arrows indicate the beginning of the fiber after the interrogators on M8. (A) iDAS-v3 P06. (B) iDAS-v3 P08. (C) iDAS-v3 P22.

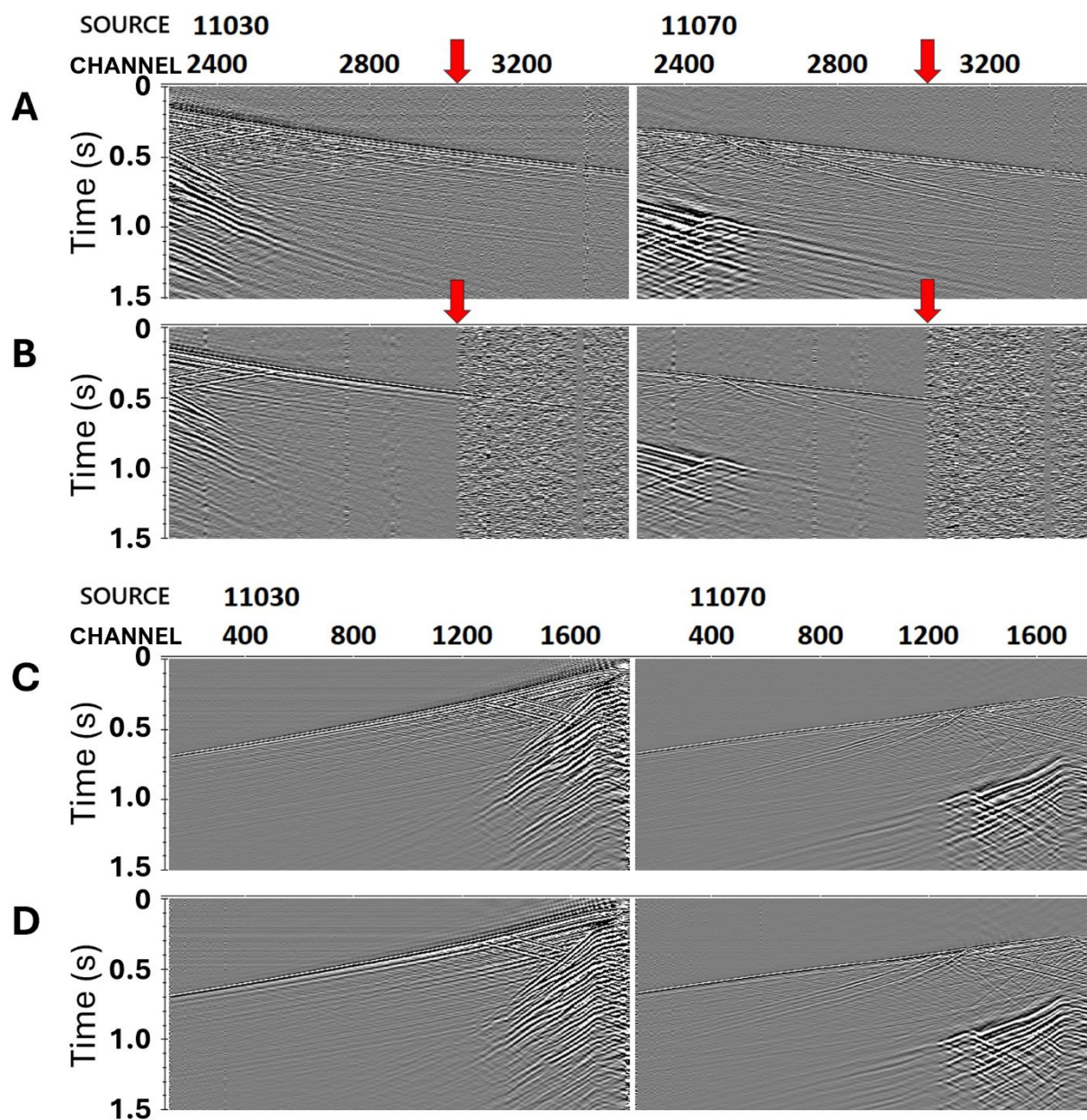


Figure 3. Four-dimensional (4D) vertical seismic profiling (VSP) data from survey vintages M8 and M9 in wells CRC-3 and CRC-4. Panels show CRC-3: (A) M8, (B) M9; CRC-4: (C) M8, (D) M9. Red arrows mark the fiber section in CRC-3 damaged by inflowing fluid, which caused progressive darkening along the fiber path and loss of signal over the affected channel range in M9. The first arrival remains visible in this interval; however, the increased noise floor prevents identification of weaker coherent events. In CRC-4, consistent data quality and comparable numbers of functional channels are observed across survey vintages. The first 1.5 s of the 3 s records are displayed.

were not used in the 4D VSP analysis.

