Seismic anisotropy estimation from VSP data: CO2CRC Otway project case study

Roman Pevzner, Andrej Bona, Boris Gurevich, Ismail Yavuz, Ali Shaiban and Milovan Urosevic,*
CO2CRC and Curtin University of Technology

Summary

We present and compare results of several methods of seismic anisotropy estimation from borehole seismic data obtained for Otway CO_2 geosequestration project, Australia. The presented methods include multicomponent velocity analysis for estimation of shear wave splitting from zero-offset VSP data, P-wave anisotropy from 3D VSP transit times, and from slownesses and polarizations in 3D 3C VSP data. The results of the methods are consistent with each other and also with the cross-dipole sonic log data.

Introduction

CO2CRC Otway project is the first Australian demonstration project of CO_2 geosequestration. It consists of a number of CO_2-rich gas injections (20% of CO_2 and 80% of CH_4) into different geological formations of Otway basin, Victoria, Australia. Phase I, conducted from year 2008 to 2009, consisted of an injection of ~ 66,000 tonnes of gas into a depleted gas reservoir located at depth of ~ 2 km (Waare C). During Phase II, which will occur in 2010, relatively small amount of the gas mixture (up to 5,000-10,000 tonnes) will be injected into the shallow saline aquifer at the depth of ~ 1.4 km. To monitor any possible leakages of the gas into other formations and to attempt to detect changes in the reservoir properties, a comprehensive monitoring and verification program was developed. The seismic part of this program includes several repeated 3D surveys (in years 2000, 2008, 2009 and 2010) (Dodds *et al.*, 2009). Two of the surveys (2008 and 2010) were acquired simultaneously with 3D VSP surveys. Several zero-offset and offset VSP surveys were also acquired in two boreholes (Naylor-1 and CRC-1) in 2007-2010. Naylor-1 well was originally drilled to produce the gas reservoir. For the purposes of the sequestration project, it was converted into a monitoring well. CRC-1 is the borehole drilled for CO_2 injection during Phase I; it is located downdip from Naylor-1 (with respect to the Waare C formation). Distance between these two wells is ~ 300 m.

Investigation of seismic anisotropy is important for the project because it could affect seismic imaging and could also be potentially used for monitoring purposes. Significant azimuthal shear wave anisotropy was previously reported for the Otway basin by Turner and Hearn (1995). In this paper we compare estimations of anisotropy parameters from zero-offset VSP and 3D VSP data.

Multicomponent velocity analysis of zero-offset VSP data

Shear wave anisotropy is often estimated by measuring shear wave splitting (Alford, 1986; Crampin, 1985) in VSP data (Figure 1). Several techniques of VSP data acquisition and analysis were suggested for these purposes (Turner and Hearn, 1995); most of them are based on measuring splitting of individual shear-wave events on VSP data.

These analyses involve measurement of the increase of the time delay between fast and slow shear waves with the depth (Figure 1A); it is particularly effective if the data is acquired with a shear-wave source. However, in many zero-offset surveys, where all shear waves are converted PS events, interference between many events and generally lower shear wave amplitudes make the analysis of time delay of individual events difficult and unreliable (Figure 1B).

However, it is possible to take advantage of the presence of a large number of interfering shear waves by using technique introduced by Pevzner *et al.* (2009). This technique is applicable to zero-offset VSP and was tested on marine VSP data. Here, we apply this technique to land zero-offset VSP data acquired in Otway basin.

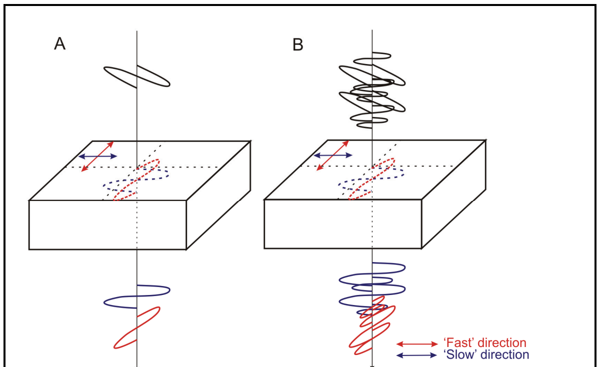

Figure 1: Shear wave splitting due to propagation through azimuthally anisotropic media phenomena

