Introduction

Understanding how faults influence fluid migration is essential for assessing the risks of vertical gas movement through fault zones and developing effective geological storage monitoring strategies in Carbon Capture, Utilization, and Storage (CCUS) projects. The shallow CO_2 release project at the CO_2CRC Otway International Test Centre provides valuable empirical data on CO_2 flow within vertical faults. Extensive feasibility and field studies were conducted before the injection phase to characterise the targeted near-surface strike-slip Brumbys Fault in detail (Sidenko et al., 2021; Feitz et al., 2022). A borehole seismic monitoring program was implemented to track gas migration within the fault. Monitoring the shallow release experiment has challenges due to the small, complex CO_2 plume, the heterogeneity of near-surface, and the fast subsurface changes. The program employed both active and passive borehole seismic methods to capture frequent, high-resolution subsurface snapshots at a relatively low cost. Several shallow wells were used, with a high-frequency electric sparker serving as the seismic source for active surveys. Two active downhole seismic techniques – 4D reverse VSP and 4D cross-hole seismic with fibre optic sensors – were used for time-lapse monitoring. Passive seismic monitoring analysed Rayleigh-wave amplitudes (Pevzner et al., 2023) recorded using fibre optic sensors.

Experiment Design

This paper details the experimental design, with a focus on active and passive seismic acquisition methodologies. The seismic monitoring program incorporated three shallow wells (Figure 1a). Each well was designated a specific function to facilitate comprehensive monitoring of CO_2 migration and fault interaction. This experiment involved the injection of 16 tonnes carbon dioxide in gas state beneath the shallow Brumbys Fault (Feitz et al., 2022). The Brumbys-3 well served as the injection site, featuring a perforated interval between approximately 77 and 87 meters. This well was instrumented with a fiber optic sensing cable installed behind its casing. The fiber optic array in Brumbys-3 was employed in a cross-hole seismic approach using the Treble+ interrogator (Terra15 Technologies Pty Ltd), allowing high-resolution subsurface imaging. The Brumbys-1 well was designated as a monitoring site and was used for deploying a high-energy downhole sparker seismic source. This seismic source generated controlled excitations, which were simultaneously utilised for active reverse vertical seismic profiling (RVSP) and cross-hole seismic acquisitions. The collected seismic data provided critical insights into the dynamic subsurface response to CO_2 injection. The Brumbys-4 well, another monitoring site, was equipped with a fiber optic cable cemented behind its casing. This fiber-sensing array was primarily dedicated to passive seismic monitoring using the iDAS-MG interrogator (Silixa Ltd, A LUNA Company). These integrated monitoring techniques provided a robust framework for capturing the evolution of the CO_2 plume and its behavior within the faulted near-surface environment.

Preliminary Results

Figure 1c and 1b displays the travel-time differences of the direct wave in the RVSP data. The left panel compares two baseline vintages, demonstrating a high degree of data repeatability. In contrast, the right panel presents the travel-time difference between a baseline survey and the last survey for a source point positioned at a depth of 90 meters - about 10 below the injection interval. The results indicate an increase in travel times of up to 3 milliseconds, suggesting the presence of gas between the source location and the surface receivers. The primary anomaly manifests as an elongated structure oriented in the North-South direction, coinciding with the location of the Brumbys Fault. Figure 1d presents the results of travel-time tomography based on RVSP data. The tomography was conducted using a straight-ray approach applied to 2D sections that intersect the source well trajectory at azimuthal intervals of 0.5 degrees. The resulting data were subsequently interpolated and visualized in 3D. Figure 4 provides a spatial representation of the CO_2 distribution as observed on the completion of the injection process.

Conclusions

The shallow CO_2 controlled release experiment offers critical insights into the mechanisms governing vertical leakage along the strike-slip fault and the migration behavior of CO_2 within near-surface geological environments. This experiment enhances our understanding of how injected CO_2 moves through subsurface formations, particularly in the presence of structural features that may serve as conduits for gas escape. A key component of this study is the seismic monitoring program, which emphasizes the use of downhole geophysical techniques. These methods have demonstrated their effectiveness in providing rapid and high-resolution data acquisition, enabling the real-time tracking of fast-evolving subsurface processes. These combined methodologies of active and passive borehole seismic approaches significantly enhance the ability to monitor and interpret gas behavior in near-surface environments, ultimately informing strategies for CO_2 storage and leakage risk assessment.

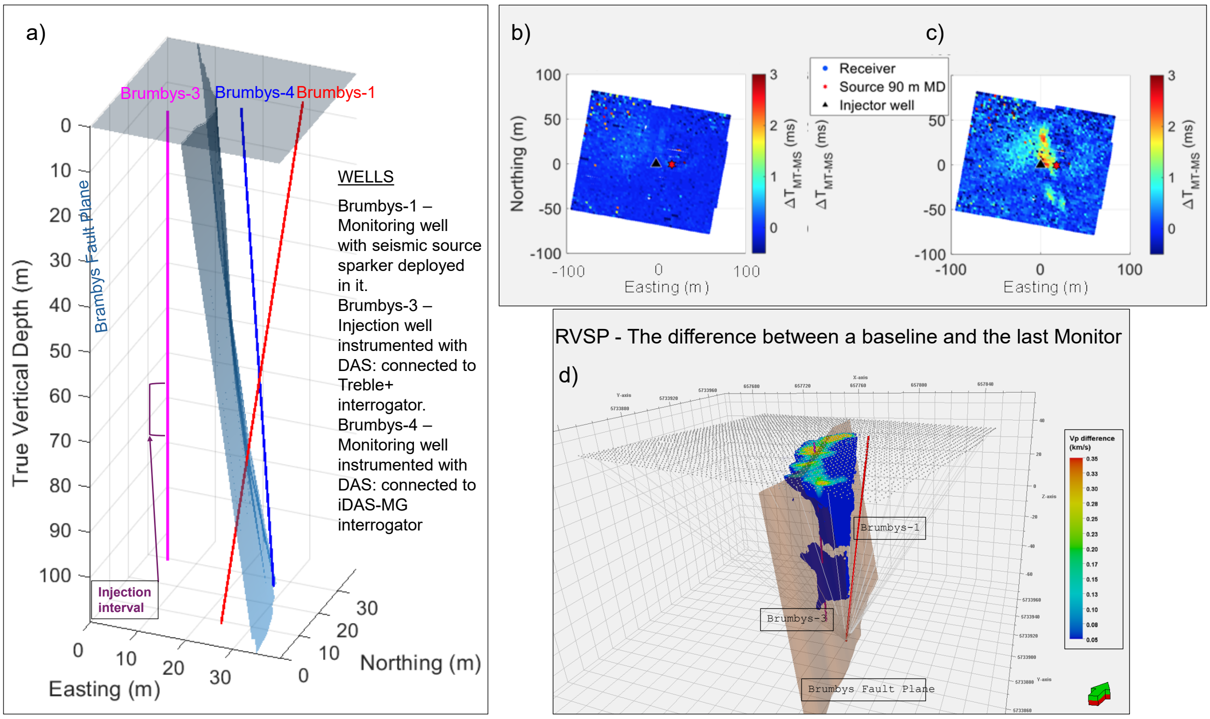

***Figure 1** a) 3D view of the Brumbys well trajectories and the Brumbys Fault plane. b) and c)Direct wave travel time difference between two baseline datasets (left) and between the baseline and last monitor (right). Positive values show an increase in travel times for the monitor vintage. d) RVSP travel time tomography results. The difference between a baseline and the last monitor vintages indicates migration patterns and distribution of CO_2 gas in the subsurface.*

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