2.4. Data processing

Time-lapse processing for Stage 4 was adapted from the DAS-VSP workflow established for Stage 3 (Figure 4), with M8 used as the baseline and M9 as the monitor survey. Each

well was treated as an independent dataset throughout the processing sequence.

Field data were acquired in the native iDAS-v3 technical data management streaming format and subsequently converted to SEG-Y. Shot locations were taken from the differential global positioning system measurements.

Along each well, DAS channel depths were tied to known cable markers, and noisy or dead channels were removed. For Stage 3 vintages, traces were stacked in 5 m depth intervals and then correlated with the source sweep. For the Stage 4 M8–M9 pair, the order was reversed: correlation with the pilot sweep was performed first, followed by channel alignment and then stacking in 5 m depth bins. This change of order was required because rerouting the surface cable between M8 and M9 (and the iDAS-v3 P06 interrogator recording issue) altered the channel-depth mapping, necessitating well-specific channel shifts to restore consistent geometry. Channel alignment, therefore, was performed on the correlated data at native channel sampling before 5 m stacking, to ensure each depth bin represented the same physical interval in M8 and M9, rather than combining misaligned depths. Both M8 and M9 were processed using this same revised workflow before time-lapse comparison. Therefore, the modified order does not introduce a vintage-dependent processing inconsistency, but instead ensures that corresponding depth bins represent the same physical interval in both surveys. The resulting M9 seismic fold at the level of the Paaratte Formation, summed over all wells, is shown in Figure 5.

After cross-equalization of the survey geometries, a two-dimensional spatial filter using a single-sample operator was applied to each shot gather across all traces to suppress coherent stripe-type noise attributed to DAS interrogator artifacts, followed by deterministic deconvolution. Direct-wave arrivals were flattened and stacked for each shot using traces recorded below 1,000 m depth to estimate the source wavelet. For a given shot position, wavelets derived from the contributing wells were averaged and scaled to a unit RMS amplitude.

The deconvolved data were then band-pass filtered with Ormsby operators (0–40–80–160 Hz and 5–10–90–180 Hz) to suppress the low-frequency ground roll and high-frequency noise. To further improve repeatability between vintages and reduce residual differences in the source signature, monitor (M9) datasets were subjected to Wiener matching filters. For each shot, direct P-wave segments were extracted from depths below 800 m within a window from –50 ms to 350 ms relative to the picked first break in every well. Traces without reliable first-break picks were excluded. The remaining traces were aligned on the first-break time and combined using a 30% trimmed mean to obtain representative baseline and monitor wavelets. This alpha-trim was used to preserve the coherent first-break wavelet while reducing contamination from outliers and residual upgoing-wave energy. A 150 ms Wiener filter was then designed for each shot by minimizing the

RMS misfit between the baseline wavelet and the filtered monitor wavelet and was applied by convolution to the full deconvolved monitor shot record. The filter length was chosen to capture most of the filter energy, with longer filters producing no meaningful change in the output. An example of M8 and M9 shot gathers after deconvolution, together with their time-lapse differences before and after Wiener matching, is shown in Figure 6A–D. The corresponding 60-ms window normalized RMS sections in Figure 6E and 6F demonstrate the reduction in non-repeatable energy achieved by this step.

Wavefield separation was carried out in the frequency–wavenumber (F–K) domain. In the first pass, an F–K filter was applied to attenuate downgoing energy. A second F–K operation, applied after flattening the upgoing P-wave to P-wave reflections, suppressed residual upgoing P-wave to S-wave and S-waves. Geometric spreading was approximated by multiplying the data by t^2 . Because the remaining S-wave energy was difficult to remove without damaging the target signal, data below the direct S-arrival were muted.

Before imaging, model-based static corrections were introduced. For each shot, direct-wave travel times were calculated using the one-dimensional isotropic velocity model derived from the zero-offset VSP in CRC-3. The misfit between these theoretical travel times and the picked first breaks was evaluated over depths below 1,400 m. Model-based statistics were then estimated independently for each vintage by taking the 33% trimmed mean of the misfit distribution for each shot and applying the resulting shift to the corresponding dataset. This procedure reduced systematic timing discrepancies between wells and vintages.

Imaging employed an in-house Kirchhoff migration based on the formulation of Dillon,¹⁶ adapted for DAS by applying a $\cos^2\theta$ weighting factor in the migration kernel, where θ is the angle between the receiver-side ray direction and the local fiber tangent at each DAS channel. This weighting accounts for the directional sensitivity of DAS receivers. The migration assumed straight-ray propagation and the actual well trajectories, with a central dip of 0° and an aperture of 15°. Data from each well were independently migrated onto a common 3D grid with a 7.5×7.5 m lateral bin size and a 1 m vertical sampling resolution.

3. Results

Time-lapse 3D DAS-VSP analysis of the M9 survey reveals coherent seismic anomalies associated with CO₂ injection within the Paaratte Formation. In a 3D VSP acquisition, shots were located at the surface, and the seismic wavefield was recorded on fiber-optic DAS arrays along the wells.