In particular, this technique is similar to the standard velocity analysis, well known from CDP data processing, but applied to traces in a given depth interval on horizontal components of 3C VSP seismogram. The main idea is to estimate the velocity of a large number of events as a function of polarisation azimuth. This is done by computing the overall coherency of all the events on a seismogram as a function of the polarisation azimuth and velocity (slope in time-depth domain). General data analysis workflow consists of the following steps:

1. We select the seismograms of the two horizontal components $H_1(t,z)$ and $H_2(t,z)$ belonging to a certain depth interval (t is time, and z is receiver depth).
2. For the whole range (0-180°) of azimuths of the polarisation, we compute the horizontal seismic 'rotated' amplitude $H(\alpha,t,z)$ as a function of azimuth α:

$$H(\alpha,t,z) = H_1(t,z)\cos\alpha + H_2(t,z)\cos\alpha \qquad (1)$$

3. To determine the apparent velocities as a function of azimuth, we need to compute the velocity spectrum in a chosen depth interval. This can be done by computing the coherency of the seismic signal along a linear travel-time line $t = t_0+\Delta z/v$, where t_0 is a reference time, Δz is the distance from the edge of depth interval and v is the apparent velocity. Note that this is different from the NMO velocity analysis, where traveltime curves are hyperbolas.

   NMO velocity analysis is usually performed using semblance coherency measure. However semblance is not particularly suitable for our purposes since it does not take into account energy of events. If a coherent event with a certain apparent velocity and polarised in a certain plane exists, it will have an equal impact on the velocity spectrum computed for any azimuth, except for the one orthogonal to the polarisation plane. To emphasise stronger events, we propose the following modified semblance function:

$$C = \sum_{j=1}^{N}\left(\sum_{i=1}^{M} D_{i,j}\right)^4 \Bigg/ M\sum_{j=1}^{N}\sum_{i=1}^{M} D_{i,j}^2 \qquad (2)$$

   where

$$D_{i,j} = H\left[\alpha, t_0 + \frac{\Delta z_i}{v} + \left(j - \frac{N}{2}\right)\Delta t, \Delta z_i\right] \qquad (3)$$

   is the j-th sample of an N-samples window on the i-th trace along the travel time curve (after rotation), M is the number of traces in the depth interval being analysed. This formula differs from the semblance function by the 4th power in the numerator, which gives larger value for stronger events.

4. Computed velocity spectrum has to be stacked along the time axis (by scanning a range of t_0 values) to determine a dominant apparent velocity of many events. If there are two sets of coherent events representing fast and slow shear wave in a given depth interval, this stacked 'azimuthal velocity spectrum' as a function of apparent velocity and azimuth of polarisation will have two different maxima, separated by 90° along the azimuth axis.
5. By performing this analysis in a sliding window along the VSP observation interval, we'll obtain a 3D volume $\Sigma_1(v,a,z)$. Interactive picking of the corresponding extrema on depth slices gives fast and slow shear wave velocities and azimuths.

An example of this technique applied to synthetic data is presented in Figure 2. The synthetic dataset contains two sets of downgoing shear waves with velocities of 1.35 and 1.5 km/s; fast shear wave is polarized in the plane oriented

