Introduction

CO2CRC Otway Project is a multi-stage research project, which involves examination of applicability of different techniques for CCS (Carbon Capture and Storage). Stage 2C of the Otway Project addressed the challenges of monitoring a relatively small injection of CO₂-rich gas (5 - 15 ktonnes) into a saline aquifer using time-lapse seismic methods. The main components of the Stage 2C monitoring were 4D surface seismic and 4D VSP (Vertical Seismic Profiling) which were acquired simultaneously with a Vibroseis source (Pevzner et al., 2017).

Quality of a seismic image can be significantly affected by anisotropy. Significant presence of anisotropy was previously reported at Otway site (Pevzner et al., 2010). In this study we extract anisotropy parameters from 3D VSP datasets acquired during last (fifth) monitor survey of the Stage 2C. This survey has wide offset and azimuthal coverage and consequently wide range of incident angles, which is crucial for anisotropy estimation. We compute the parameters from P-wave arrival times of two sets of VSP data: acquired with geophone and DAS (Distributed Acoustic Sensing) receivers.

In this study we analyse advantages and limitations of DAS and geophone VSP for anisotropy analysis, provide approximation that gives the best fit to the observed travel time curves, provide resulting anisotropy parameters and speculate about the cause of anisotropy field at the Otway site.

The current study is limited by two wells with VSP measurements. However, Otway project is now progressing towards the Stage 3, which will be focusing on multi-well monitoring and will provide an opportunity to obtain more detailed anisotropic velocity model with seven monitoring wells.

Data used for travel time analysis

For the travel time analysis we use 3D VSP data acquired during Monitor 5 (M5) survey at Otway site. Figure 1 shows seismic acquisition map with buried receivers (blue dots) for surface seismic and CRC-1 and CRC-3 wells instrumented with 3D VSP measurements.

![Figure 1](image)

**Figure 1** Acquisition map for Monitor 5 survey of Stage 2C of the Otway Project.

In this study we use the following 3D VSP acquired during M5 survey:
- CRC-1 well: eight 3C geophones covering the depth range 760 m - 895 m with 15 m spacing;
• CRC-3 well: a single 3C high-sensitivity geophone at a depth 775 m and DAS cable cemented along the entire depth of the well (0 – 1430 m).

The CRC-1 and CRC-3 wells are about 630 m apart. Data was acquired using Vibrators as a source with a single sweep at each shot point.

Figure 2 shows DAS and geophone raw common receiver gathers from CRC-3 VSP (775 m depth) from one shot line. Geophone data has much better signal-to-noise ratio and allows tracking first arrivals much easier. Even after noise removal from the DAS data, it is still impossible to detect P-wave arrivals on far offsets. This is due to DAS being mostly sensitive to seismic waves polarised and propagating along the cable. This directional sensitivity is the main limitation of DAS. However, the main advantage of DAS is that we can have 3D VSP data for the entire depth of the well, which we use in this study.

Analysis of travel times of the direct wave from geophone and DAS data

In order to investigate the degree of anisotropy, we computed time difference between observed (picked) P-wave travel times and those theoretically calculated using ray-tracing for isotropic 1D media. Interval velocities for estimation of the theoretical direct wave arrival times were taken from zero-offset VSP (covering the entire CRC-1 and CRC-3 wells). An example of such time-difference map computed from geophone data in CRC-1 well at a depth of 760 m is shown in the Figure 3 (left). For an isotropic medium the travel time pattern should be circular. Yet the map shows strong ellipticity of the travel times, and hence significant deviation of the observed model from isotropic. We can extract two symmetry axes from this map, which means that the media has azimuthal anisotropy. One of the axes represents slow direction of wave propagation (time difference is higher). Another axis coincides with fast direction. The right image in the Figure 3 shows RMS amplitude of the time-lapse surface seismic signal between Baseline survey and Monitor 5 acquired two years after injection of the supercritical CO2. The plume appears to be spreading from the CRC-2 injector well along the fast direction, which suggests that the seismic anisotropy may be stress-induced.

We also analyze such misfit maps obtained from DAS data for the entire depth of the well. As was noted, DAS does not allow to obtain travel times for far offsets. However, 1 km offset at a depth 760 m is enough to track the elliptic misfit trend. Analysis of misfit maps for other depths using DAS demonstrates that the anisotropy character is changing with depth.

Figure 2 Comparison of geophone and DAS VSP common receiver gather. CRC-3 well at a 775 m depth.
Approximation of travel time curves

To estimate polar and azimuthal anisotropy, we combine elliptical approximation proposed by Corrigan et al (1996) to describe azimuthal anisotropy and Alkhalifah and Tsvankin (1995) equation:

\[ t^2(r, \varphi) = t^2_0 + K(\varphi) \frac{r^2}{v^2} - \frac{2\eta r^4}{K(\varphi) \left[ t^2_0 \frac{v^2}{K(\varphi)} + (1 + 2\eta)r^2 \right]} \]

where \( K(\varphi) = 1 - \sigma \cos(2(\varphi - \omega)) \);

\( t_0 \) is zero-offset P-wave travel time; \( r \) is offset; \( v \) is NMO velocity; \( \sigma \) is azimuthal velocity ellipticity; \( \varphi \) is shot-receiver azimuth; \( \omega \) is fast velocity azimuth; and \( \eta \) is anellipticity in the vertical plane.

Anisotropy was estimated by non-linear fitting of the observed travel times to the theoretical predictions. The known parameters for inversion are observed travel times, offset and shot-receiver azimuth corresponding to each pair of seismic source and receiver. All the other parameters were inverted for. The initial parameters for inversion were taken from isotropic assumption, geological information and previous studies conducted at the area.

Figure 3 shows the inverted parameters. The results from geophone and DAS data are consistent. The misfit between the CRC-1 and CRC-3 wells is relatively small. NMO-velocity is monotonically increasing with depth. Azimuthal anisotropy significantly varies with depth: from negligibly small in the shallow part (above 600 m) and sharp increase below, which suggests a change of the stress field at this depth. Vertical-plane anellipticity remains almost constant at 0.1. The azimuth of the fast direction varies with depth as well by about 10 degrees from 150° azimuth in a shallow part to 140° azimuth at a depth of 1400 m.

Conclusions

We observe significant variation of direct-wave arrival times from isotropic case. Our analysis demonstrates a complex anisotropic case with both azimuthal and polar anisotropy. The character of anisotropy is changing with depth: the shallow part is much less anisotropic compared to deep part in target intervals.

DAS 3D VSP allows estimation of anisotropy parameters for the entire depth range. Directivity of DAS precludes first break picking at far offsets. However, the remaining range of offsets/angles is sufficient
for estimation of effective anisotropy parameters with accuracy useful for subsurface imaging from surface seismic data.

Figure 4 Inverted anisotropy parameters from DAS and geophone 3D VSP data. Red curves show parameters obtained from DAS data from the CRC-3 well; blue dot – single geophone from the CRC-3 well; green curves – results from geophone data from the CRC-1 well (bottom part of the well was taken from an old 3D survey, which had a different acquisition pattern).

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References