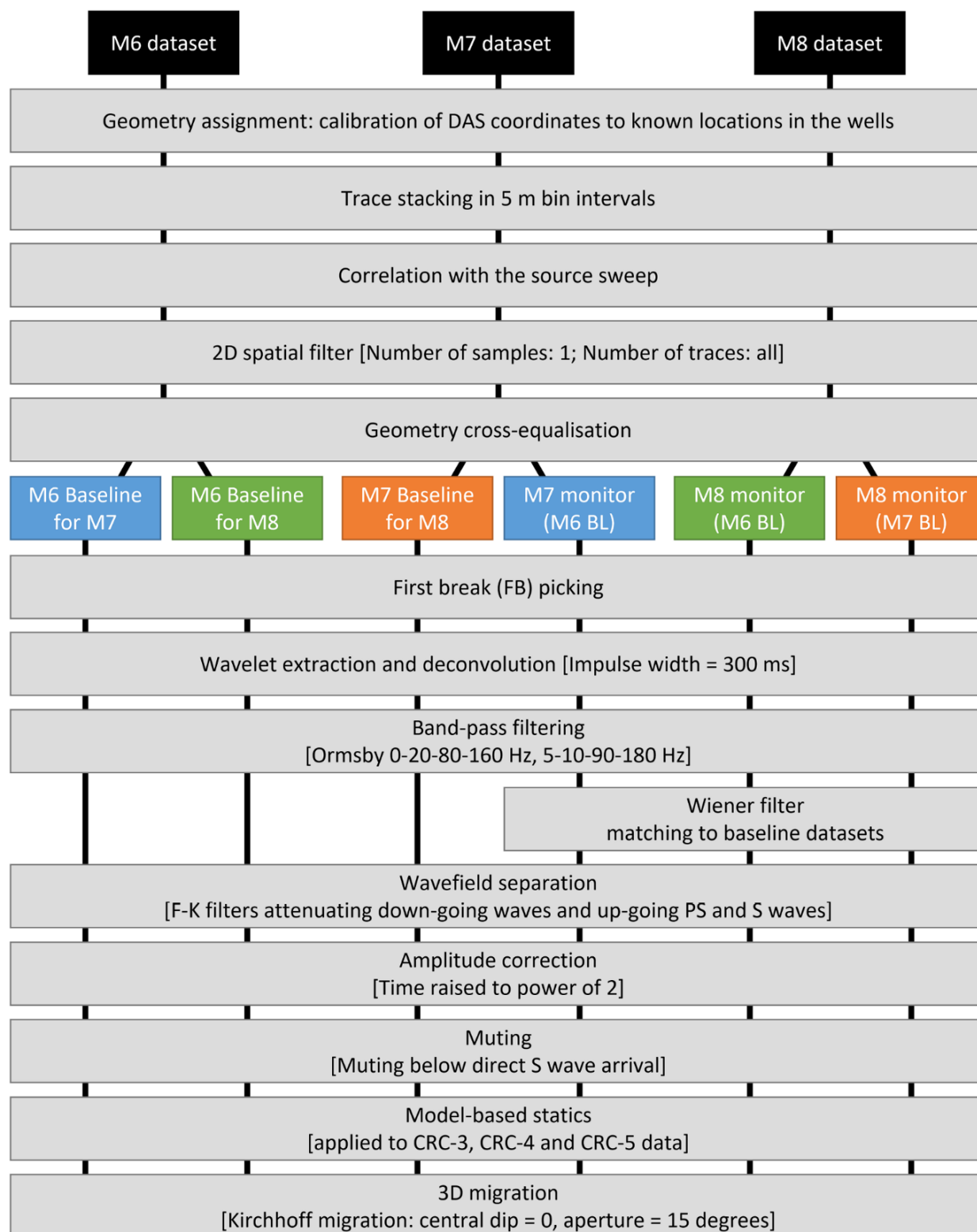


Figure 4. Processing workflow for Stage 3 DAS-VSP datasets. Reprinted with permission from Yurikov *et al.*⁸ Copyright © 2022 Elsevier Ltd. Abbreviations: 3D: Three-dimensional; DAS: Distributed acoustic sensing; F-K: Frequency-wavenumber; VSP: Vertical seismic profiling.