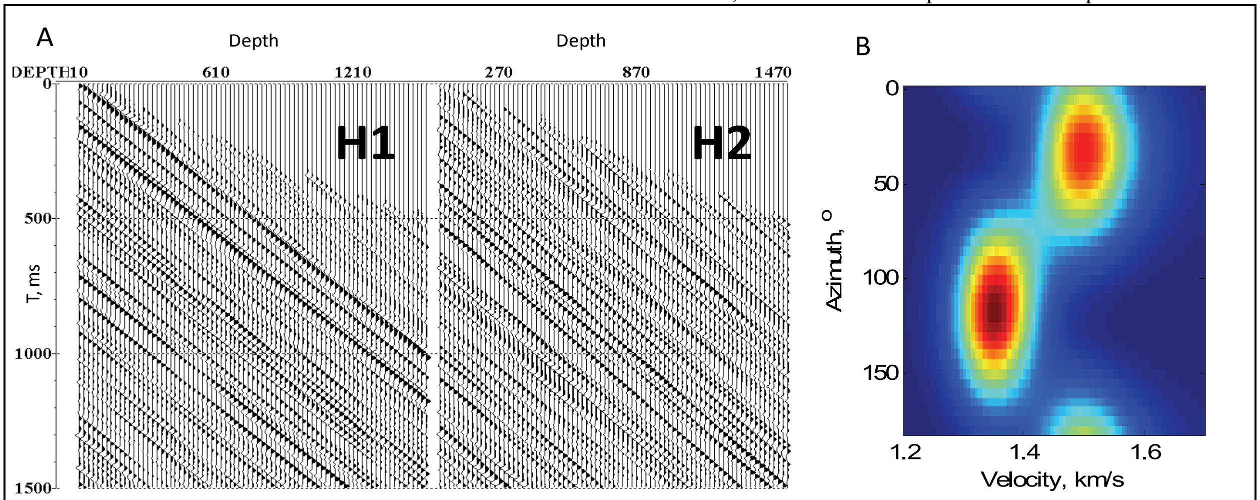

Figure 2: A) Synthetic VSP data example, two horisontal componets with sets of events representing fast (1.5 km/s, azimuth of polarisation 30°) and slow (1.35 km/s, 120°) waves. B) corresponding azimuthal velocity spectrum showing these two waves.

at 30°, slow – at 120° (Figure 2A). Both velocities and polarization azimuths can be clearly seen on the azimuthal velocity spectrum presented in Figure 2B.

Shear wave azimuthal anisotropy from ZVSP data: real data analysis

Acquisition parameters of the zero-offset VSP surveys acquired within CO2CRC Otway project are given in Table 1.

Table 1. ZVSP acquisition parameters

Well	CRC-1	Naylor-1
Date	December, 2007 January, 2010	May, 2006
VSP down hole tool	3C Schlumberger VSI tool	
Source	2007 : Weight drop, H F 9 and HF10, operational weight 720 kg and 1425 kg respectively 2010: Vibroseis, IVI Mini-Buggy, at 9000 lbs, 12.5 s sweep 10-150 Hz + Weight drop, HF10	Vibroseis, MiniVib T1500, at 6000 lbs, 15 s sweep 10-150 Hz
Acquisition interval	2007: 457-2211 m; 2010: 517-1900 m	120-2010 m
Receiver spacing	15 m (517-1575 m); 7.5 m (1575-2211 m)	10 m (120-1710 m);5 m (1730-2010 m)
Shot point location	Azimuth 105.5°, offset 89.7 m	Azimuth 115°, offset 186 m

An example of azimuthal velocity spectra for the same depth interval for both CRC-1 and Naylor-1 boreholes is presented in Figure 3. In both boreholes we observe shear wave splitting with fast direction at ~ 140° and slow direction at ~ 50°.

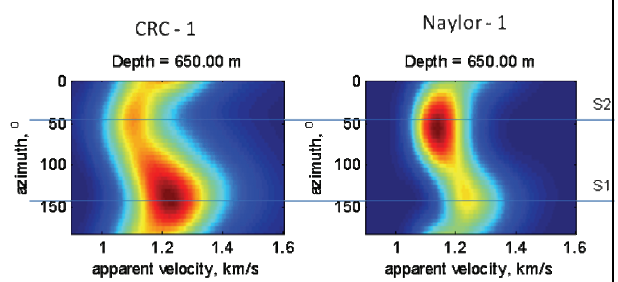

Figure 3: Examples of azimuthal velocity spectra for the CRC-1 and Naylor-1 boreholes

In general, azimuthal anisotropy estimates from VSP data in CRC-1 and Naylor-1 show good agreement with one another. Comparison of shear wave splitting parameters estimated from VSP and cross-dipole sonic log data is presented in Figure 4.

Seismic anisotropy from 3D VSP data

3D/3C VSP data were acquired in CRC-1 borehole in 2007/2008 and 2010 simultaneously with surface 3D seismic surveys. In the first survey we used weight drop HF10, whereas the second survey was acquired with IVI Mini-Buggy as a seismic source.

