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Time-lapse Seismic Anisotropy Analysis for CO2 Geosequestration Using 3D 3C VSP Data

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SUMMARY

We present a quantitative analysis of the change of the seismic anisotropy observed after CO2 injection within the CO2CRC Otway Basin Project. We invert two 3C 3D VSP datasets for the density scaled stiffness tensors and compute the difference of the resulting compliance tensors. The results are in good agreement with the observed changes in the time-lapse zero-offset VSP experiments and with the available sonic log data.

Introduction

Seismic anisotropy is manifested by changes of seismic velocities with direction. Such a directional dependence on the azimuth is usually caused by fractures or a dominant stress direction. Changes at the reservoir level, such as production of oil and gas or water/gas injection, cause changes in the pore pressure, which might result in changes of the stress field not only at the reservoir level, but also in the overburden (Crampin, 1990; Herwanger and Horne, 2009).

The presented work focuses on estimates of the seismic anisotropy in the CRC-1 borehole of the CO2CRC Otway project, which is the first Australian demonstration project of CO_2 geosequestration. The project consists of a number of CO_2-rich gas injections (80% of CO_2 and 20% of CH_4) into different geological formations of Otway basin, Victoria, Australia. Stage I, conducted from year 2008 to 2009, consisted of an injection of about 64,000 tonnes of gas into a depleted gas reservoir located at depth of 2 km (Waare C). There were two 3D VSP surveys acquired (2007 and 2010), which provide good data for the anisotropy estimation in the borehole. The datasets were acquired using 8-10 level 3C Schlumberger VSI tool located at 1500-1600 m depth. Depth receiver interval was 15 m. The first surevey was acquired using around 1,100 shot points, all these points we repeated in the second survey, when around 1,100 shot points were added (29 shot lines, 100 m line spacing, 20 m shot point spacing).

Significant azimuthal shear wave anisotropy was previously reported for the Otway basin by Turner and Hearn (1995). The azimuthal anisotropy is also corroborated by the asymmetric distribution of the dip of the polarisation vectors shown in Figure 1. To further motivate our study of time-lapse anisotropy,

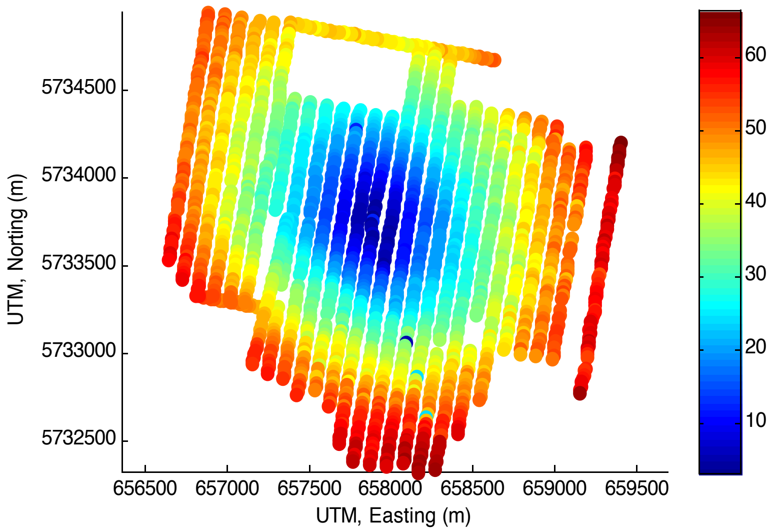

Figure 1 *Dip of the polarisation vectors of the direct P-wave for the receiver depth of* 1545*m is shown at the location of the corresponding source location.*

we plotted in Figure 2 the rose diagrams of the horizontal polarisation distribution of S-waves for different depths for 2007 and 2010 surveys. The figure shows small time-lapse changes in the polarisation orientation. To quantify this effect, we estimate the density scaled stiffness tensors for the two different surveys.

Method and Theory

To estimate the density scaled stiffness tensor, we use the polarisation, **A**, and the phase slowness, **p**, of elastic body waves. The polarisations and slownesses were used for the estimate of the elasticity properties by van Buskirk et al. (1986) for laboratory measurements, and by Dewangan and Grechka

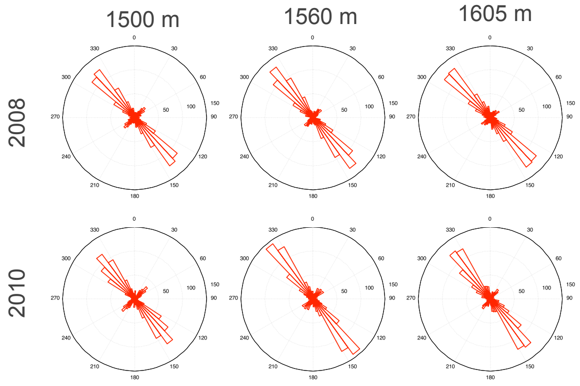

Figure 2 Directions of the horizontal projections of the polarizations of the S-waves at different depths and years.