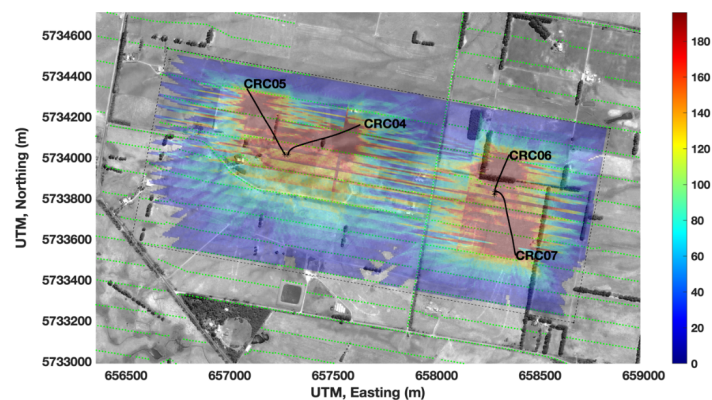


Figure 5. Seismic fold for the M9 survey computed for receiver spacing of 5 m and 7.5×7.5 m bin size, combined for all wells at the depth of Paaratte Formation

Abbreviation: UTM: Universal Transverse Mercator.

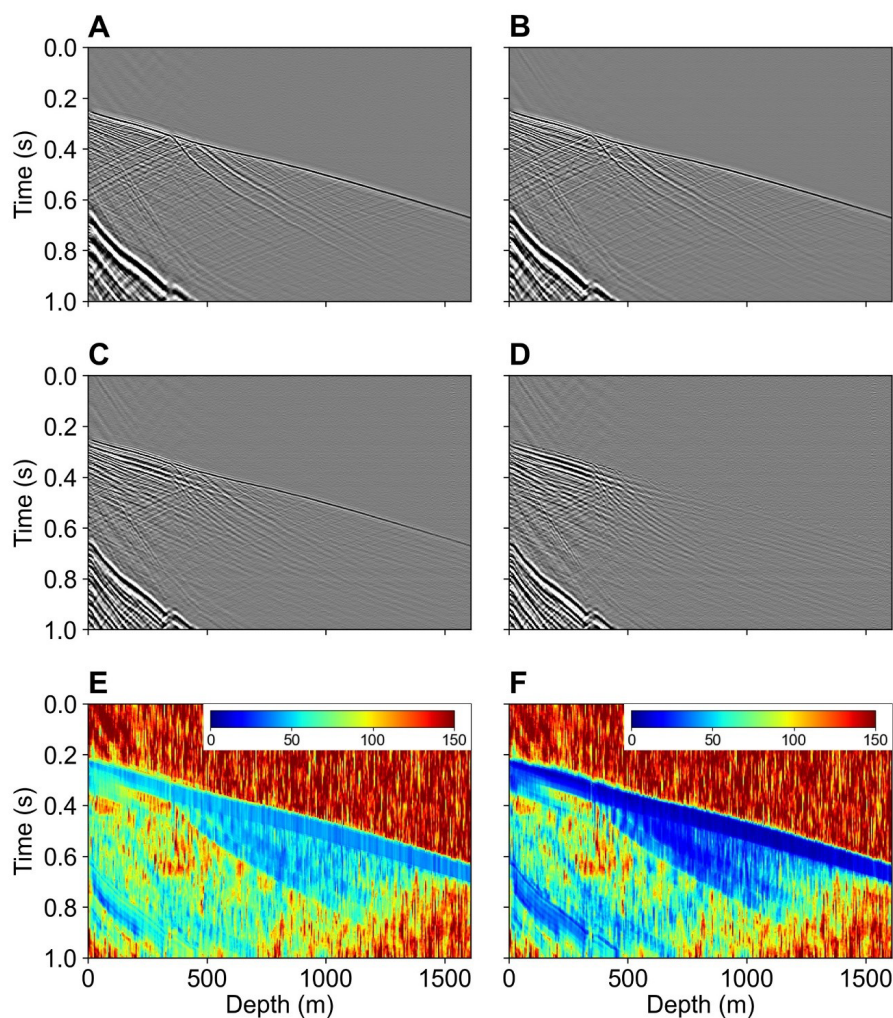


Figure 6. Example of (A) M8 and (B) M9 shot records after deconvolution from the same source location and receiver well, and their time-lapse difference (C) before and (D) after application of the Wiener matching filter. Panels (E) and (F) show the normalized root mean square (NRMS) (%) of the 60 ms window before and after Wiener filtering, respectively, demonstrating the reduction of non-repeatable noise and improved time-lapse repeatability along the primary reflection corridor.

Each well, therefore, provides an independent view of the subsurface that can be compared and correlated with images from the other wells.

Figure 7 presents a vertical cross-section through the migrated M9 3D DAS-VSP volumes for CRC-4, CRC-5, CRC-6 and CRC-7. The section displays continuous reflectors and high-quality seismic data at the depth of the Paaratte Formation, providing a suitable basis for identifying time-lapse amplitude anomalies at the Stage 4 injection interval.

Figure 8 illustrates the time-lapse difference (M9–M8) along the A–A' line intersecting the injector, extracted from the migrated volumes of M8 and M9, and highlights the seismic changes associated with CO₂ injection. Clear anomalies are visible at the depth of the Paaratte Formation near the CRC-4, CRC-5, and CRC-7 wells. Plan-view maps

of the maximum RMS difference (M9–M8) over 1,400–1,500 m true vertical depth subsea, shown in Figure 9, further clarify the lateral extent and spatial distribution of these changes.

