Introduction
Carbon capture and storage (CCS) is a promising approach to minimize emission of CO₂ into the atmosphere. To be able to store carbon dioxide in the subsurface, CO₂ reservoirs must be monitored progressively to understand the behavior of CO₂ in reservoirs (Pevzner et al., 2017). Shallow downhole seismic surveys are frequently implemented in monitoring and characterization of near surface CO₂ injections and experiments. Downhole time-lapse seismic datasets generally have better quality and resolution than that of surface seismic. Moreover, hydrophones could be implemented as alternative seismic sensors due to simpler deployment and their relatively inexpensive cost.

The project SRD3.3 is focused on the prediction and verification of shallow CO₂ migration, associated with a controlled release of carbon dioxide within a near surface fault. The project aims to gain better understanding of CO₂ leakage in shallow faults under highly controlled conditions in sedimentary basins and establish reliable imaging of the CO₂ migration behaviour. Cross-hole seismic approach was implemented to trial the method as one of the monitoring tools and to obtain information about seismic velocities in a space between wells. Previous studies characterized near surface geology of Otway CO2CRC project site (Feitz et al., 2017). Three layers from top to bottom of near surface geology at the project site were Pliocene Hanson Plain Sand of high clay content and poor permeability with varying thickness of 3 -5 m, stratified and karstified Miocene Port Campbell Limestone with various permeability and 121 m thick, and impermeable Miocene Gellibrand Marl (Feitz et al., 2018). Moreover, the Brumbys fault, which was imaged in a previous feasibility study, was interpreted as a strike slip fault (Feitz et al., 2017). Hence its bends and dilational jogs can be appropriate target of CO₂ injection (Feitz et al., 2018). However, near surface geology at the project site must be characterized in more details in order to obtain comprehensive 3D model.

The objective of this study is to characterize shallow Brumbys fault using cross-hole seismic with low-powered and high frequency source (sparker) and hydrophones.

Cross-well acquisition setup
Two stratigraphic wells were drilled to investigate the near surface geology and confirm the target interval for the injection (Feitz et al., 2018). The Brumbys 1 well has depth of 126 m, azimuth and declination of 200° and 80° respectively. The well traversed Port Campbell Limestone, targeted a low permeability portion at depth of 100 m. The Brumbys 2 well has depth of 36 m, azimuth and declination 250° and 45° respectively and targeted a high permeable portion of the fault (Feitz et al., 2018). A 1.2 kJ electrical sparker was deployed in the Brumbys 2 well with depth coverage and source spacing of 4 – 36 m and 4 m respectively (Tertyshnikov et al., 2019). The Brumbys 1 well was equipped with two sets of hydrophones of 24 and 14 channels with different depth coverage and receiver spacing. Depth coverage and receiver spacing of 24 channels are 32 – 78 m and 2 m respectively (Figure 1) (Tertyshnikov et al. 2019). On the other hand, depth coverage and receiver spacing of 14 channel hydrophones are 35 – 126 m and 7 m respectively. Sampling rate and record length of the survey are 0.25 ms and 2 s respectively (Tertyshnikov et al. 2019).

Data Processing
The cross-hole trial was a part of a comprehensive study of the near surface settings for the SRD3.3 project. 3D and check-shot VSP survey was conducted within the scope of geophysical investigations (Tertyshnikov et al., 2019), some of these data were utilised for the cross-hole analysis. Firstly, zero offset VSP data acquired using a weight drop source and hydrophones were processed to obtain 1D velocity model. This 1D velocity model was as an initial one for the cross-hole tomography inversion. Secondly, cross-hole tomography inversion was performed to obtain a 2D velocity model between the wells.

Processing steps of zero-offset VSP are as follows; assigning geometry, summing shot gathers (vertical stack of the repeated excitations on a shot location), picking first breaks and building a velocity model. Processing steps of cross-hole tomography: setting up geometry, summing shot gathers, picking first breaks, constructing image plane that best fits sparker and hydrophone positions, preparing input parameters for tomography inversion and performing cross-hole seismic tomography inversion. Since the wells have different azimuths and inclinations, they are not located on a same image plane. The utilised tomography inversion code assumes the coordinates of sources and receivers
are on the same plane. Hence, an image plane that fits best the coordinates of a sparker and hydrophones. The next step is projection of sparker and hydrophones coordinates into the plane and representing their 3D coordinate into 2D coordinates on the plane using orthonormal basis (Figure 1). Before performing cross-hole tomography inversion, input parameters must be prepared. The parameters are consisted of 2D coordinates of a sparker and hydrophones on the image plane, source – receiver distances, times of first arrivals and initial velocity model.