(2003) for VSP measurements. In the VSP case, the polarisations are recorded by the 3C geophones in the well. The vertical components of the slownesses are approximated by the difference in the picked travel time divided by the difference in the depth of the receivers. The horizontal components of the slowness are conserved along the rays in horizontally layered media, which is a good geological model for the Otway site. This conservation allows us to measure the horizontal slownesses at the surface as the ratio of the difference in the picked travel time and the difference in the source location.

The polarisations and the slownesses are related by the stiffness tensor, c, as expressed by the Christoffel equation:

$$c_{ijkl}p_jA_kp_l = \rho A_i. \tag{1}$$

This expression can be viewed as a linear equation for the density scaled stiffness tensor, $a = c/\rho$, with the coefficients given by the measured quantities $\mathbf{A}$ and $\mathbf{p}$. Since all of these quantities are subject to measurement errors, to find a, we have to use the generalised least squares (errors in variables) method. This method minimises the errors in all of the measured quantities by searching for the best density scaled tensor. Our implementation is based on a local search and requires good initial estimate of the tensor. For this estimate we use the method that was used by Dewangan and Grechka (2003) to find their final estimate, namely, this estimate is obtained from equation 1 using the standard least-squares method that assumes no errors in variables on the left-hand side of the equation.

Results

The inverted density weighted stiffness tensor for the 2007 survey from the depth of 1545m is given by the following Voigt matrix.

$$a_{2007} = \begin{pmatrix} 11.9 & 3.0 & 4.3 & -0.5 & -0.2 & -0.4 \\ 3.0 & 9.6 & 3.8 & 0.2 & 0.5 & -0.3 \\ 4.3 & 3.8 & 10.0 & 0.1 & -0.1 & -0.2 \\ -0.5 & 0.2 & 0.1 & 3.2 & 0.2 & -0.2 \\ -0.2 & 0.5 & -0.1 & 0.2 & 3.0 & 0.2 \\ -0.4 & -0.3 & -0.1 & -0.1 & 0.2 & 3.5 \end{pmatrix} \mathrm{km}^2/\mathrm{s}^2 \tag{2}$$

The vertical velocities computed from the inverted tensor are $v_{S2} = 1.7$ km/s, $v_{S1} = 1.8$ km/s, and $v_P = 3.2$ km/s. The polarisation of the fast shear wave has azimuth$_{S1} = 150°$. These data are in very good agreement with the sonic log data shown in Figure 3, which was acquired in 2007.

The inverted density weighted stiffness tensor for the 2010 survey from the depth of 1545m is given by

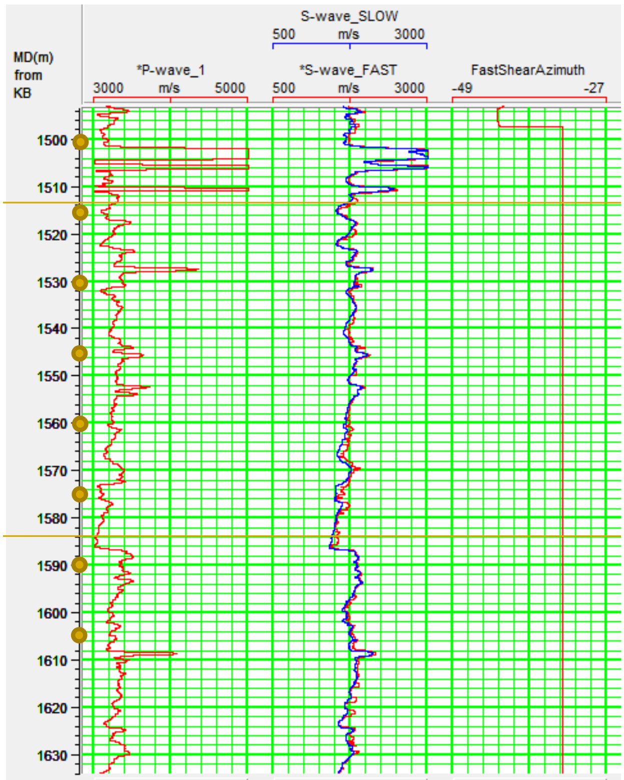

Figure 3 *2007 sonic log from CRC-1. The circles on the depth axis indicate the location of the receivers.*

the following Voigt matrix.