CRC-4 and CRC-5 anomalies are associated with the Stage 4 CO₂ injection, whose outlines are overlain on the RMS difference maps shown in Figure 9. In CRC-4, CO₂ plume contours were delineated from the RMS difference volume by thresholding to retain only voxels with high values (> 99.9th percentile); the visible areal extent was then manually outlined. The threshold was used as a statistical detection criterion rather than as a direct petrophysical cutoff, with the aim of isolating the strongest spatially coherent time-lapse response above the residual non-repeatable background. In CRC-5, the CO₂ plume outline was visually interpreted from the RMS difference map view between M8 and M9, corresponding to the horizon

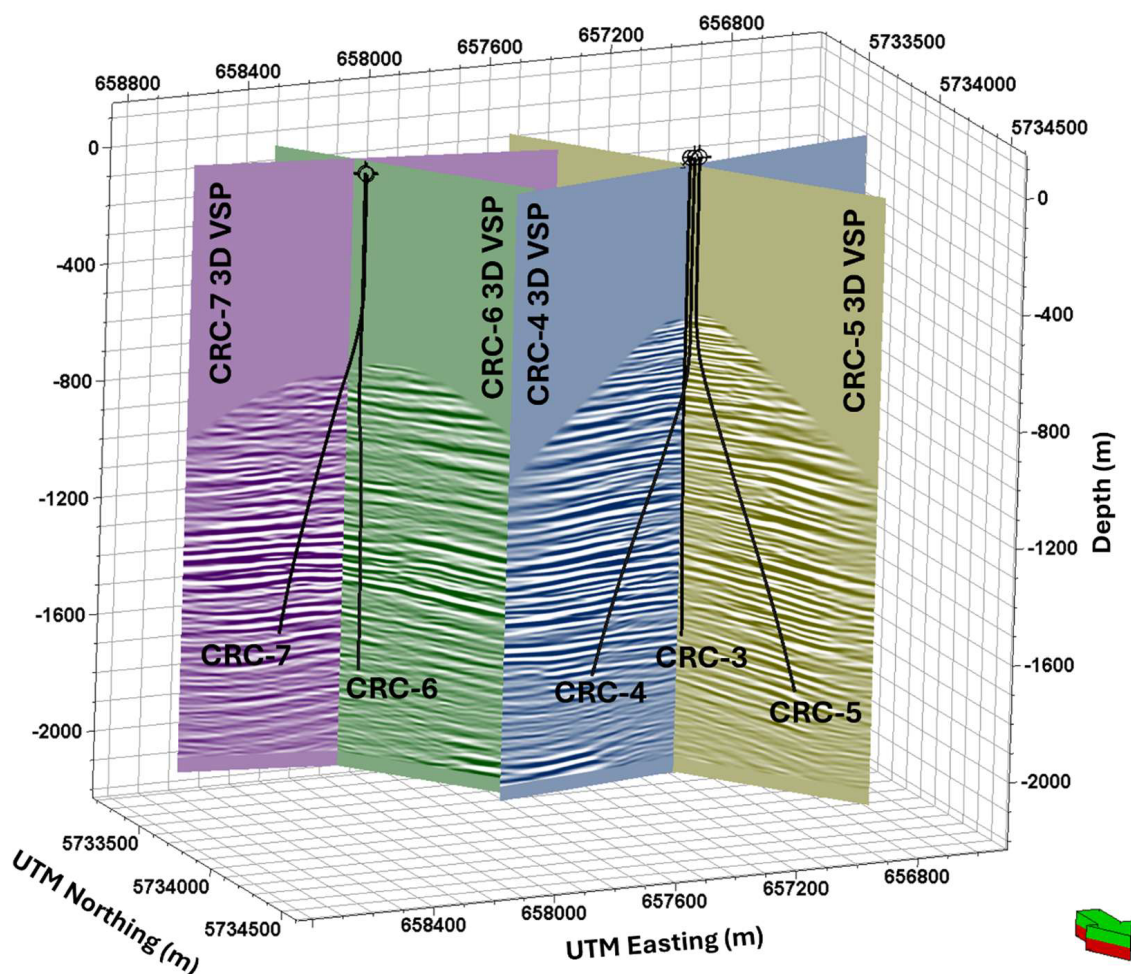


Figure 7. Cross-section of the migrated M9 3D DAS-VSP volumes from four wells: CRC-4 (blue), CRC-5 (yellow), CRC-6 (green), CRC-7 (purple). Abbreviations: 3D: Three-dimensional; DAS: Distributed acoustic sensing; UTM: Universal Transverse Mercator; VSP: Vertical seismic profiling.