The acquisition parameters in 2010 were: source line separation =100 m, total 30 lines, source increment = 20 m; total number of shots = 2196 (Figure 4). Odd-numbered source lines were used in 2007 only, so total number of shots was ~ 1100. Downhole tool (Schlumberger VSI) was located at the depth of 1500-1605 m; distance between neighboring shuttles within the tool was 15 m.

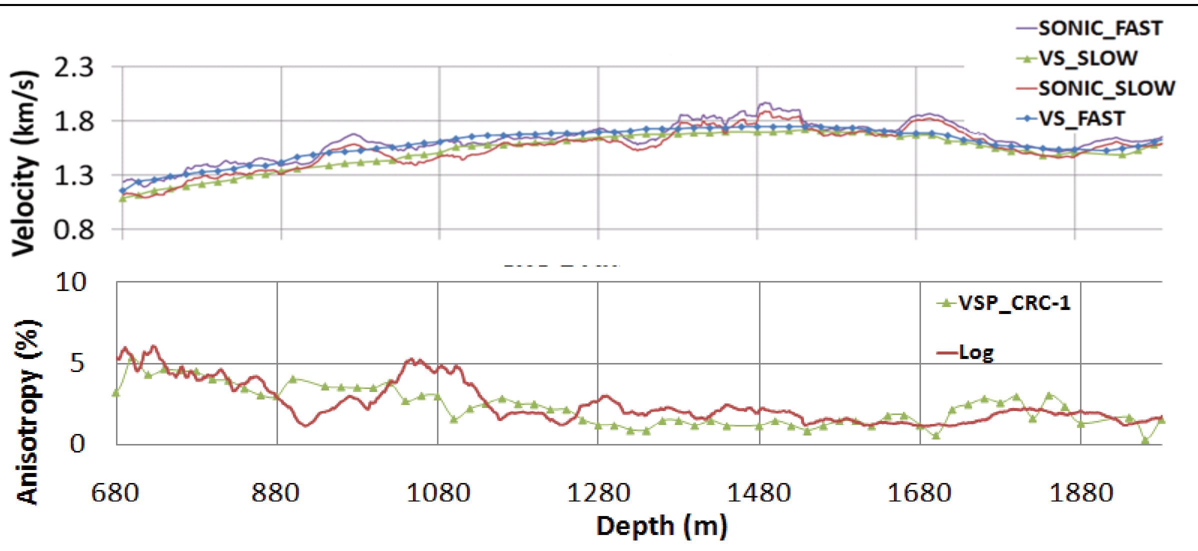

Figure 3: Comparison of velocities of fast and slow shear waves derived from ZVSP and log data for CRC-1 borehole

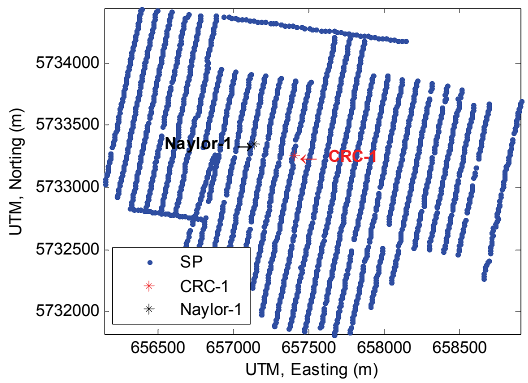

Figure 4: 3D VSP survey shot point positions

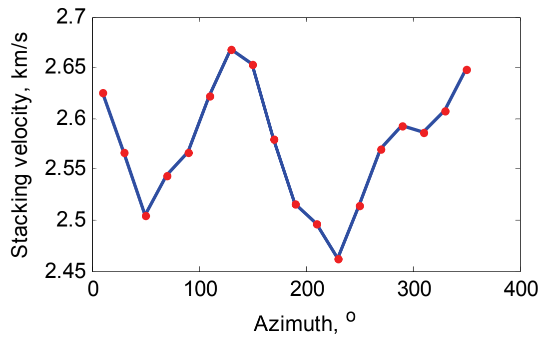

Figure 5. Stacking velocity for the level of 1500 m as a function of azimuth derived from 3D VSP data