$$a_{2010} = \begin{pmatrix} 11.8 & 5.0 & 4.2 & -0.4 & -0.3 & -0.3 \\ 5.0 & 9.2 & 4.0 & 0.2 & 0.3 & 0.0 \\ 4.2 & 4.0 & 10.3 & 0.1 & -0.1 & -0.2 \\ -0.4 & 0.2 & 0.1 & 3.3 & 0.1 & 0.0 \\ -0.3 & 0.3 & -0.1 & 0.1 & 3.1 & 0.2 \\ -0.3 & 0.0 & -0.2 & 0.0 & 0.2 & 2.4 \end{pmatrix} \mathrm{km}^2/\mathrm{s}^2 \tag{3}$$

The vertical velocities computed from the inverted tensor are $v_{S2} = 1.8$ km/s, $v_{S1} = 1.8$ km/s, and $v_P = 3.2$ km/s. The polarisation of the fast shear wave has azimuth$_{S1} = 159°$. Similar change in the orientation of the fast shear wave polarisation was also observed in zero-offset VSP data, which was presented by Pevzner et al. (2010), however, the unoriented VSP data has large error bars compared to such small changes.

If the observed anisotropy change is caused by the changed stress field, then the natural way to study this effect is to look at the change in the compliance tensors, namely,

$$\Delta S = \begin{pmatrix} 0.0153 & -0.0351 & 0.0102 & 0.0001 & 0.0048 & 0.0098 \\ -0.0351 & 0.0279 & 0.0018 & -0.0047 & 0.0025 & -0.0125 \\ 0.0102 & 0.0018 & -0.0082 & 0.0021 & -0.0029 & 0.0025 \\ 0.0001 & -0.0047 & 0.0021 & -0.0060 & 0.0066 & -0.0080 \\ 0.0048 & 0.0025 & -0.0029 & 0.0066 & -0.0065 & -0.0015 \\ 0.0098 & -0.0125 & 0.0025 & -0.0080 & -0.0015 & 0.0659 \end{pmatrix}. \tag{4}$$

The spatial properties of this compliance tensor can be illustrated by a virtual wavefronts corresponding to this compliance tensor. We call these wavefronts virtual, since they do not correspond to a real material. The virtual P-wave wavefront is shown in Figure 4, which shows the "fast" direction along the prolonged shape of the wavefront.

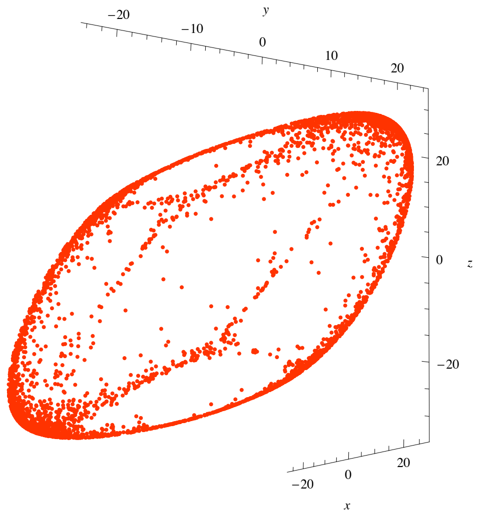

Figure 4 *P-wave wavefront corresponding to the virtual material with the compliance tensor ΔS. The shape of the wavefront indicates the "fast" direction.*

Conclusions

We observed changes in the polarisations, and to smaller extend in slownesses, of the repeated 3D VSP surveys. These changes can be expressed as changes in the stiffness tensors describing the elasticity properties of the material in the vicinity of the receiver. The changes in the tensors are relatively small, which indicates that the slowness-polarisation inversion produces stable results. The time-lapse changes in the elasticity properties could be caused by many factors, however the consistence of the results with the cross-dipole sonic log data recorded in CRC-1 borehole and with the zero-offset VSP allows us to speculate that the changes are related to the change of the stress field above the injection zone of CO_2. The inspection of the difference of the compliance tensors indicates that the direction of the stress field above the injection zone is not vertical at depth of 1545m. The observed changes might be related to the changes at the reservoir level, however, more investigations, including geodynamic modelling, are required to reveal their nature.

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