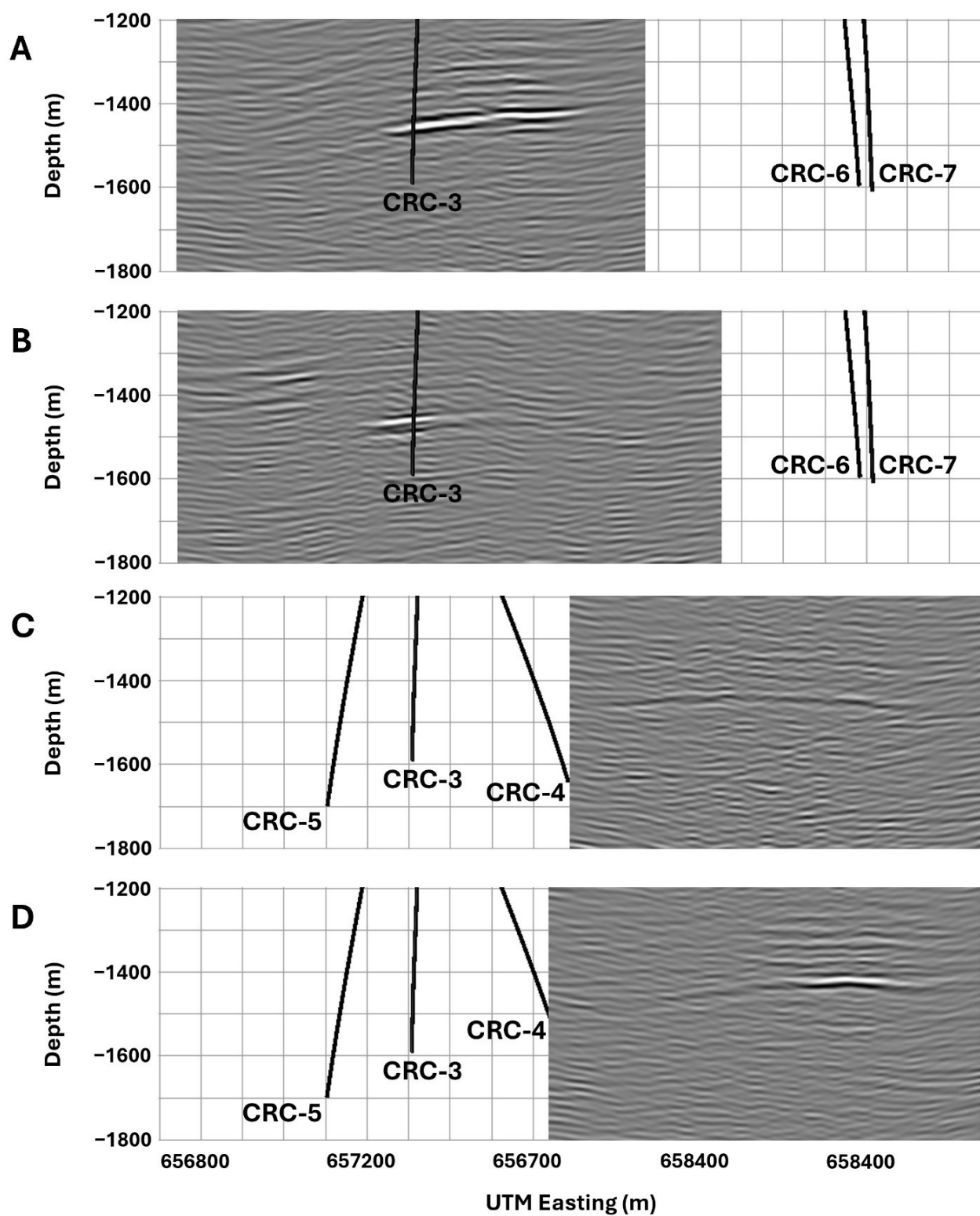


Figure 8. Time-lapse difference (M9 minus M8) vertical slices along line A-A' (see Figure 9 for line location), extracted from the 3D migrated DAS-VSP volumes for wells (A) CRC-4, (B) CRC-5, (C) CRC-6, and (D) CRC-7