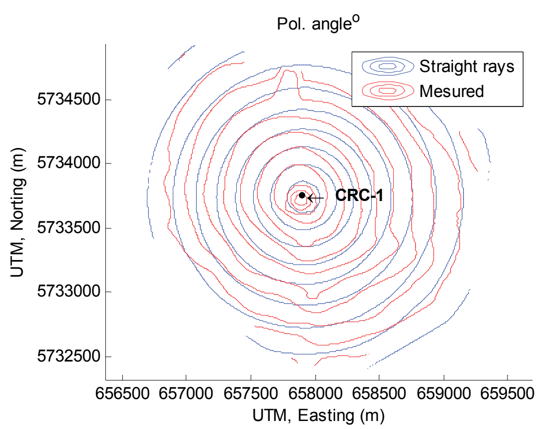

Figure 6. Comparison of incident angle of P-wave computed from 3D VSP data

3D/3C VSP can be used to characterize anisotropy both in the observation interval and in the overburden. Figure 5 shows estimation of stacking velocities computed from transit time picks for one of the receiver levels as a function of azimuth. One can see strong azimuthal anisotropy with the same orientations of the fast and slow directions as obtained from shear waves.

Seismic anisotropy from 3D 3C VSP data

Polarization of direct wave is also significantly affected by the anisotropy, as shown in Figure 6. However polarization, unlike stacking velocities, can be affected by properties of the medium located in the vicinity of the receiver, but not the whole overburden. To derive the full stiffness tensor for the depth interval covered by 3D VSP survey, we apply method proposed by Dewangan and Grechka (2003). In particular, we use the fact that in horizontally layered media the horizontal components of the slownesses (ray parameters) are preserved along the rays. Thus, the horizontal slownesses, measured as derivatives of transit time with respect to the positions of the sources, are the same at the receiver. The vertical slownesses are computed as derivative of the transit times with respect to the location of the receiver. The horizontal and vertical slownesses form the slowness vector at the receiver, where we measure the polarizations as well. The polarization A and slowness p are related to the density scaled stiffness tensor c as follows

$$c_{ijkl} p_j p_l A_k = A_i \; . \qquad (4)$$

For many measurements, this forms an (over-determined) system of linear equations for c. The calculated values of the stiffness tensor yield the P and S velocity anisotropy consistent with the results obtained by the other methods discussed in this paper.

Conclusions

We found that all the techniques used for anisotropy estimation produce results consistent with each other and also with the cross-dipole sonic log data recorded in CRC-1 borehole. The orientations of the fast and slow directions are consistent with the principal axis of the regional stress field. This leads us to speculate that the seismic anisotropy observed for the Otway basin is stress induced and, as such, could be used for stress field monitoring.

Acknowledgements

This work was sponsored in part by Australian Commonwealth Government through CO2CRC and the Curtin Reservoir Geophysics Consortium. We thank Shoichi Nakanishi, Christian Dupuis, Anton Kepic and other our colleagues from Curtin University, CSIRO and Schlumberger for the help with data acquisition and analysis.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2010 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Alford, R. M., 1986, Shear data in the presence of azimuthal anisotropy: 56th Annual International Meeting, SEG, Expanded Abstracts, S9.6.

Crampin, S., 1985, Evaluation of anisotropy by shear-wave splitting: Geophysics, **50**, 142–152, doi:10.1190/1.1441824.

Dewangan, P., and V. Grechka, 2003, Inversion of multicomponent, multiazimuth, walkaway VSP data for the stiffness tensor: Geophysics, **68**, 1022–1031, doi:10.1190/1.1581073.

Dodds, K., T. Daley, B. Freifeld, M. Urosevic, A. Kepic, and S. Sharma, 2009, Developing a monitoring and verification plan with reference to the Australian Otway CO2 pilot project: The Leading Edge, **28**, no. 7, 812–818, doi:10.1190/1.3167783.

Pevzner, R., B. Gurevich, and G. Duncan, 2009, Estimation of Azimuthal Anisotropy from VSP Data Using Multicomponent Velocity Analysis, 71st Conference & Exhibition incorporating SPE Europec, EAGE, Expanded Abstracts, P-182.

Turner, B., and S. Hearn, 1995, Shear-wave splitting analysis using a single-source, dynamite VSP in the Otway Basin: Exploration Geophysics, **26**, no. 4, 519–526, doi:10.1071/EG995519.