**Figure 1** Image plane, projection of sparker points onto the plane (black), projection of 24 channel (red) and 14 channel (blue) hydrophone sets onto the image plane. Note that depth interval of 32 to 78 m were sampled with finer sampling interval than deeper depth from 78 to 126 m.

**Results and Discussion**

Three features can be observed from this 1D velocity model as shown in Figure 2. Firstly, the velocity of subsurface steadily increases with depth. In fact, the interval velocity increases from 1.8 m/ms at depth of 7 m to 2.5 m/ms at depth of 117 m. Similarly, mean velocity showed a gentle increase from 1.7 m/ms at shallow depth of 7 m to 1.97 m/ms at 124 m. Secondly, the subsurface is consisted of layers with alternating, high and low, velocities. Moreover, the high velocity layers are relatively thicker than that of low velocity layers. This observation agrees with previous study that indicated that Port Campbell Limestone is a stratified layer with imbedded soft marly to marly limestone (Bailey et al., 2017). Hence the thin low velocity layers might correspond with marly to marly limestone, whereas high velocity are associated with Port Campbell Limestone. Thirdly, a prominent high velocity anomaly was observed at depth of 90 m. Since a fault zone is generally indicated by low velocity, this high velocity anomaly is not related to Brumby’s fault. The high velocity anomaly might be related to the end of cementation with the installation of bentonite around that depth.

**Figure 2** 1D velocity model obtained from zero offset VSP at Brumby's 1 where horizontal and vertical axes correspond to velocity in m/ms and depth in m respectively. Three main features can be observed in the 1D velocity model: velocity increases with depth, subsurface is comprised of layers of high and low velocities, and high velocity anomaly at depth of 90 m.
Tomograms associated with three different grid sizes of 1.5, 2.0, 2.5 and 3.0 m and initial velocity of 2.7 m/ms are shown in Figure 3. A high initial velocity was selected so that profound contrast between low velocity anomaly of fault and high background velocity can be observed in the tomograms. Three main features are indicated in all tomograms. Firstly, a wide zone of low velocity between 1.8 to 2.2 m/ms from depth of 40 to 120 m. Previous studies suggested that Brumbys fault was a strike-slip fault (Feitz et al., 2018) which was intersected by Brumbys 1 at depth of about 90 m MD to 120 m MD (Tertyshnikov et al., 2019). Hence, this low velocity anomaly might be related to fractures and cracks associated with strike-slip fault at shallow depth. Secondly, a high velocity anomaly at depth of about 30 m at Brumbys 1. Precisely, high velocity of about 2.7 m/ms to 2.9 m/ms at the well. This high anomaly might be associated with the beginning of cement interval at that depth. Thirdly, a low velocity anomaly was observed from 5 to 15 m. This low velocity anomaly might be related to shallow Hanson Plain Sand layer. Note that the profound low velocity anomaly between depth of 32 to 78 m is due to the overlapping of hydrophone sets (2 m and 7 m spacing interval). Hence velocities were resolved quiet well. However, deeper low velocity anomaly (depth of 80 to 120 m) were not resolved quiet well due to the coarser depth sampling of 7 m hydrophone were imaged using fine grid size of 2 m.

Conclusions

An extensive geophysical program was implemented to characterise near surface formations and determine the robust monitoring strategy for the SRD3.3 Otway shallow CO2 release project. The program was focused on the borehole seismic techniques. As a part of this study, cross-hole seismic method has been trialed. Obtained seismic cross-hole data is of the high quality and allow building an accurate velocity model for the near surface part of the geological formations in the vicinity of the Brumbys -1 and 2 wells. Fractures and cracks of Brumbys fault were observed from depth of 40 to 120 m (between Brumbys 1 and 2 wells) with velocity range of 1800 – 2200 m/ms. Cross-well tomography using a high frequency source (sparker) and hydrophones performed well in subsurface characterization and should be considered as part of monitoring strategy for the shallow injection experiment. Alternative acquisition setup for monitoring is a reverse VSP approach. The method utilises downhole seismic sources and surface deployed receivers. High resolution could be achieved by this approach by using sparker seismic sources with a frequency rang ~1 kHz, this method will also allow rapid repeated acquisitions. The cross-hole seismic acquisition would complement the monitoring program as it could be recorded simultaneously with the 3D reverse VSP survey using permanently installed seismic sensors in the injection/observation wells.

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Three main velocity anomalies were observed: a wide zone of low velocity from depth of 40 to 120 m; high velocity at depth of 30 m at Brumbys 1; and low velocity anomaly at shallow depth of 5 to 15 m.

References