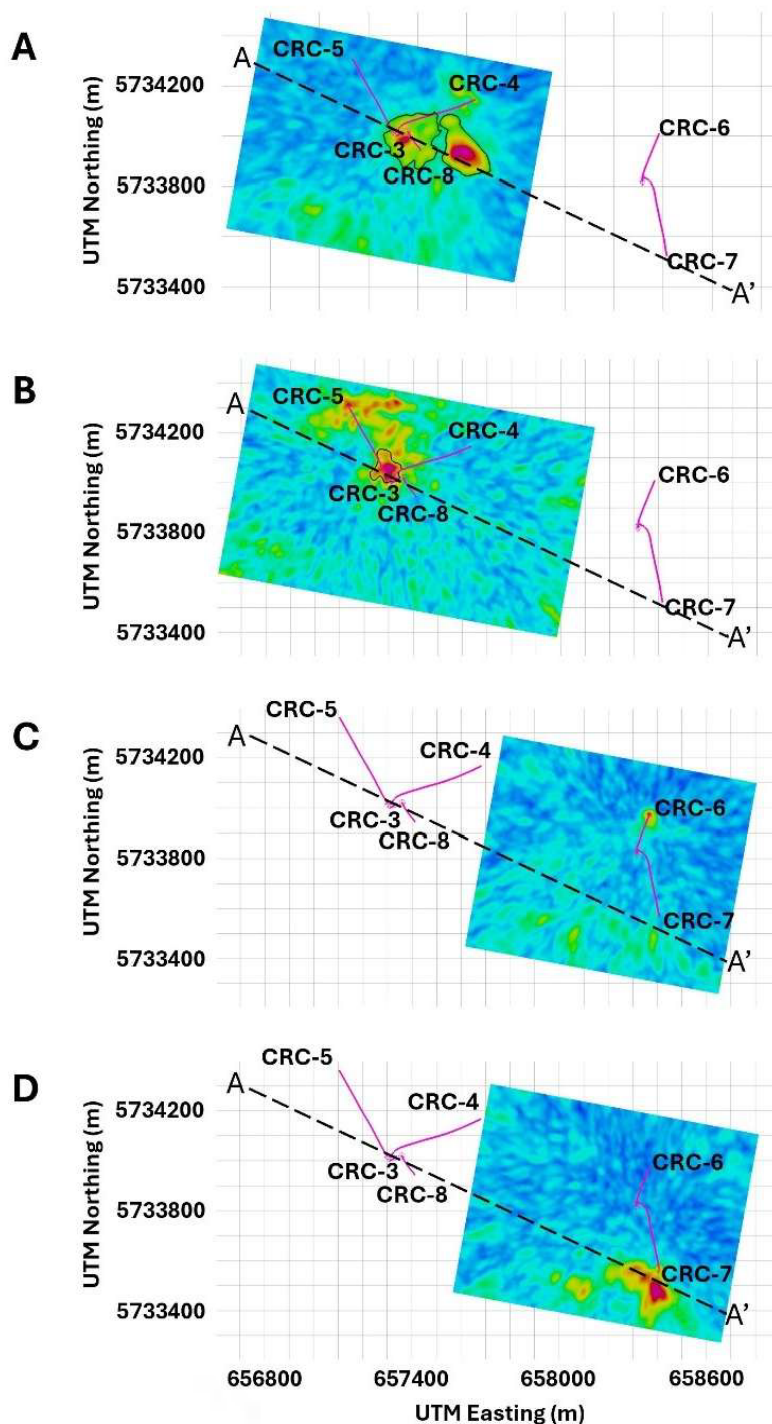


Figure 9. Plan-view maps of the maximum root mean square (RMS) difference between three-dimensional migrated data acquired at observation wells: (A) CRC-4, (B) CRC-5, (C) CRC-6, and (D) CRC-7 during M8 and M9 (M9-M8) over the representative depth interval 1,400 to 1,500 m true vertical depth subsea. Warm colors (pink, red, yellow) indicate stronger RMS differences likely associated with the presence of carbon dioxide, while cool colors (blue) denote minimal change. Pink lines indicate well trajectories. The black contours on the CRC-4 and CRC-5 maps mark the interpreted areal extent of the Stage 4 carbon dioxide plume. The black dashed line shows the position of line A-A' used in Figure 8.

of the strongest seismic response. These interpreted plume extents should be considered approximate rather than exact boundaries, with uncertainty arising from the threshold selection, manual outlining, migration resolution, and residual non-repeatable noise. CRC-6 data show no coherent anomaly. At CRC-7, the observed seismic anomaly is interpreted as related to a combination of CO₂ injected during Stage 2C and Stage 3, most likely due to subsequent migration of the plume into the area between surveys M8 and M9. This finding is consistent with published Stage 3 4D DAS-VSP results, which indicated that the newly injected CO₂ reached and remobilized a previous plume in the same formation.^{8,17}

4. Discussion

Operationally, the M9 survey highlighted two acquisition risks: surface cable rerouting and downhole cable integrity. Rerouting of surface cables between M8 and M9 altered the mapping between DAS channels and physical depth; however, because the rerouting affected only the surface cable sections while the downhole fibers remained cemented in place, this effect was addressed using well-specific channel shifts as a first-order correction. This procedure restored practical cross-vintage comparability for time-lapse interpretation. In contrast, the fiber in CRC-3 was irreversibly damaged by fluid ingress during perforation, rendering the cemented cable segment unusable for 4D monitoring. This is an important precedent demonstrating that cables installed behind the casing can act as a leakage pathway if perforation and completion design do not explicitly protect the fiber. To reduce the likelihood of similar failures in future permanent installations, oriented perforation schemes or gravel-packed completions confined to defined azimuthal sectors are preferable to full 360° perforation around the wellbore.

Following the failure of the CRC-3 fiber, the SMF connected to the OptoDAS interrogator remained operational in that well. The absence of an OptoDAS baseline complicates direct inclusion of the CRC-3 Stage 4 response into the M8–M9 4D analysis, which is currently limited to the iDAS-v3 Carina data. Reconciling the OptoDAS CRC-3 measurements with the existing iDAS-v3 vintages through cross-calibration of instrument responses and noise characteristics is therefore an important topic for subsequent work, as it would restore the well as a central control point for future time-lapse surveys.

A key limitation of the present Stage 4 dataset is that no usable M8–M9 4D response is available from the injector well CRC-3 itself. Therefore, interpretation of the Stage 4 plume geometry relies on observations from neighboring wells, rather than on direct time-lapse constraints within

the injector.

Multi-well DAS-VSP data were processed per well, consistent with the Stage 3 workflow. In a multi-well DAS geometry, each borehole acts as an independent VSP experiment with its own interrogator, fiber installation, noise characteristics, and illumination pattern. Processing wells separately allows geometry calibration, deconvolution, wavefield separation, and statics to be optimized for the local acquisition conditions, rather than forcing a single processing parameter set onto datasets with different directional sensitivities and amplitude responses. Comparison between wells is then performed at the interpretation stage, by aligning depth-registered sections and attribute maps, rather than by merging the data into a single processing flow.

From a reservoir engineering perspective, the current workflow provides qualitative yet operationally valuable information: a map of the plume outline obtained from the 4D DAS-VSP anomaly envelopes. This delineation already provides a critical consistency check for dynamic reservoir models and can be used to discriminate between scenarios with markedly different lateral plume spread or vertical migration. However, for rigorous history matching, a quantitative link between flow simulation variables and observed seismic attributes must be established. This will involve defining robust 4D observables that can be predicted from reservoir simulations and formulating misfit measures to assimilate these attributes into history-matching workflows. Developing and validating such quantitative integration strategies, including cross-calibration of different interrogator types and explicit treatment of multi-stage injection history, constitutes the next step towards fully exploiting multi-well DAS-VSP data for reservoir management and long-term conformance assessment at the Otway site and similar storage projects.

The observed time-lapse anomalies underline both the strengths and the limitations of the current monitoring configuration. At CRC-4 and CRC-5, the coherent RMS-difference anomalies at the Paaratte Formation depth are geometrically consistent with the Stage 4 injection interval and provide a clear qualitative outline of the new plume. The anomaly in the vicinity of CRC-7 is spatially separated from the current injector and, given its location, is most plausibly associated with the spreading of the Stage 2C and/or Stage 3 plume into that area between the two surveys rather than with the Stage 4 injection. This behavior emphasizes that the multi-well DAS-VSP system is sensitive to both legacy and recently injected CO₂, and that multiple injection stages need to be considered jointly when interpreting 4D responses.

At the same time, the CRC-7 response illustrates an

important limitation of time-lapse seismic for quantitative characterization. The seismic anomalies primarily reflect changes caused by free-phase CO₂, but seismic data alone cannot provide a reliable saturation estimate. Methods for deriving CO₂ saturation from seismic observations remain subject to significant uncertainty and require site-specific calibration.¹⁸ Consequently, in the present study, 4D seismic is used qualitatively to detect and outline the CO₂ plume.

5. Conclusion

The M9 multi-well 3D DAS-VSP survey conducted during the Otway Stage 4 Project provided high-quality time-lapse data that are consistent and comparable with the M8 baseline using the adapted Stage 3 processing workflow. The resulting time-lapse images demonstrate that multi-well DAS-VSP monitoring enables reliable tracking of the CO₂ plume, thereby strengthening confidence in storage conformance and containment.

Time-lapse analysis reveals seismic anomalies around the CRC-4 and CRC-5 wells, which are spatially aligned with the Stage 4 CO₂ injection interval within the Paaratte Formation, indicating the presence and evolution of the plume. At CRC-7, the observed anomaly is interpreted as residual CO₂ from Stage 2C/3, highlighting the method's ability to capture both recent and legacy injection signals.

Surface cable rerouting effects were corrected by applying a uniform shift to all channels in the affected wells. In contrast, the damage in the CRC-3 fiber precludes its use for acquisition or time-lapse analysis. Overall, the M9 results confirm that permanent multi-well DAS-VSP offers a practical and effective technology for high-resolution time-lapse monitoring of CO₂ injection and storage.

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Conflicts of interest

Boris Gurevich and Roman Pevzner are Editorial Board Members of this journal, but were not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. The authors declare no conflicts of interest.

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Availability of data

Data are available on request to CO2CRC Ltd. (info@co2crc.com.au).

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